Chapter 4

The Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin, Wyoming

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Volume Title Page

By Ronald C. Johnson, Thomas M. Finn, Mark A. Kirschbaum, Stephen B. Roberts, Laura N. R. Roberts, Troy Cook, and David J. Taylor

Chapter 4 of
Petroleum Systems and Geologic Assessment of Oil and Gas in the Wind River Basin Province, Wyoming

Compiled by USGS Wind River Basin Province Assessment Team

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Table

1. Summary of undiscovered oil and gas resources that have the potential for additions to reserves, Cretaceous and Lower Tertiary Composite Total Petroleum System 4

The Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin, Wyoming

By Ronald C. Johnson, Thomas M. Finn, Mark A. Kirschbaum, Stephen B. Roberts, Laura N. R. Roberts, Troy Cook, and David J. Taylor

Abstract

The Cretaceous-Lower Tertiary Composite Total Petroleum System (TPS) of the Wind River Basin Province includes all strata from the base of the Lower Cretaceous Cloverly Formation to the base of the Waltman Shale Member of the Paleocene age Fort Union Formation and, where the Waltman is absent, includes strata as young as the Eocene Wind River Formation. Locally, Cretaceous-sourced gas migrated into strata as old as the Mississippian Madison Limestone, and in these areas the TPS extends stratigraphically downward to include these reservoirs. The extensive vertical migration of gases in highly fractured areas of the Wind River Basin led to the commingling of gases from several Upper Cretaceous and lower Tertiary sources, thus only two petroleum systems are recognized in these rocks, the Cretaceous-Lower Tertiary Composite TPS, the subject of this report, and the Waltman Shale TPS described by Roberts and others (Chapter 5, this CD-ROM).

The Cretaceous-lower Tertiary Composite TPS was subdivided into (1) seven continuous gas assessment units (AU): (a) Frontier-Muddy Continuous Gas AU, (b) Cody Sandstone Continuous Gas AU, (c) Mesaverde–Meeteetse Sandstone Gas AU, (d) Lance-Fort Union Sandstone Gas AU, (e) Mesaverde Coalbed Gas AU, (f) Meeteetse Coalbed Gas AU, and (g) Fort Union Coalbed Gas AU; (2) one continuous oil assessement unit– Cody Fractured Shale Continuous Oil AU; and (3) one conventional assessment Unit–Cretaceous-Tertiary Conventional Oil and Gas AU.

Estimates of undiscovered resources having the potential for additions to reserves were made for all but the Cody Fractured Shale Continuous Oil AU, which is considered hypothetical and was not quantitively assessed. The mean estimate of the total oil is 41.99 million barrels, mean estimate of gas is 2.39 trillion cubic feet, and mean estimate of natural gas liquids is 20.55 million barrels. For gas, 480.66 billion cubic feet (BCFG) is estimated for the Frontier-Muddy Continuous Gas AU, 115.34 BCFG for the Cody Sandstone Continuous Gas AU, 383.16 BCFG for the Mesaverde-Meeteetse Sandstone Continuous Gas AU, 711.30 BCFG for the Lance-Fort Union Sandstone Gas AU, 107.18 BCFG for the Mesaverde Coalbed Gas AU, 21.29 BCFG for the Meeteetse Coalbed Gas AU, and 118.08 BCFG for the Fort Union Coalbed Gas AU. All the undiscovered oil and 98.94 BCFG of undiscovered gas is in the Cretaceous-Tertiary Conventional Oil and Gas AU.

Introduction

The Cretaceous-Lower Tertiary Composite Total Petroleum System (TPS) in the Wind River Basin Province (fig. 1) produces hydrocarbons sourced largely, if not entirely, from Upper Cretaceous through lower Tertiary rocks. Reservoirs are in sandstones and coal beds of mainly Cretaceous through early Tertiary age; however, at Madden anticline in the north-central part of the basin (fig. 1) Upper Cretaceous-sourced gas is believed to have migrated across the thrust fault bounding the south flank of the anticline into the Mississippian Madison Limestone (Schelling and Wavrek, 1999), and the TPS was expanded in this limited area to include the Madison.

Fewer petroleum systems were recognized in the Wind River Basin than were defined in other U.S. Geological Survey (USGS) assessments in the region, such as that of the Southwestern Wyoming Province in which the thick interval of Upper Cretaceous and lower Tertiary rocks was subdivided into five TPSs and three composite TPSs (USGS Southwestern Wyoming Province Assessment Team, 2005). Most of the gas in each of those petroleum systems was thought to have been generated from source rocks within the TPS, but the possibility that some gas had migrated between petroleum systems was also recognized (Johnson and others, 2005). However, in the Wind River Basin, the extensive vertical migration of gases in highly fractured areas has led to the commingling of gases from several Upper Cretaceous and lower Tertiary sources, so subdividing the thick Upper Cretaceous and lower Tertiary interval into separate petroleum systems was not feasible. Accordingly, in the Wind River Basin we defined only two

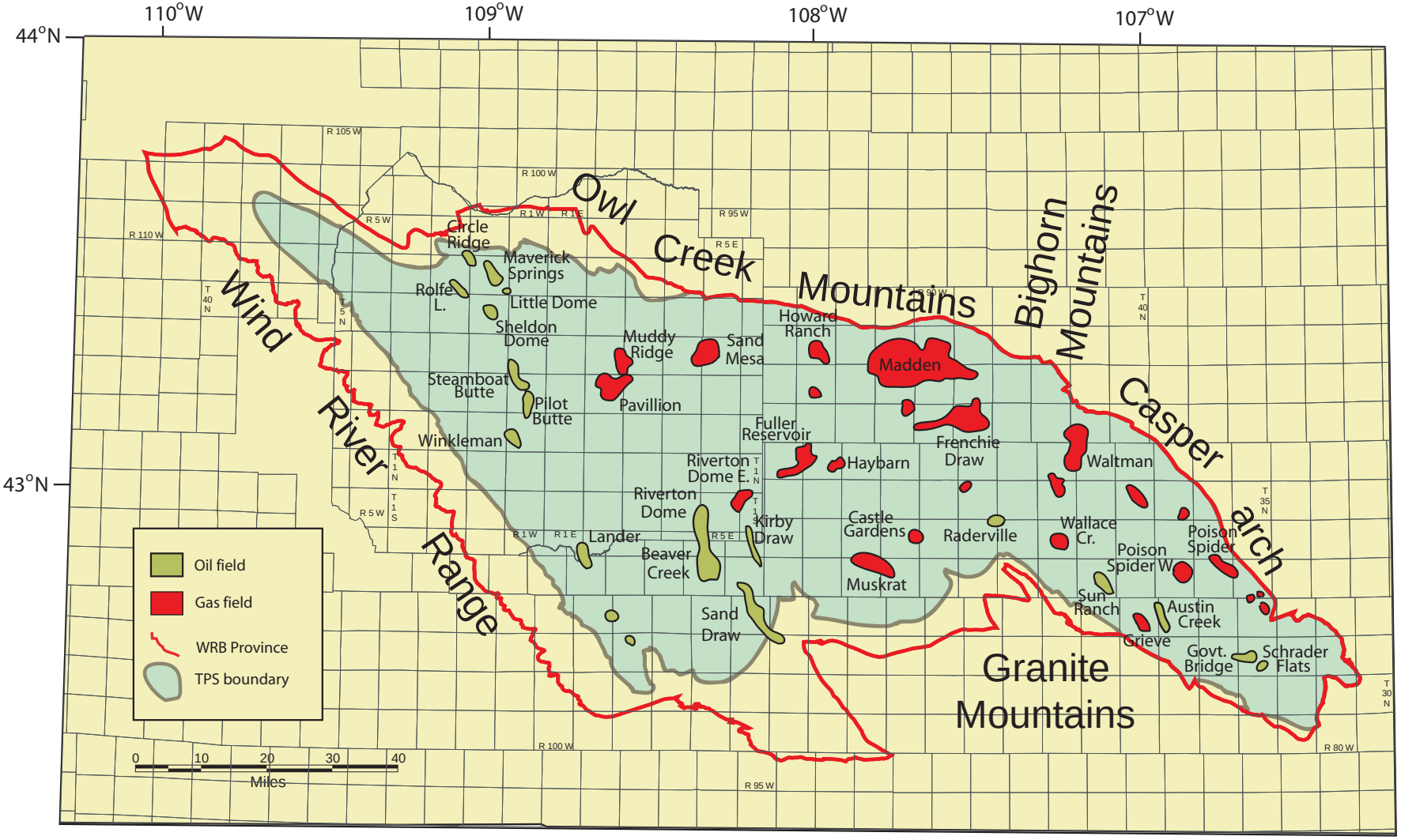

Figure 1. Area of the Cretaceous-Lower Tertiary Composite Total Petroleum System (TPS) (light blue) and locations of oil and gas fields in the Wind River Basin (WRB) Province, (heavy red line), Wyoming.

petroleum systems in Upper Cretaceous and lower Tertiary rocks—the Cretaceous-Lower Tertiary Composite TPS and the Waltman Shale TPS (Roberts and others, Chapter 5, this CD-ROM). These two petroleum systems are separated by the Waltman Shale, which is believed to act as a seal between the two systems. Gases from the Waltman Shale Member of the Fort Union Formation and younger strata are isotopically lighter than gases from the underlying Cretaceous-Lower Tertiary Composite TPS and were presumably sourced by the Waltman Shale Member (Johnson and Rice, 1993).

The Cretaceous-Lower Tertiary Composite TPS(503502) is divided here into nine assessment units (AUs): eight unconventional continuous-type assessment units—Frontier-Muddy Continuous Gas AU (50350261), Cody Sandstone Continuous Gas AU (50350262), Cody Fractured Shale Continuous Oil AU (50350263), Mesaverde-Meeteetse Sandstone Continuous Gas AU (50350264), Lance-Fort Union Sandstone Gas AU (50350265), Mesaverde Coalbed Gas AU (50350281), Meeteetse Coalbed Gas AU (50350282), and Fort Union Coalbed Gas AU (50350283), and one conventional AU—Cretaceous-Tertiary Conventional Oil and Gas AU (50350201). (Note: the numbers refer to the coding system used by the USGS to identify TPs and AUs worldwide).

Most of the gas production in the Cretaceous-Lower Tertiary Composite TPS is from structural closures and plunging anticlinal noses (fig. 1); enhanced natural fractures on these structures also play a critical role in this production (Dunleavy and Gilbertson, 1986). The shallower production is largely conventional, with the gas having migrated vertically many thousands of feet from underlying mature source rocks (Johnson and Rice, 1993) into permeable reservoirs that may exhibit gas-water contacts. Reservoir permeabilities generally decline into the tight (low permeability) range (0.1 millidarcy or less) with depth, and significant overpressuring is commonly encountered. Water production from these overpressured reservoirs can be high when compared to overpressured reservoirs in other Rocky Mountain basins, but there does not appear to be a single gas-water contact; rather, water appears to be distributed throughout these structures at varying depths and stratigraphic levels (Nelson and Kibler, Chapter 7, this CD-ROM).

The deeper production from fractured reservoirs associated with structural features constitutes the “sweet spots” in the continuous sandstone gas AUs in the Wind River Basin. A decrease in fracturing away from the crest of a fold rather than a loss of gas saturation largely controls economic production in Cretaceous and Tertiary gas fields in the basin. For example, although productivity in the lower part of the Fort Union Formation drops off considerably from the crest to the flanks of Madden anticline, some gas is still produced from the flanks, and drillstem tests indicate that no gas-water contact is present (Nelson and Kibler, Chapter 7, this CD-ROM). Furthermore, gas is not wholly confined to structures but appears to be pervasive in Cretaceous and lower Tertiary strata that lie off-structure throughout the deeper areas of the basin (Johnson and others, 1996a; Surdam and others, 2004; Nelson and Kibler, Chapter 7, this CD-ROM); these deep off-structure reservoirs also can be highly overpressured (Bilyeu, 1978; Johnson and others, 1996a). Pervasive gas saturations, low permeabilities, and abnormally pressured conditions are characteristics of basin-centered (continuous-type) accumulations (Spencer, 1987).

Tabulated results of undiscovered oil, gas, and natural gas liquids in the Cretaceous-Lower Tertiary Composite TPS that have the potential for additions to reserves are listed in table 1. The mean estimate of total oil is 11 million barrels of oil (MMBO), mean total gas is 2.075 trillion cubic feet (TCF), and the mean estimate of natural gas liquids is 13.140 million barrels of natural gas liquids (MMBNGL). With respect to undiscovered gas resources, 481 billion cubic feet (BCFG) is estimated for the Frontier-Muddy Continuous Gas AU, 115 BCFG for the Cody Sandstone Continuous Gas AU, 383 BCFG for the Mesaverde-Meeteetse Sandstone Continuous Gas AU, 711 BCFG for the Lance-Fort Union Sandstones Continuous Gas AU, 107 BCFG for the Mesaverde Coalbed Gas AU, 21 BCFG for the Meeteetse Coalbed Gas AU, and 118 BCFG is in the Fort Union Coalbed Gas AU. The Cretaceous-Tertiary Conventional Oil and Gas Assessment Unit contains all of the undiscovered oil (11 MMBO) and 139 BCFG. The Cody Fractured Shale Continuous Oil AU is considered to be hypothetical and was not assessed.

Structural and Tectonic History

The Wind River Basin is a northwest-trending structural depression formed during the Laramide orogeny (Late Cretaceous through Eocene). The basin is surrounded by Laramide uplifts, including the Wind River Range on the southwest, the Owl Creek and southern Bighorn Mountains on the north, the Casper arch on the east, and the Granite Mountains on the south (fig. 1). Along the south and west margins of the basin, the sedimentary strata dip 10º-20º basinward; whereas, along the north and east margins the dips are commonly vertical to overturned. Thus, the basin is markedly asymmetric, with the structurally deepest parts close to the Owl Creek and Bighorn Mountains on the north and the Casper arch on the east. The basin interior is covered by nearly flat-lying lower Eocene rocks, which mask the structural features of the older rocks except along the basin margins and adjacent mountain flanks.

During the Laramide orogeny, which began in latest Cretaceous time, the central part of the Rocky Mountain foreland basin, an extensive area of downwarping extending from The Arctic to the Gulf of Mexico, was gradually partitioned into much smaller basins such as the Wind River Basin. The intensity of deformation increased through the Paleocene, and culminated in earliest Eocene time as high mountains were uplifted. Clastic debris, stripped from the flanks of the rising mountain arches, was shed basinward on all sides, and a complete record of orogenic events is preserved

Table 1. Summary of undiscovered oil and gas resources that have the potential for additions to reserves, Cretaceous and Lower Tertiary Composite Total Petroleum System.

[MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MBNGL, thousand barrels of natural gas liquids; CBG, coalbed gas. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents 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. Gray shade indicates not applicable]

	Total Petroleum Systems (TPS) and Assessment Units (AU)	Field type	*Oil (MMBO)*				*Total undiscovered resources Gas (BCFG)*				*NGL (MBNGL)*			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Conventional Oil and Gas Resources	**Cretaceous-Tertiary TPS**													
	Cretaceous-Tertiary Conventional Oil and Gas AU	*Oil*	3	10	23	11	10	35	84	40	230	820	2,130	950
		Gas					30	92	190	99	230	720	1,620	790
	Total Conventional Resources		**3**	**10**	**23**	**11**	**40**	**127**	**274**	**139**	**460**	**1,540**	**3,750**	**1,740**
Continuous Gas Resources	**Cretaceous-Tertiary TPS**													
	Frontier-Muddy Continuous Gas AU	*Gas*					198	430	934	481	110	320	970	400
	Cody Sandstone Continuous Gas AU	*Gas*					48	103	224	115	10	30	10	40
	Cody Fractured Shale Continuous Oil AU	*Oil*	Not quantitatively assessed											
	Mesaverde-Meeteetse Sandstone Gas AU	*Gas*					163	345	732	383	360	960	2,580	1,150
	Lance-Fort Union Sandstone Gas AU	*Gas*					373	668	1,198	711	2,670	7,700	22,250	9,480
	Mesaverde Coalbed Gas AU	*CBG*					45	96	205	107	70	210	570	250
	Meeteetse Coalbed Gas AU	*CBG*					9	19	41	21	10	40	120	50
	Fort Union Coalbed Gas AU	*CBG*					49	106	228	118	10	20	70	30
	Total Continuous Resources						**885**	**1,767**	**3,562**	**1,936**	**3,240**	**9,280**	**26,570**	**11,400**
	Total Undiscovered Oil and Gas Resources		**3**	**10**	**23**	**11**	**925**	**1,894**	**3,836**	**2,075**	**3,700**	**10,820**	**30,320**	**13,140**

in the many thousands of feet of nonmarine sedimentary rocks in the Lance, Fort Union, Indian Meadows, and Wind River Formations (fig. 2) that accumulated in the areas of greatest subsidence. Basin subsidence and mountain uplift had virtually ended by the close of early Eocene time. Renewed folding and faulting of existing structural features took place after deposition of the Eocene Wind River Formation, but with few exceptions these movements were minor and did not significantly modify the structural patterns that had already been established.

The southwest margin of the Wind River Basin is formed by the northeast flank of the Wind River Range. This large uplift is bounded on the southwest by the Wind River thrust (fig. 3). The White Rock thrust (fig. 3) bounds the Wind River Basin Province at its westernmost margin (fig. 3). The next thrust system to the northeast includes the Wind Ridge, Coulee Mesa, and Red Creek thrusts, mapped in the northwestern part of the basin (Blackstone, 1990). To the southeast, beginning with the Rolff Lake fault, is another northwest-trending series of thrust faults that can be traced by surface geologic mapping and on seismic reflection profiles for nearly 75 miles (mi); faulted anticlines along this trend include Sheldon, Steamboat Butte, Pilot Butte, Winkleman Dome, Sage Creek, Lander, Dallas and Derby Domes (Keefer, 1970). There is a minor southwest offset between Pilot Butte and Winkleman Dome (fig. 3). The next thrust system to the northeast, called in part the Circle Ridge/Maverick Springs thrust, is exposed in the Cody Shale south of Maverick Springs anticline (Keefer, 1970; Blackstone, 1990) and also is visible on seismic data. The structure is defined on the surface by Circle Ridge, Maverick Springs, and Little Dome anticlines before being covered to the southeast by the Wind River Formation, but it apparently continues in the subsurface to about T. 1 N., R. 4 E. for a total length of at least 35 mi. (fig. 3); the structure includes the Pavillion gas field on the hanging wall of the thrust. Although not proven conclusively, this structure may extend still farther to the southeast and continue into the Emigrant Trail fault that is considered to be the southern thrusted margin of the Granite Mountains (Love and Christianson, 1985). The Riverton Dome and Beaver Creek oil fields also have mostly northwest-trending thrust faults on the southwest margins that appears on seismic to merge or terminate against the Emigrant Trail fault (fig. 3). A series of northwest-plunging anticlines along the south margin of the basin include, from west to east; the Alkali Butte, Rogers Mountain/Conant Creek, Muskrat, Dutton Basin, and Rattlesnake Hills anticlines (Keefer, 1970). These structures terminate against the North Granite Mountains normal fault system south along which there is a downdropped block of Precambrian granite (Love, 1970). The easternmost northwest-trending structure is the Casper arch thrust.

Although most of the structures in the Wind River Basin trend northwest, a few major features—including the Granite Mountains, Casper Mountain and Owl Creek Mountains trend east-west. These two different orientations were considered to

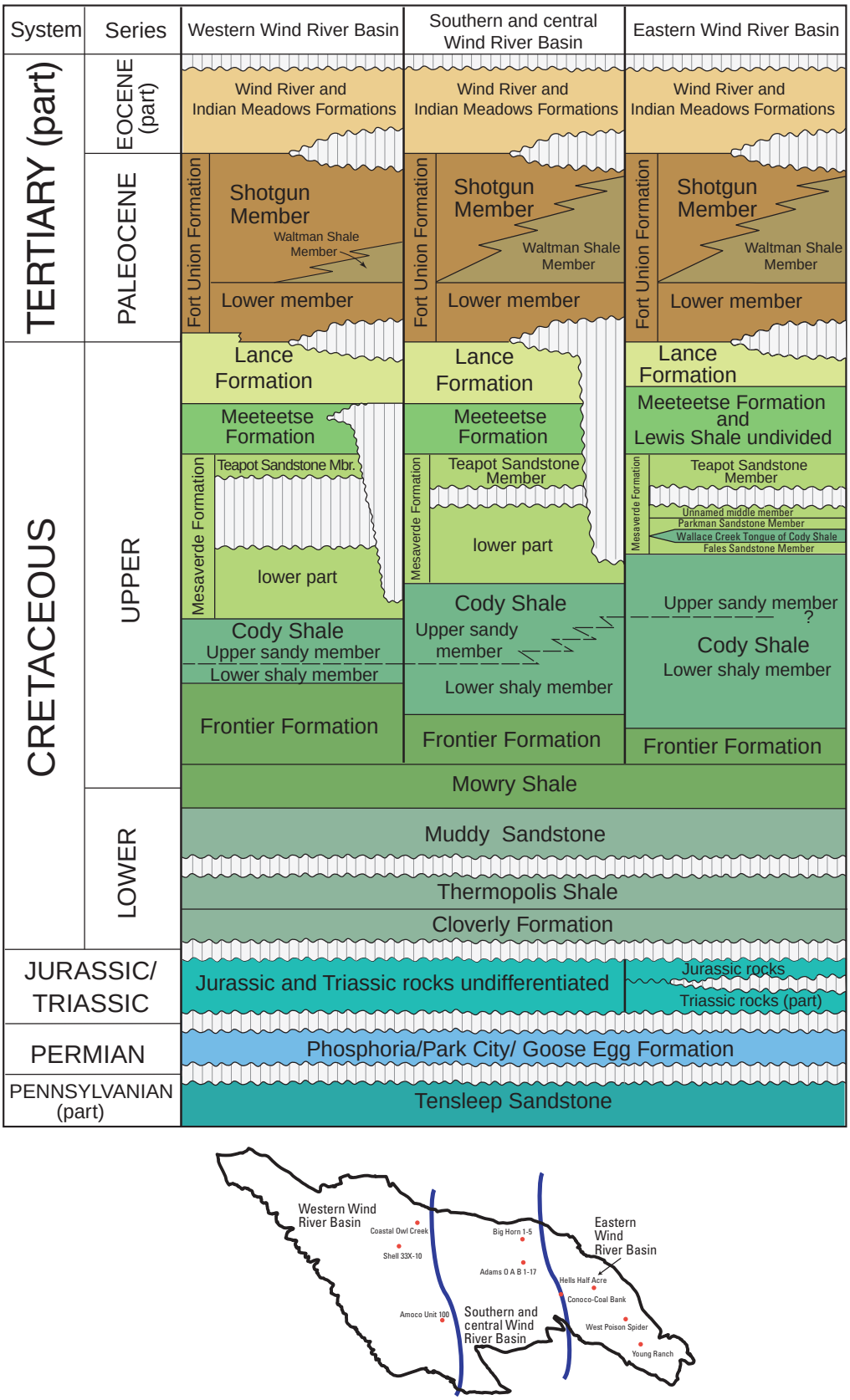

Figure 2. Generalized stratigraphic columns and correlations of Mississippian through Eocene strata in the Wind River Basin, Wyoming.

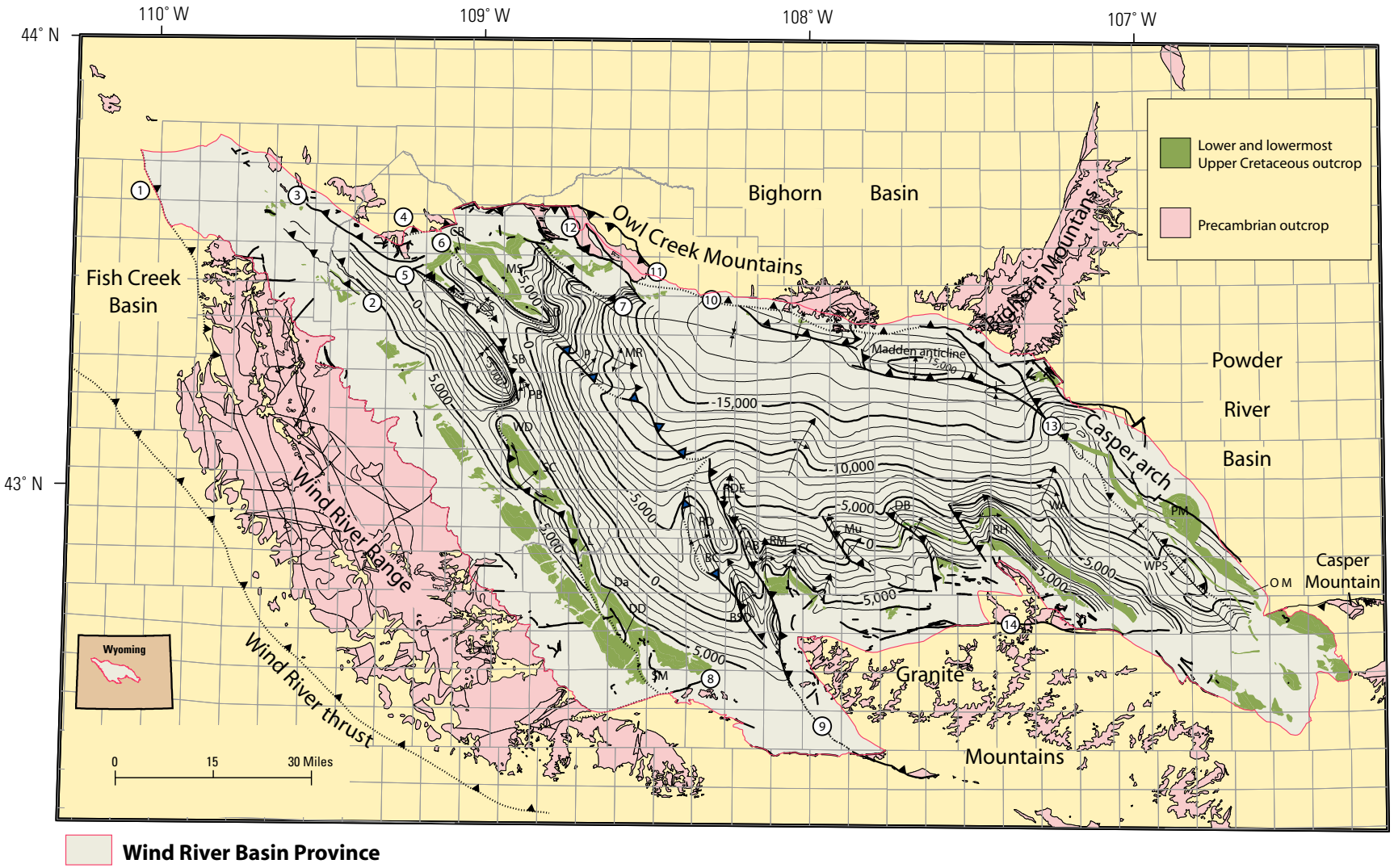

Figure 3. Generalized tectonic map of the Wind River Basin Province and adjoining areas, Wyoming. All structures are from Love and Christiansen (1985), unless otherwise stated, and are shown in black; dashed where inferred in subsurface. Numbered faults: 1, White Rock thrust; 2, Wind Ridge and Coulee Mesa thrust system; 3, Black Mountain thrust; 4, Red Creek thrust (Blackstone, 1990); 5, Rolff Lake fault; 6, Circle Ridge/Maverick Springs thrust; 7, Shotgun Butte thrust; 8, Clear Creek fault; 9, Emigrant Trail fault; 10, south Owl Creek fault; 11, north Owl Creek fault; 12, Cottonwood Creek fault; 13, Casper arch thrust; 14, North Granite Mountains fault system. Anticlines: AB, Alkali Butte; BC, Beaver Creek; BSD, Big Sand Draw; CC, Conant Creek; CR, Circle Ridge; Da, Dallas; DB, Dutton Basin; DD, Derby Dome L, Lander; LD, Little Dome; MS, Maverick Springs; Mu, Muskrat; MR, Muddy Ridge; OM, Oil Mountain; P, Pavillion; PB, Pilot Butte; PM, Pine Mountain; RD, Riverton Dome/Beaver Creek; RDE, Riverton Dome east; RH, Rattlesnake Hills; RM, Rogers Mountain; S, Sheldon; SB Steamboat Butte; SC, Sage Creek; SM, Sheep Mountain; WA, Waltman arch; WD, Winkleman Dome; WPS, West Poison Spider. Green areas are outcrops of the Cloverly Formation, Thermopolis Shale, Muddy Sandstone, Mowry Shale, and Frontier Formation (may include some Jurassic rocks) from Love and Christiansen (1985).

be the result of a single stress field applied to a lithologically and structurally heterogeneous Precambrian basement (Blackstone, 1990; Stone, 2002). Gries (1983), on the other hand, related these different orientations to an overall change in the stress field during the late Laramide. Molzer and Erslev (1995; and references therein) suggested the stress field did not change and at least two of the structures, Casper Mountain and the Owl Creek Mountains, are the result of oblique slip. Stone (2002) suggested that the orientation is due to preexisting Precambrian fabric reactivated during Laramide compression also by oblique slip. Evidence for sinistral oblique slip is best documented in the Owl Creek Mountains (Molzer and Erslev, 1995). Models for this type of slip show a striking resemblance to the series of north stepping en-echelon thrust slices of the Owl Creek, Cottonwood Creek and Shotgun Butte thrusts as shown by Blackstone (1990).

Stratigraphy of Cretaceous and Lower Tertiary Strata

Upper Cretaceous and lower Tertiary strata can be subdivided into two intervals: (1) foreland basin strata that predate the onset of the Laramide orogeny, and (2) strata deposited during the Laramide. Foreland basin strata included in the present study extend from the base of the Lower Cretaceous Cloverly Formation through the Upper Cretaceous Meeteetse Formation (fig. 2), although there is some evidence for minor Laramide movement during deposition of the Meeteetse Formation. Laramide strata extend from the base of the Upper Cretaceous Lance Formation through the Eocene Wind River Formation (fig. 2).

Cloverly Formation

The Lower Cretaceous Cloverly Formation is the oldest Cretaceous unit in the Wind River Basin (fig. 2) and consists of about 100-200 feet (ft) of conglomerate, medium-to coarse-grained sandstone and variegated mudstone of continental origin (May and others, 1995). This unit also is called the Lakota or Dakota in drilling reports (IHS Energy Group, 2005). Reservoirs in the Cloverly consist of as much as 100 ft of conglomerate and sandstone that was deposited by confined fluvial systems flowing from southwest to northeast across the basin (Meyers and others, 1992; May and others, 1995).

Thermopolis Shale

The Thermopolis Shale consists of marine shales and siltstones of Albian (Early Cretaceous) age that were deposited during the initial transgression of the Cretaceous sea (Burtner and Warner, 1984). The shales are dark gray to black and contain thin layers of siltstone, sandy claystone, and bentonite. The basal contact is gradational with the underlying Cloverly Formation; the upper contact is sharp and unconformable with the overlying Muddy Sandstone. In the Wind River Basin, the Thermopolis ranges in thickness from approximately 100 to 175 ft. There is no direct evidence to indicate that the formation is a source rock; however, because of its marine origin and based on source rock studies in the Bighorn Basin by Hagen and Surdam (1984) and a regional study by Burtner and Warner (1984), it is believed that the Thermopolis has the potential to be a source rock in the Wind River Basin. Hagen and Surdam (1984) and Burtner and Warner (1984) report that the Thermopolis Shale is composed primarily of Type III organic matter, with some Type II organic matter. Total organic carbon values range from 0.8 to 3.6 weight percent and average 1.6 weight percent.

Muddy Sandstone

Exposures of the Lower Cretaceous Muddy Sandstone (fig. 2) show the formation to consist of 20 to 134 ft of sandstone and mudstone deposited in shoreface, estuarine, lagoonal, and coastal plain environments (Dresser, 1974). The Muddy also was interpreted as containing deltaic/strand plain, bayfill and fluvial to estuarine valley fill deposits (Gustason and others, 1989). The unit is 0 to 120 feet thick in the subsurface at Grieve Field (fig.1) (Mitchell, 1978). The Muddy is dominated in the eastern part of the basin by northwest-trending estuarine and fluvial valley fill deposits (Dresser, 1974; Mitchell, 1978; Pritchard, 1993) that grade into southwest-northeast-trending shoreline and deltaic deposits (Dresser, 1974; Curry, 1978; Dolson and others, 1991).

Mowry Shale

The Mowry Shale (fig. 2) consists of laminated and bioturbated organic-rich mudrock (Byers and Larson, 1979). High resistivity values on geophysical logs generally correspond to siliceous shales and low resistivity and high gamma-ray values signify bentonites (Nixon, 1973). The shale is siliceous due to the presence of abundant radiolaria 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 that preserved the radiolarian tests and organic matter (Byers and Larson, 1979; Burtner and Warner, 1984). The laminated mudrock grades upward and landward (westward) into bioturbated mudstone and sandstone, indicating more oxygen-rich conditions, shallower water, and closer proximity to the clastic source area (Burtner and Warner, 1984).

Frontier Formation

The Upper Cretaceous (Cenomanian through Coniacian) Frontier Formation (fig. 2) mainly consists of very fine- to medium-grained sandstone of marginal marine and deltaic origin and shale of marine origin. The unit ranges in thickness from about 700 to 1,200 ft, with the thickest sections in the south-central part of the Wind River Basin (Johnson and others, 1996a; Finn, Chapter 9, this CD-ROM). Three members are recognized, which are, in ascending order: (1) the Belle Fourche Member, (2) the Emigrant Gap Member, and (3) the Wall Creek Sandstone Member (fig. 4). Total sandstone ranges in thickness from about 85 to 280 ft (Johnson and others, 1996b) in as many as seven major units (Borgerding, 1989). Individual sandstones are continuous over many miles and pinch out in all directions into marine shale (see Finn, Chapter 9, this CD-ROM). The Frontier contains minor continental deposits, including thin coals beginning near Lander, Wyoming, and extending northeastward into the northeastern part of the basin (see Merewether, Chapter 11, this CD-ROM). The unit also contains fine- to medium-grained, cross-bedded, lenticular sandstones of continental origin but with some indications of brackish water influence, based on the presence of *Teredolites*.

Cody Shale

The Cody Shale consists of marine shale, sandstone, and siltstone that were deposited during a major transgressive-regressive cycle that Kauffman (1977) referred to as the Niobrara Cyclothem. The formation ranges in thickness from 3,250 ft in the western part of the Wind River Basin to as much as 5,500 ft in the eastern part (fig. 5). The lower and upper contacts are conformable and interfinger extensively with the underlying Frontier and overlying Mesaverde Formations (fig. 6) (see Finn, Chapter 9, this CD-ROM). Four members are recognized, these are, in ascending order: (1) the lower shaly member (Thompson and White, 1954; Yenne and Pipiringos, 1954; and Keefer and Troyer, 1964), (2) the upper sandy member (Thompson and White, 1954; Yenne and Pipiringos, 1954; and Keefer and Troyer, 1964), (3) the "Conant Creek tongue" (Szmajter, 1993), and the (4) Wallace Creek Tongue (Barwin, 1959) (fig. 6) (Finn, Chapter 9, this CD-ROM). The age of the Cody Shale ranges from Coniacian to middle Campanian (Keefer, 1972).

The lower shaly member is about 1,750 ft thick in the western part of the basin and thickens to the east to more than 2,250 ft (fig. 7). It is composed of gray to black shale and bentonite, and is locally calcareous. Keefer and Troyer (1964) described a glauconitic sandstone about 5 ft thick that contains black chert pebbles as much as 1 inch in diameter 990 ft above the base of the shaly member. It was traced in the subsurface eastward to the east edge of the Wind River Indian Reservation (fig. 4) by Keefer and Johnson (1993) where it appears to wedge out. A persistent calcareous zone is recognized on geophysical logs in the lower 100-300 ft of the shaly member. This zone is known as the "chalk kick" and can be traced in the subsurface throughout most of the basin (see Finn, Chapter 9, this CD-ROM).

The upper sandy member is about 1,800 ft thick in the western part of the basin and thickens to the east to about 3,500 ft (fig. 8). It consists of light to medium gray sandstones, bentonite beds, and tan and gray shales. The sandstones are the most important reservoirs for oil and gas in the Cody Shale in the Wind River Basin. Dunleavy and Gilbertson (1986) referred to the most productive units as the "Sussex and Shannon" sandstones (fig. 6) (Finn, Chapter 9, this CD-ROM). According to them (Dunleavy and Gilbertson, 1986), these sandstones are older than the Sussex and Shannon sandstones interval in the Powder River Basin and grade westward into time-equivalent nonmarine sandstones, shales, and coals of the Mesaverde Formation and eastward into marine shale.

The "Conant Creek tongue" (fig. 6) (Finn, Chapter 9, this CD-ROM) occupies the central part of the basin and is separated from the upper sandy member by an eastward-prograding tongue of marginal marine and nonmarine rocks known as the "Alkali Butte member" of the Mesaverde Formation (Szmajter, 1993; Hogle and Jones, 1991). The "Conant Creek tongue" is typically 400 to 900 ft thick, but thins to zero to the west, where it grades into the Mesaverde Formation. (fig. 6) (Finn, Chapter 9, this CD-ROM).

The Wallace Creek Tongue of the Cody Shale, present only in the eastern and southeastern parts of the Wind River Basin, is a westward thinning tongue of marine shale that splits the lower Fales Sandstone Member of the Mesaverde Formation from the main body of the Mesaverde Formation (Barwin, 1961) (fig. 6) (Finn, Chapter 9, this CD-ROM). According to Barwin (1961), the Wallace Creek Tongue at the type section in the Rattlesnake Hills is approximately 180 ft thick, but it thins to zero in the northern part of the Rattlesnake Hills; the unit is nearly 500 ft thick in the southeastern corner of the basin.

Mesaverde Formation

The Upper Cretaceous Mesaverde Formation (fig. 2) was deposited in late Campanian (Late Cretaceous) time in coastal plain and fluvial settings as the shoreline of the Cretaceous interior seaway retreated eastward out of the present-day Wind River Basin. The Mesaverde Formation is over 2,200 ft thick in the extreme western part of the basin but thins to less than 500 ft in the eastern part (fig. 9) as the lower part progressively grades eastward into marine Cody Shale (fig. 10). The formation is truncated toward the Wind River Range along the southwest margin of the basin. Fluvial channel sandstones and marginal marine sandstones compose the majority of reservoirs in the Mesaverde Formation, with marginal marine sandstones confined to the lower part. Typically there are one or two marginal marine sandstones in the lower few hundred feet of the formation; however, near the east margin of the Wind River Indian Reservation, more than 500 ft of

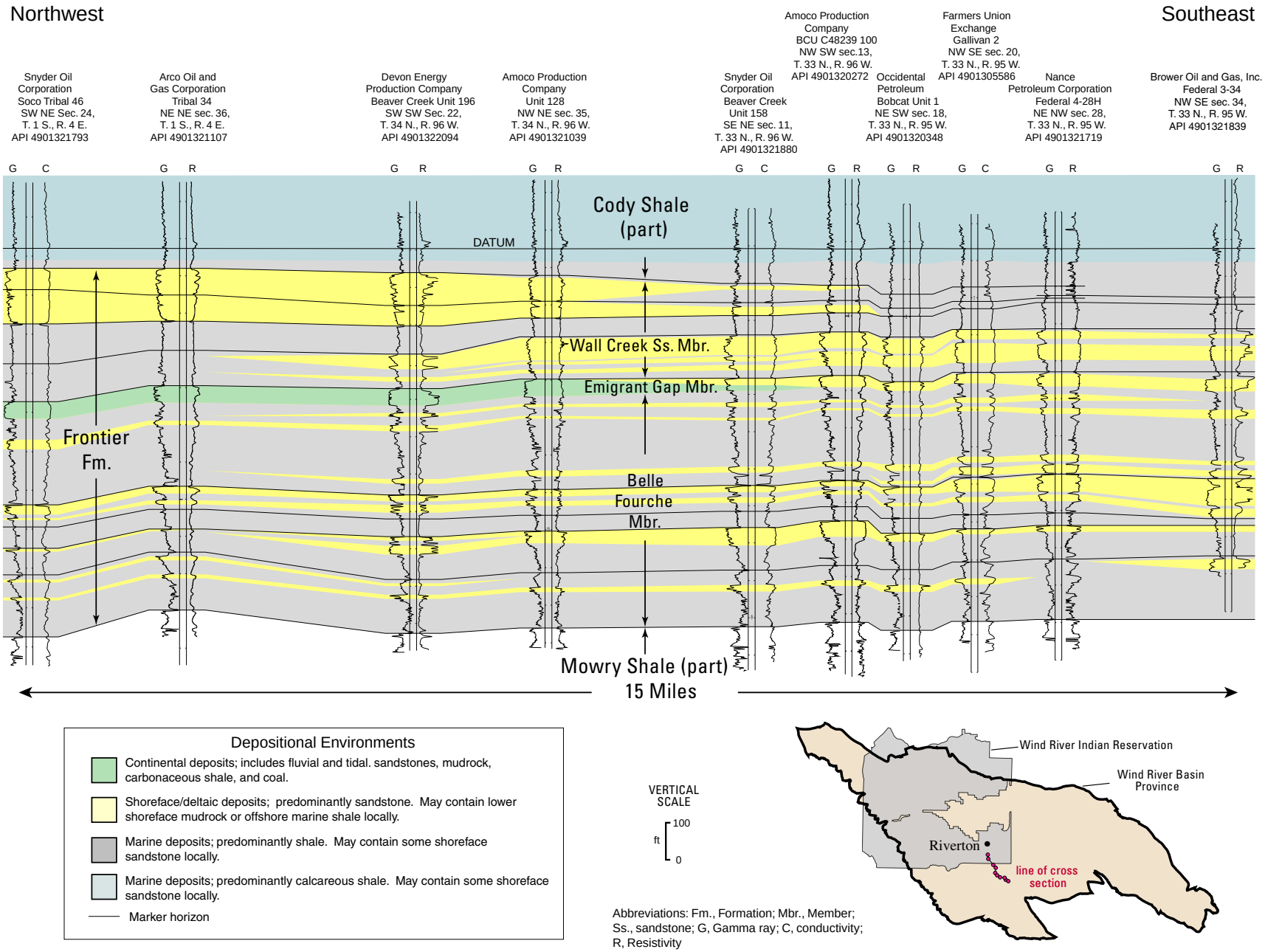

Figure 4. Cross section of the Frontier Formation, south-central Wind River Basin, showing member intervals, and general lithologies.

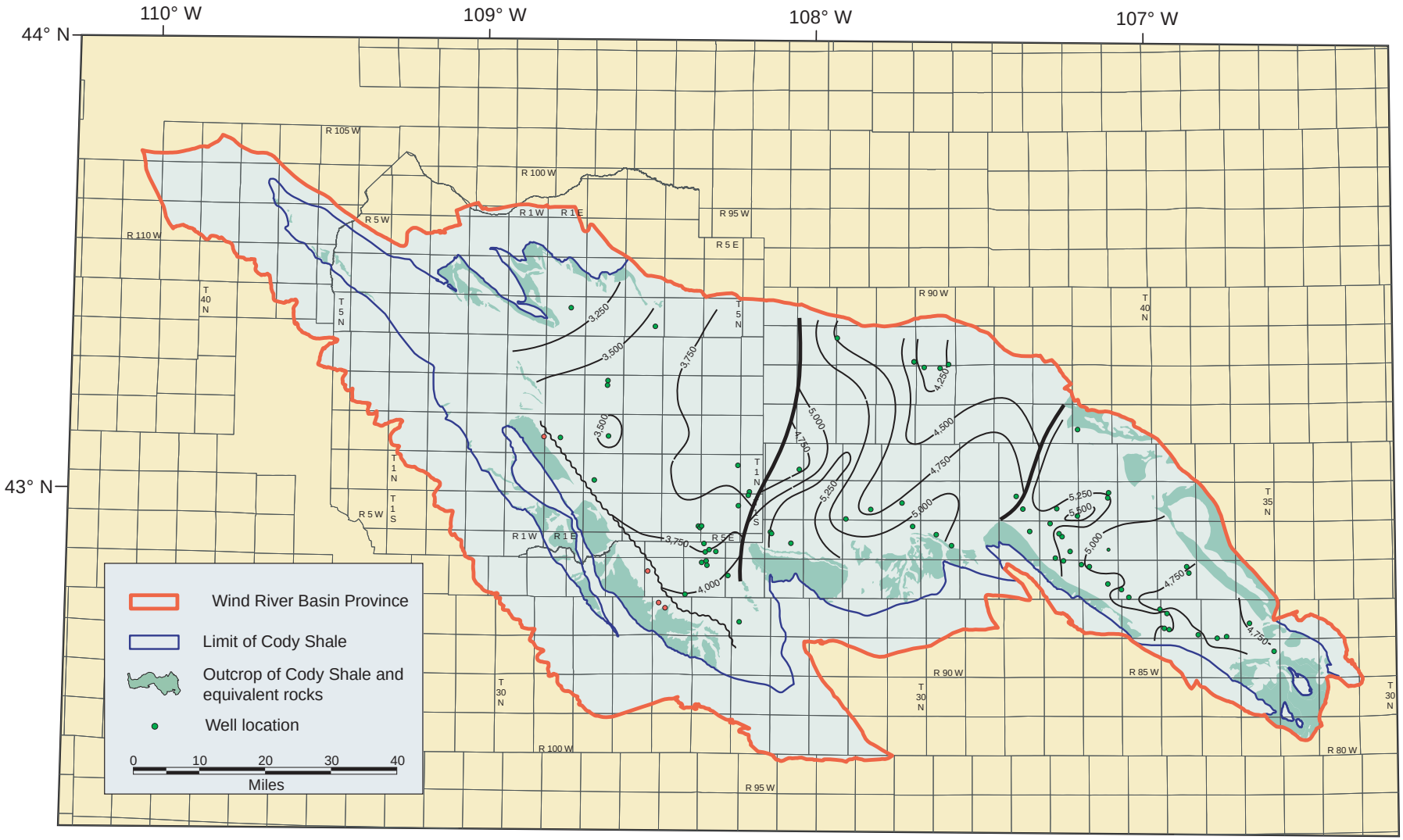

Figure 5. Isopach map of the Cody Shale, Wind River Basin, Wyoming. The isopached interval in the central part of the basin includes the "Alkali Butte member" of the Mesaverde Formation, and the "Conant Creek tongue" of the Cody Shale. Heavy black lines indicate places where top of Cody changes stratigraphically. The isopached interval in the eastern part of the basin includes the Fales Sandstone Member of the Mesaverde Formation and the Wallace Creek Tongue of the Cody Shale. (See fig. 6 for stratigraphic relations of the Cody Shale).

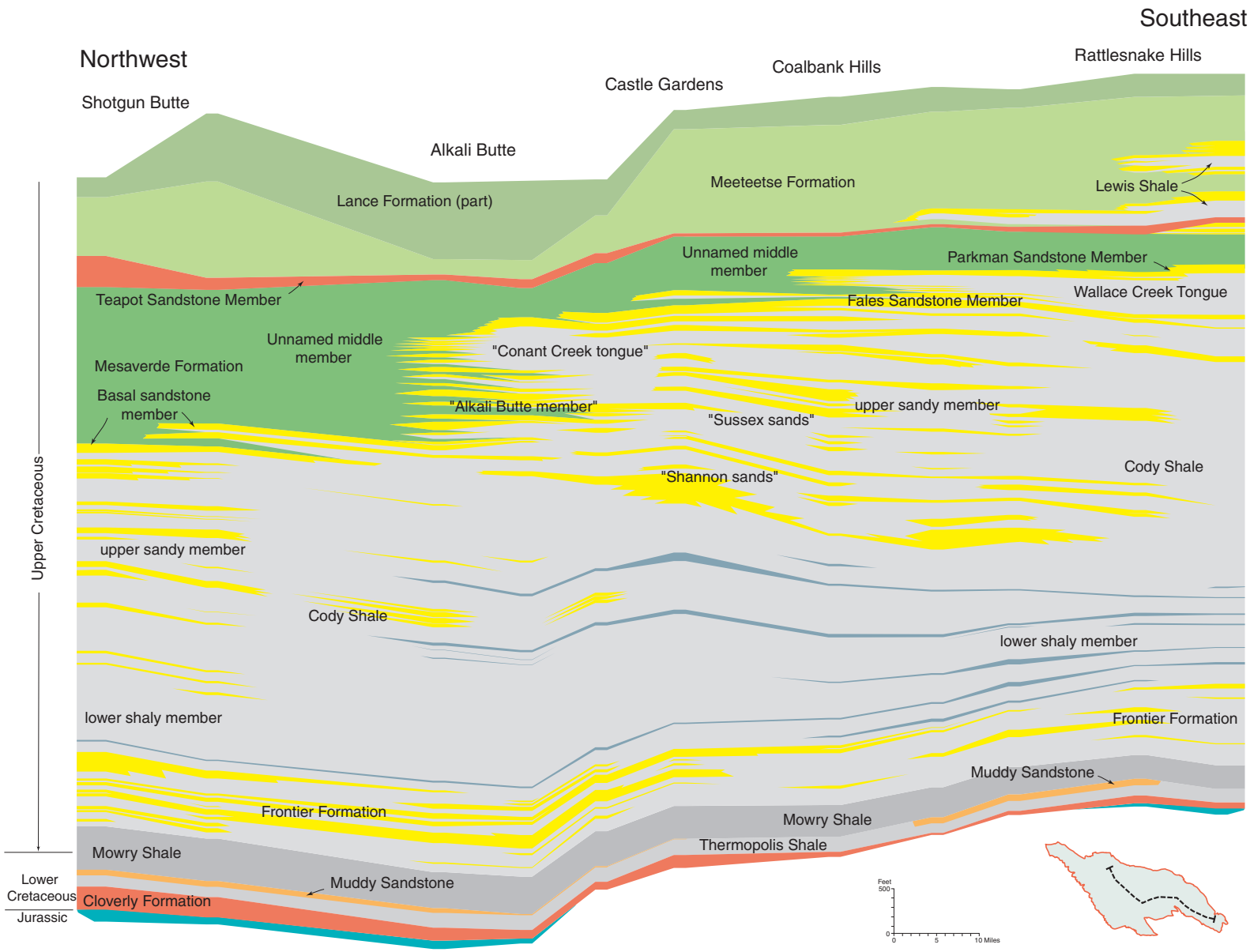

Figure 6. Regional east-west stratigraphic cross section of the Cody Shale and associated rocks, Wind River Basin, Wyoming. Colors represent different lithologies and environments of deposition: red, fluvial sandstone and conglomerate; yellow, marine and marginal marine sandstone and siltstone; orange, fluvial and estuarine sandstone; various shades of gray are marine shales; various shades of green are coastal plain and flood plain sandstones, shales, and coals.

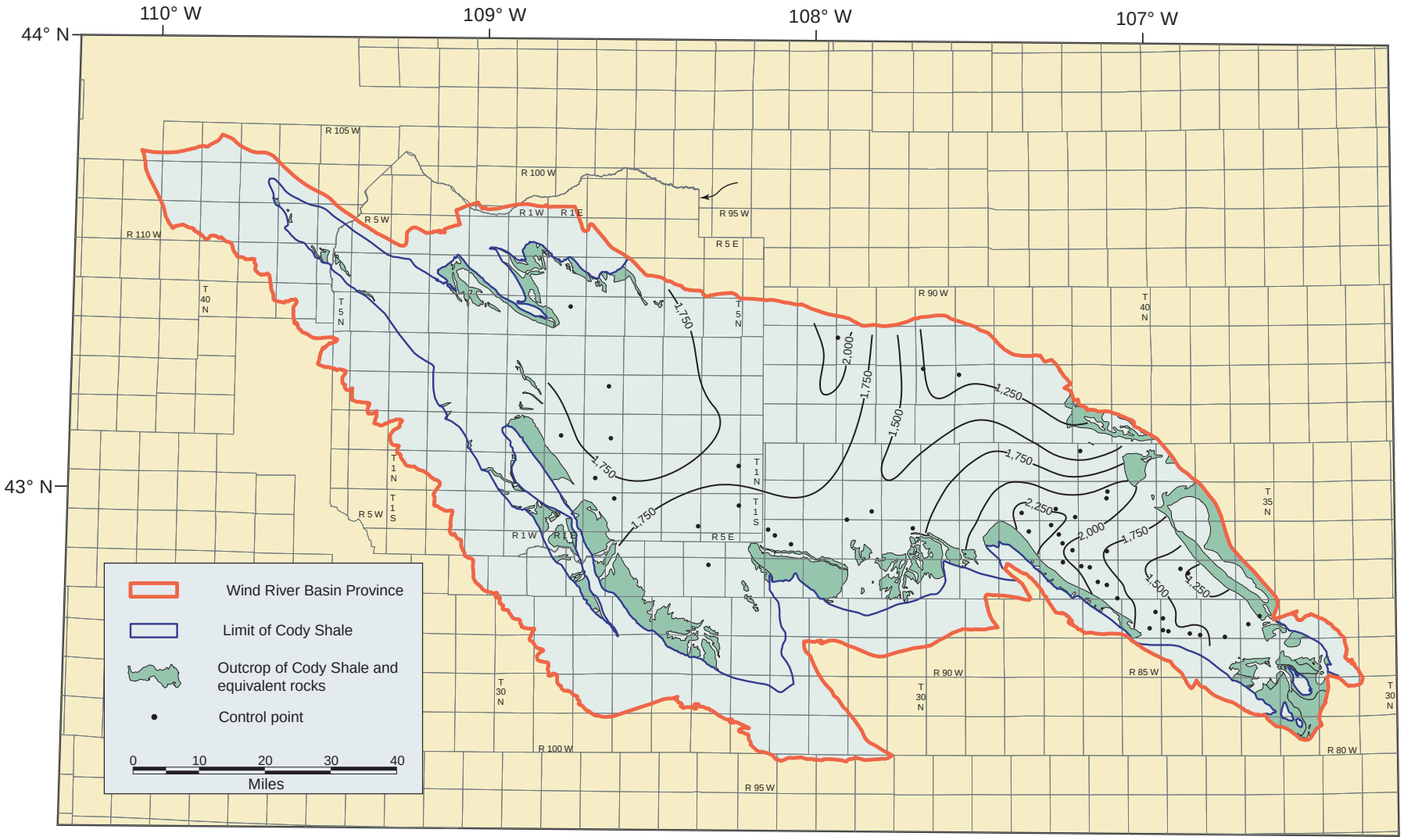

Figure 7. Isopach map of the lower shaly member of the Cody Shale, Wind River Basin, Wyoming. Modified from Johnson and others (1996b). Contour interval: 250 feet.

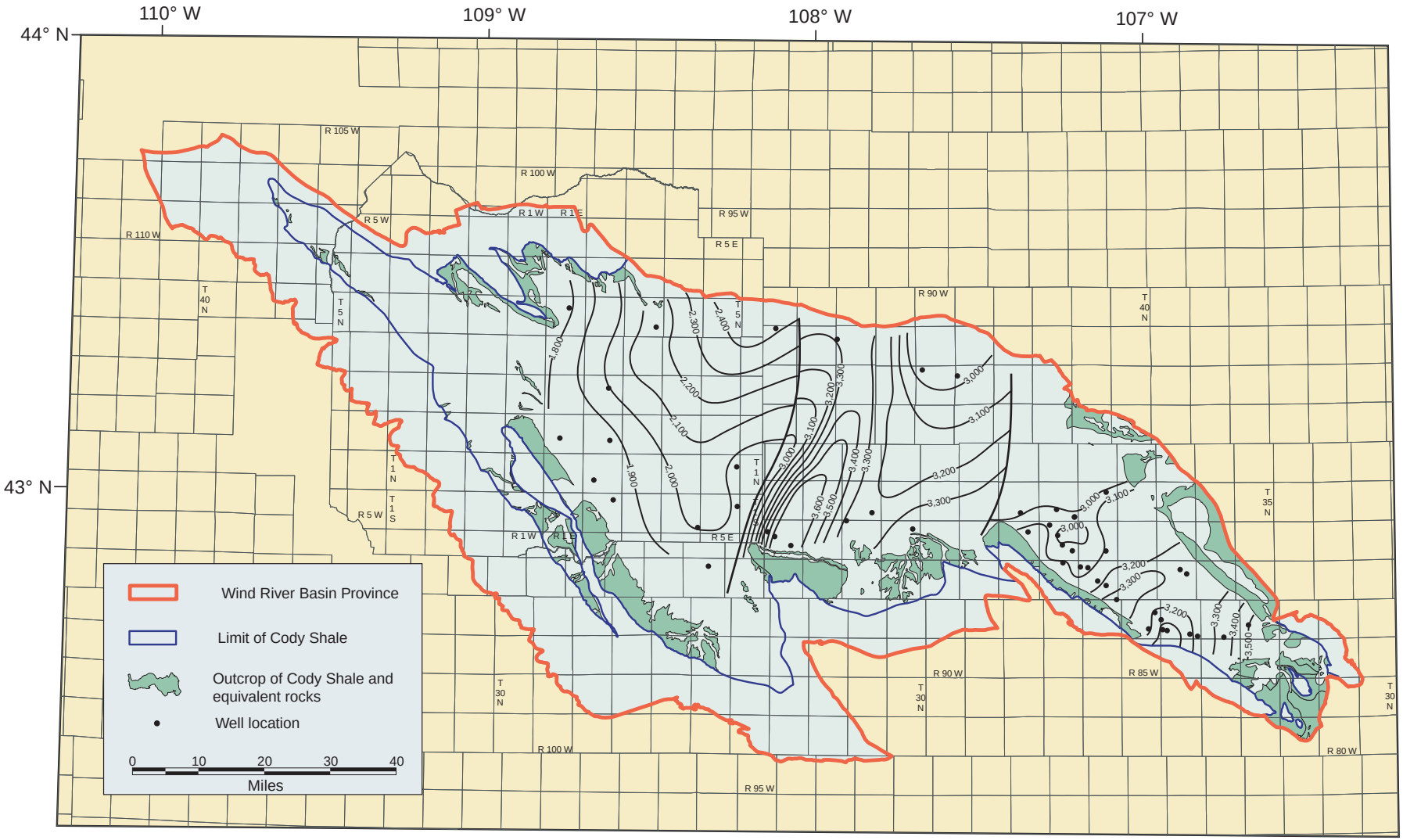

Figure 8. Isopach map of the upper sandy member of the Cody Shale, Wind River Basin, Wyoming. The isopached interval in the central part of the basin includes the "Alkali Butte member" of the Mesaverde Formation and the "Conant Creek tongue" of the Cody Shale. The isopached interval in the eastern part of the basin includes the Fales Sandstone Member of the Mesaverde Formation and the Wallace Creek Tongue of the Cody Shale. Modified from Johnson and others (1996b). Contour interval: 100 feet.

total marginal marine sandstone accumulated in a 1,200-ft-thick interval in the lower part, as the eastward migration of the seaway stalled and fluctuated over a limited area for a considerable period of time (figs. 11 and 12). These sandstone bodies are largely elongated in a north-south direction parallel to paleo-shoreline (Johnson and others, 1996b). Fluvial channel sandstones in the Mesaverde typically range from about 10 to 35 ft thick, but these sandstones are commonly stacked and amalgamated into units exceeding 100 ft in thickness (Johnson and others, 1996b; Johnson, Chapter 10, this CD-ROM). Total thickness of fluvial channel sandstones in beds 10 ft thick or greater varies from more than 1,200 ft in the western part of the basin to less than 100 ft in the eastern part (fig. 13). The tendency toward amalgamation is greatest in the Teapot Sandstone Member at the top of the Mesaverde Formation particularly in the western part of the basin where the Teapot can be more than 500 ft thick and consist predominantly of stacked sandstones to more than 120 ft thick (Johnson and others, 1996b; Johnson, Chapter 10, this CD-ROM). The Teapot thins to less than 50 ft in the eastern part of the basin and was deposited in a marginal marine environment in the easternmost part of the basin (Johnson and others, 1996b).

Meeteetse Formation and Lewis Shale

The Meeteetse Formation and Lewis Shale were deposited in poorly drained coastal plain, marginal marine and offshore marine settings in late Campanian and early Maastrichtian (Late Cretaceous) time (fig. 2) during a complex series of events in which depositional patterns appear to have become influenced by tectonic movements in portions of the Wind River Range and Granite Mountains (Johnson, Chapter 10, this CD-ROM). Marine rocks are present throughout the northeastern half of the basin (fig. 14), where tongues of Lewis Shale consisting of marine shale and sanding-upward marine cycles are interbedded with nonmarine fluvial sandstone, mudstone, carbonaceous mudstone and coal of the Meeteetse Formation (fig. 14). Marine influence might have extended even farther to the southwest than is shown on figure 14, but this could not be verified on the basis of just geophysical logs as well as the poorly exposed outcrops that typify the Meeteetse-Lewis interval throughout most of the basin (Johnson, Chapter 10, this CD-ROM).

Thickness variations in the Meeteetse Formation are poorly constrained due to the limited number of control points, but the formation generally thickens from less than 500 ft in the southwestern part of the basin to more than 1,750 ft along the basin trough just south of the Bighorn Mountains (fig. 14). This thinning is due to a combination of slower rates of subsidence toward the Wind River uplift, truncation of the Meeteetse Formation beneath the Lance Formation, and the upper part of the Meeteetse grading toward the southwest into sandy Lance Formation as sandy sediments from the rising Wind River uplift pushed ever farther into the basin. The Meeteetse is truncated beneath younger rocks along a fairly narrow belt paralleling the Wind River uplift (fig. 14). Keefer and Troyer (1964) noted that the Meeteetse thinned over Laramide folds in the Shotgun Butte area in the northern part of the Wind River Indian Reservation (fig. 14), indicating that deposition of the Meeteetse overlapped with early Laramide movement in that area.

Lance Formation

The Lance Formation is Maastrichtian (Late Ctetaceous) in age (fig. 10) and was deposited in continental settings after the Cretaceous seaway retreated east of the Wind River Basin and after Laramide uplifts in the central Rocky Mountain region began to partition the Cretaceous foreland basin into much smaller Laramide basins including the Wind River Basin. The Lance is more than 5,000 ft thick along the trough of the basin, just south of the Bighorn Mountains (fig. 15), thins markedly toward the south and southwest margins of the basin, and is completely truncated beneath younger units toward the Wind River Range to the southwest. Fluvial channel sandstones in the formation commonly amalgamate into thick complexes along discrete linear trends (fig. 10), indicating that channel systems remained relatively stationary for extended periods of time (Johnson, Chapter 10, this CD-ROM).

Fort Union Formation

The Fort Union Formation is a highly variable unit consisting of sandstone, gray mudstone and shale, carbonaceous shale, and coal that can be generally subdivided into two intervals: (1) a lower interval deposited in poorly-drained fluvial and paludal settings, and (2) an upper interval deposited in fluvial and marginal lacustrine settings in and adjacent to a major lake, Lake Waltman (Keefer 1961a; 1961b; 1965; 1969). The lower fluvial and paludal interval, consisting of sandstone, gray shale, carbonaceous shale and coal, is referred to as the lower member. The upper interval was divided into two members: the Waltman Shale Member, consisting mainly of offshore lacustrine shale, and the Shotgun Member, consisting of fine-to coarse-grained, in part conglomeratic, fluvial and marginal lacustrine rocks.

The lower member of the Fort Union thickens from less than 500 ft along the south and west margins to more than 3,500 ft along the basin trough (fig. 16). As with the Lance Formation, fluvial channel sandstones in the lower unnamed member commonly amalgamate into thick, complex units along discrete linear trends, indicating that channel systems remained relatively stationary for extended periods of time (Johnson, Chapter 10, this CD-ROM).

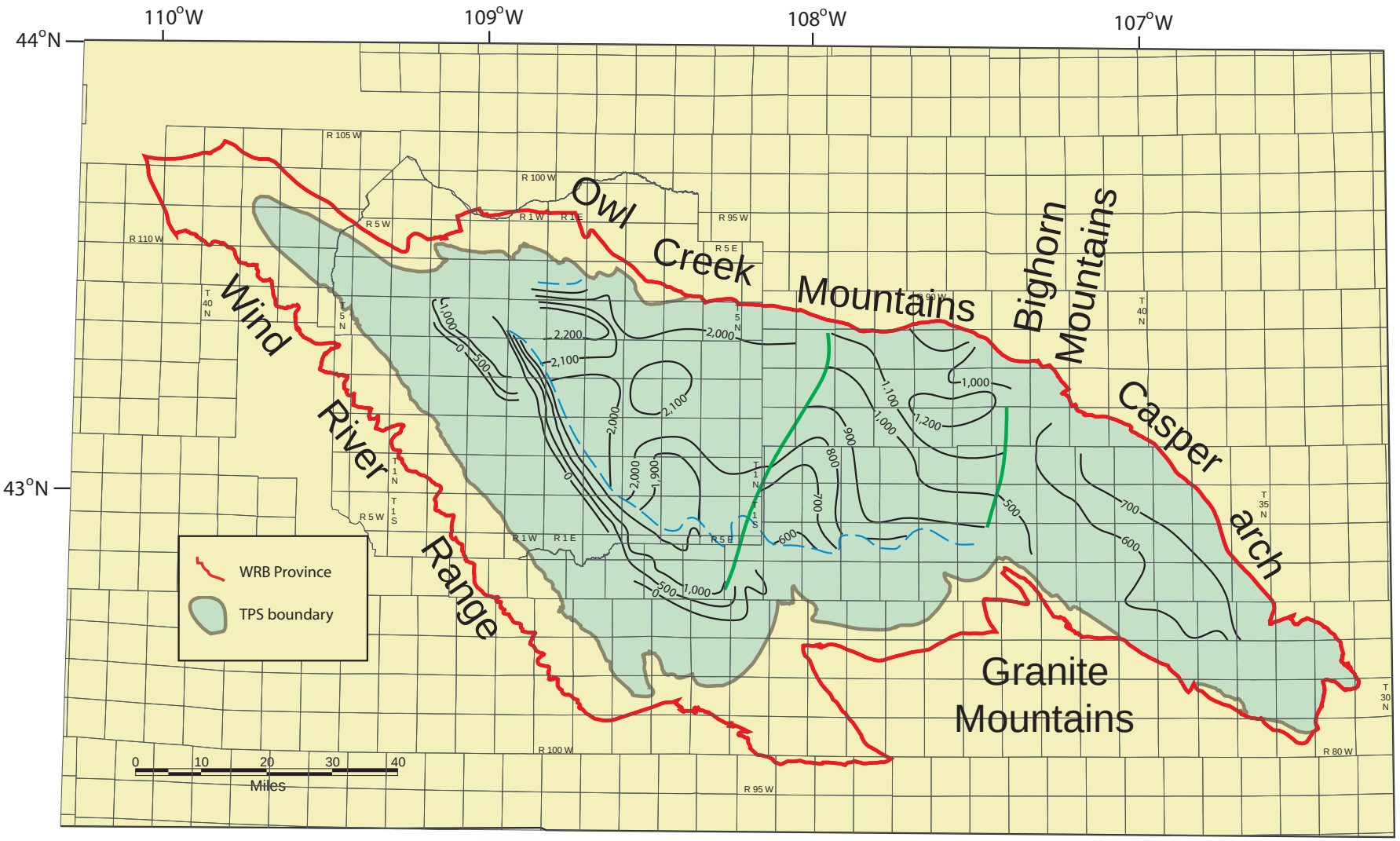

Figure 9. Isopach map of the Upper Cretaceous Mesaverde Formation, Wind River Basin (WRB), Wyoming. The Mesaverde is partly to completely truncated beneath younger units southwest of the dashed blue line along the southwest margin of the basin. Heavy green lines mark major jumps in section. Marginal marine rocks in the "Alkali Butte member" are not included east of western heavy green line, and Fales Sandstone Member of the Mesaverde Formation is not included east of eastern heavy green line. Modified from Johnson and others (1996b). Contour interval: 100 feet. TPS, Total Petroleum System.

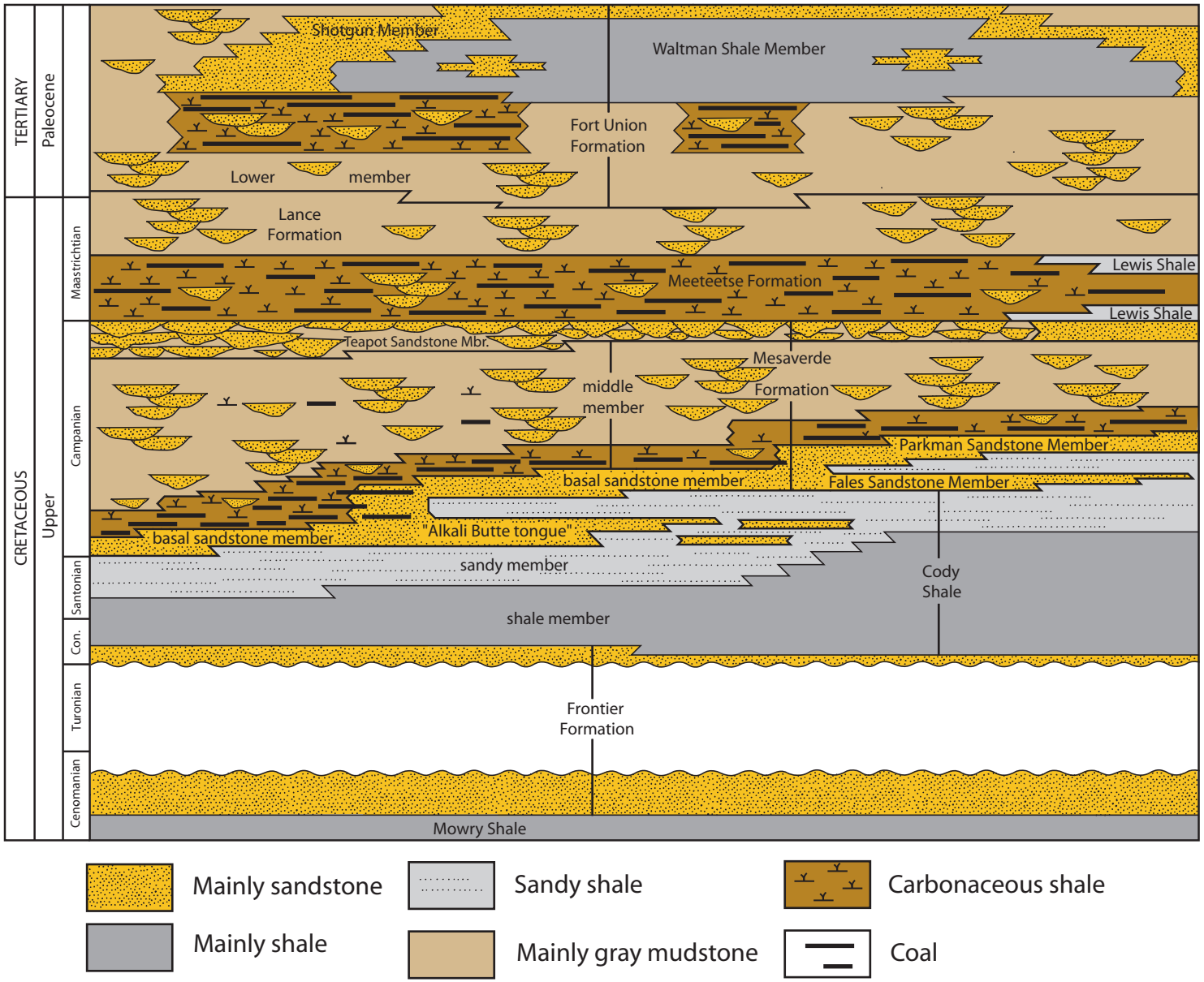

Figure 10. Detailed east-west correlation diagram across the Wind River Basin, Wyoming, showing stratigraphic units and generalized sedimentary facies within Upper Cretaceous and Paleocene rocks. Modified from Johnson and others (1996b).

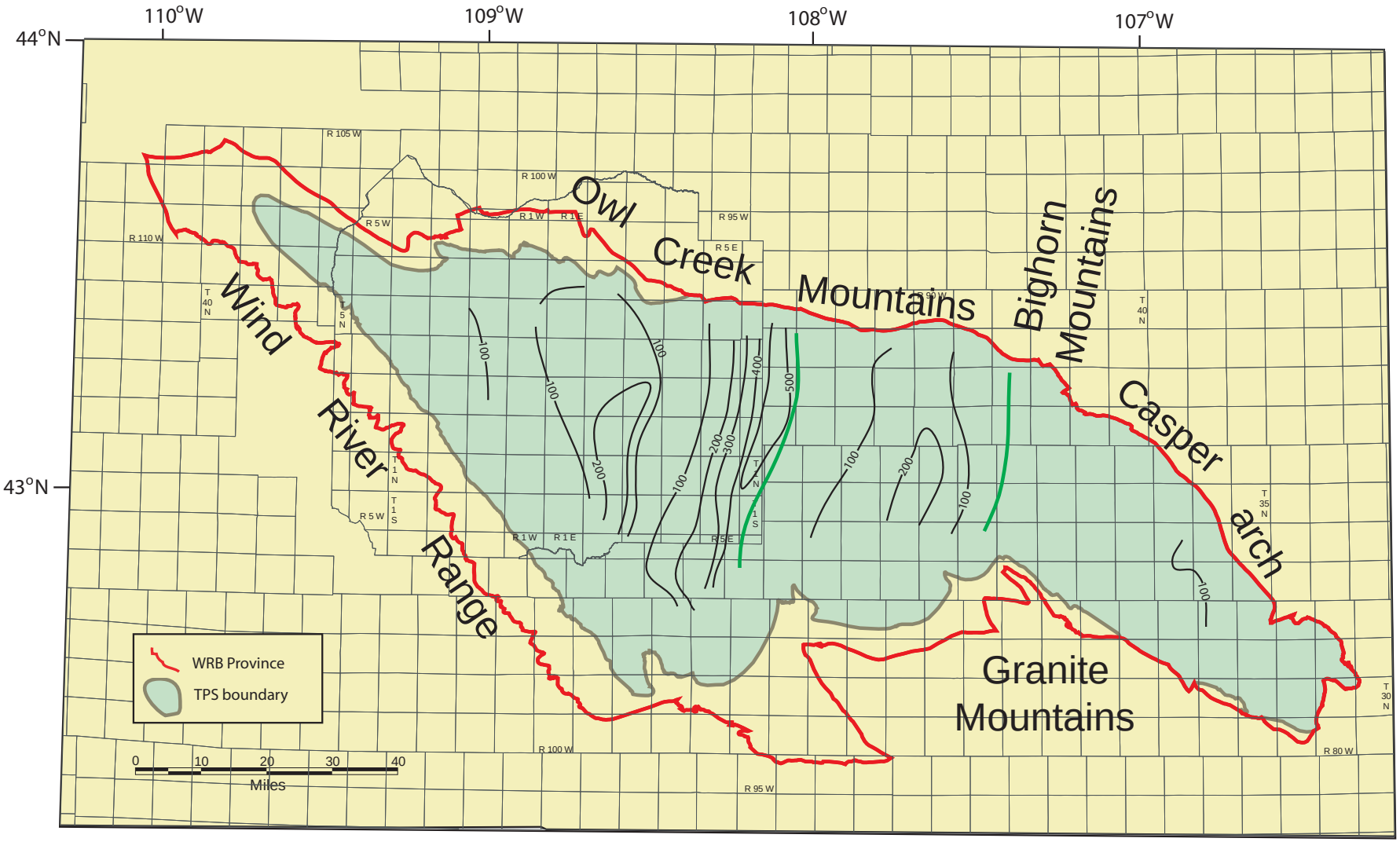

Figure 11. Isopach map of total sandstone in beds 10 feet or more thick in the marginal marine interval of the Mesaverde Formation, Wind River Basin (WRB), Wyoming. Marginal marine rocks in the "Alkali Butte member" are not included east of western heavy green line, and Fales Sandstone Member of the Mesaverde Formation is not included east of eastern heavy green line. Modified from Johnson and others (1996b). Contour interval: 100 feet. TPS, Total Petroleum System.

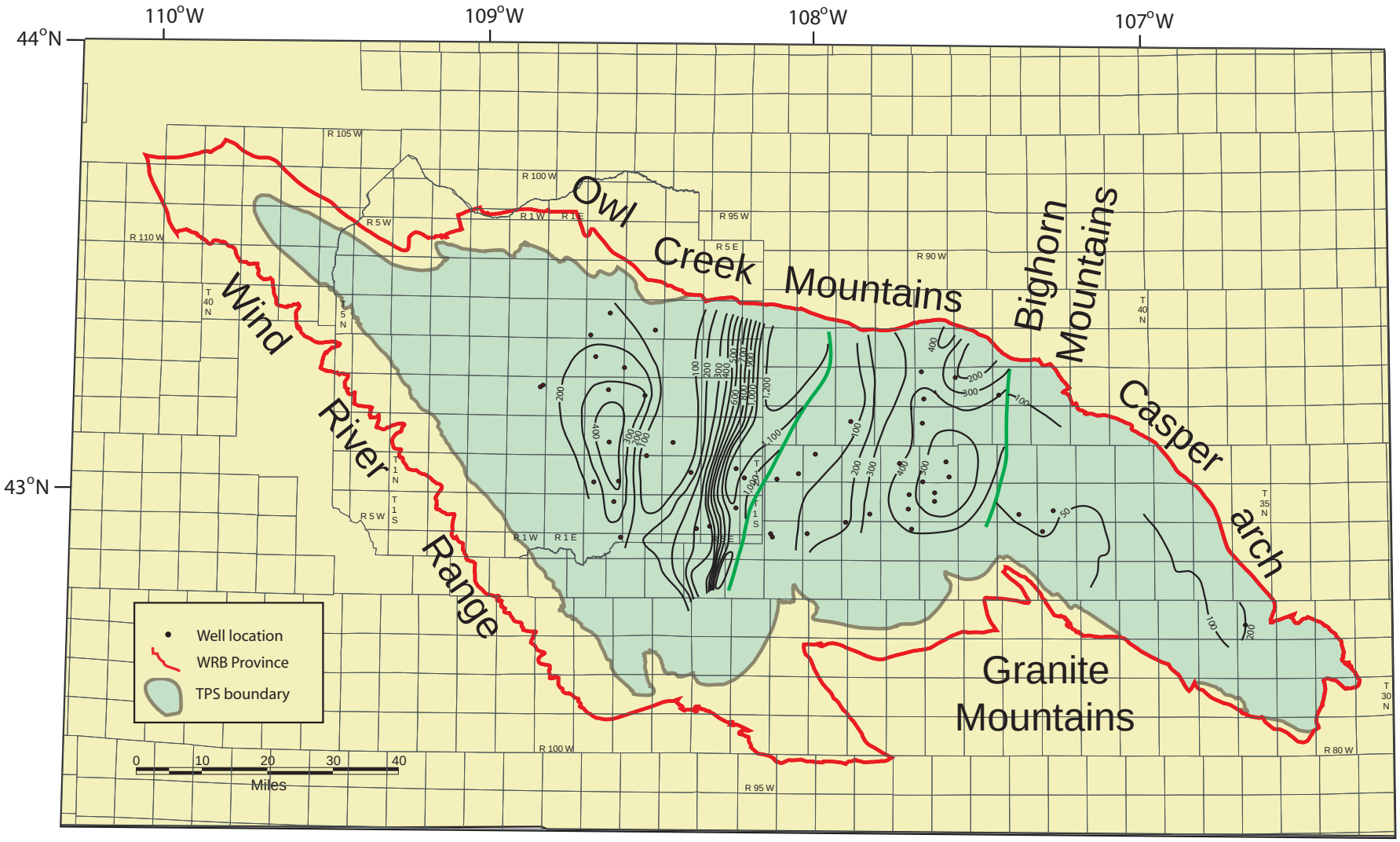

Figure 12. Isopach map of the marginal marine interval in the lower part of the Upper Cretaceous Mesaverde Formation, Wind River Basin (WRB), Wyoming. Marginal marine rocks in the "Alkali Butte member" are not included east of western heavy green line, and Fales Sandstone Member of the Mesaverde Formation is not included east of eastern heavy green line. Modified from Johnson and others (1996b). Contour interval:100 feet. TPS, Total Petroleum System.

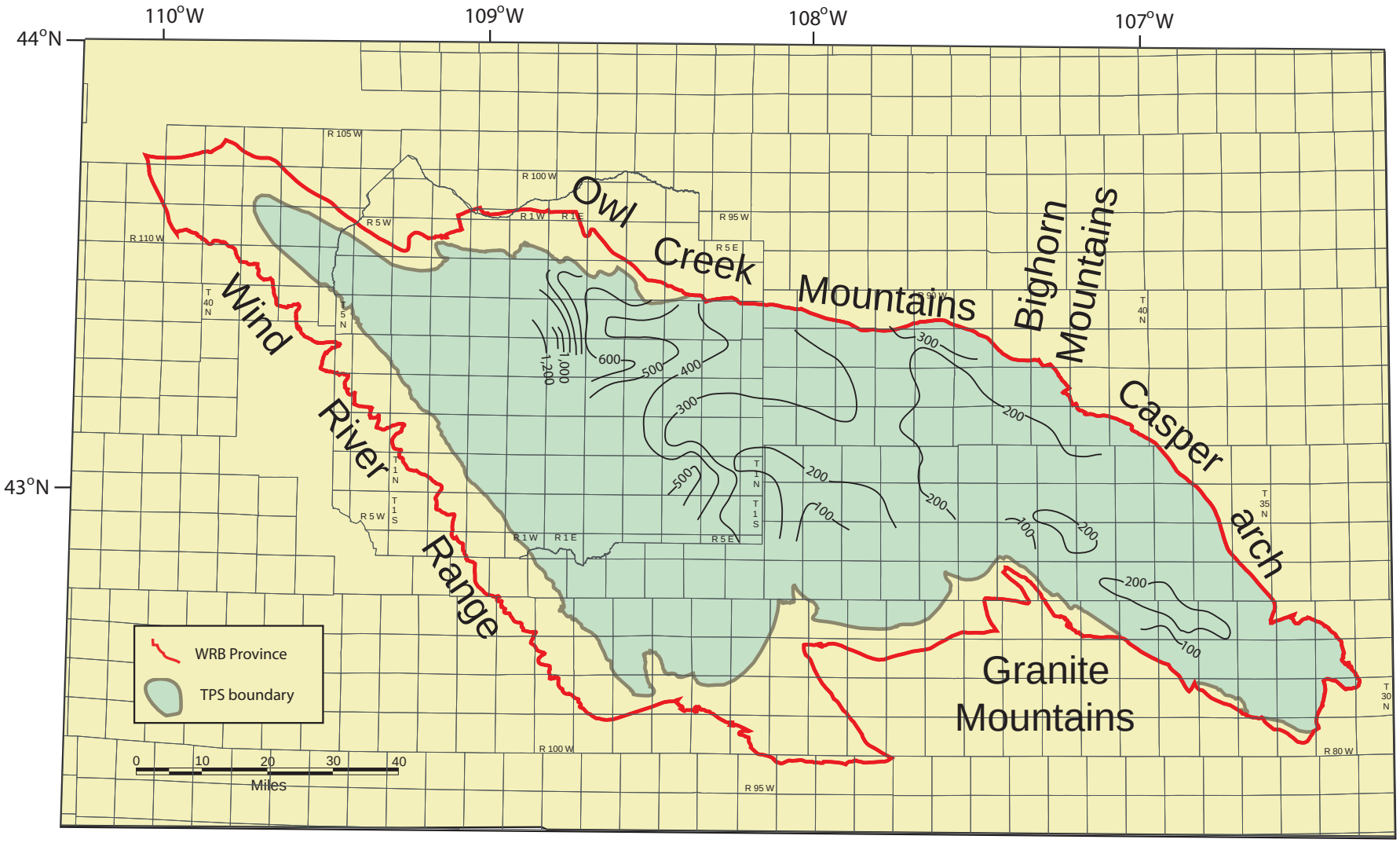

Figure 13. Isopach map of total sandstone in beds 10 feet or more thick in the middle member and the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation, Wind River Basin (WRB), Wyoming. Modified from Johnson and others (1996b). Contour interval: 100 feet. TPS, Total Petroleum System.

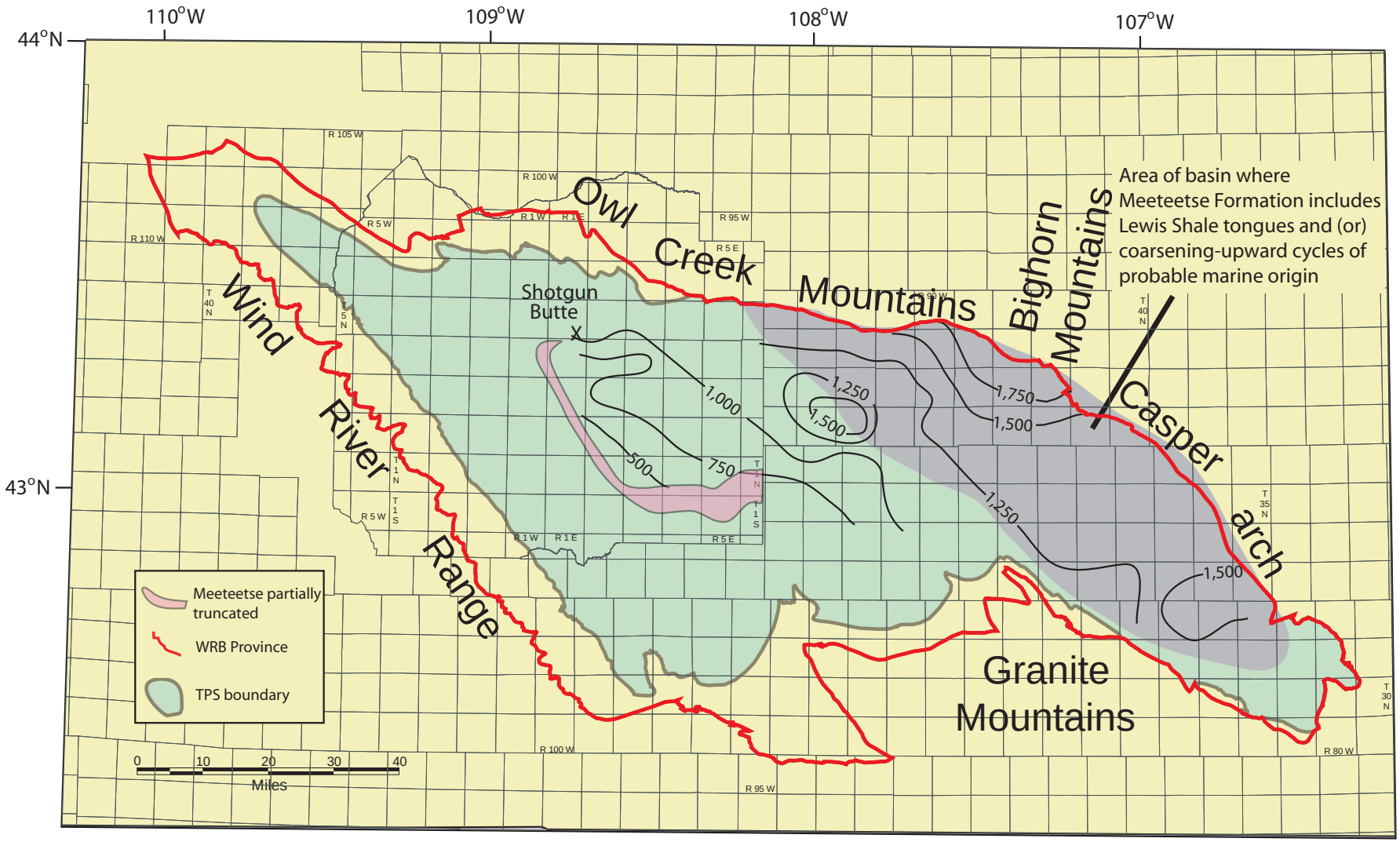

Figure 14. Isopach map of the Meeteetse Formation and Lewis Shale of Late Cretaceous age, Wind River Basin (WRB), Wyoming. The area of the basin where the Meeteetse includes marine shale tongues also is shown. Area along the southwest margin of the basin where the Meeteetse is partially truncated is from Keefer and Johnson (1993); relation is shown only for area within the Wind River Indian Reservation. Contour interval: 250 feet. TPS, Total Petroleum System.

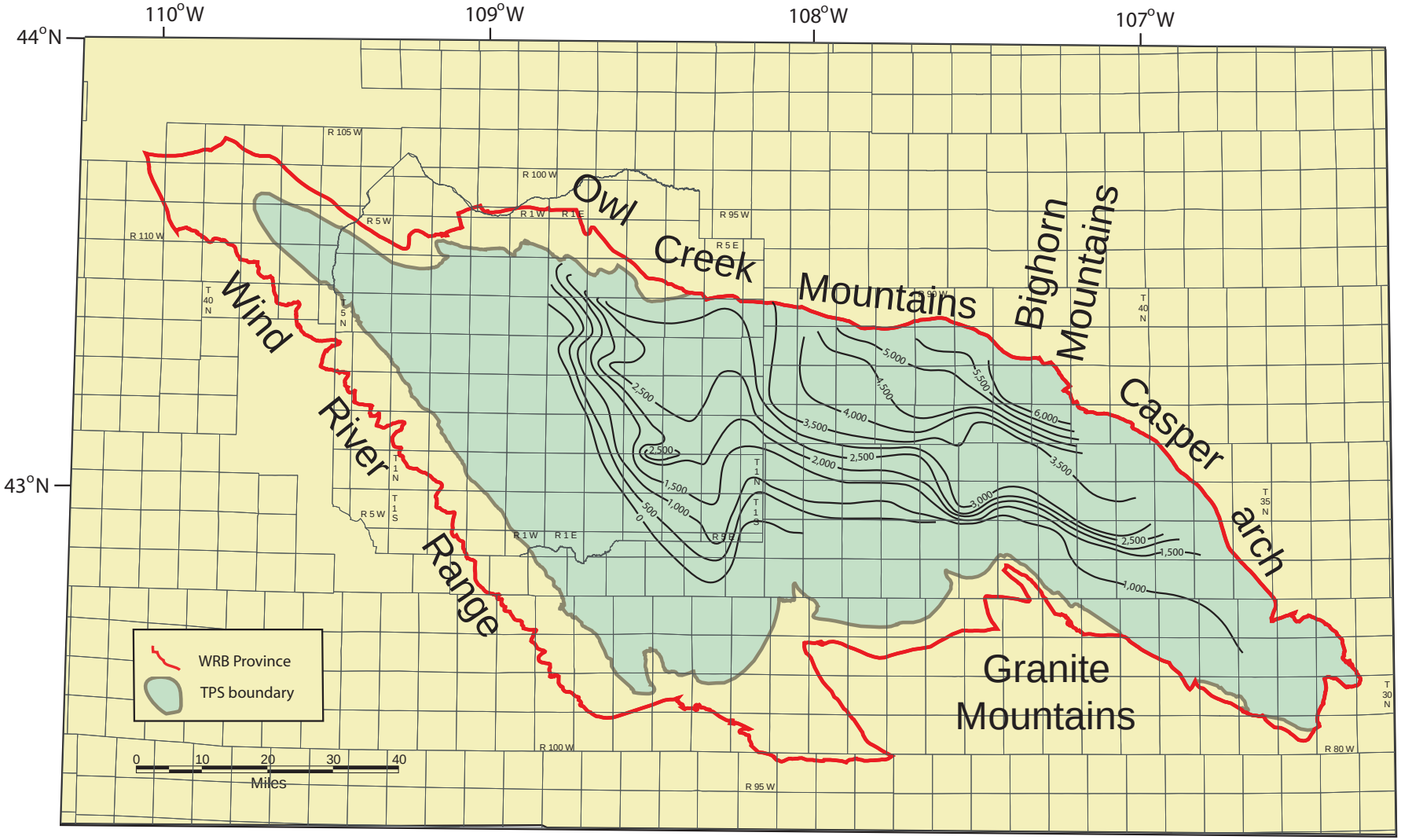

Figure 15. Isopach map of the Lance Formation, Wind River Basin (WRB), Wyoming. Contour interval: 500 feet. TPS, Total Petroleum System.

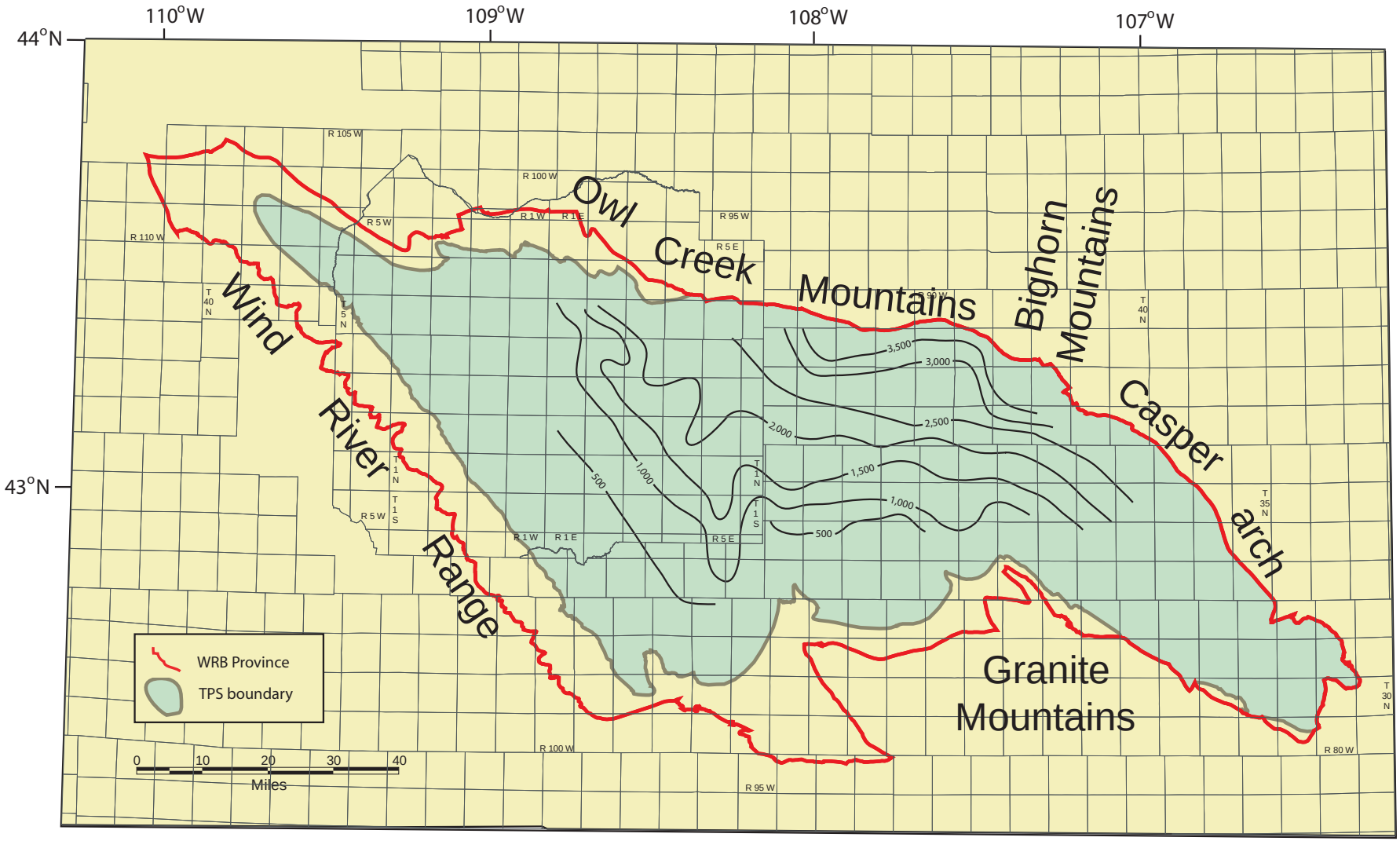

Figure 16. Isopach map of the lower unnamed member of the Paleocene Fort Union Formation, Wind River Basin (WRB), Wyoming. Contour interval: 500 feet. TPS, Total Petroleum System.

Hydrocarbon Source Rocks

Source rocks in the Cretaceous-Lower Tertiary Composite TPS include organic-rich marine shale in the Thermopolis Shale, Mowry Shale, Belle Fourche Member of the Frontier Formation, Cody Shale, coal and carbonaceous shale in the Mesaverde and Meeteetse Formations, and coal and carbonaceous shale in the lower member of the Fort Union Formation. The Mowry and Cody Shales contain predominantly Type II and Type III organic matter (fig. 17) with total organic carbon (TOC) values as high as 3.46 percent reported for Mowry in the Wind River Basin and TOC values as high as 5.85 percent for cuttings of the lower part of the Cody Shale (see Finn, Chapter 8, this CD-ROM). TOC values in the lower Cody generally increase toward the east.

Coal in the Mesaverde Formation is concentrated in a north-south trend just west of the east boundary of the Wind River Indian Reservation, where total coal thicknesses locally exceed 120 ft (figs. 4 and 18). The coal beds in that area are interbedded with north-south-trending marginal marine sandstones (fig. 6) and were deposited in a lower coastal plain setting as the eastward retreat of the Late Cretaceous shoreline stalled for a considerable period of time. Total coal thicknesses for the Meeteetse Formation vary irregularly across the basin from less than 10 ft to more than 50 ft (fig. 19).

Most of the coal in the Fort Union Formation is in the lower unnamed member (Johnson, Chapter 10, this CD-ROM), and is concentrated in an elongated northwest-trending area along the south flank of the basin and south of the basin trough, where total coal thickness locally exceeds 100 ft (fig. 20). A mud-dominated facies that lacks coal occupied the basin trough at this time (Johnson and others, 1994; Johnson, Chapter 10, this CD-ROM). Much of the coal in this area is in the upper 500 to 1,400 ft of the lower unnamed member, but a coal zone also is present in the lowermost part of the unnamed member in the western part of the basin (Johnson, Chapter 10, this CD-ROM). Another, but less extensive coal, with total thicknesses of more than 100 ft, is in a northwest-trending structural trough, south of Little Dome anticline (figs. 3 and 20). These beds also are probably in the lower unnamed member of the Fort Union Formation, but control is sparse. Coal-forming mires were largely replaced by lacustrine deposition as Lake Waltman expanded rapidly in late Paleocene time to cover much of the basin (Johnson, Chapter 10, this CD-ROM; Roberts and others, Chapter 5, this CD-ROM).

Source Rock Maturation

Figures 21, 22, 23, and 24 are maps showing variations in levels of thermal maturity using vitrinite reflectance (R_o) values at the top of the Upper Cretaceous Frontier Formation (Johnson and others, 1996a), base of the Upper Cretaceous Mesaverde Formation (Finn, Chapter 9, this CD-ROM), base of the Upper Cretaceous Meeteetse Formation (Nuccio and others, 1996) and base of the Waltman Shale Member of the Paleocene Fort Union Formation (Nuccio and others, 1996), respectively. Thermal maturities at the top of the Frontier Formation are poorly constrained but probably vary from less than 0.6 percent R_o along the basin margins to well over 3 percent R_o in the deeper parts of the basin. Thermal maturities at the base of the Mesaverde Formation and base of the Meeteetse Formation increase from less than 0.6 percent R_o in the shallow areas around the margins of the basin to much greater than 3 percent R_o in the deeper parts of the basin (figs. 22 and 23). Maximum R_o level at the base of the Waltman Shale Member is somewhat greater than 1.1 percent in a limited area in the west-central part of the basin (fig. 24).

Reconstructions of burial histories were made for nine wells within the Cretaceous-Lower Tertiary Composite TPS for which detailed R_o profiles were available. Roberts and

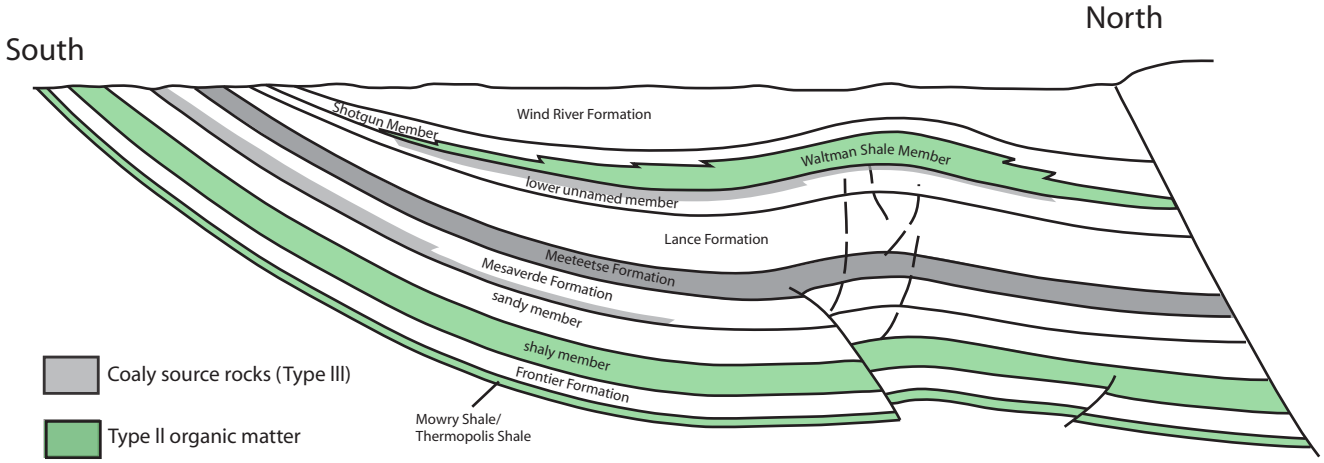

Figure 17. Schematic cross section showing intervals with Type III coaly source rocks (gray) and Type II marine shale source rocks (green), Wind River Basin, Wyoming, in a general south to north line through the Madden anticline area.

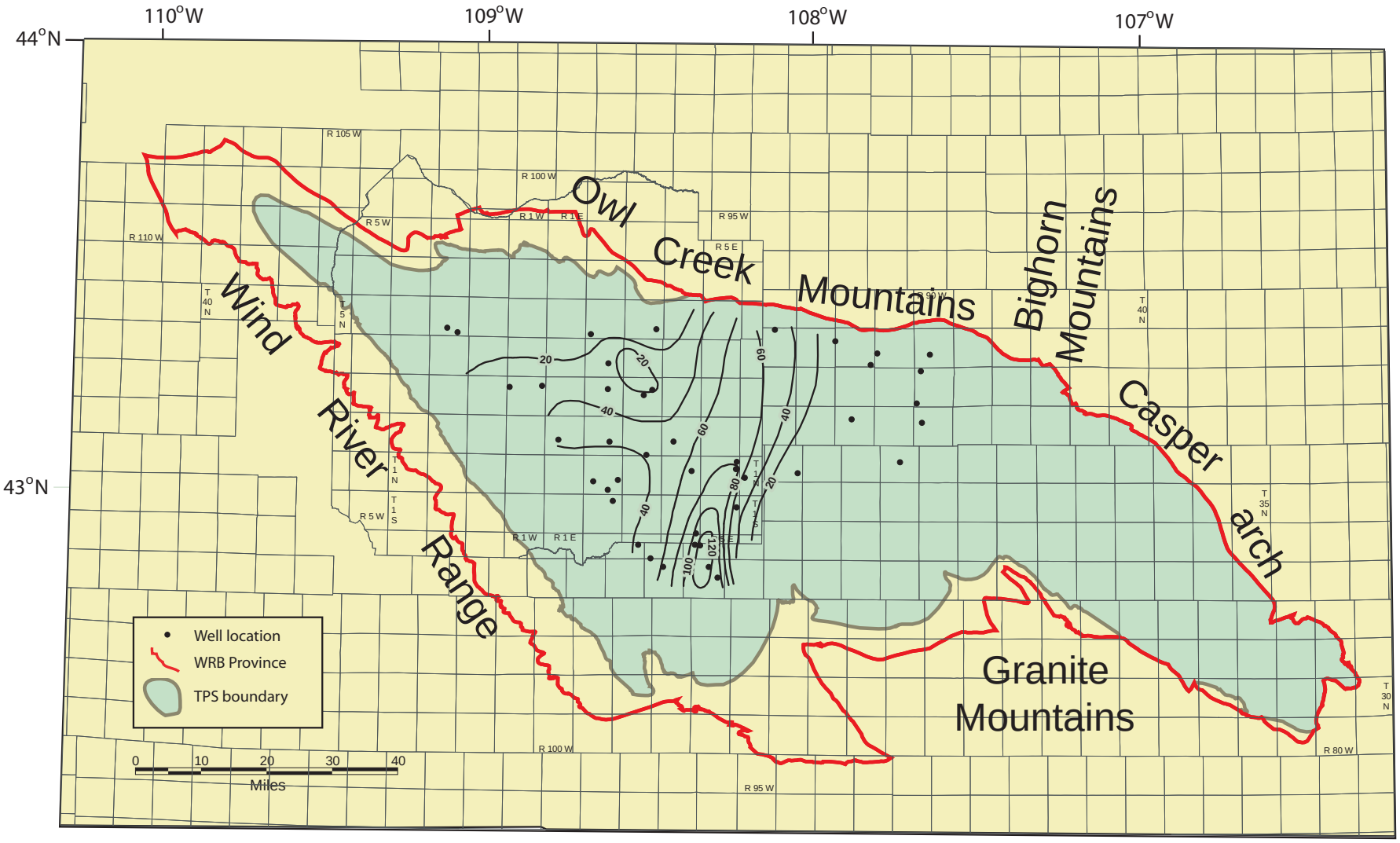

Figure 18. Isopach map of total coal in beds 2 feet or more thick in the Upper Cretaceous Mesaverde Formation, Wind River Basin (WRB), Wyoming. Modified from Johnson and others (1996b). Drill holes used for control are shown as black dots. Contour interval: 20 feet. TPS, Total Petroleum System.

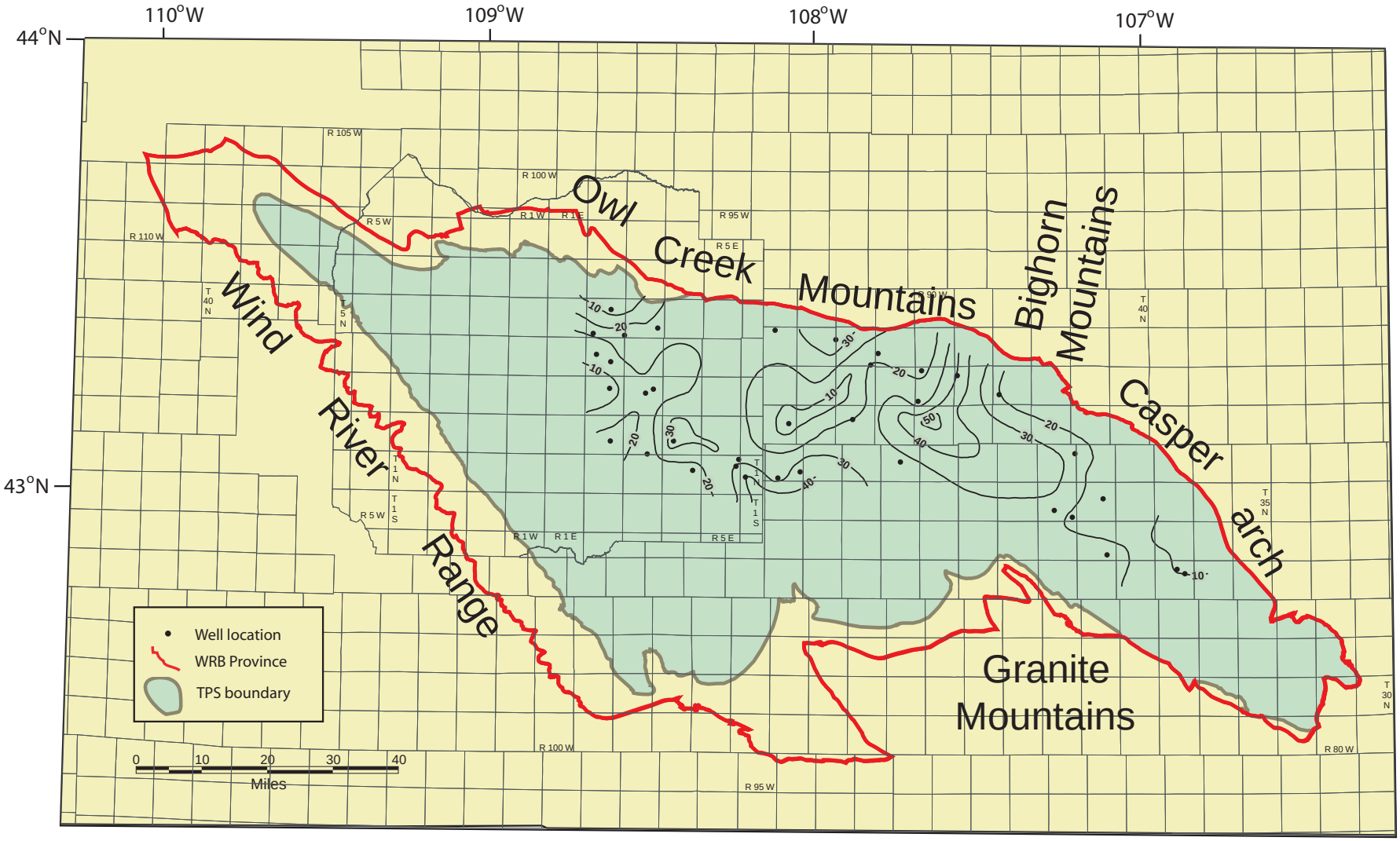

Figure 19. Isopach map of total coal in beds 2 feet or more thick in the Upper Cretaceous Meeteetse Formation, Wind River Basin (WRB), Wyoming. Drill holes used for control are shown as black dots. Modified from Johnson and others (1996b). Contour interval: 10 feet. TPS, Total Petroleum System.

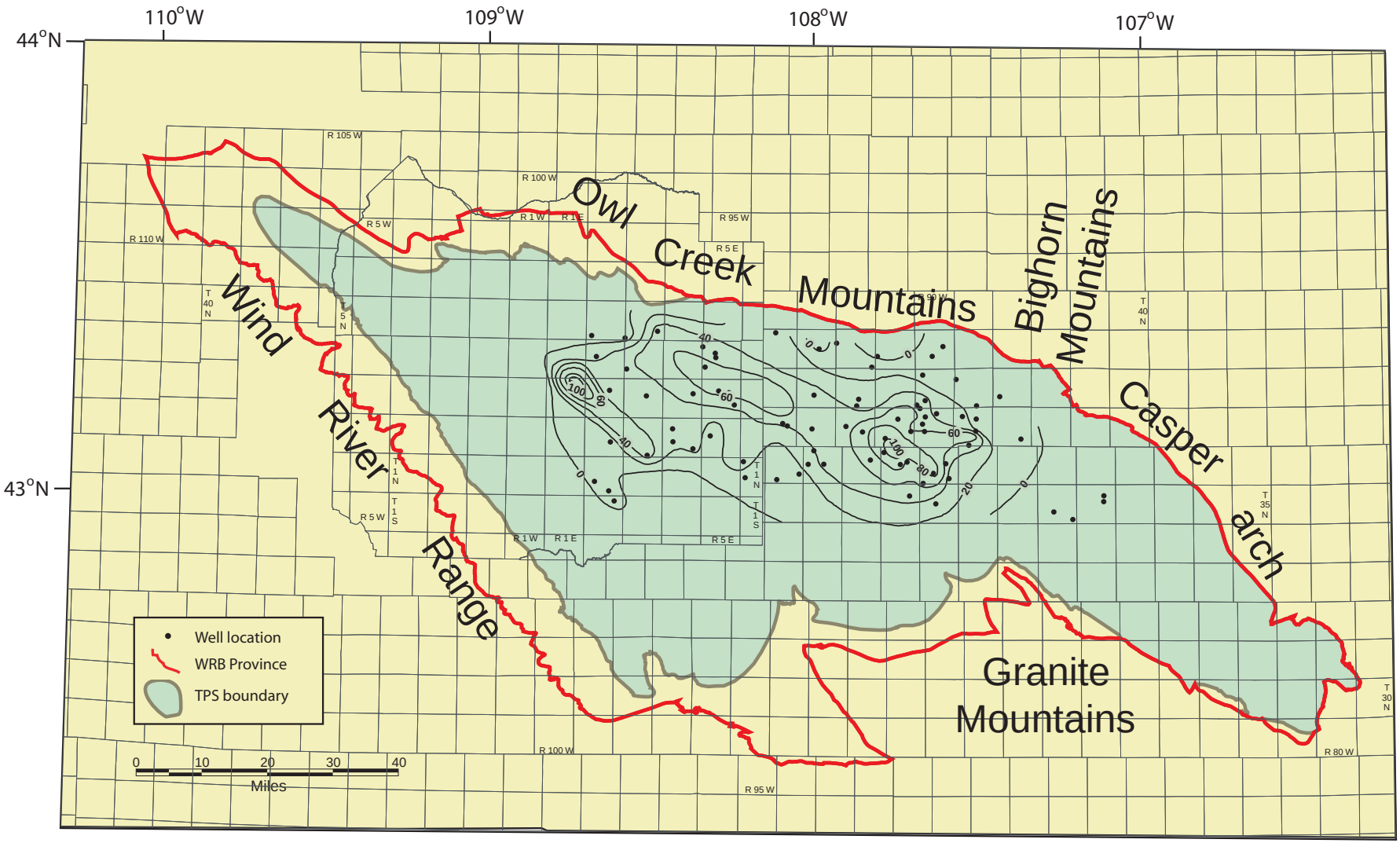

Figure 20. Isopach map of total coal in beds 2 feet or more thick in the Paleocene Fort Union Formation, Wind River Basin (WRB), Wyoming. Drill holes used for control are shown as black dots. Modified from Johnson and others (1996b). Contour interval: 20 feet. TPS, Total Petroleum System.

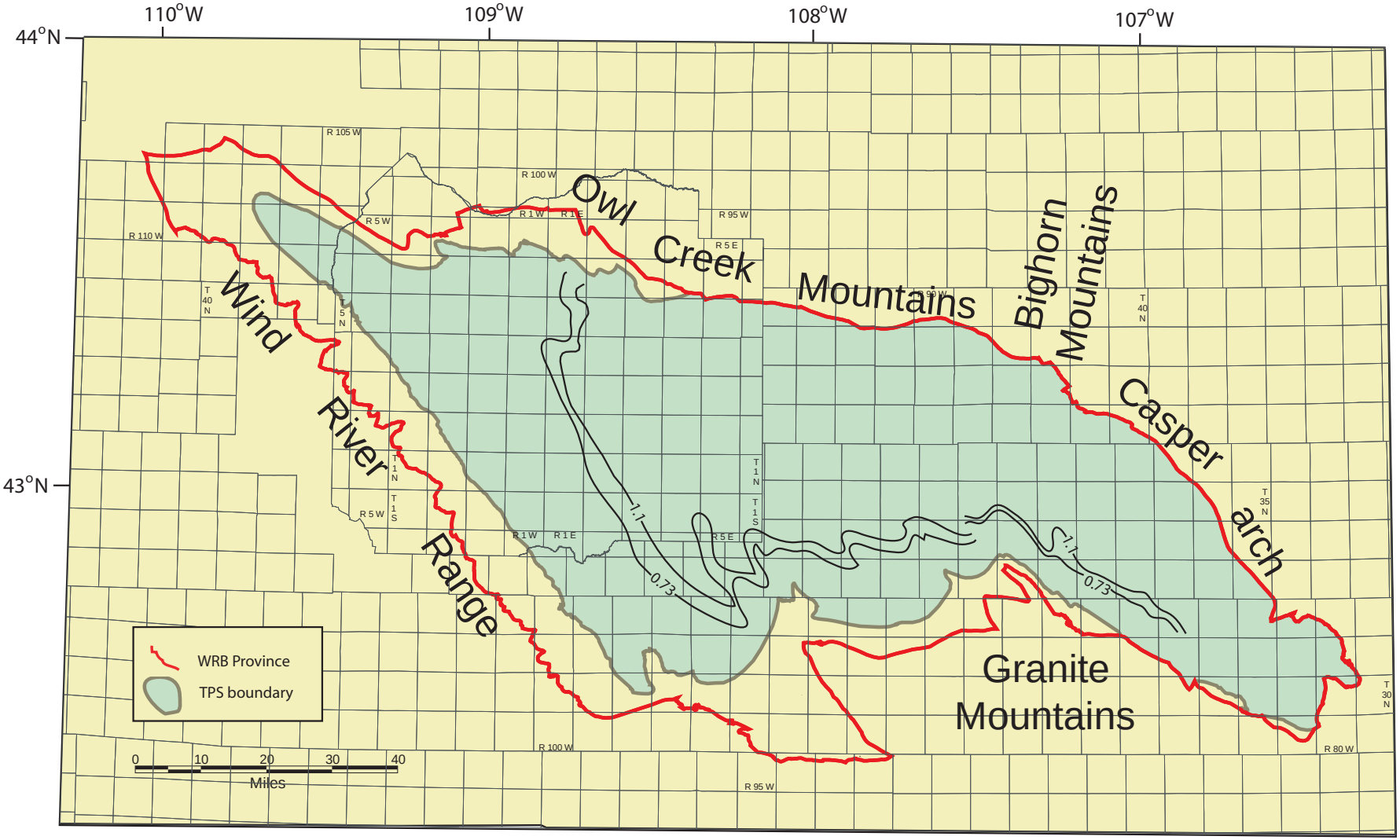

Figure 21. Variations in vitrinite reflectance levels at the top of the Upper Cretaceous Frontier Formation, Wind River Basin, Wyoming. Modified from Johnson and others (1996a). TPS, Total Petroleum System.

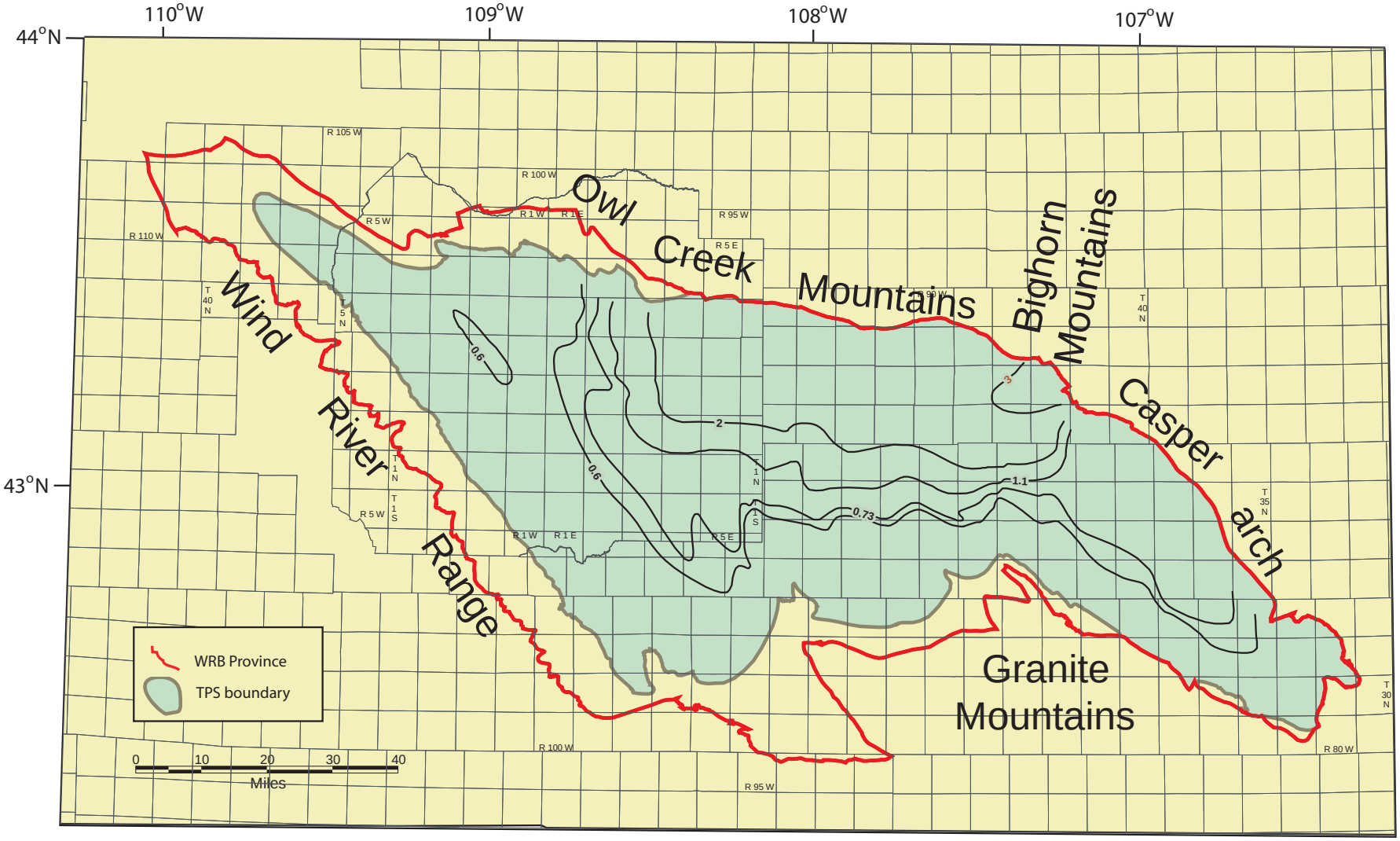

Figure 22. Variations in vitrinite reflectance levels at base of the Upper Cretaceous Mesaverde Formation, Wind River Basin (WRB), Wyoming. TPS, Total Petroleum System.

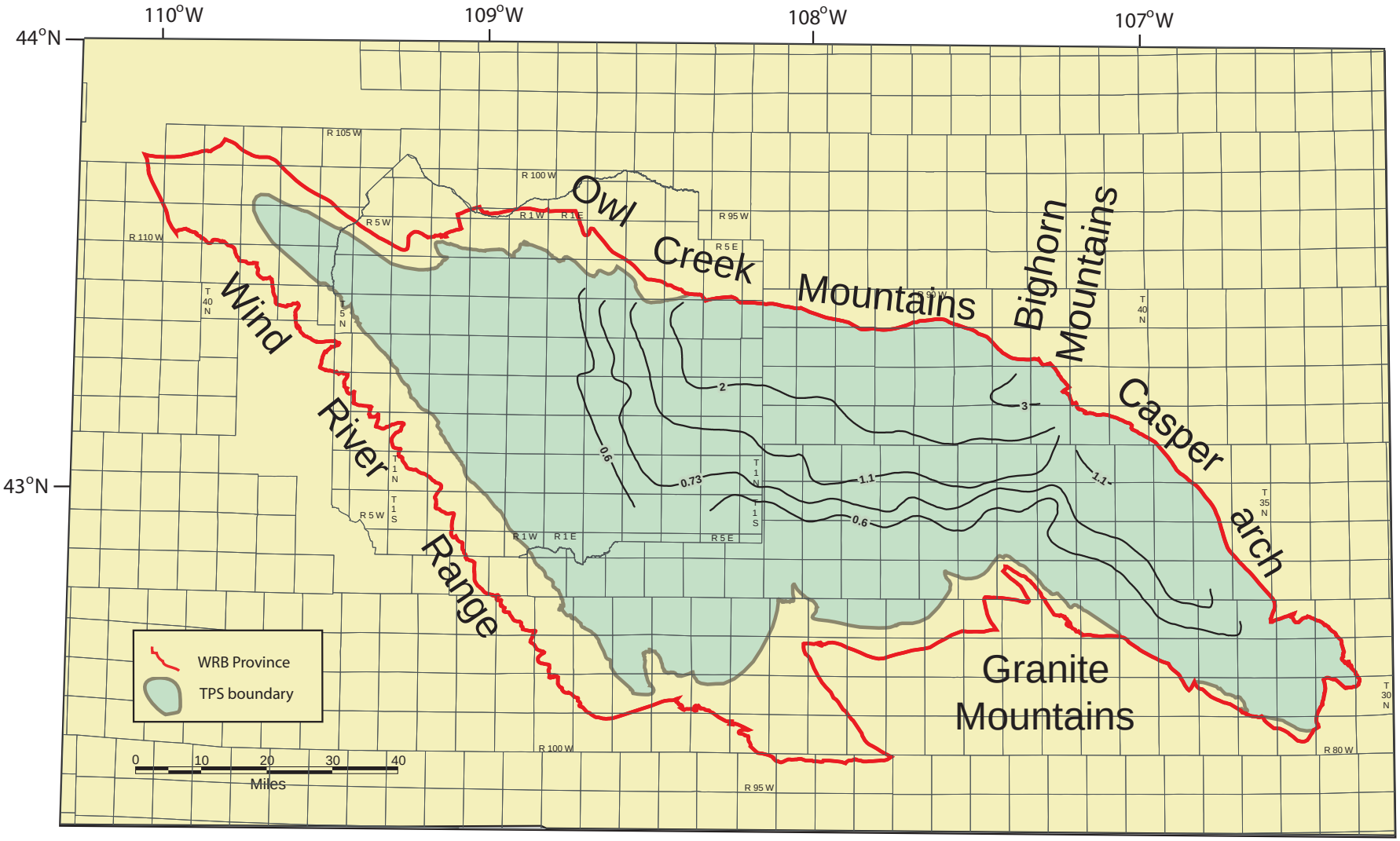

Figure 23. Variations in vitrinite reflectance levels at base of the Upper Cretaceous Meeteetse Formation, Wind River Basin (WRB), Wyoming. Modified from Nuccio and others (1996). TPS, Total Petroleum System.

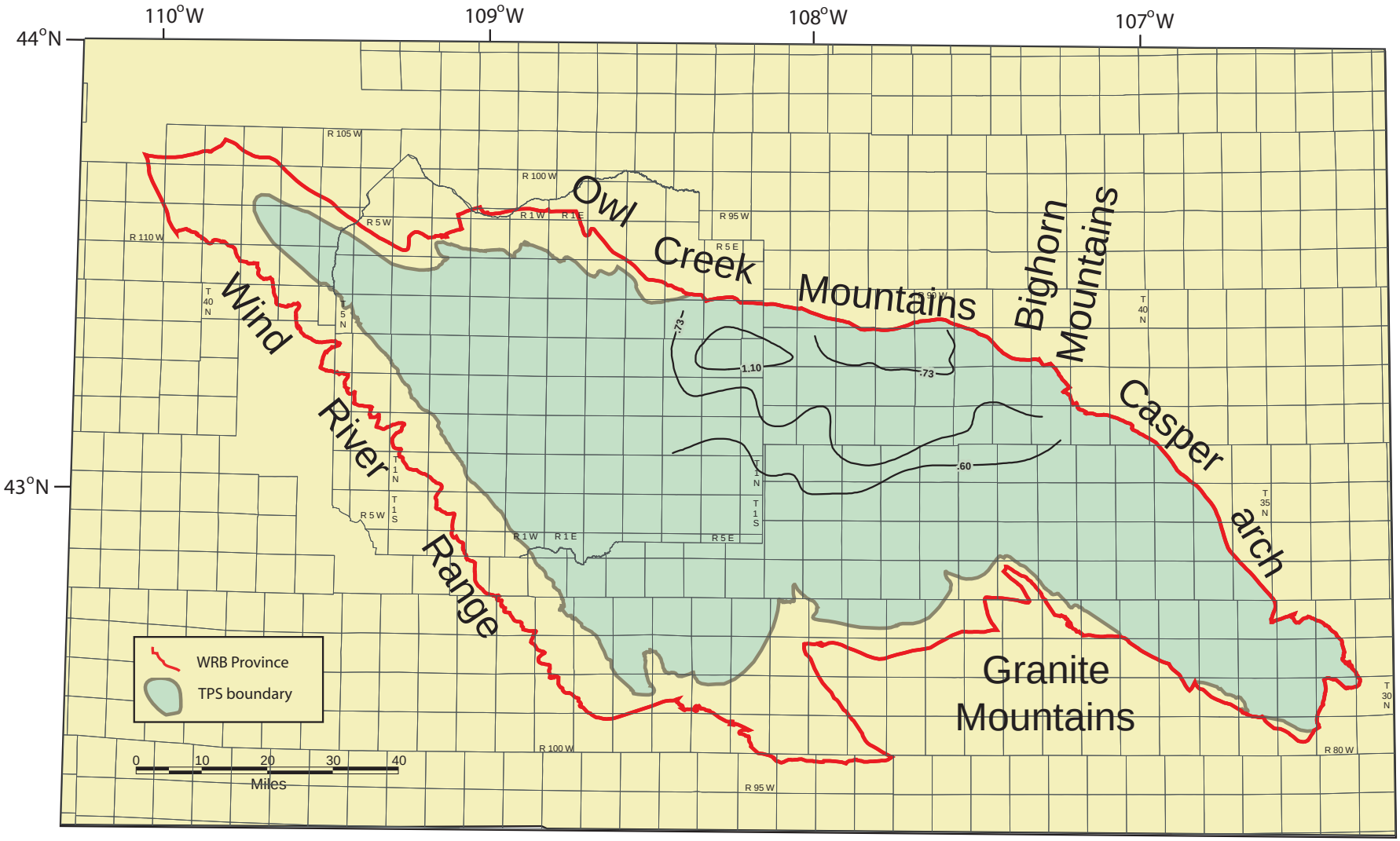

Figure 24. Variations in vitrinite reflectance levels at base of the Waltman Shale Member of the Paleocene Fort Union Formation, Wind River Basin (WRB), Wyoming. Modified from Nuccio and others (1996). TPS, Total Petroleum System.

others (Chapter 6, this CD–ROM), applied time-temperature modeling to the burial reconstructions to estimate the timing of hydrocarbon generation for source rocks containing Type III organic matter. The model is calibrated using observed R_o levels in wells where the burial histories are well constrained. Roberts and others (Chapter 6, this CD-ROM) used a kinetic model to reconstruct maturation of Type II organic matter. Kinetic modeling uses time and temperature integrated with results of laboratory hydrous-pyrolysis experiments (Lewan and Ruble, 2002; Tsuzuki and others, 1999) to predict timing and type of hydrocarbon generation.

Hydrocarbon Migration

Oil was generated by Type II source rocks in the Mowry Shale and lower shaly member of the Cody Shale throughout most of the deep basin, but present-day thermal maturities are too high for oil to be preserved in these source rocks except in the marginal areas of the basin. Oil generated by these oil-prone source rocks early in the subsidence history of the basin might have migrated into shallow reservoirs where present-day maturities are low enough to preserve oil, but evidence is lacking. Hydrocarbon gases, which are far more abundant than oil in the Cretaceous-Lower Tertiary Composite TPS are thought to have migrated vertically many thousands of feet and commingled in faulted and fractured zones along anticlines and structural noses (Johnson and Rice, 1993; Schelling and Wavrek, 2001; Lillis and Johnson, 2005). Figure 25 is a conceptual model showing where gases might have migrated from the various Cretaceous and lower Tertiary source rocks but does not address when migration occurred. The model assumes that much of the gas would have migrated vertically and laterally into the first available sandstone reservoir. Thus, much of the gas generated by Cretaceous marine source rocks below the Frontier Formation probably migrated no farther than sandstone reservoirs in the Frontier, and gases generated by organic-rich intervals in the shaly member of the Cody are largely in the overlying sandy member or lower part of the Mesaverde Formation. However, in faulted and fractured zones, these gases migrated vertically much farther–into reservoirs as young as the lower unnamed member of the Paleocene Fort Union Formation (figs. 25*A* and *B*). The thick Waltman Shale Member, where present, is thought to act as a seal inhibiting farther vertical migration of these gases into younger Paleocene and Eocene rocks; however, west of the pinchout of the Waltman, there is good evidence that mature gases from deep sources migrated into units as young as the Eocene Wind River Formation (Johnson and Rice, 1993; Johnson and Keighin, 1998). Although migration distances are thought to be much shorter away from fractured zones, they are still significant. Johnson and Rice (1993) sampled Coalbed gases in the lower part of the Mesaverde Formation along the southwest flank of the basin, away from any known fractured zone, and observed that a component of thermogenic gases likely migrated vertically thousands of feet from mature source rocks in the underlying Cody and Mowry Shales.

Coals in the Meeteetse and Mesaverde Formations and lower unnamed member of the Fort Union Formation also generated gas where relatively and thermally mature (figs. 25*C*, *D*, and *E*). The Waltman Shale has generated mainly oil, and this oil has migrated both vertically and laterally (fig. 25*F*). As uplift and erosion proceeded in the Wind River Basin, ground water pushed progressively farther into the basin, producing an alteration zone where microbial activity both generated biogenic methane from source rocks and degraded ethane in preexisting gas accumulations (fig. 25*G*). Mixtures of biogenic and thermogenic gas were recovered from coal beds in the Mesaverde Formation on the Wind River Indian Reservation (Johnson and Rice, 1993), and biogenic gas is produced from the Wind River Formation at Waltman field (fig. 1) (Johnson and Keighin, 1998; Lillis and Johnson, 2005). Biodegradation of ethane has occurred at Pavillion and East Riverton dome fields (fig. 1) (Lillis and Johnson, 2005). Microbial activity is greatest at formation temperatures of 75° C or less.

Figure 25*H* is a summary for all of the source rocks. Note that highly fractured zones contain mixtures of gases from multiple sources, and also that available gas was possibly insufficient to charge all the sandstone reservoirs everywhere in the basin leaving irregularly-shaped pockets where reservoirs are predominantly water saturated (white zones on fig. 25*H*). These pockets are within the continuous accumulation, where source rocks are scarce or fault and fracture systems have strongly channeled migrating hydrocarbons thus causing areas of less-fractured reservoir rocks to be bypassed (fig. 25*H*). This is somewhat different from “transition zones” that lie above and marginal to continuous accumulations. It has long been recognized that gas available to charge reservoirs around the margins of a continuous accumulation might be insufficient to drive the water out of all of the sandstone reservoirs, and the term “transition zone” is generally used to describe these zones (see for example: Johnson and others, 1987; 1996a; 1999; Johnson and Roberts, 2003). A transition zone also can be created around a continuous accumulation that is “degrading” during uplift and exhumation (Meissner, 1978; Law and Dickenson, 1985).

Summary of Reservoirs, Traps and Seals

The events chart (fig. 26) 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. Timing of hydrocarbon generation are from Roberts and others (Chapter 6, this CD-ROM).

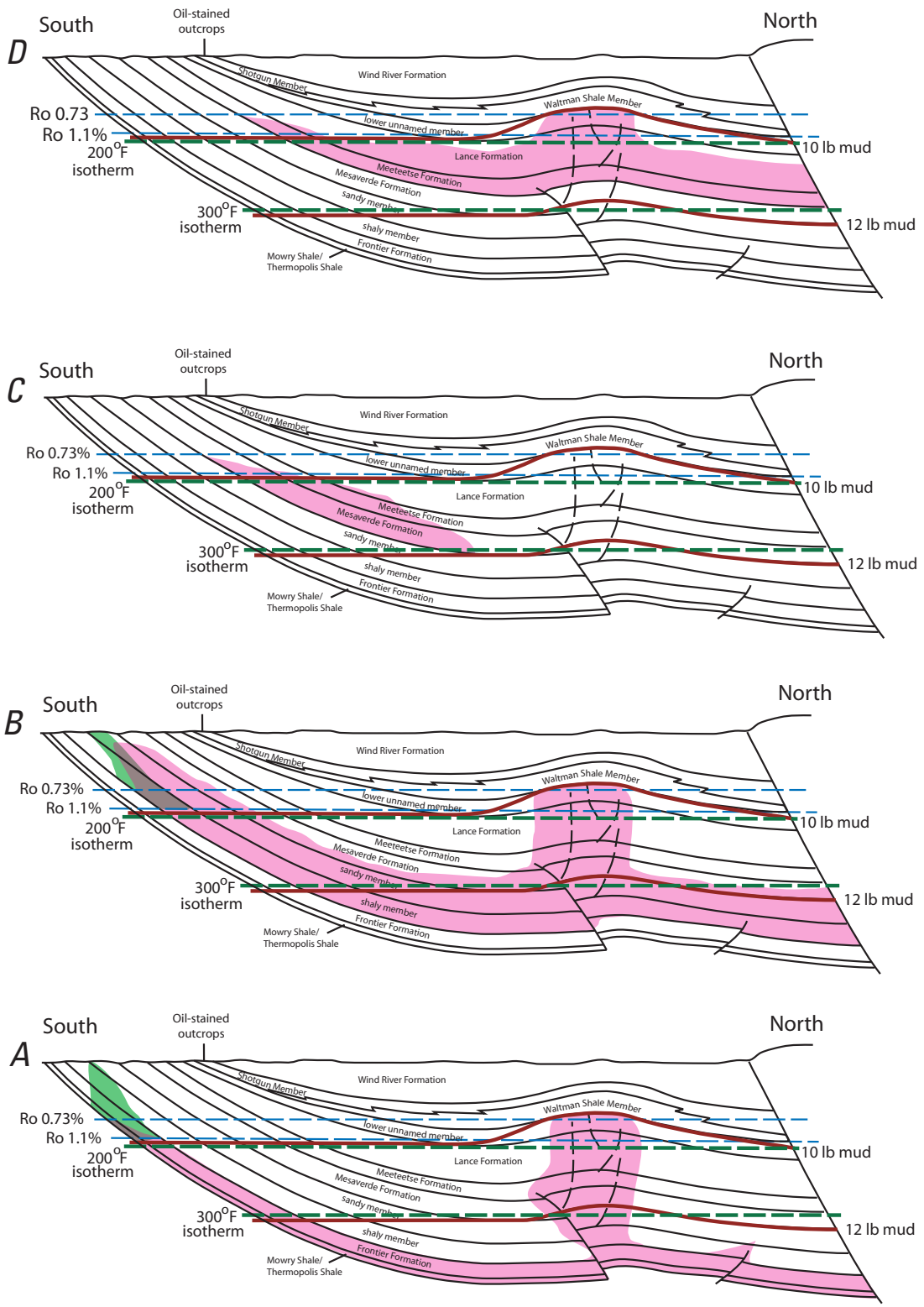

Figure 25*A*–*D*. Generalized model showing migration of hydrocarbons from Upper Cretaceous and Paleocene source rocks in the Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin, Wyoming. 25*A*: Mowry Shale, 25*B*: shaly member of the Cody Shale, 25*C*: Mesaverde Formation, 25*D*: Meeteetse Formation. The cross section generally runs south to north through the Madden anticline area. Colors: pink, thermogenic gas; and green, oil. Variations in thermal maturity using vitrinite reflectance (R_o), depths where 10-pound (lb) mud and 12-lb mud were used while drilling, and the 300° F isotherm are from Johnson and others (1996a, fig. 6).

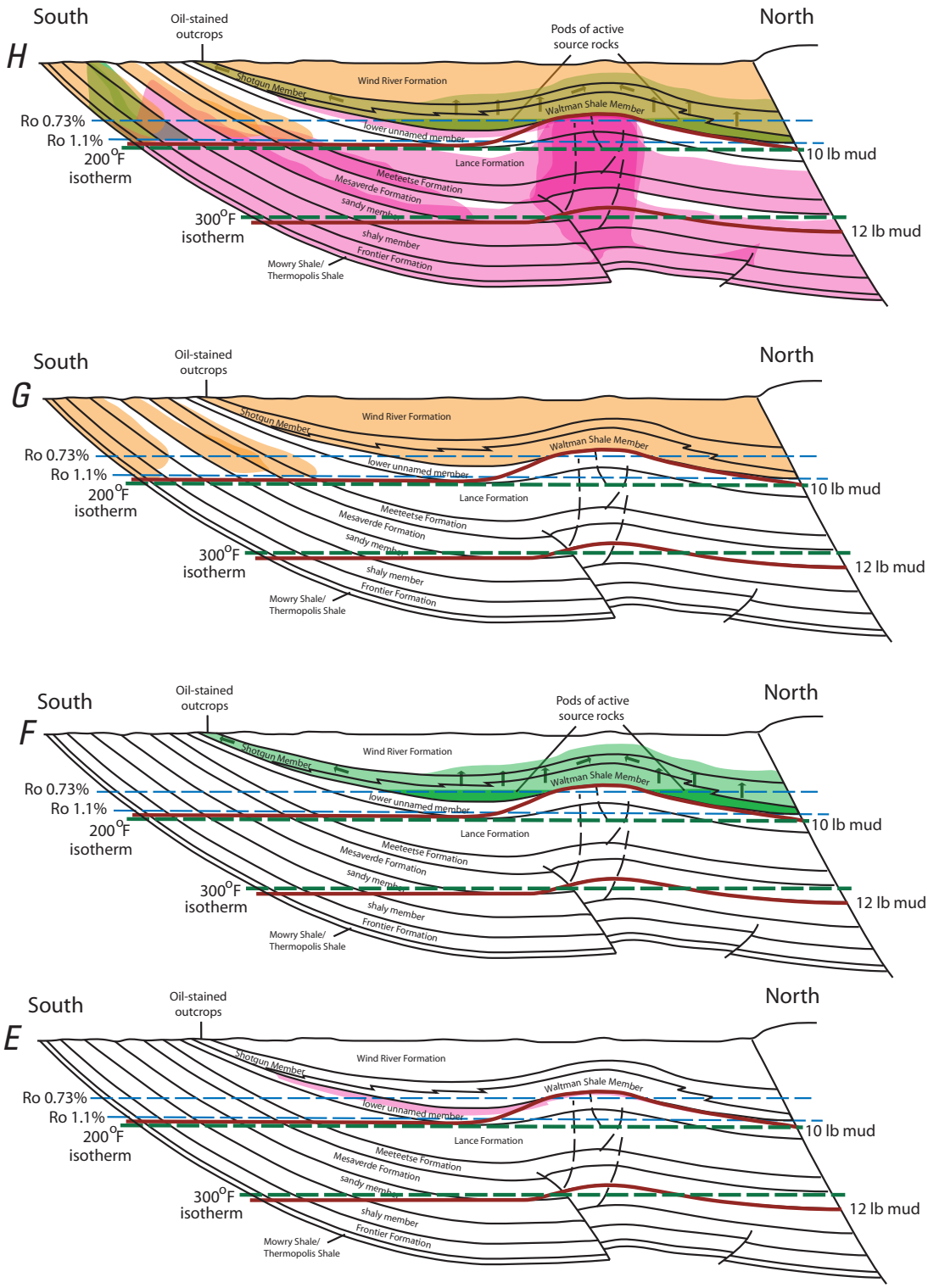

Figure 25*E-H*. Generalized model showing migration of hydrocarbons from Upper Cretaceous and Paleocene source rocks in the Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin, Wyoming. 25*E*: lower unnamed member of the Fort Union Formation, 25*F*: Waltman Shale Member of the Fort Union Formation, 25*G*: zone of potential biogenic gas, and 25*H*: summary diagram. The cross section generally runs south to north through the Madden anticline area. Colors: pink, thermogenic gas; orange, biogenic gas; and green, oil. Variations in thermal maturity using vitrinite reflectance (R_o), depths where 10-pound (lb) mud and 12-lb mud were used while drilling, and the 300° F isotherm are from Johnson and others (1996a, fig. 6). Arrows indicate migration of hydrocarbons.

Marine source rocks were deposited from Early to Late Cretaceous time (~105–80 Ma) and include the Thermopolis Shale, Mowry and Cody Shales, and Frontier Formation. Nonmarine coal and carbonaceous shale in the Mesaverde, Meeteetse, and Fort Union Formations, ranging in age from Late Cretaceous to Paleocene (~82–55 Ma), also are believed to be source rocks. Reservoir rocks range in age from Early Cretaceous to early Eocene (~134–50 Ma) and include fluvial sandstones and conglomerate in the Cloverly Formation, fluvial and estuarine sandstone in the Muddy Sandstone, marine sandstones in the Frontier Formation, marine sandstone and possibly fractured shale in the Cody Shale, marginal marine and fluvial sandstones, and coal beds in the Mesaverde and Meeteetse Formations, nonmarine sandstone in the Lance Formation, nonmarine sandstone and coal beds in the Fort Union Formation, and nonmarine sandstones in the Wind River Formation. The Thermopolis, Mowry, Cody, Lewis, and Waltman Shales provide thick regional seals. In addition, intraformational shales within each unit provide local seals. Important structural traps formed during the Laramide orogeny when compressional tectonics formed numerous anticlines along the margins of the basin. Permeability in tight basin-centered accumulations was enhanced by fractures resulting from Laramide deformation. Based on burial history and petroleum-generation modeling, gas generation began in the Mowry and Thermopolis Shales, the oldest source rocks in the basin, by about 80 Ma in the deepest parts of the basin (Roberts and others, Chapter 6, this CD-ROM). Continued subsidence and deposition progressively buried the younger source rocks until they achieved levels of thermal maturity sufficient to generate hydrocarbons. In deeper parts of the basin, generated oil reached thermal maturities sufficient enough to initiate thermal cracking of oil to gas. Computer modeling also indicates that in some of the shallower parts of the basin generation continues at a diminished rate to the present day (Roberts and others, Chapter 6, this CD-ROM).

Assessment Results

Figure 27 is a schematic cross section of the Wind River Basin showing the approximate extent of the eight continuous AUs in the Cretaceous-Lower Tertiary Composite TPS. Conventional AUs are marginal, above and below the continuous AUs.

Frontier-Muddy Continuous Gas Assessment Unit (AU 50350261)

Gas accumulations in the Frontier-Muddy Continuous Gas AU (fig. 28) are of the continuous type (unconventional) based on the criteria established by Schmoker (1996); they have the following characteristics: (1) lack of downdip water contacts, (2) little or no water production, (3) production extends downdip off structure into synclinal areas (fig. 29), (4) abnormally pressured (either high or low), (5) production and shows are independent of structural closure (fig. 29), and (6) reservoirs are in close association with source rocks. These conditions are generally reached at depths of 8,000 to 12,000 ft because of the interrelations of heat flow, source rock maturity, and overpressuring due to gas generation in low-permeability rocks (Law, 1984, figs. 10, 12; Spencer, 1987, fig. 5).

The limits of the Frontier-Muddy Continuous Gas AU (figs. 28 and 29) generally coincide with the 1.1 percent or greater R_o contour of Johnson and others (1996a), but was modified to exclude areas that have characteristics of conventional accumulations. Two significant deviations from the 1.1 R_o contour are in the Riverton Dome and Riverton Dome East field areas (fig. 1). At Riverton Dome, the AU boundary is placed at the west margin of the structure defined by a buried thrust based on seismic interpretation, and at Riverton Dome East, where there are reported hydrocarbon-water contacts (Little, 1989), the AU boundary is placed on the back (east) side of the structure. Another deviation is in the southeastern part of the basin, where the 1.1 percent R_o contour extends north from a line that connects a northwest-trending series of fields (Wallace Creek, Sun Ranch, Grieve, and Austin Creek) producing from the Muddy Sandstone (fig. 1). The northern boundary of the AU matches the Wind River Basin Province boundary defined by the major Owl Creek structure.

Exploration of the province began in 1886 (IHS Energy Group, 2005) and since then 51 wells are interpreted to have tested the Frontier-Muddy Continuous Gas AU for petroleum; of these wells, 22 are listed as producers and 29 are interpreted to be dry holes (figs. 28 and 29). Estimated ultimate recoveries (EUR) were calculated for the 22 producing wells; in one well, the EUR was determined to be below the minimum of 0.02 billion cubic feet of gas (BCFG). Tested cells for the Frontier-Muddy Sandstone Continuous Gas AU were counted using the criteria shown in figure 30. Only wells with minimum recoveries of more than 0.02 BCFG were used to calculate the EUR distributions, as EURs less than this minimum are not considered to be a significant resource with respect to a 30-year forecast span (Klett and Schmoker, 2003).

The EUR distribution, including only wells producing above the minimum (0.02) was used to help predict the potential recoveries for future addition to reserves in the Frontier-Muddy Continuous Gas AU (fig. 31). For details of the methods used to calculate EUR's see Cook (2005). The use of EUR thirds for determining the exploration history is not of much use in this AU because of the small number of producing wells.

The size of the AU is estimated to be about 1,750,000 acres (Appendix A). 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 based on the numbers estimated for the Frontier and Muddy equivalents in the Green River Basin (Kirschbaum and Roberts, 2005).

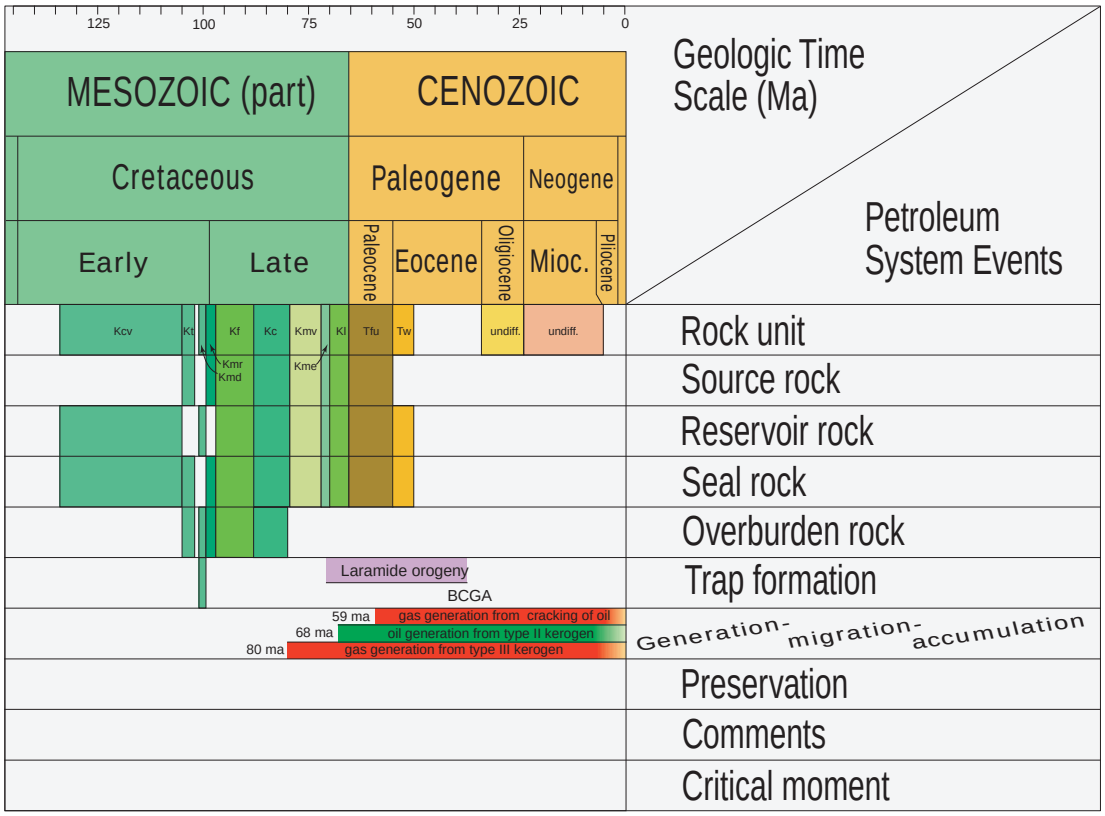

Figure 26. Events chart showing relation of essential geological elements and processes for the Cretaceous-Lower Tertiary Composite Total Petroleum System and assessment units, Wind River Basin, Wyoming. Kcv, Cloverly Formation; Kt, Thermopolis Shale; Kmd, Muddy Sandstone; Kmr, Mowry Shale; Kf, Frontier Formation; Kc, Cody Shale; Kmv, Mesaverde Formation; Kme, Meeteetse Formation; Kl, Lance Formation; Tfu, Fort Union Formation; Tw, Wind River Formation; undiff., undifferentiated Oligocene or Miocene deposits.

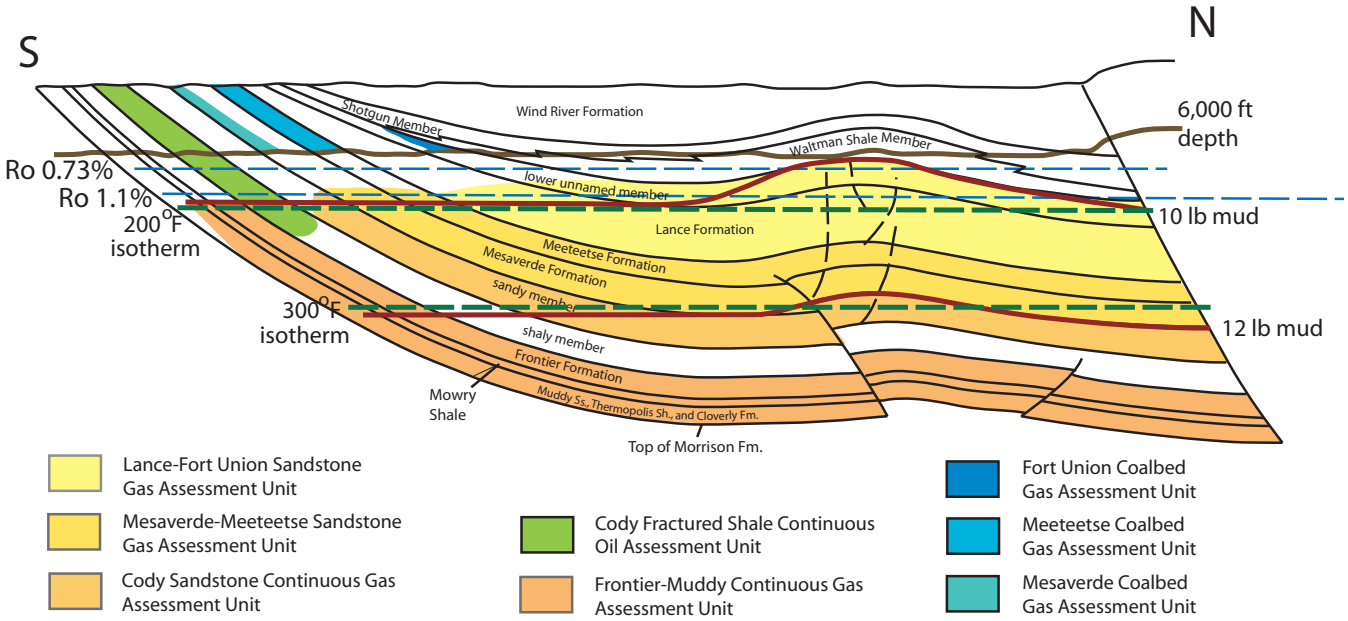

Figure 27. Schematic cross section showing the eight continuous assessment units in the Wind River Basin Province, Wyoming. Variations in thermal maturity, depths where 10-pound (lb) mud and 12-lb mud were used while drilling, and the 300° F isotherm are from Johnson and others (1996a, fig. 6). The cross section generally runs south to north through the Madden anticline.

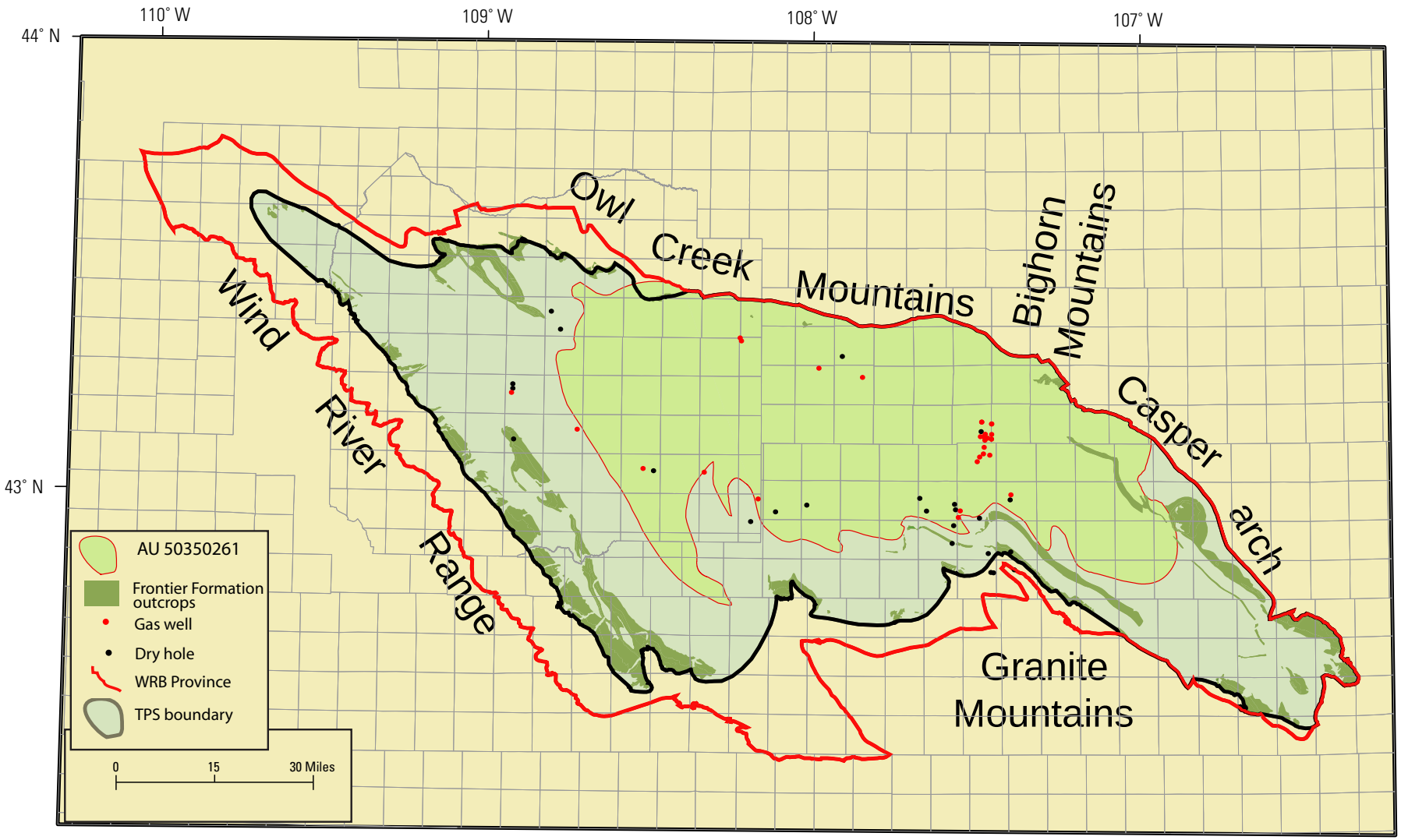

Figure 28. Area of Frontier-Muddy Continuous Gas Assessment Unit (AU 50350261), Cretaceous-Lower Tertiary Composite Total Petroleum System, and Wind River Basin Province (WRB), Wyoming. Dry holes (black) and producing gas wells (red) of the AU also are shown. TPS, Total Petroleum System.

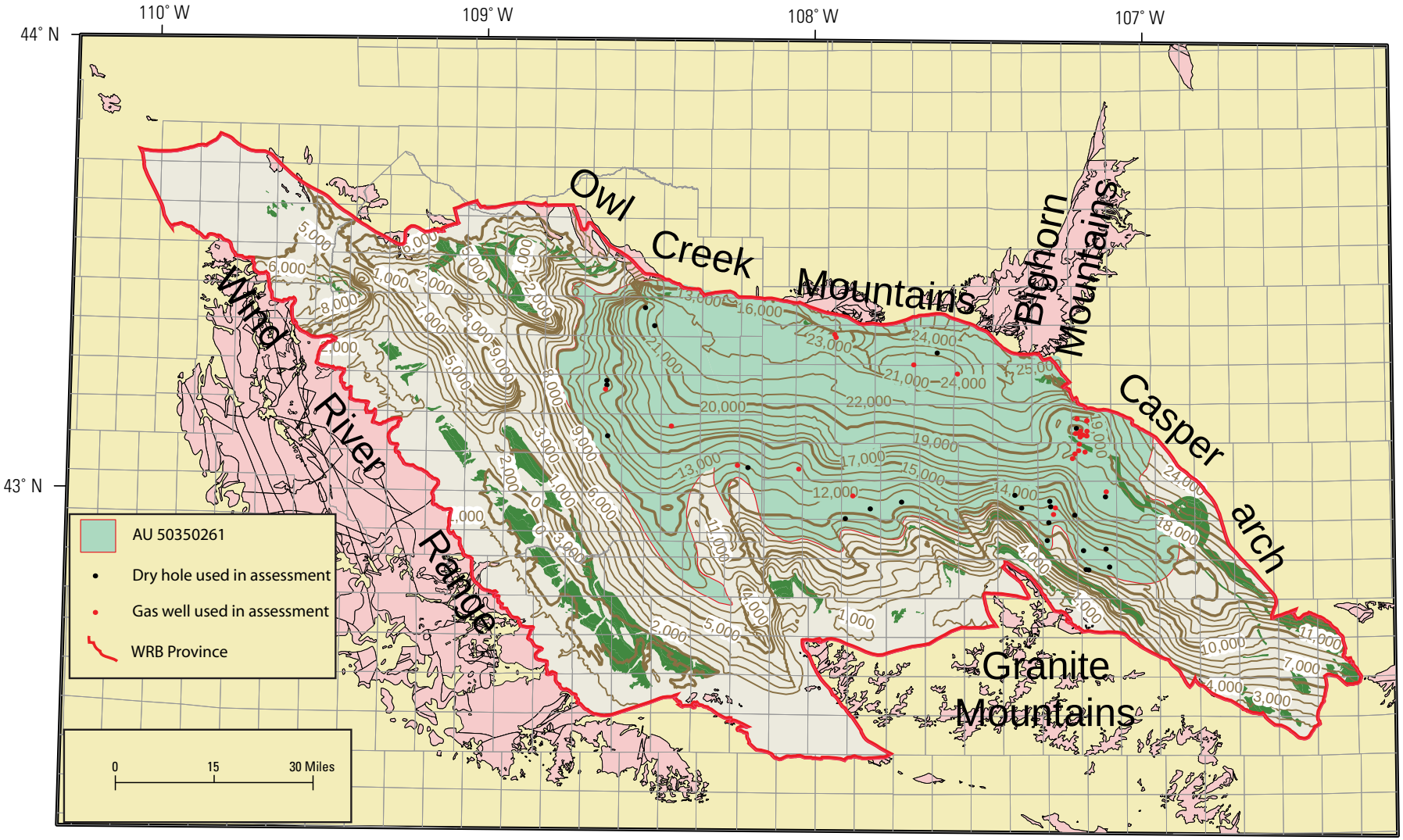

Figure 29. Depth to top of the Frontier Formation, Wind River Basin, Wyoming and area of Frontier-Muddy Continuous Gas Assessment Unit (AU 50350261) Wind River Basin (WRB), Wyoming. Contour interval: 1,000 feet.

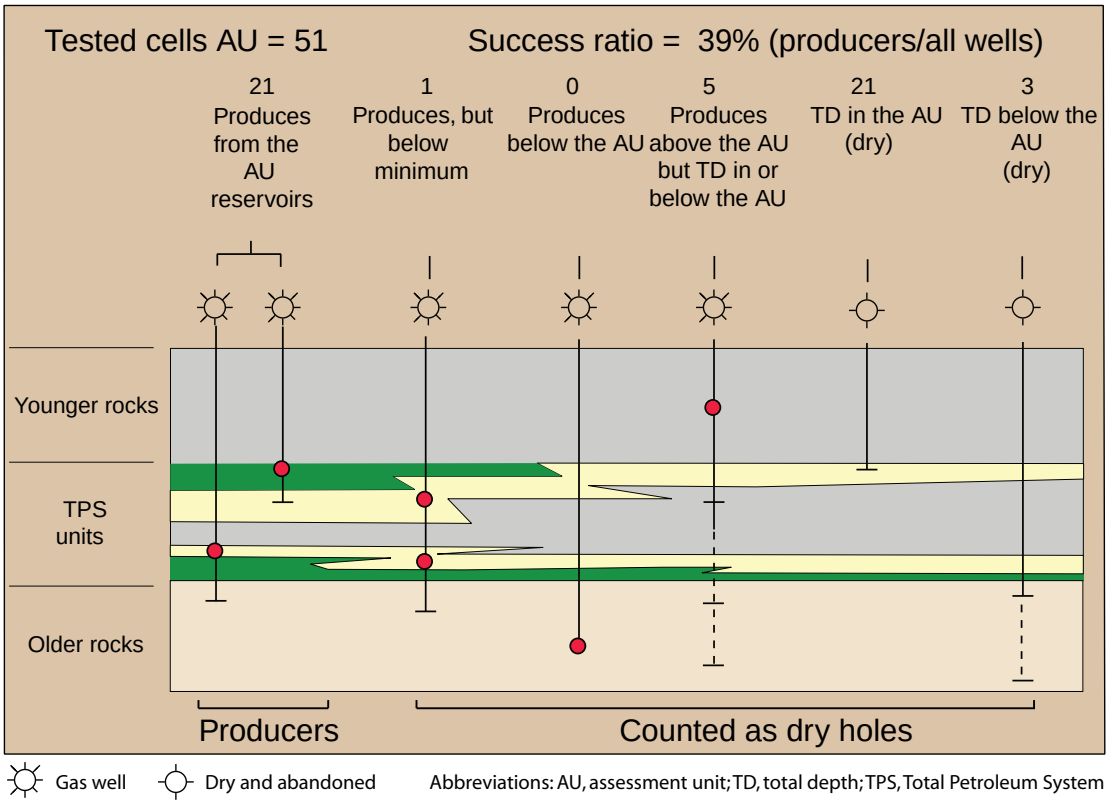

Figure 30. Criteria used to determine if a well tested the Frontier-Muddy Continuous Gas Assessment Unit.

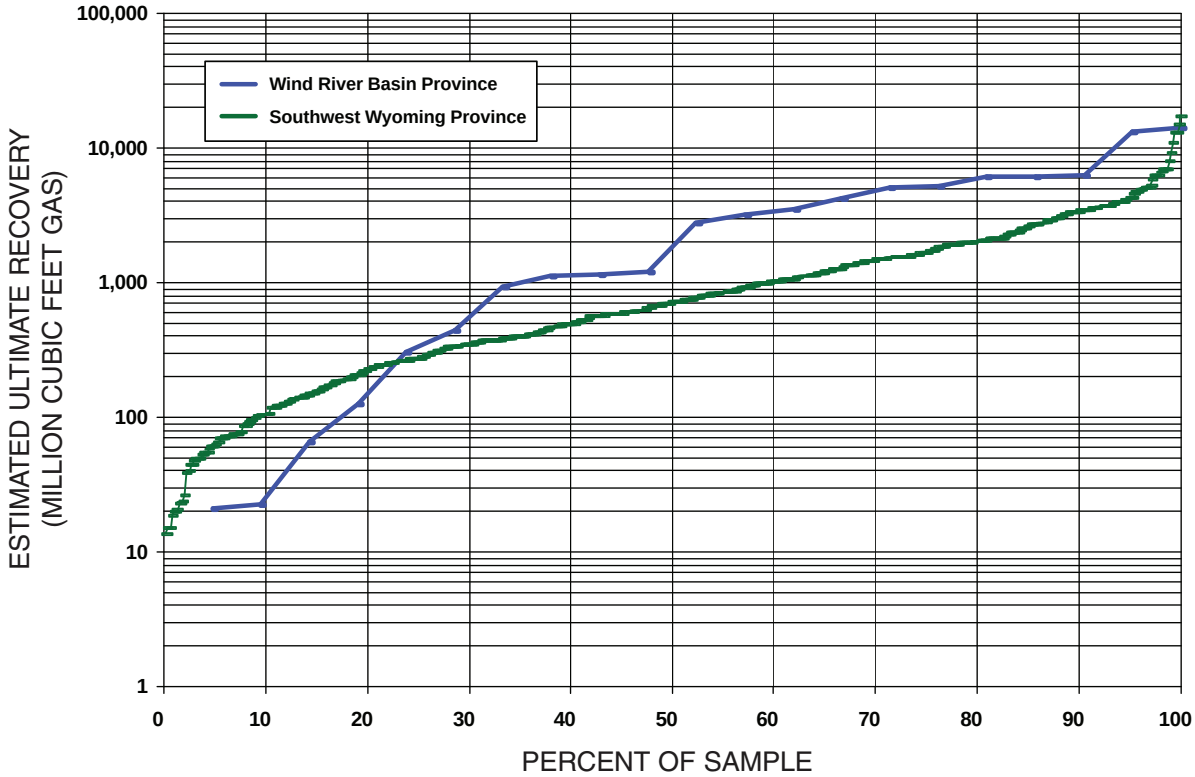

Figure 31. Distribution of estimated ultimate recoveries (EURs) for 22 gas wells within the Frontier-Muddy Continuous Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas are shown. Distribution of EURs for the Mowry Composite Continuous Gas Assessment Unit, Southwestern Wyoming Province also shown as a comparison.

The untested area, that is interpreted to have potential, about 99 percent of the 1.7 million acres, is based on the concept that the low permeability sandstones require enhanced natural fracturing or better than normal porosity for production to equal or exceed the minimum EUR.

A mean value of about 6 percent of the untested assessment unit area is thought to have potential for additions to reserves (Appendix A). The EUR distribution used for the untested area is based on historic values, but excludes wells below the 0.02 minimum (fig. 31). The median estimated EUR of 0.7 is based on data for the Green River Basin, which was used because of the sparce production in this province.

Potential for adding to reserves could come from: (1) infill drilling around existing production; (2) recompletions in the Frontier from producing holes in the Madison (3) hypothetical accumulations in the Frontier including: (a) fractured areas around the plunging anticlines on the south side of the basin, (b) top-truncated lowstand deltas in the Frontier similar to units described by Bhattacharya and Willis (2001) for the Powder River Basin, and (c) sandstone-rich intervals within valleys of the Muddy and Cloverly.

Infill drilling is expected to have a better success ratio than the historical ratio of 39 percent (Appendix A), stepout drilling is expected to have a similar success ratio, and in undrilled areas, the ratio is expected to be less than the historical success ratio. The Frontier-Muddy Continuous Gas AU has a mean estimate of 480.66 (table 1).

Cody Sandstone Continuous Gas Assessment Unit (AU 50350262)

The Cody Sandstone Continuous Gas AU produces gas from low permeability sandstone reservoirs, and encompasses approximately 1,800 square mile (mi^2) in the north-central part of the Wind River Basin (fig. 32). The north and northeast boundaries, coinciding with the TPS and province boundaries, define the approximate limits of the Cody Shale where it extends into the subthrust blocks of the Owl Creek Mountains and Casper arch. The west, south, and southeast boundaries of the AU were drawn using well data that generally separates updip areas where drillstem test results produce water and have nearly normal pressure gradients from downdip areas that have little or no recoveries of water and show greater than normal pressure gradients. The overall area closely coincides with the 1.1 percent vitrinite reflectance contour at the top of the sandy member of the Cody Shale (fig. 22). Nearly all wells within the AU that were tested had gas shows or produced natural gas.

The gas accumulations in the Cody are of the continuous-type (unconventional) using the criteria established by Schmoker (1996), and have the following characteristics: (1) lack of downdip water contacts (Brown and Shannon, 1989), (2) little or no water production (Wyoming Oil and Gas Conservation Commission, 2005; IHS Energy Group, 2005), (3) production extends downdip off structure into synclinal areas (fig. 33 and 34), (4) abnormally pressured (either high or low), (5) production and shows are independent of structural closure (figs. 33 and 34), and (6) reservoirs are in close association with source rocks.

Kuuskraa (1999) reported a pressure gradient of 0.765 pound per square inch per foot of depth (psi/ft) for Madden field, and Brown and Shannon (1989) reported an initial reservoir pressure of 13,000 psi at 17,123 ft for a similar pressure gradient of 0.76 psi/ft. Bilyeu (1978), Dunleavy and Gilbertson (1986), and Brown and Shannon (1989), reported that mud weights as much as 15 pounds per gallon were used to drill the Cody section in the central deeper part of the basin, and well log headers commonly report mud weights greater than 10 pounds per gallon for wells drilled in that area.

The Cody Sandstone Continuous Gas AU is lightly explored, with approximately 90 wells penetrating the section (fig. 35). Producing intervals range in depth from 13,500 to nearly 21,000 ft. According to the IHS Energy Group (2005), most of the production to date is from the crest of Madden anticline (fig. 36), a large Laramide feature located in the northern part of the AU. According to Dunleavy and Gilbertson (1986) and Kuuskraa (1999) the most prolific wells are located on the crest of the anticline where natural fractures enhance reservoir productivity (fig. 36). Potential for future discoveries would most likely be “sweet spots” formed by fractures associated with Laramide compressional features, including anticlinal trends, thrust faults, and normal faulting associated with post-Laramide extension.

Input data for assessing the undiscovered resources in the Cody Sandstone Continuous Gas AU is shown on the FORSPAN ASSESSMENT MODEL FORM, (Appendix B). The minimum and maximum areas estimated for the AU are 1,077,000, and 1,191,000 acres, respectively, with a calculated mean of 1,134,000 acres. The reason for the uncertainty is the structural complexity in the northern part and a general lack of well data along the south and west boundaries. The AU as indicated above is mostly untested, with only 90 wells penetrating the Cody section for a mean percentage of only 2 percent of the total AU area tested. Of the 90 wells, 83 that tested the Cody; 35 wells were producers with minimum EURs of 0.02 for a historical success ratio of 42 percent. A minimum of 0.8 percent and maximum of 8 percent of the untested AU area has potential for additions to reserves, with a calculated mean of 3.4 percent (see Appendix B). The minimum area assumes that no new “sweet spots” will be discovered and the only remaining potential is in the undrilled areas of the Madden anticline. The maximum area represents undrilled “sweet spots” throughout the AU associated with anticlinal trends, faults and fault zones, and plunging noses.

The estimated ultimate recovery distribution for Cody wells are shown by the graphs in figure 37. Figure 37*A* shows the distribution for all wells greater than the minimum cutoff of 0.02 BCFG, and figure 37*B* shows the distribution of wells greater than the minimum cutoff by discovery thirds. [Note: “Thirds” refers to the division into three parts of the number

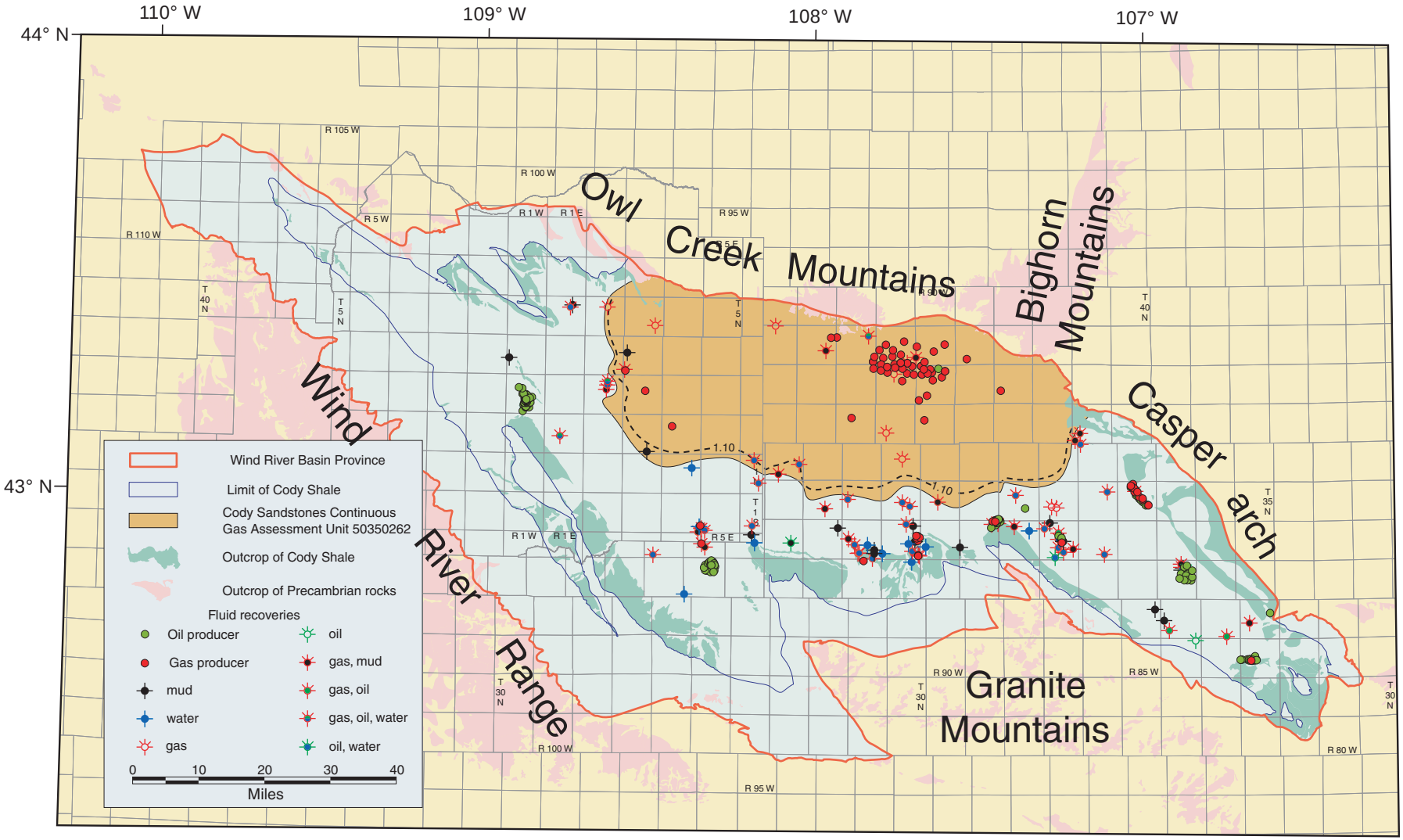

Figure 32. Areal extent of the Cody Sandstone Continuous Gas Assessment Unit (AU 50350262), producing wells, oil and gas shows, and dry holes. The dashed line is the 1.1 percent isoreflectance line at the top of the Cody Shale.

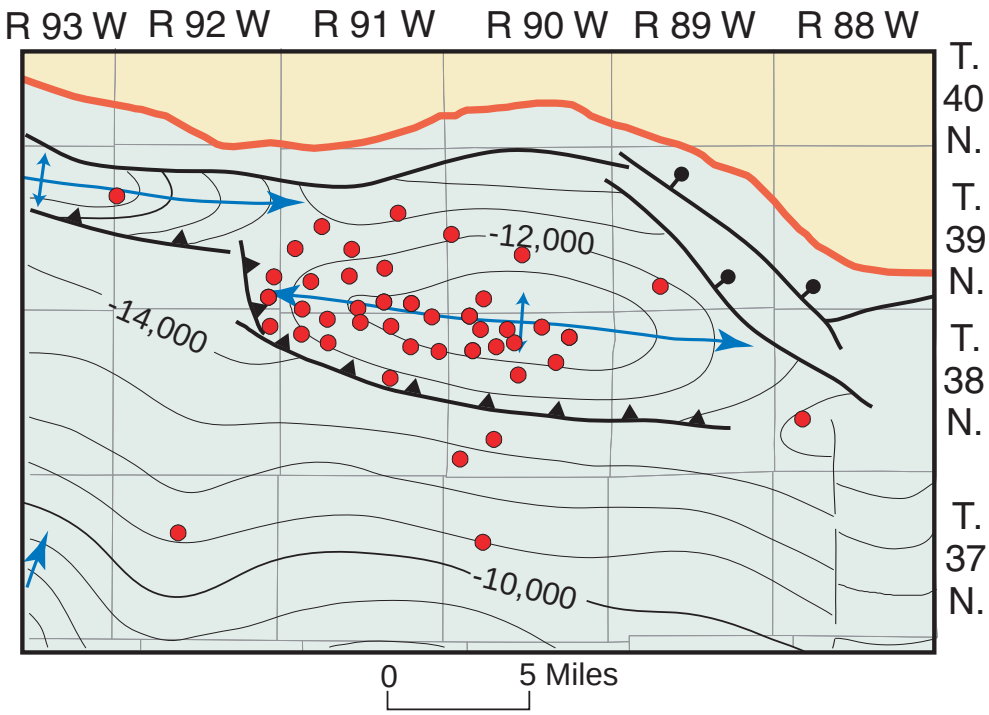

Figure 33. Wells (red circles) that produce gas from sandstone reservoirs of the Cody Shale both on adjacent to the Madden anticline.

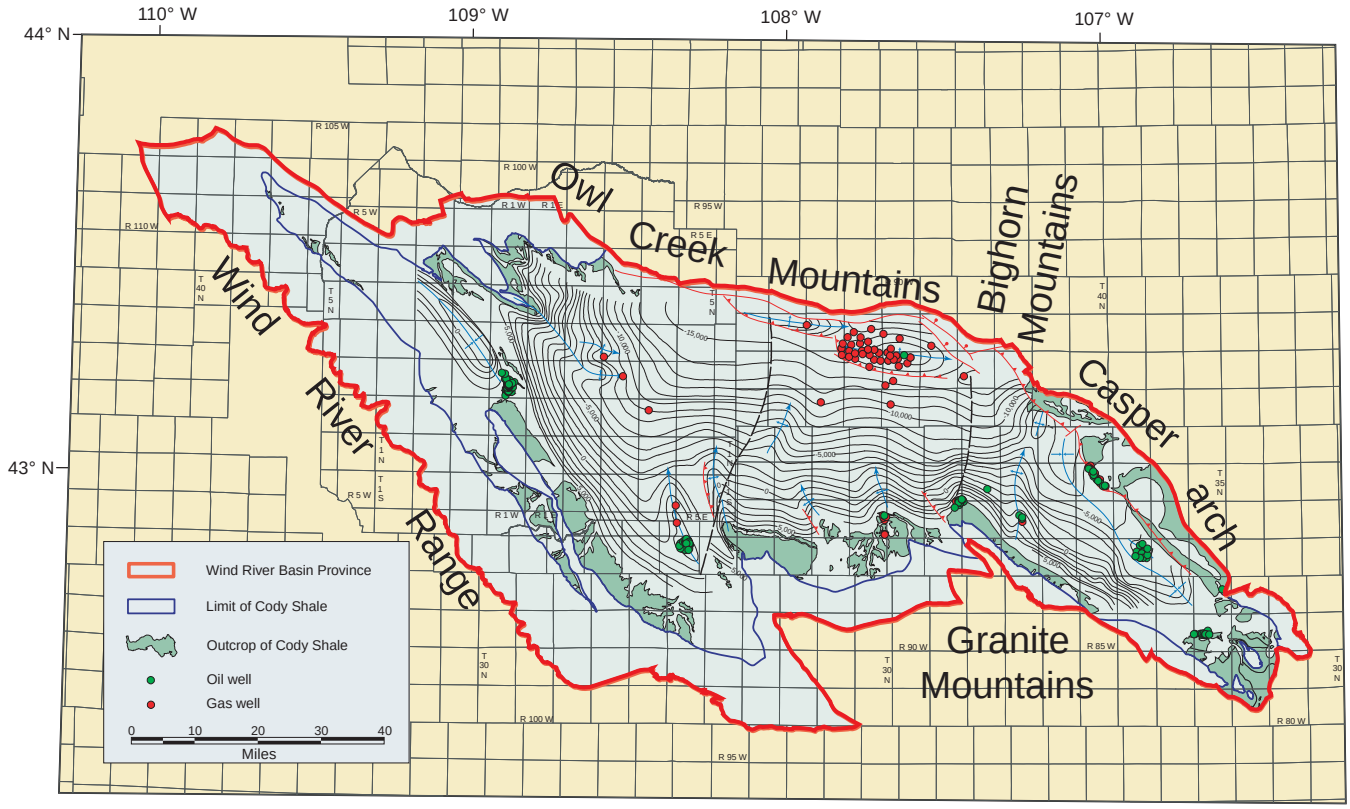

Figure 34. Structure contour map on top of the Cody Shale showing relation of gas production to structure. Most productive wells are associated with anticlinal crests. Heavy dashed lines indicate where Fales Sandstone Member (eastern line) and the "Alkali Butte member" of Mesaverde Formation (western line) join the main body of the Mesaverde Formation. Top of the Cody Shale drops stratigraphically west of these two lines. Structure contours modified from Johnson and others (1996b). Contour interval: 1,000 feet.

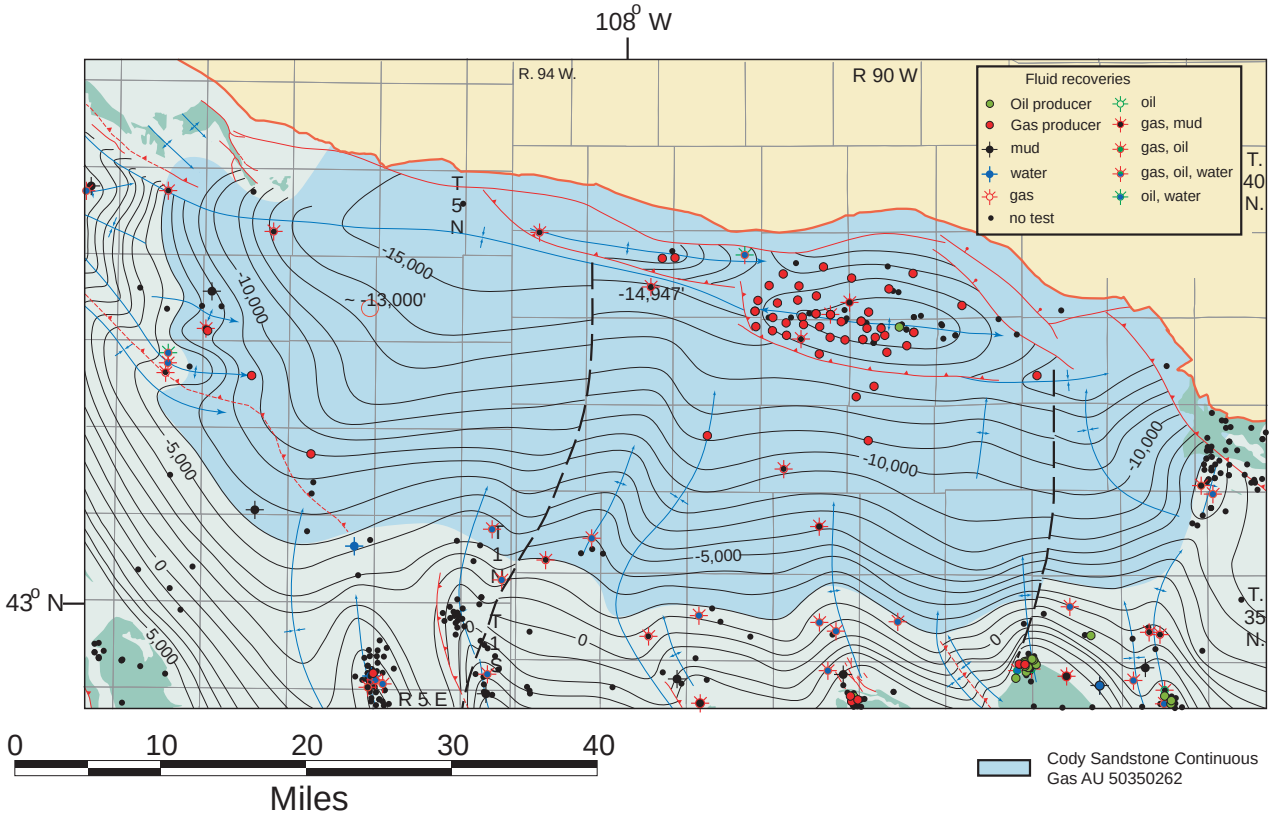

Figure 35. Detailed map of the Cody Sandstone Continuous Gas Assessment Unit (AU 50350262) showing all wells that penetrate the Cody Shale, producing wells, oil and gas shows, and structure contours at top of the Cody Shale. Contour interval: 1,000 feet. Heavy dashed lines indicate where the Fales Sandstone Member (eastern line) and the "Alkali Butte member" of the Mesaverde Formation (western line) join the main body of the Mesaverde Formation. Top of Cody Shale drops stratigraphically west of these two lines.

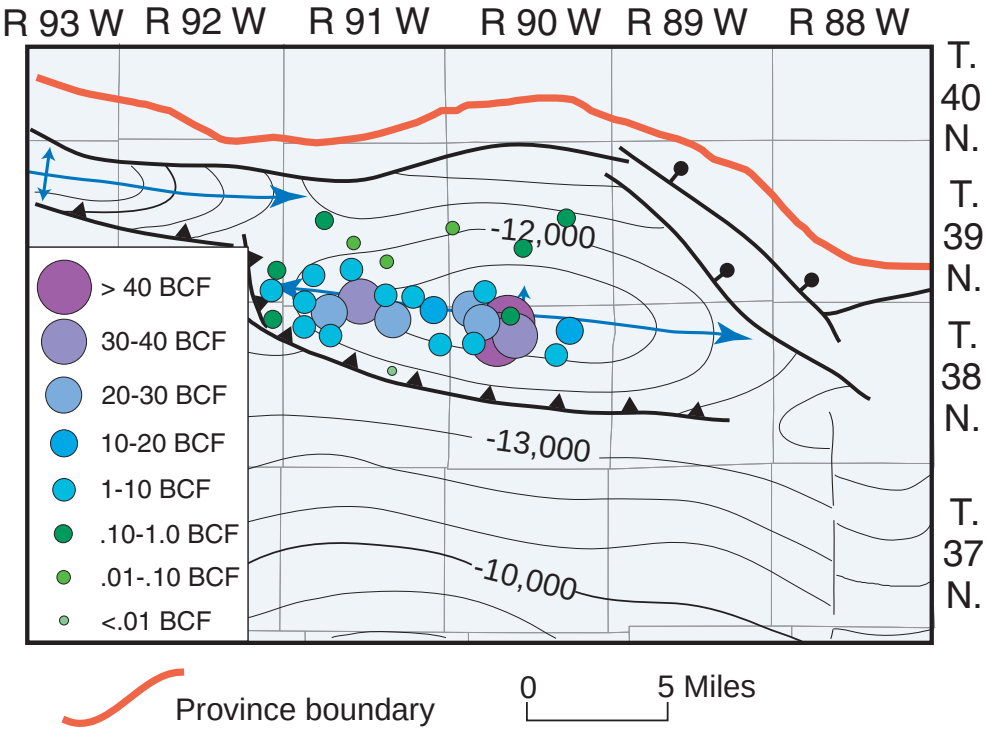

Figure 36. Cumulative production from Cody reservoirs at Madden anticline. Colored circles represent estimated ultimate recoveries for individual wells, in billions of cubic feet (BCF) of gas.

of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third (most recent) "third" of the wells drilled in order to investigate how the well EURs have changed with time.] Thus, the number of wells in each discovery third is the same, but the time span represented by each third is different. The median EUR for all wells greater than the minimum is 1.3 with a maximum of 50. The wells with the greatest cumulative production values are located on the crest of Madden anticline (fig. 36) where fracturing has enhanced production (Kuuskraa, 1999; Dunleavy and Gilbertson, 1986). Median EURs for the first, second and third discovery thirds are 1.2, 7.5, and 0.59 (Appendix B), respectively.

The minimum, median, and maximum total recovery per cell for untested cells having potential for additions to reserves is 0.02, 0.4, and 20 , respectively, with a calculated mean of 0.88 (Appendix B). The maximum value of 20 BCFG is much smaller than the maximum 50 BCFG because the belief is the best locations on Madden have already been drilled. The median value of 0.4 BCFG is lower than that of the historical third "third" of 0.59 BCFG because many of the best locations were probably drilled early, and that new wells will probably be located outside of the Madden "sweet spot."

The minimum, mode, and maximum area per cell of untested cells having the potential for additions to reserves is 40, 160, and 640 acres, respectively, with a calculated mean of 280 acres. The minimum and modal values reflect the analysis of production data at Madden anticline by Kuuskraa (1999), who used production data and type-curve matching to determine that drainage areas for the "Sussex and Shannon" sands range from approximately 40 to 160 acres. The maximum drainage value reflects the field spacing at Madden field of 640 acres (Brown and Shannon, 1989), and also because of unpublished reports that indicate some communication exists between wells that are in some cases miles apart. This wide range in drainage areas reflects the variable production that can be typical of many fractured reservoirs (Dunleavy and Gilbertson, 1986).

The mean estimate for undiscovered gas resources that have potential for additions to reserves in the Wind River Basin is 115.34 BCFG. Tabulated results for the Cody Sandstone Continuous Gas AU (50350262) for undiscovered, gas, and natural gas liquids that have potential for additions to reserves are summarized in table 1.

Cody Fractured Shale Continuous Oil Assessment Unit (AU 50350263)

The Cody Fractured Shale Continuous Oil AU is a hypothetical assessment unit that is believed to have the potential to produce oil from fractured calcareous shale reservoirs in the lower shaly member of the Cody Shale. The AU occupies approximately 1,200 mi^2 and is located in the southeastern third of the Wind River Basin (fig. 38). The northeast boundary is drawn arbitrarily at the crest of the Casper arch, which coincides with the Cretaceous-Lower Tertiary Composite TPS and Wind River Basin Province boundaries. The south and southwest boundaries are defined as the base of the Cody outcrop (fig. 38). Because the AU is believed to be self-sourced, the northwest boundary is arbitrarily drawn to coincide with the more hydrogen-rich and organic-rich source rocks of the lower shaly member of the Cody Shale (Finn, Chapter 8, this CD-ROM). The Cody Fractured Shale Continuous Oil AU is characterized as a continuous-type (unconventional) accumulation because of geologic similarities with the Niobrara production in the Sand Wash Basin portion of the Southwest Wyoming Province (Finn and Johnson, 2005; Vincelette and Foster, 1992). Potential for future discoveries would most likely be "sweet spots" associated with fracture development along folds and faults. The AU was not quantitatively assessed because of the lack of production data.

Mesaverde-Meeteetse Sandstone Continuous Gas Assessment Unit (AU 50350264)

The limits of the Mesaverde-Meeteetse Sandstone Continuous Gas AU shown in figure 39, generally follow variations in thermal maturity at the base of the Mesaverde Formation, falling between R_o values of 0.73 and 1.1 percent. Muddy Ridge and Madden fields produce virtually all of the gas in the AU. The AU extends into thermal maturities of slightly less than R_o 0.73 percent locally to include all Mesaverde and Meeteetse production in the Pavillion field, as the R_o 0.73-percent line runs through the middle of the field (fig. 39). There is no reliable permeability data reported for Mesaverde and Meeteetse production at Muddy Ridge field, and the gas accumulation there might be more conventional than continuous. Muddy Ridge field also produces gas from the Upper Cretaceous Lance, Paleocene Fort Union, and Eocene Wind River Formations, but only the Mesaverde and Meeteetse production is considered continuous, as conventional permeabilities have been reported from these younger units (Mueller, 1989a, 1989b).

The Mesaverde-Meeteetse Sandstone Continuous Gas AU covers a mode of 1,204,000 acres with a minimum of 1,088,000 acres and a maximum of 1,325,000 acres (Appendix C). A large uncertainty of plus or minus 10 percent was applied to the mode because the limits of the continuous accumulation are poorly defined, due to the limited number of tests in the Mesaverde and Meeteetse Formations, and because there appears to be a gradation between continuous-type reservoirs and more conventional reservoirs. Tests in the upper part of the underlying Cody Shale also were used to help define the limits of the AU, as both the lower part of the Mesaverde and upper part of the Cody Shale contain similar

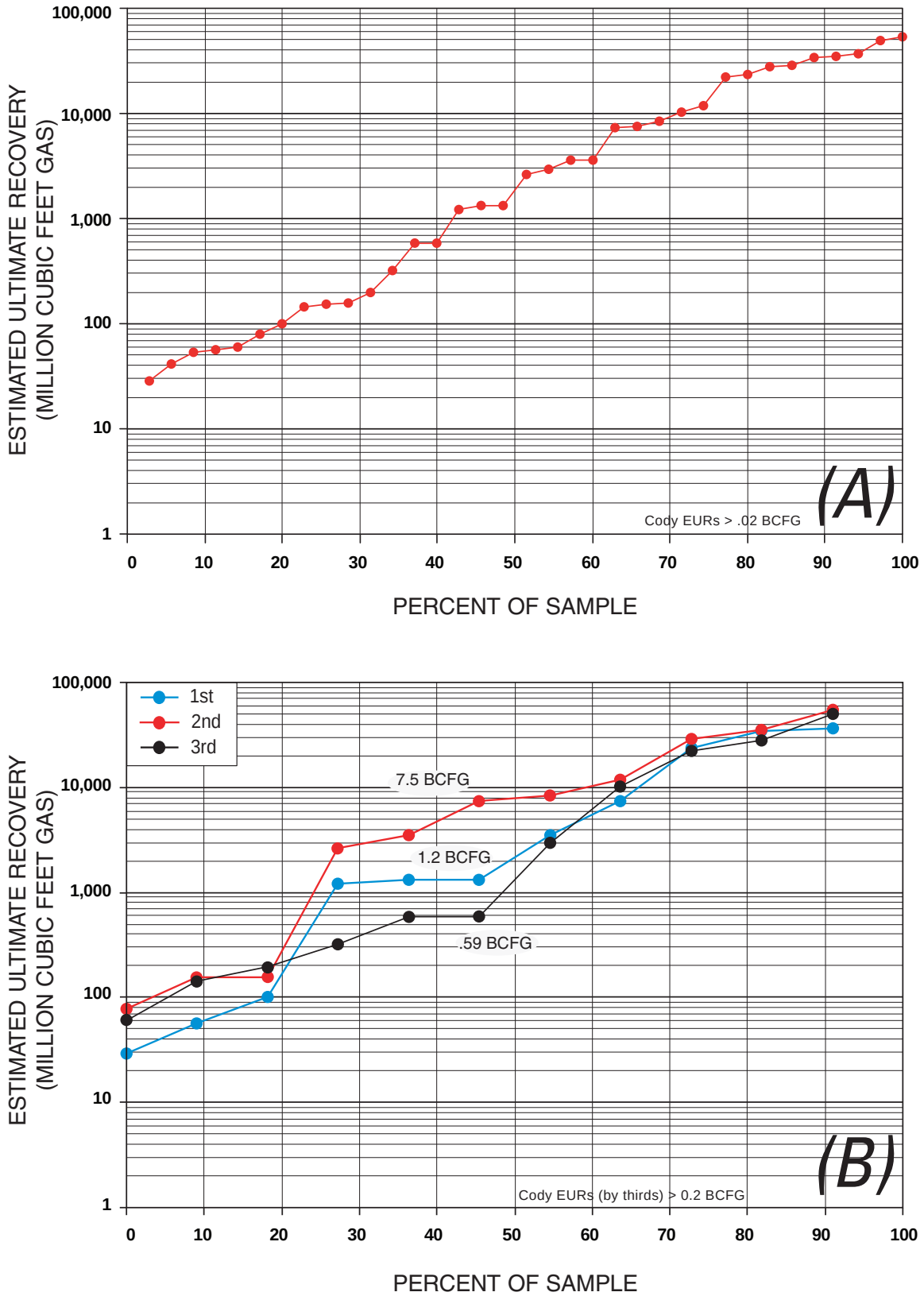

Figure 37. Estimated ultimate recovery (EUR) in billions of cubic feet of gas (BCFG) for wells in the Cody Sandstone Continuous Gas Assessment Unit (AU): *A*, EUR distribution for all wells; *B*, EUR distribution by discovery thirds. Discovery thirds refers to the division into three equal parts of the 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 to determine the change in EURs with time.

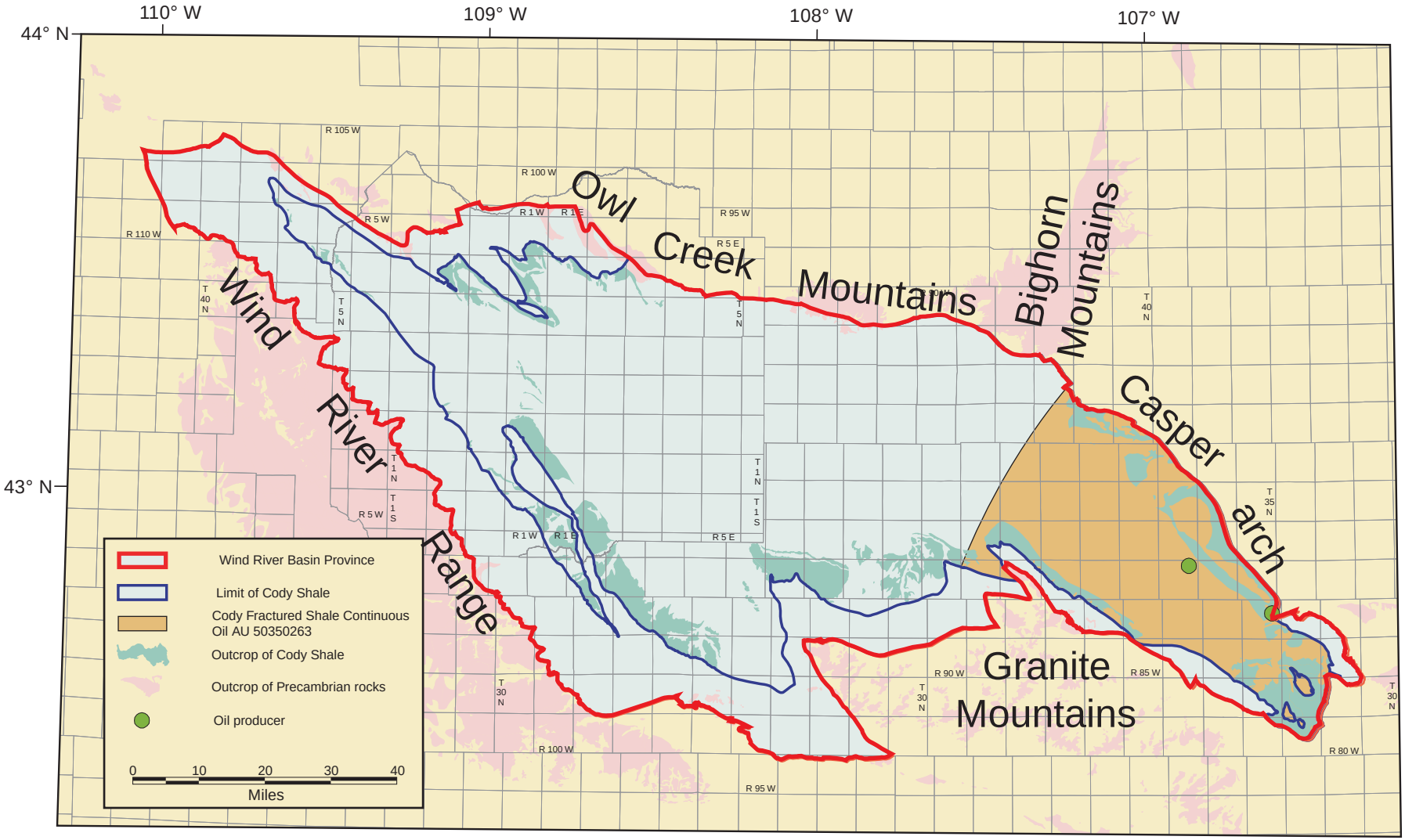

Figure 38. Extent of the Cody Fractured Shale Continuous Oil Assessment Unit (AU 50350263).

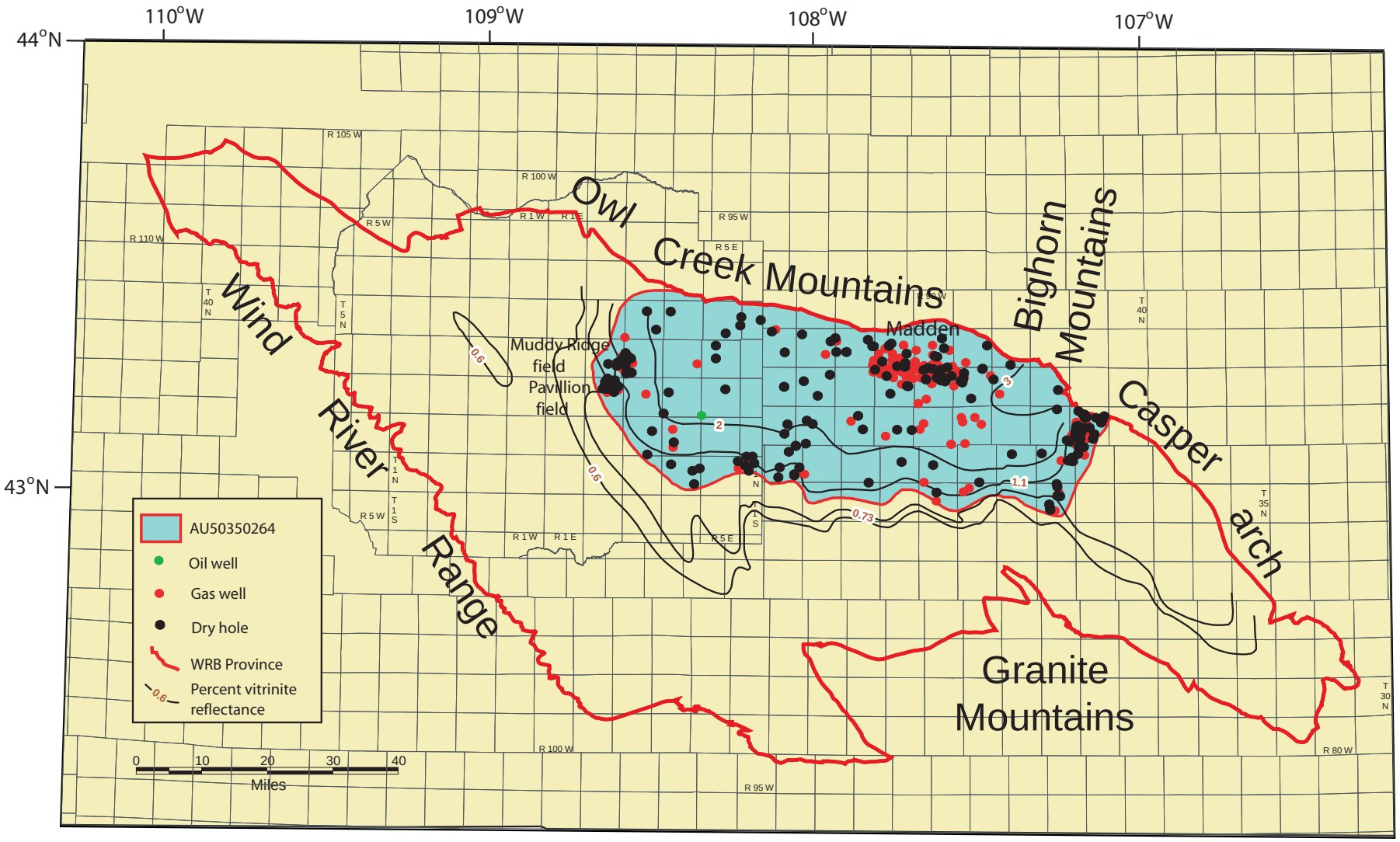

Figure 39. Extent of the Mesaverde-Meeteetse Sandstone Gas Assessment Unit (AU 50350264) in the Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin (WRB) Province, Wyoming. Producing gas wells shown in red and dry holes shown in black. Madden and Muddy Ridge fields produce almost all of the gas from the AU. The Mesaverde-Meeteetse producers shown at Waltman field bottom in the uppermost Meeteetse but produce from the overlying Lance Formation.

blanket-like marginal marine sandstones, and the limits of the continuous-type gas accumulation in these reservoirs should be similar. As a result, the limit of the Mesaverde-Meeteetse Sandstone Continuous Gas AU coincides with that of the Cody Sandstone Continuous Gas AU to the south, but extends farther toward the east and west basin margins than does the Cody AU, in order to incorporate tests and production that were deemed to be continuous. The Mesaverde-Meeteetse Sandstone Gas AU is overpressured in the deeper parts of the basin (Bilyeu, 1978; Dunleavy and Gilbertson, 1986; Johnson and others, 1996a).

Johnson and others (1996a), in their calculation of in-place gas resources in the continuous accumulations in the Wind River Basin, compared variations in mud weights used while drilling, variations in thermal maturity, and variations in temperature in an attempt to define the basin-centered accumulations in the basin. They observed that an R_o of 1.1 percent generally coincides with the first use of 10-pound mud or greater while drilling, indicating that an R_o of 1.1 percent could generally be used to define the limits of the overpressured continuous accumulations in the basin. An R_o of 1.1 percent is the approximate thermal maturity level where the expulsion of significant amounts of hydrocarbon gases from coals begins (Levine, 1993), thus providing a source of gas to form a continuous accumulation in a coal-rich interval like the Upper Cretaceous and lower Tertiary interval in the Wind River Basin. In addition, Johnson and others (1996a) established a transition zone, which had both conventional and continuous reservoirs, between the R_o levels of 0.73 and 1.1 percent. Johnson and others (1996b) used an R_o of 1.1 percent at the base of the Mesaverde to define the limits of the continuous accumulation in the Mesaverde and an R_o of 1.1 percent at the base of the Meeteetse to define the continuous accumulation in the Meeteetse. An R_o between 0.73 and 1.1 percent was used to define a “transition zone” with characteristics of both continuous and conventional reservoirs. The Mesaverde and Meeteetse Formations are combined into one AU in this assessment, and a transition zone was not established because of a lack of data.

Time-temperature modeling by Roberts and others (Chapter 6, this CD-ROM) using data from four wells within the Mesaverde-Meeteetse Sandstone Continuous Gas AU (fig. 40), indicates that gas generation began in the deepest part of the AU near the end of the Cretaceous, peaked in the middle Paleocene, and ended in the middle Eocene; whereas, gas generation continues today in the shallower areas of the AU. The onset of gas generation for Type III organic matter, R_o 0.5 percent, began at the base of the Mesaverde in the Big Horn 1-5 well (fig. 40) at 66 Ma; the peak for gas generation, R_o 0.8 percent, was at 59 Ma; and the end of gas generation, R_o 2 percent, was at 48 Ma. The Bighorn well is the most thermally mature well in the AU. In the Shell 33X-10 well, the least thermally mature of the four wells in the AU, gas generation at the base of the Mesaverde began 51 Ma and peak generation has not yet occurred. The onset of gas generation for Type III organic matter at the base of the Meeteetse Formation in the Bighorn 1-5 well was at 65 Ma, the peak was at 57 Ma, and the end was at 43 Ma; whereas, the onset of gas generation in the Shell 33X-10 well at that stratigraphic level was at 47 Ma.

There are 157 tested cells in the AU, of which 34 are projected to produce above the minimum of 0.02 BCFG, for a success ratio of 22 percent. Of this total, 37 tests and 19 producers are at Muddy Ridge field and 39 tests and 13 producers are at Madden field (field location shown on fig. 1). Outside these two fields, there are 81 tests and only 3 producers. Cells within Mesaverde-Meeteetse Sandstone Continuous AU were counted using the following criteria:

1. Wells that bottomed in the Mesaverde and Meeteetse Formations were considered as tests.
2. Wells that penetrated more than 300 ft of Meeteetse were considered as tests, but wells that bottom in the uppermost part of the Meeteetse and produce from the overlying Lance and Fort Union Formations were eliminated tests, as the top of the Meeteetse was probably used by the driller as a marker to know that the entire Lance had been penetrated.
3. Wells that produce from units below the AU were not included as tests.
4. Wells that penetrated below the AU but were dry holes were included as tests.
5. Any Cody gas wells that were recompleted up hole were considered as tests even if the recompletion was above the Mesaverde and Meeteetse.

Figure 41 shows the EURs for all Mesaverde and Meeteetse wells exceeding the minimum of 0.2 BCFG. Figure 42 shows EURs for Mesaverde and Meeteetse wells exceeding the minimum divided into discovery “thirds”. The median EUR for all wells is 1.2 BCFG; whereas, EURs by “thirds” are 1.8 BCFG for the first “third”, 2 BCFG for the second “third”, and 1.1 BCFG for the third “third”.

One factor that may have contributed to the decline in EURs for the most recent “third” is interference among wells drilled at closer than optimal spacing, particularly at Muddy Ridge field. Figure 43 shows EURs for the Mesaverde and Meeteetse Formations at just Muddy Ridge field where 19 out of 35 of the producers are located, and figure 44 shows “thirds” for the field. The median EUR for these wells at Muddy Ridge is 0.9; whereas, EURs by thirds are 1.2 BCFG for the first “third”, 1.5 BCFG for the second “third”, and 1.2 BCFG for the most recent “third”. The productive area for the 37 Mesaverde and Meeteetse tests at Muddy Ridge is about 1,920 acres, for an average well spacing of about 52 acres. The slight decline from the second to most recent third indicates that the optimum well spacing at Muddy Ridge should be about 60 acres. Median EURs for Mesaverde and Meeteetse wells at Madden field is 2.8 (fig. 45), but there are too few producers to generate a EUR distribution divided into “thirds”. The productive area for the 39 Mesaverde and Meeteetse tests at Madden is about 11,140 acres, yielding an average well spacing of about 285 acres. It is unlikely that Mesaverde and Meeteetse reservoirs there are being completely drained at 285 acres, so optimum well spacing is likely to be somewhat

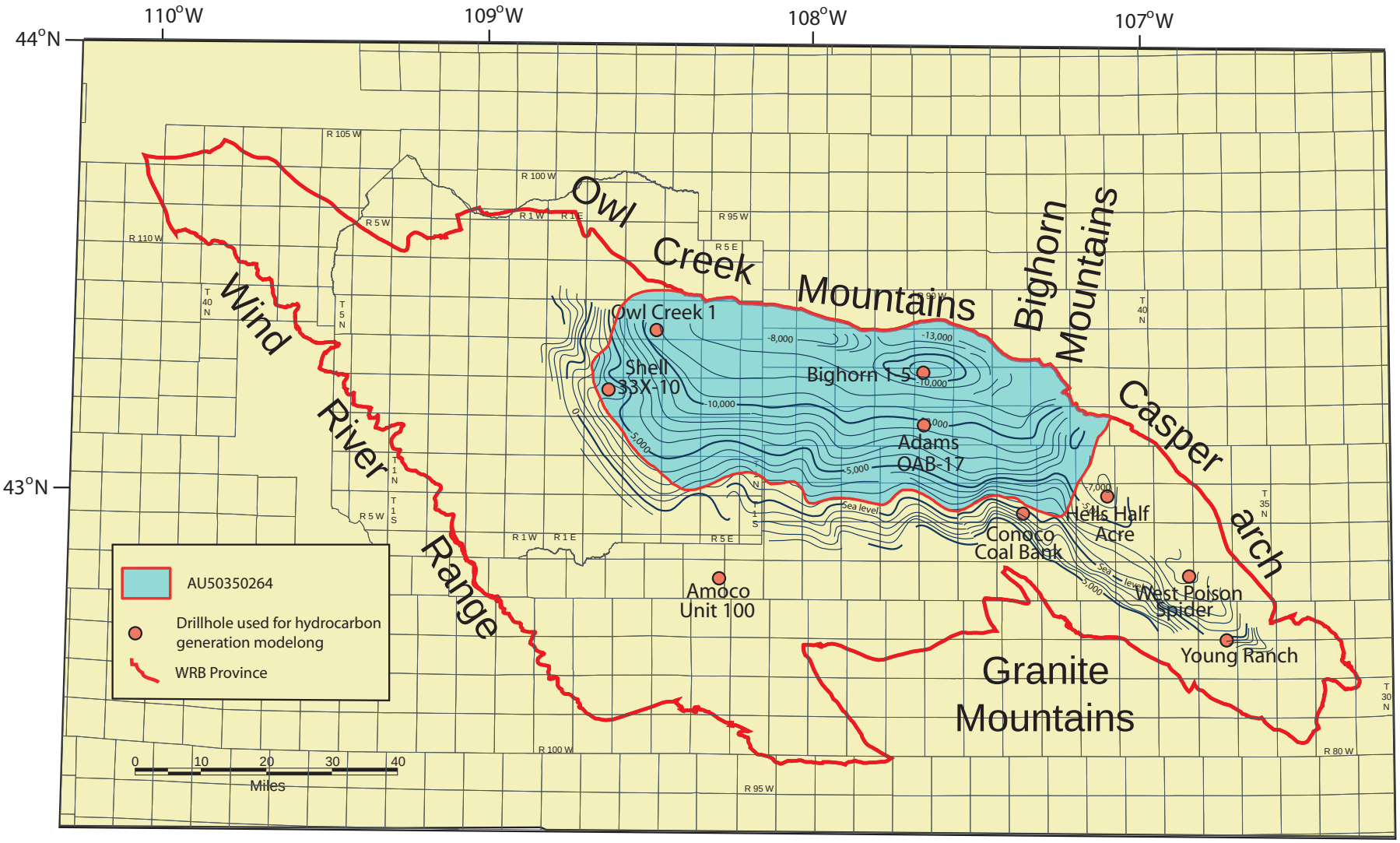

Figure 40. Locations of nine wells used by Roberts and others (this CD-ROM) for modeling the timing of hydrocarbon generation in the Wind River Basin (WRB) Province, Wyoming. Four of the wells are in the Mesaverde-Meeteetse Sandstone Gas Assessment Unit (AU 50350264). Structure contour map is on top of the Mesaverde Formation and is modified from Johnson and others (1996b). Contour interval: 1,000 feet.

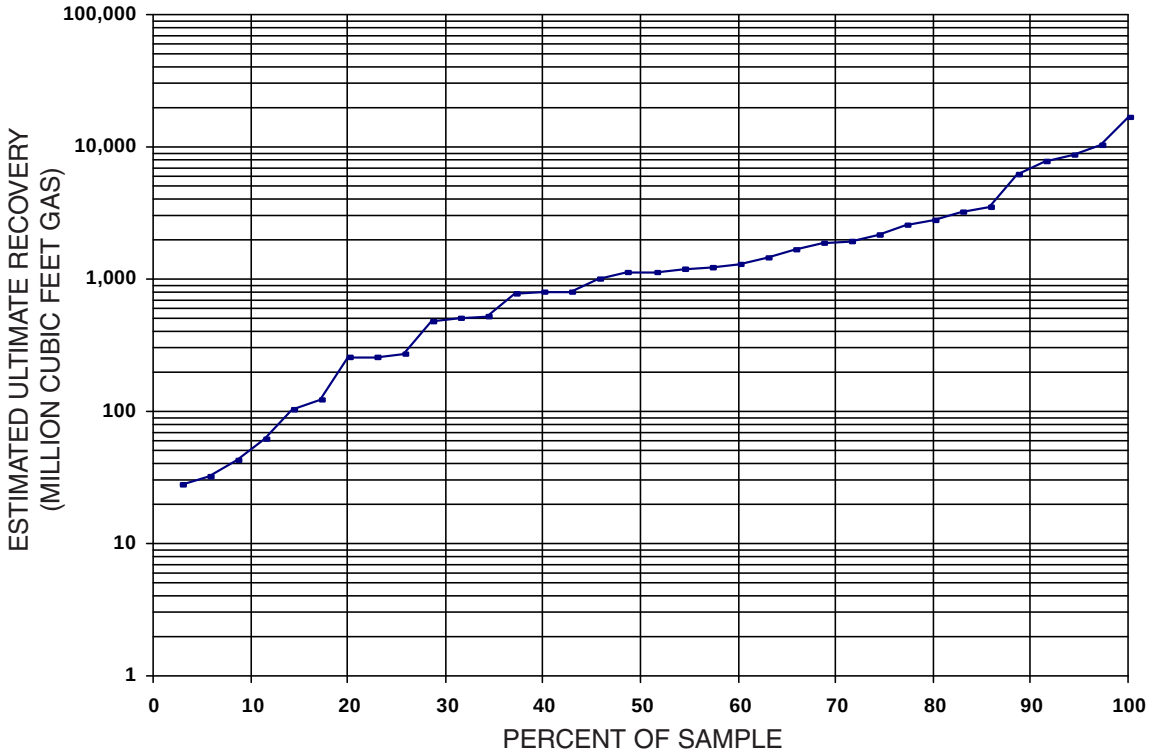

Figure 41. Distribution of estimated ultimate recoveries (EURs) for gas wells within the Mesaverde-Meeteetse Sandstone Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming. Only wells with minimum EURs exceeding 20 million cubic feet of gas (MMCFG) are shown.

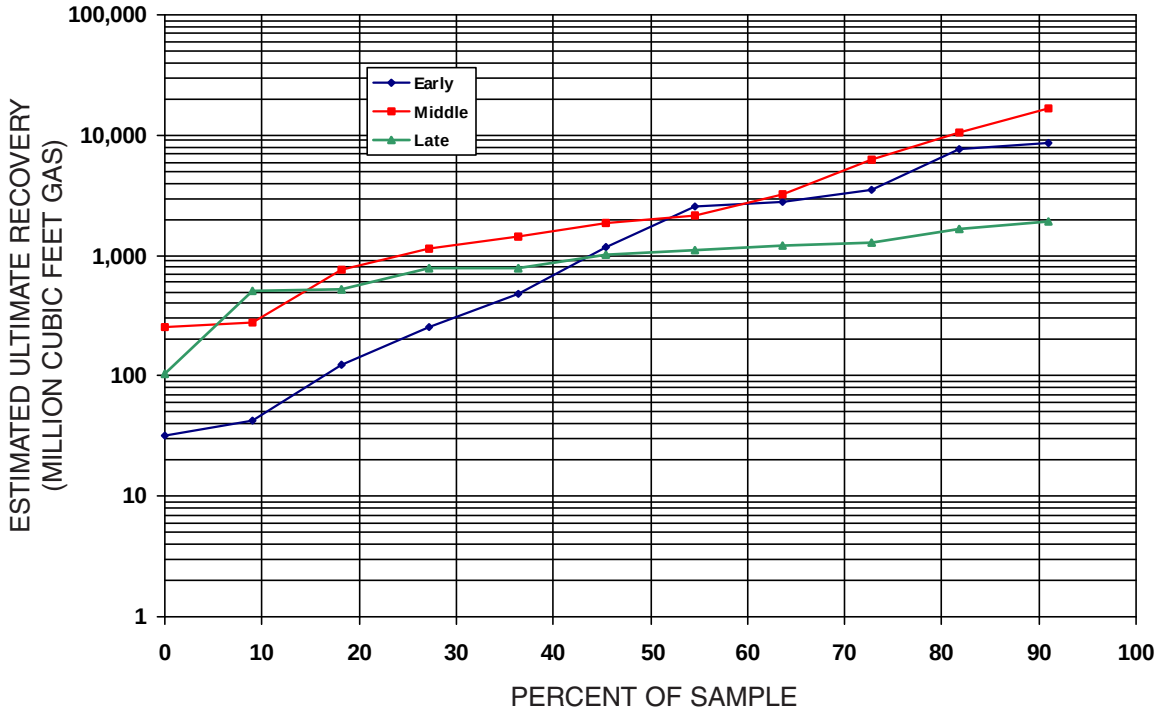

Figure 42. Dstribution of estimated ultimate recoveries (EURs) by "thirds" for gas wells completed within the Mesaverde-Meeteetse Sandstone Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming. "Thirds" refers to the division into three parts of the number of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third "third" of the wells drilled to determine changes in EURs with time. Only wells with minimum EURs exceeding 20 million cubic feet of gas (MMCFG) are shown.

less. Kuuskraa (1999) estimated that the Margaret 1-6 well completed in the Mesaverde Formation at Madden anticline (not shown on fig. 40) drained from 80 to 100 acres. The productive Mesaverde reservoirs at Madden appear to be marginal marine blanket-like sandstones with larger drainage areas than the productive lenticular channel sandstones at Muddy Ridge field.

Minimum, mode, and maximum area per cell of untested cells within the Mesaverde-Meeteetse Sandstone Continuous Gas AU having potential for additions to reserves are 20, 50, and 180 acres (Appendix C). The mode assumes that productive cells in the future will consist of a mix of lenticular fluvial sandstones and blanket-like marginal marine sandstone.

The estimates of minimum, mode, and maximum percentages of total untested assessment unit area are 98.5, 99.1, and 99.4 (Appendix C). The mode assumes that the 1,920 acres at Muddy Ridge field are completely tested, and that each of the tests outside Muddy Ridge tested 80 acres.

Minimum, mode, and maximum percentages of total assessment area that has potential for additions to reserves are 0.5, 1.5, and 7 percent, with a calculated mean of 3 percent. These comparatively low percentages reflect the belief that future discoveries will most likely be similar to those of the past, and will be sweet spots of relatively limited extent. The optimistic area of 7 percent could only be achieved if a large number of sweet spots were discovered, or if future discoveries cover larger areas than those of the past.

Minimum, median, and maximum recovery per untested cell with potential for additions to reserves are 0.02, 0.5 and 15 BCFG, with a calculated mean of 0.91. The maximum of 15 is similar to the maximum EUR for Mesaverde wells drilled thus far at Madden anticline and it is unlikely that future Mesaverde wells will exceed this maximum. Madden produces from marginal marine, blanket-like sandstones in the lower part of the Mesaverde, reservoirs that are similar in many respects to the highly productive underlying marine sandstones in the upper part of the Cody Shale at Madden. The high EURs from some of the wells in these upper Cody and basal Mesaverde sandstones is thought to be due to a combination of the blanket-like geometry and the highly fractured nature of the Madden anticline (Dunleavy and Gilbertson, 1986). Lenticular fluvial sandstones form most of the potential reservoirs in the Mesaverde Formation, and maximum EUR for wells completed in these reservoirs at Muddy Ridge field is about 6 (fig. 43). Mean estimate of undiscovered resources that have the potential for additions to reserves in the Mesaverde-Meeteetse Sandstone Continuous Gas AU is 383 BCFG (table 1).

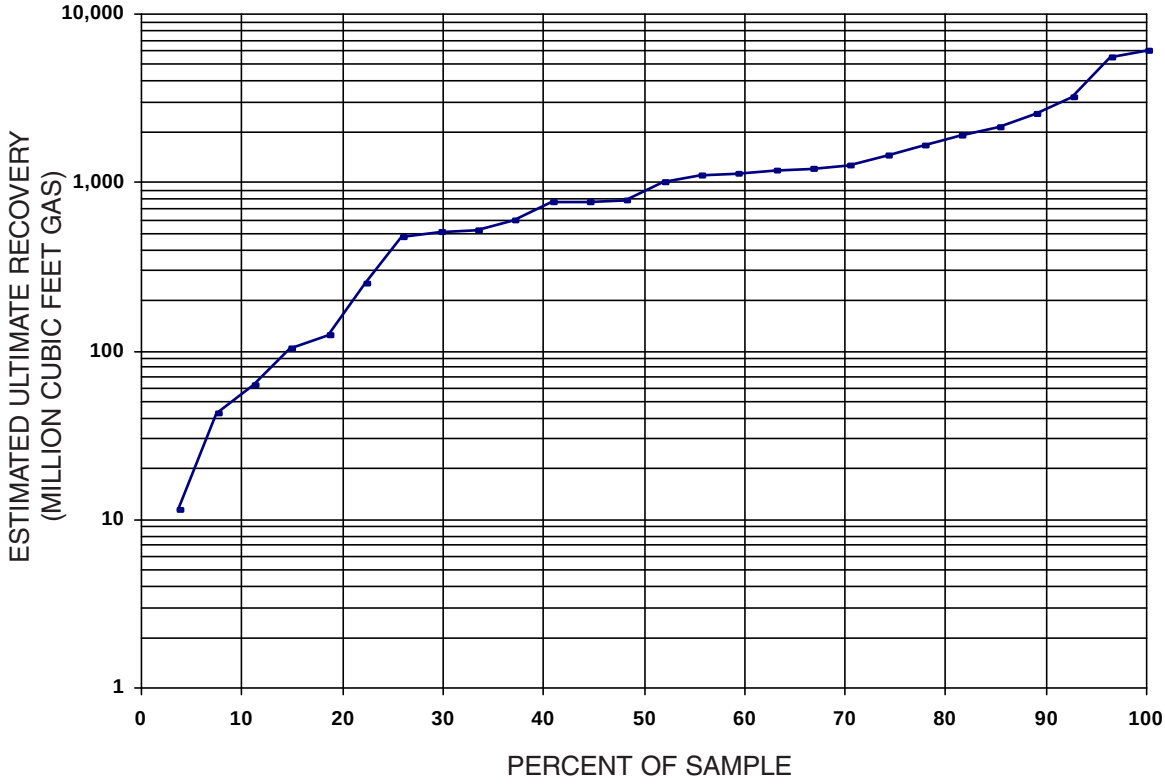

Figure 43. Distribution of estimated ultimate recoveries (EURs) for the 27 gas wells from Muddy Ridge field completed within the Mesaverde-Meeteetse Sandstone Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming.

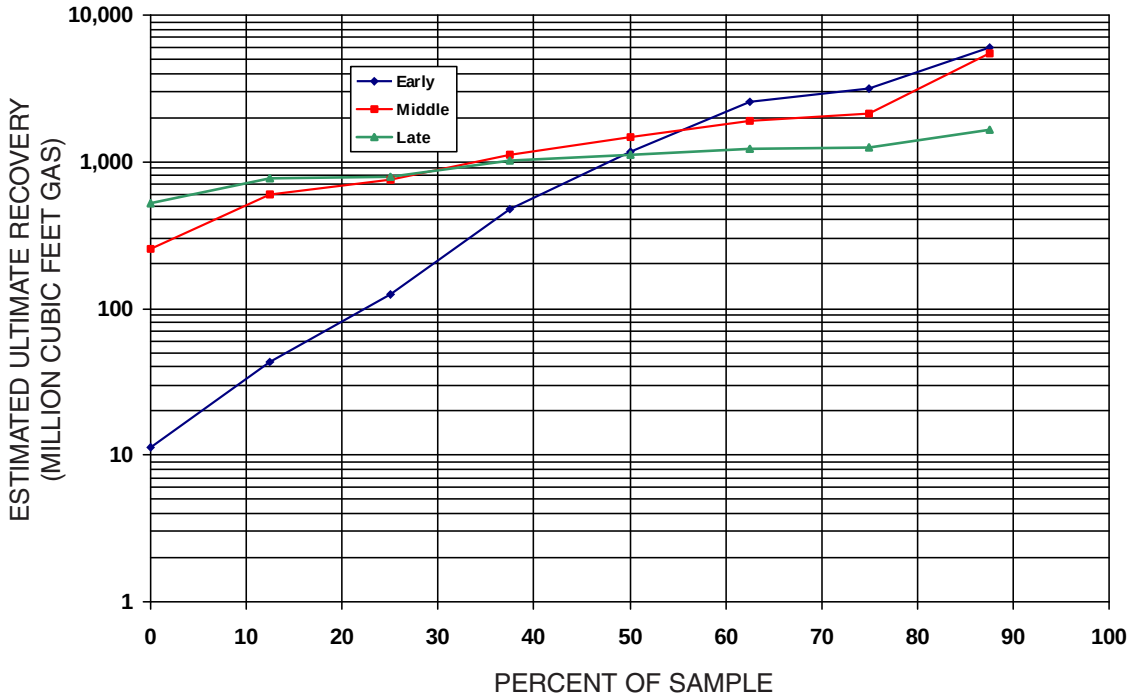

Figure 44. Distribution of estimated ultimate recoveries (EURs) by "thirds" for gas wells from Muddy Ridge field completed within the Mesaverde-Meeteetse Sandstone Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming. "Thirds" refers to the division into three parts of the number of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third "third" of the wells drilled to determine changes in EURs with time.

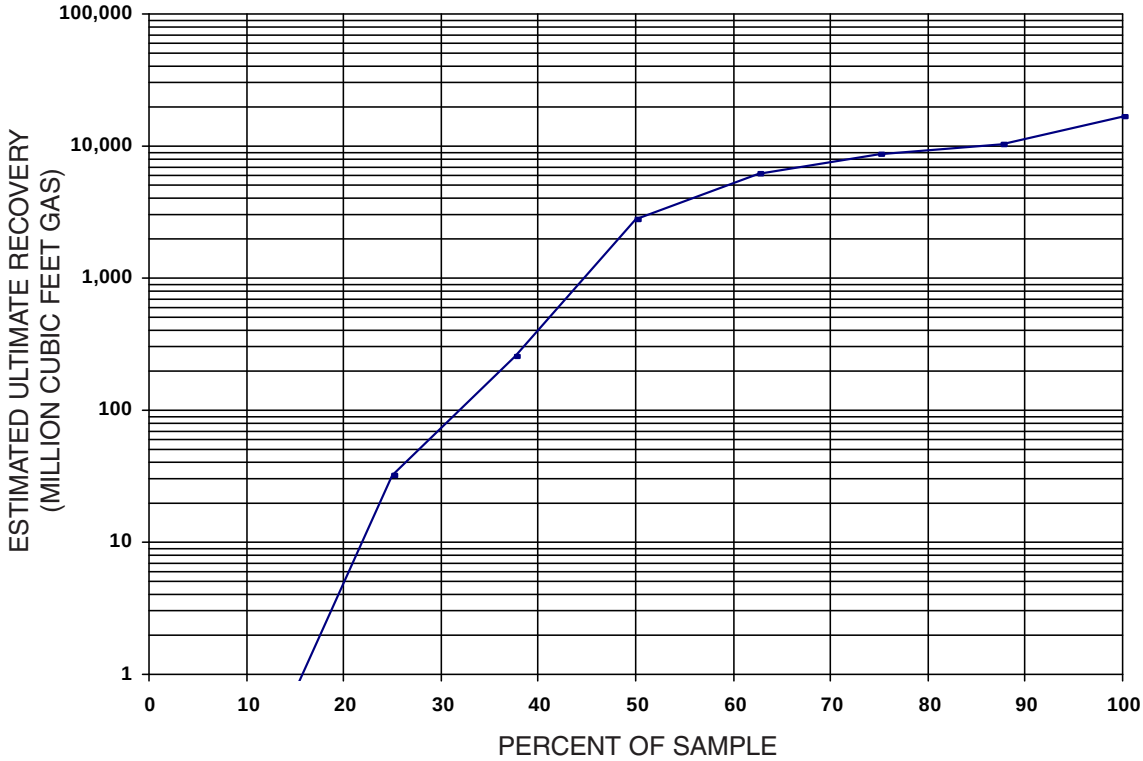

Figure 45. Distribution of estimated ultimate recoveries (EURs) for the 7 gas wells from Madden field completed within the Mesaverde-Meeteetse Sandstone Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming.

Lance-Fort Union Sandstone Gas Assessment Unit (AU 50350265)

The Lance-Fort Union Sandstone Gas AU (fig. 46) is defined by the R_o level of 1.1 percent at the base of the Meeteetse Formation, a likely source for much of the gas in the AU. As with the Mesaverde-Meeteetse Sandstone Continuous Gas AU, there is considerable uncertainty as to the boundaries of the continuous accumulation, and it is likely that there is a transition zone in which there are reservoirs with both conventional and continuous characteristics. Oil wells shown in figure 46 produce Waltman-sourced oil from the uppermost part of the lower member or the Shotgun Member of the Fort Union Formation and are included in the Waltman Shale TPS (Roberts and others, Chapter 5, this CD-ROM). The general extent of the AU in cross section in the basin is shown in figure 27. Although coal is sparse in the Lance Formation, abundant coal is present in the underlying Meeteetse Formation (fig 19), and gas expelled from these coals probably migrated vertically into reservoirs of the Lance-Fort Union Sandstone Gas AU. Abundant coal also is present in the lower member of the Fort Union Formation (fig. 20), and these coals also probably contributed gas, but thermal maturities are markedly lower than those at the base of the Meeteetse (figs. 23 and 24). Johnson and others (1996a) also used an R_o level of 1.1 percent at the base of the Lance-top of Meeteetse Formation to define the continuous accumulation in the Lance. The Lance and lower member of the Fort Union are combined into one continuous AU because the stratigraphic boundary between the two units is poorly defined in the central part of the basin, and there are a number of wells that report commingled production from both the Lance and Fort Union. The AU extends stratigraphically from the base of the Lance to the top of the lower member of the Fort Union Formation and is overlain by the Waltman Shale Member of the Fort Union. The Lance ranges in thickness from less than 1,500 ft to more than 5,000 ft (fig. 15), and the lower member of the Fort Union is about 1,500 to more than 3,500 ft thick (fig. 16). The AU covers a mode of 887,216 acres with a minimum of 798,494 acres and a maximum of 975,938 acres (Appendix D).

Time-temperature modeling by Roberts and others (Chapter 6, this CD-ROM) on three wells in the AU (fig. 47) indicates that gas generation began in the deepest parts of the AU during the early Eocene and continues today. The onset of gas generation, R_o 0.5 percent, began at the base of the Lance Formation in the Bighorn 1-5 well (fig. 47) at 62 Ma, the peak gas generation, R_o 0.8 percent, was at 55 Ma, and the end of gas generation, R_o 2 percent, was at 23 Ma. The onset and peak of gas generation in the lower member of the Fort Union occurred 53 and 38 Ma, respectively, and generation is continuing.

There are 346 tests in the AU, with 216 producing more than the minimum of 0.02 (Appendix D). Of these, 122 tests and 110 producers are on Madden anticline, 52 tests and 51 producers are at Frenchie Draw, and 172 tests and 55 producers are elsewhere in the AU. Median recovery for all producers is 0.85 (fig. 48), with 0.9 for the first “third”, 1.9 for the second “third” and 0.4 for the third “third” (fig. 49). The decline in EURs for the third “third” is striking, and for a better understanding of this, the producers were subdivided into four different subsets: (1) Madden Fort Union producers, (2) Madden Lance producers, (3) Frenchie Draw producers, and (4) producers outside of Madden and Frenchie Draw fields.

Fort Union producers make up the great majority (98 out of 122) of the Lance and Fort Union wells at Madden anticline. Median EUR for Fort Union producers in the field was 1.2 BCFG (fig. 50); whereas, modes for the “thirds” are 7.5, 1.3, and 0.3 BCFG, respectively (fig. 51). Median EUR for Lance wells at Madden is 0.5 BCFG (fig. 52); whereas, modes for the “thirds” are 8, 0.55, and 1.2 BCFG, respectively (fig. 53). Thus, EURs for Fort Union wells at Madden declined rapidly for the second and third “thirds” ; whereas, EURs for the last “third” of Lance wells improved markedly. Kuuskraa (1999) documented some decline in productivity for Fort Union wells along the crest of the anticline when well spacing was dropped to 80 acres, and suggested that optimum well spacing should be somewhat greater than 80 acres.

EURs for all Lance and Fort Union wells at Frenchie Draw is 0.6 BCFG (fig. 54), and modes for the “thirds” are 0.4, 1.4, and 0.4 BCFG, respectively (fig. 55). The decline in productivity for the last “third” of producers at Frenchie Draw suggests that the present well spacing of about 120 acres might be somewhat closer than optimum, and that some depleted reservoirs were encountered in the most recently drilled wells.

Figure 56 shows the locations of 29 producers in the Lance and Fort Union Continuous Sandstone Gas AU outside of Madden and Frenchie Draw fields with sufficient production histories to estimate an EUR. Studying these wells might give some insight into what future production will look like in the AU away from known sweet spots. Median EUR for these wells is less than 0.2 BCFG (fig. 57); however, the thirds for these wells indicates that EURs have steadly improved from about 0.12 for the first “third” to 0.5 for the last “third” (fig. 58).

Minimum, mode, and maximum area per cells with potential for additions to reserves are 20, 60, and 160 acres, with a calculated mean of 80 acres (Appendix D). The mean is somewhat less than optimum well spacing for Madden anticline and Frenchie Draw fields; future sweet spots may be less fractured than these two established fields and thus may require closer well spacing to drain the resource.

Minimum, mode, and maximum percentages of total untested assessment-unit area are 95, 96.6, and 97.4 percent, respectively, with a calculated mean of 96.3 percent (Appendix D). The mode assumes that: (1) Frenchie Draw field, which covers about 7,872 acres is completely drilled; (2) 4,830 acres of Madden anticline where well spacing is closer that 80 acres is completely drilled; and (3) the remaining tests at Madden and elsewhere in the basin tested 80 acres each.

Minimum, mode, and maximum of total assessment-unit area that has potential for additions to reserves are 2, 4, and 12 percent, respectively, with a calculated mean of 6 percent.

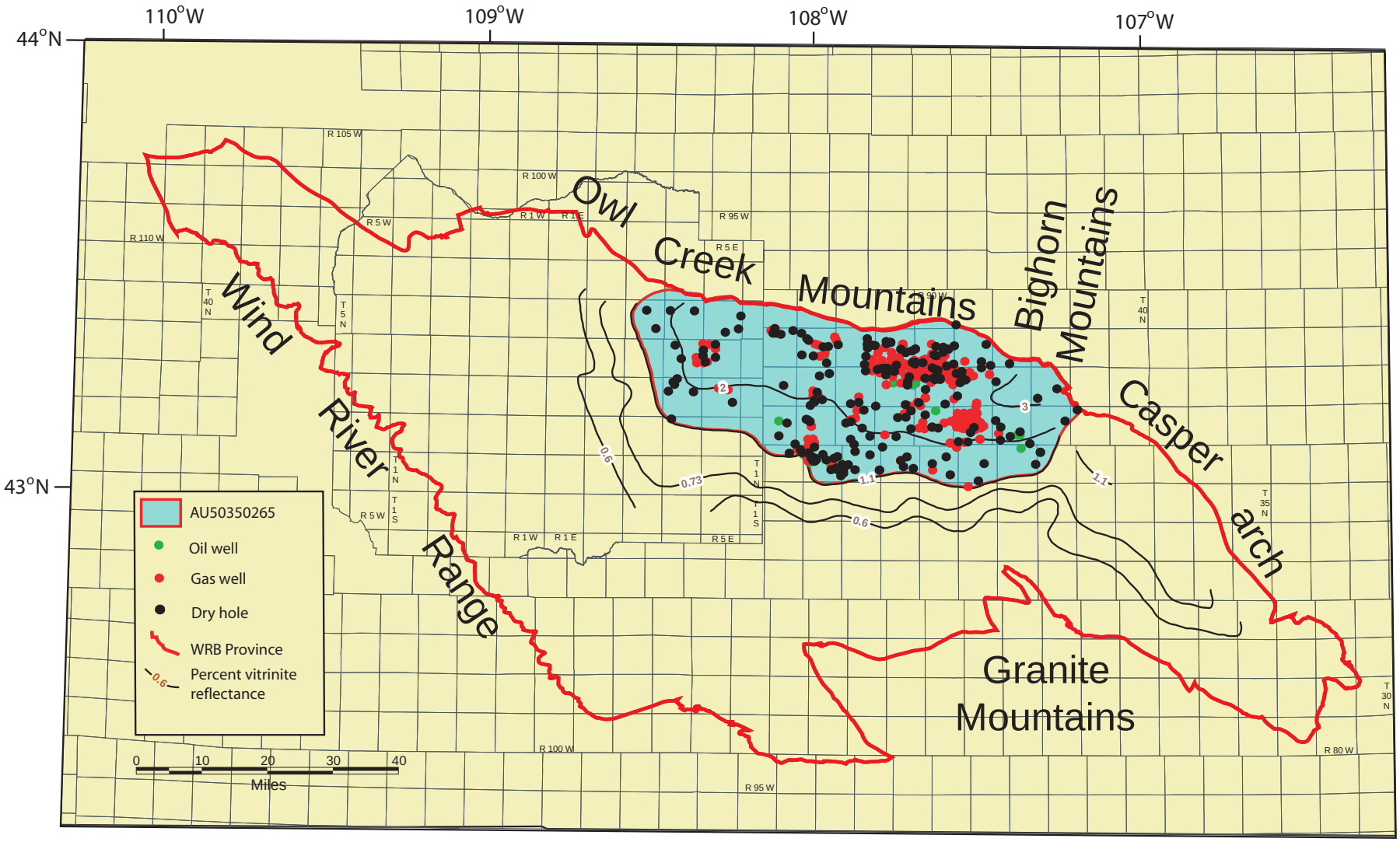

Figure 46. Extent of the Lance-Fort Union Sandstone Gas Assessment Unit, Wind River Basin Province, Wyoming. Producing gas and oil wells shown in red and green respectively, dry holes shown in black. Oil wells produce Waltman-sourced oil from the uppermost part of the lower member of Shotgun Member of the Paleocene Fort Union Formation and are included in the Waltman Total Petroleum System (Roberts and others, Chapter 5, this CD-ROM).

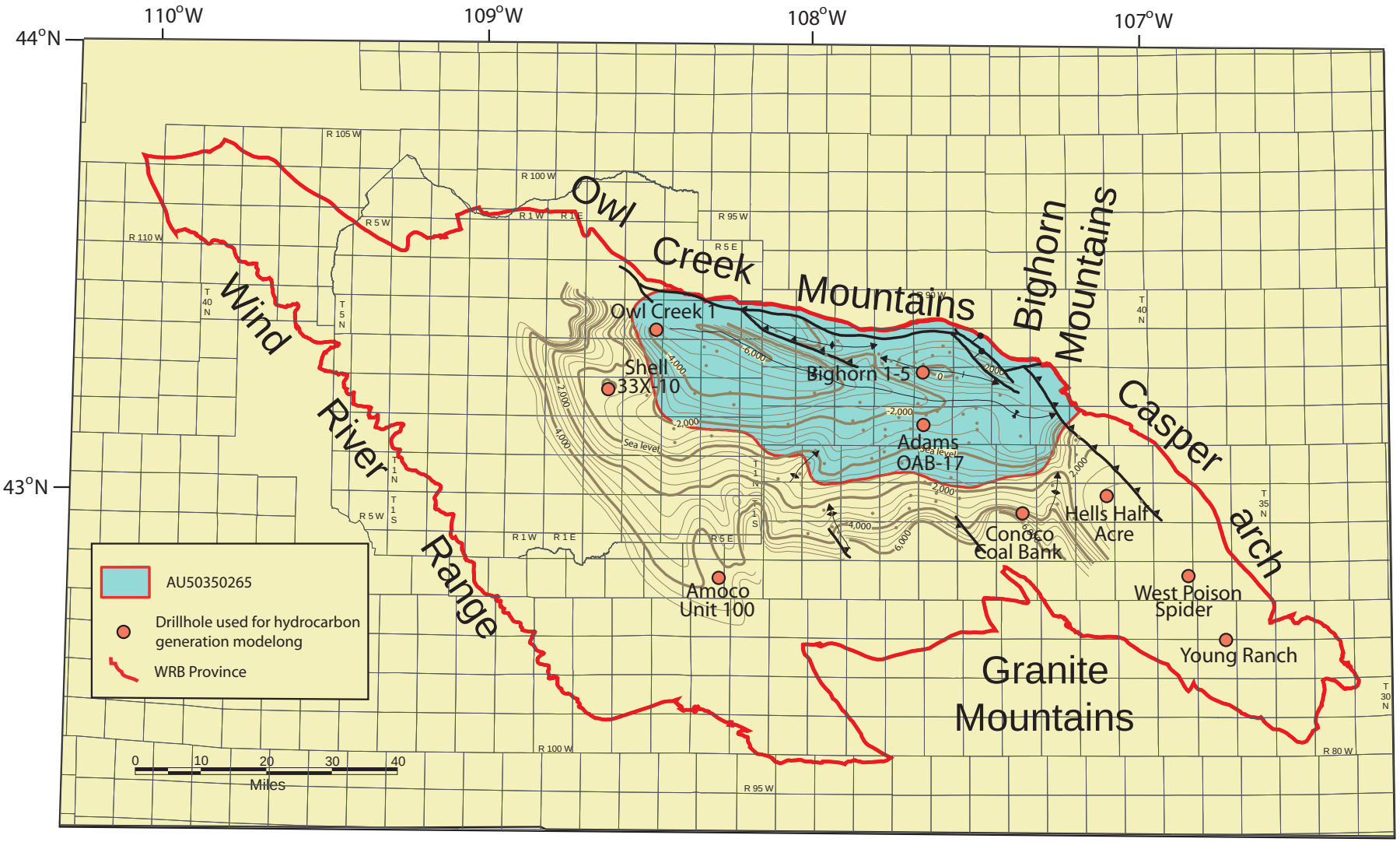

Figure 47. Locations of nine wells used by Roberts and others (Chapter 5, this CD-ROM) for estimating timing of hydrocarbon generation in the Wind River Basin (WRB) Province, Wyoming. Three of the wells are in the Lance-Fort Union Sandstone Gas Assessment Unit. Structure contours are on the base of the Waltman Shale Member of the Fort Union Formation based on Johnson (Chapter 10, this CD-ROM). Contour interval: 500 feet.

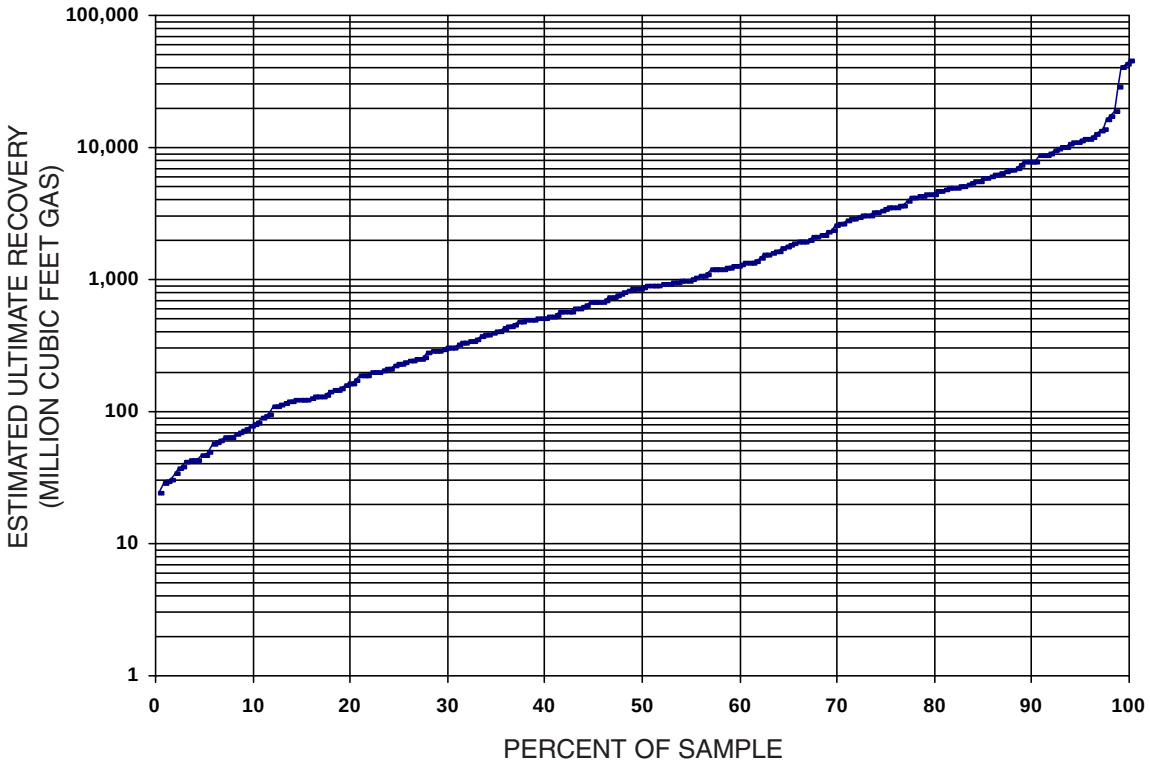

Figure 48. Distribution of estimated ultimate recoveries (EURs) for gas wells within the Lance-Fort Union Sandstone Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming. Only wells with minimum EURs exceeding 20 million cubic feet of gas (MMCFG) are shown.

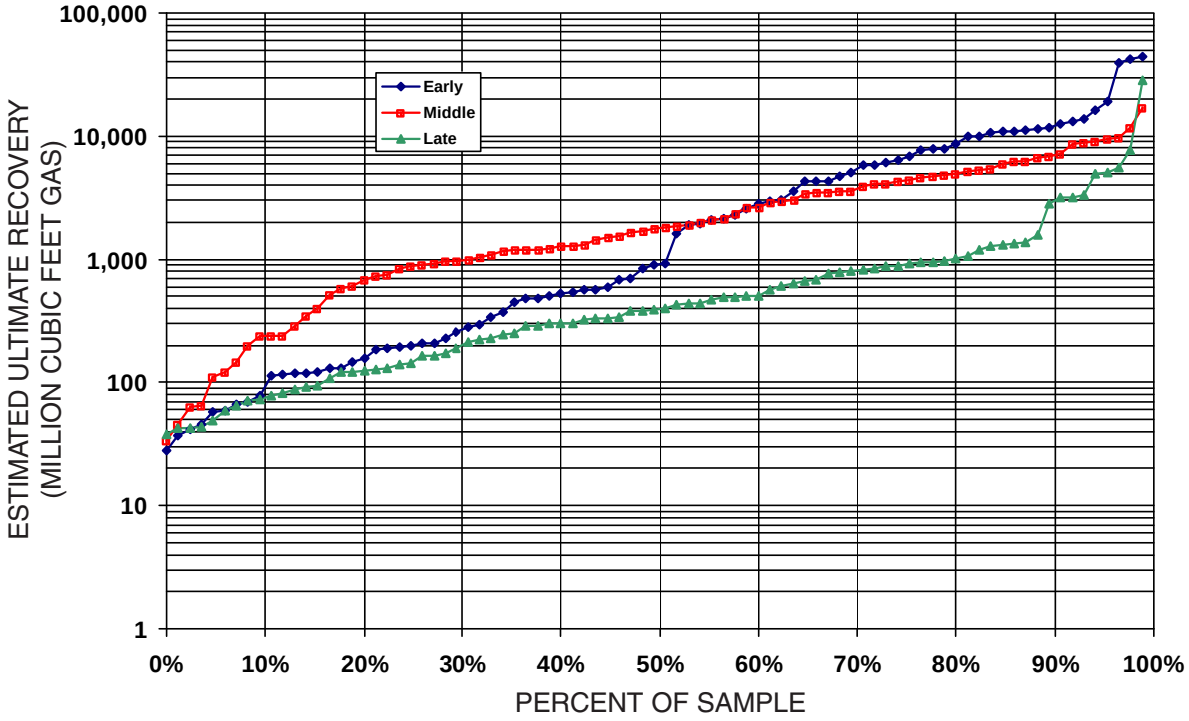

Figure 49. Distribution of estimated ultimate recoveries (EURs) by "thirds" for gas wells completed within the Lance-Fort Union Sandstone Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming. "Thirds" refers to the division into three parts of the number of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third "third" of the wells drilled to determine changes in EURs with time. Only wells with minimum EURs exceeding 20 million cubic feet of gas (MMCFG) are shown.

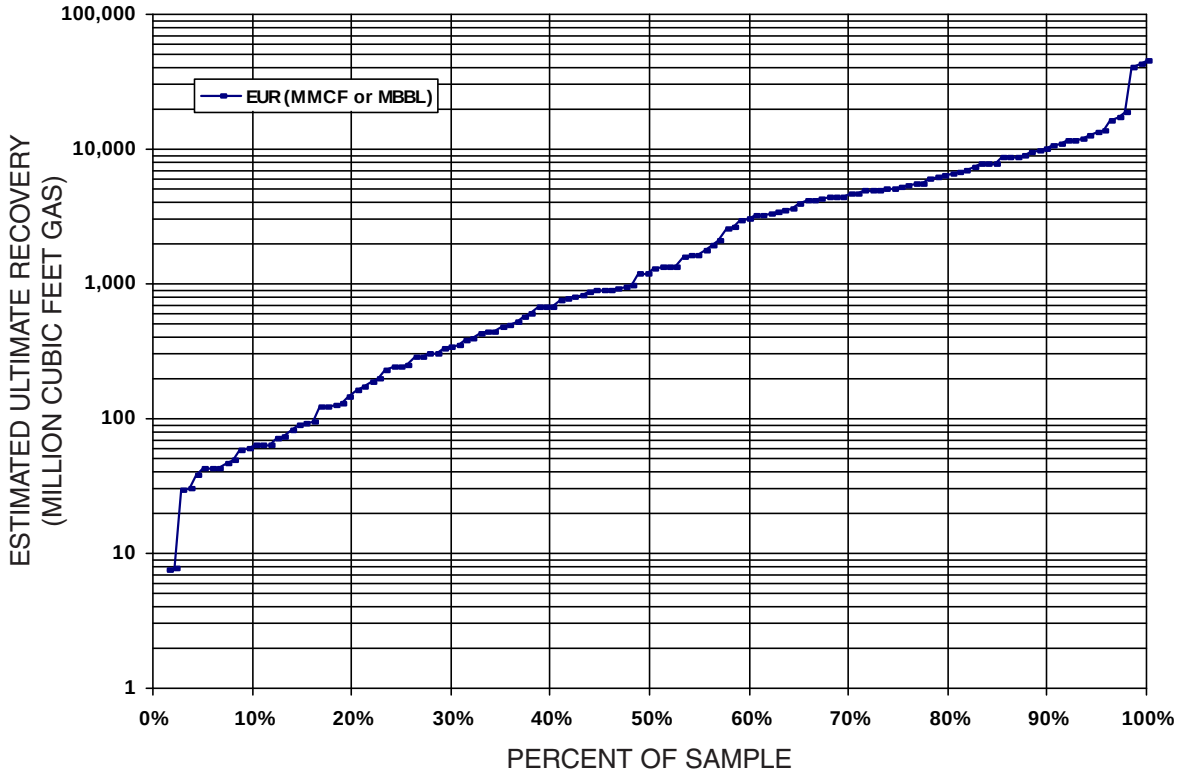

Figure 50. Distribution of estimated ultimate recoveries (EURs) for the 98 gas wells from Madden field completed within the lower unnamed member of the Paleocene Fort Union Formation.

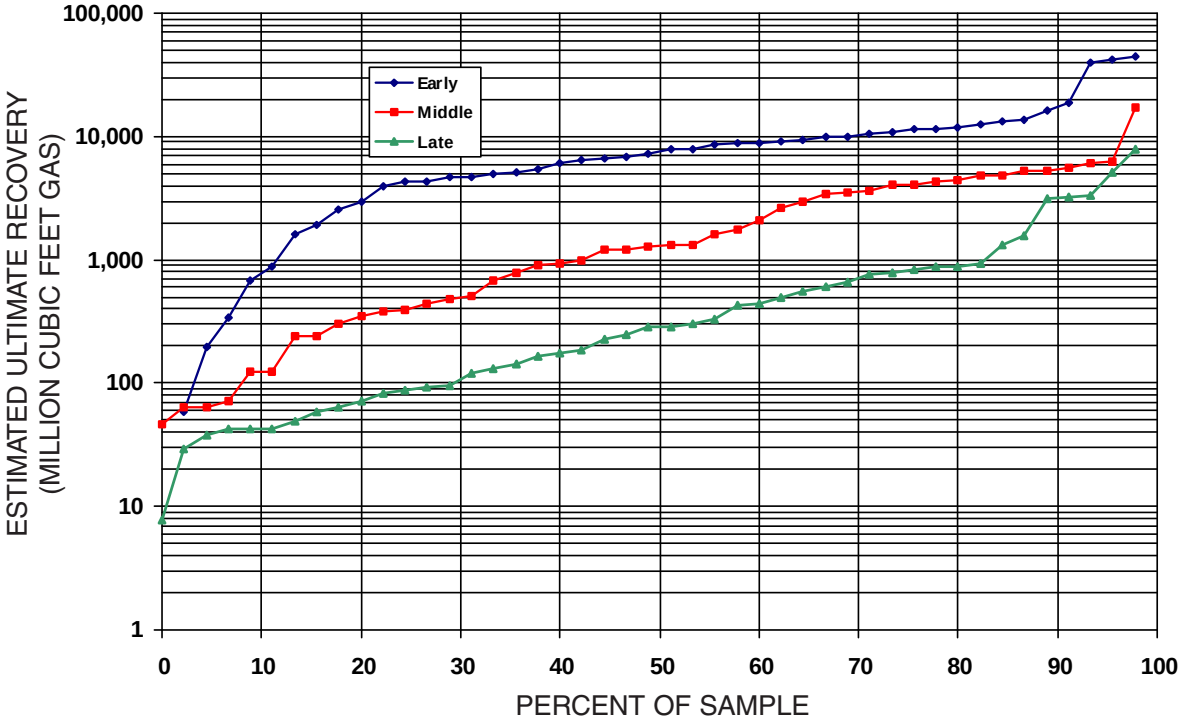

Figure 51. Distribution of estimated ultimate recoveries (EURs) by "thirds" for gas wells from Madden field completed within the lower member of the Paleocene Fort Union Formation. "Thirds" refers to the division into three parts of the number of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third "third" of the wells drilled to determine changes in EURs with time.

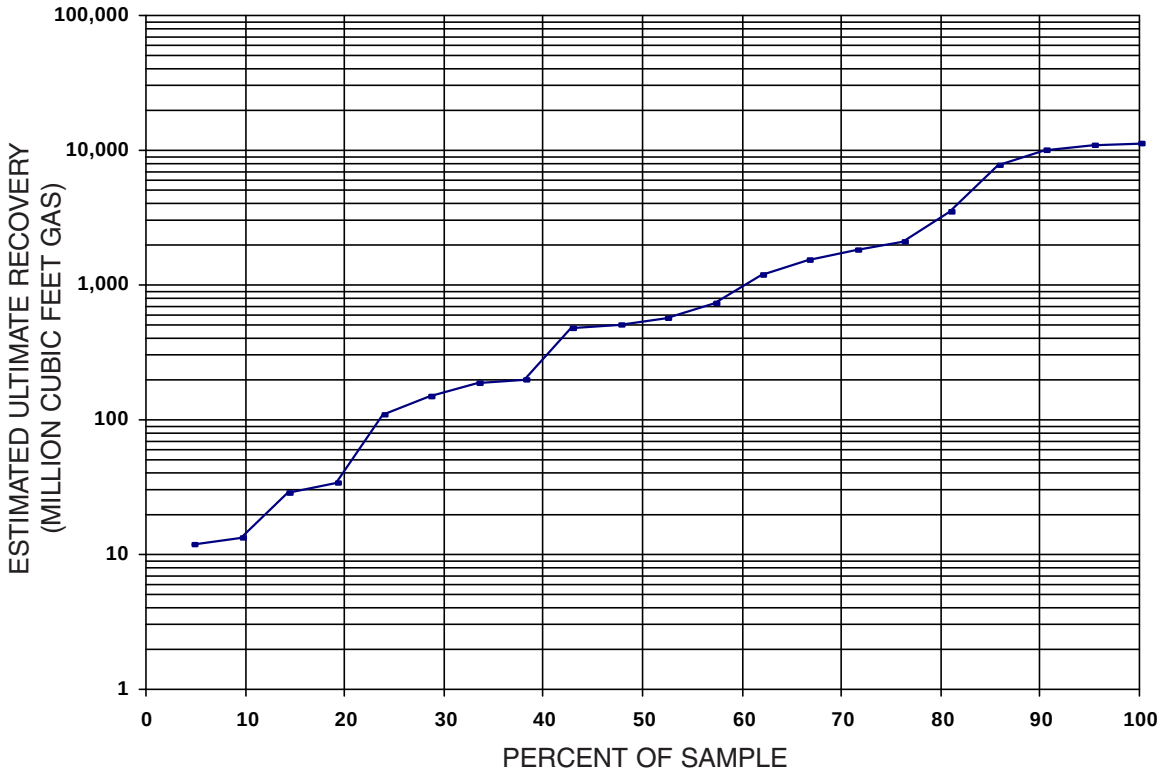

Figure 52. Distribution of estimated ultimate recoveries (EURs) for the 21 gas wells from Madden field completed within the Upper Cretaceous Lance Formation.

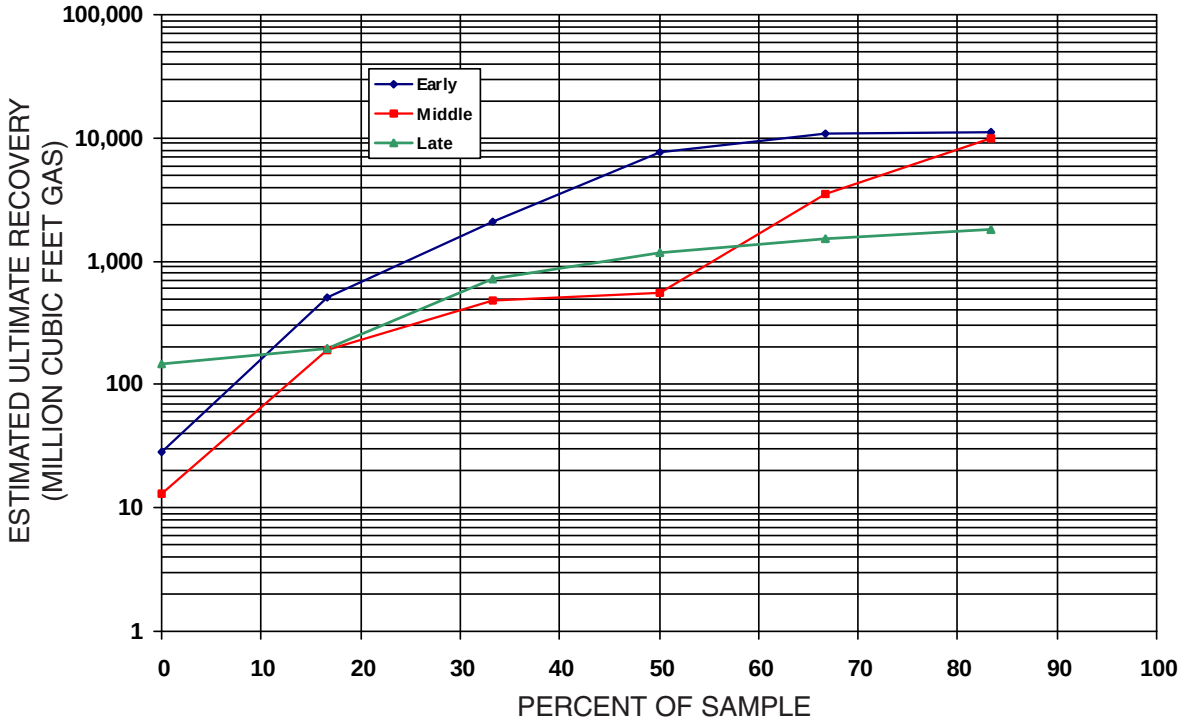

Figure 53. Distribution of estimated ultimate recoveries (EURs) by "thirds" for gas wells from Madden field completed within the Upper Cretaceous Lance Formation. "Thirds" refers to the division into three parts of the number of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third "third" of the wells drilled to determine changes in EURs with time.

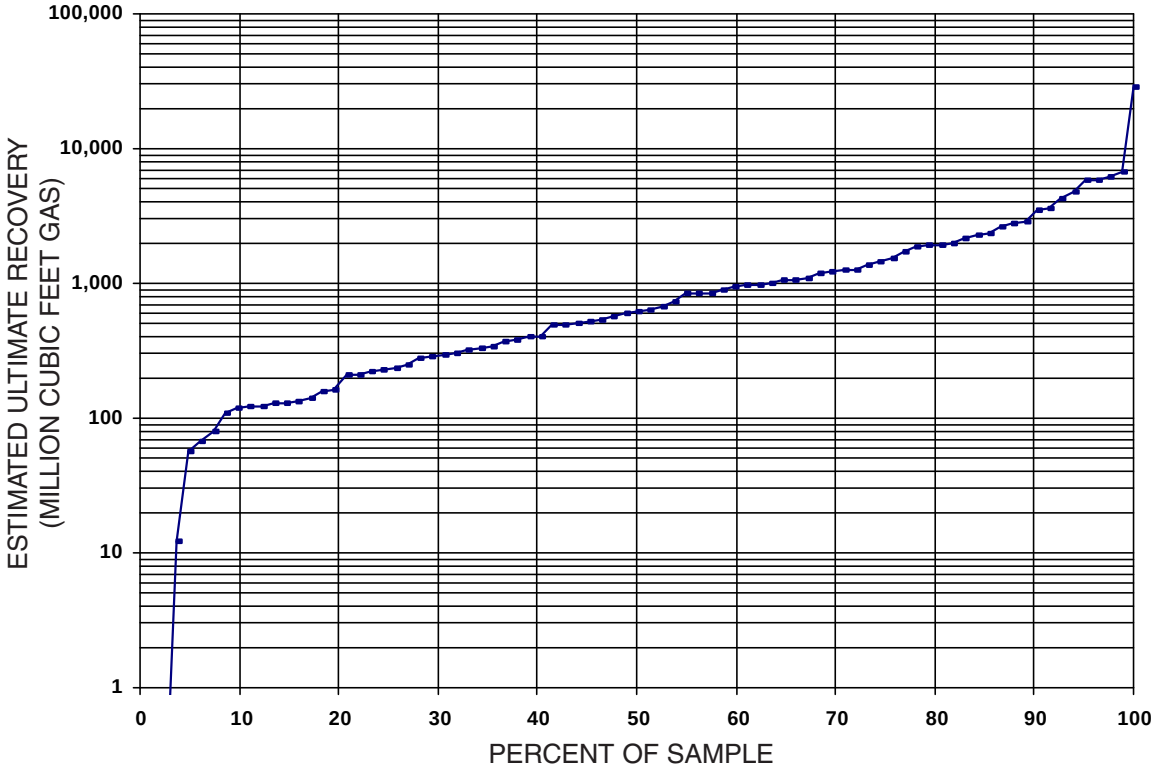

Figure 54. Distribution of estimated ultimate recoveries (EURs) for gas wells in Frenchie Draw field completed within the Lance-Fort Union Sandstone Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming.

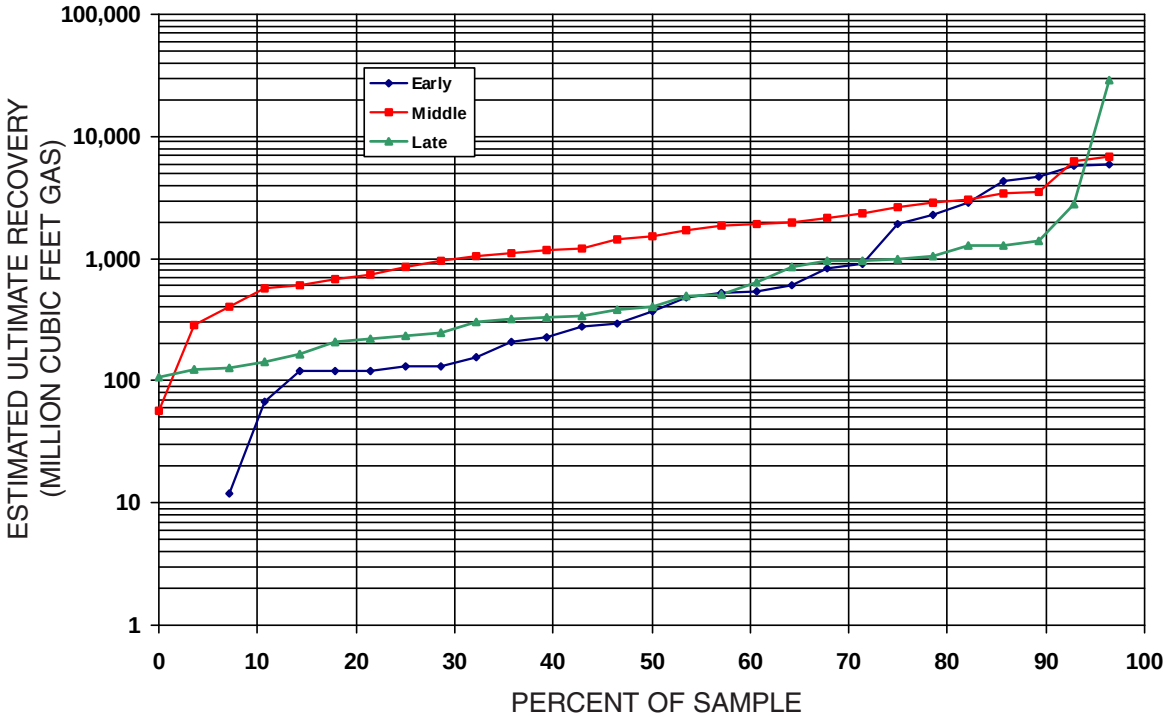

Figure 55. Distribution of estimated ultimate recoveries (EURs) by "thirds" for gas wells from Frenchie Draw Field completed within the Lance-Fort Union Sandstone Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming. "Thirds" refers to the division into three parts of the number of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third "third" of the wells drilled to determine changes in EURs with time.

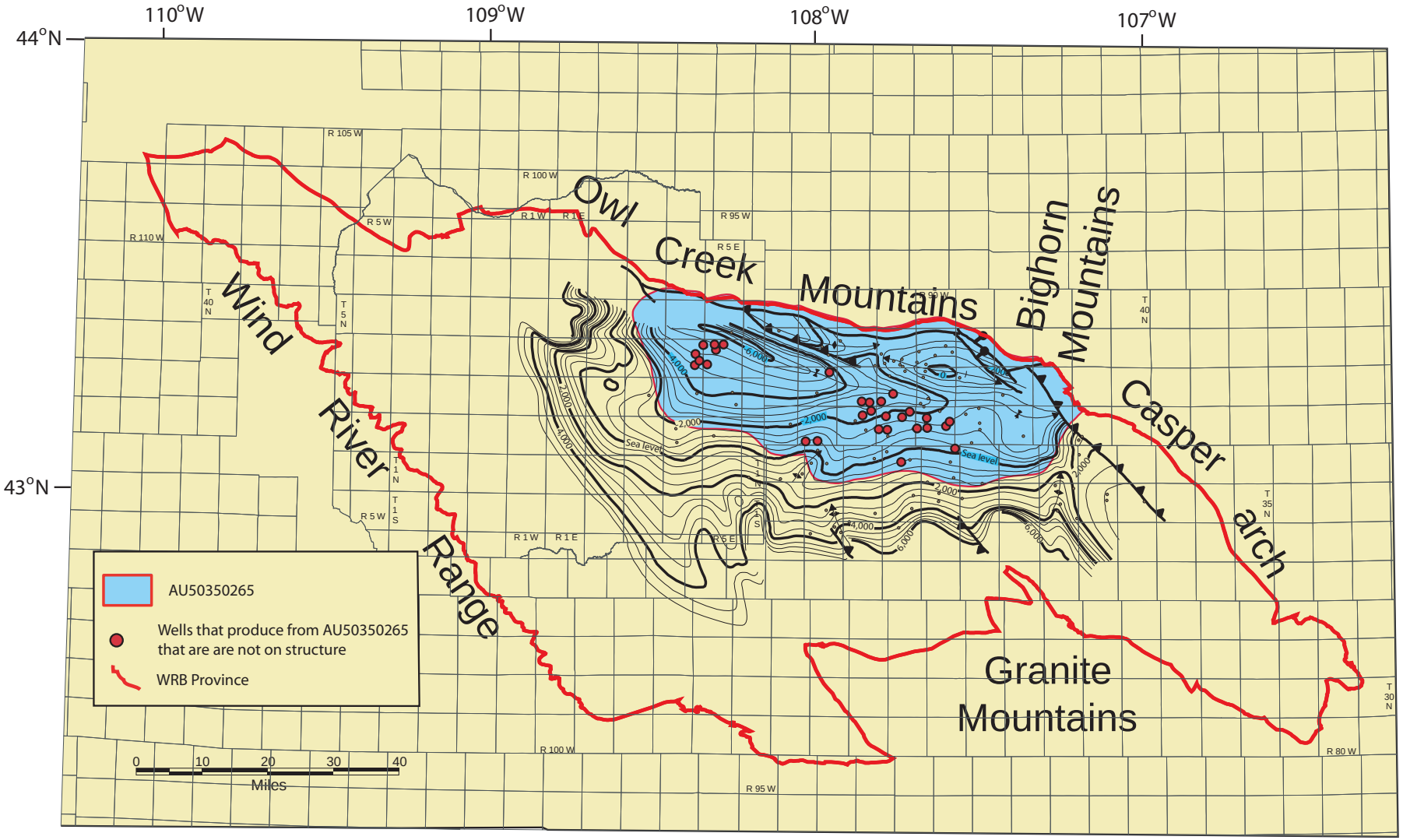

Figure 56. Locations of 29 wells that produce from the Lance-Fort Union Sandstone Gas Assessment Unit outside of Madden and Frenchie Draw fields, Wind River Basin (WRB) Province, Wyoming. Contours on base of Waltman Shale Member of the Paleocene Fort Union Formation are from Johnson (Chapter 10, this CD-ROM). Contour interval: 500 feet.

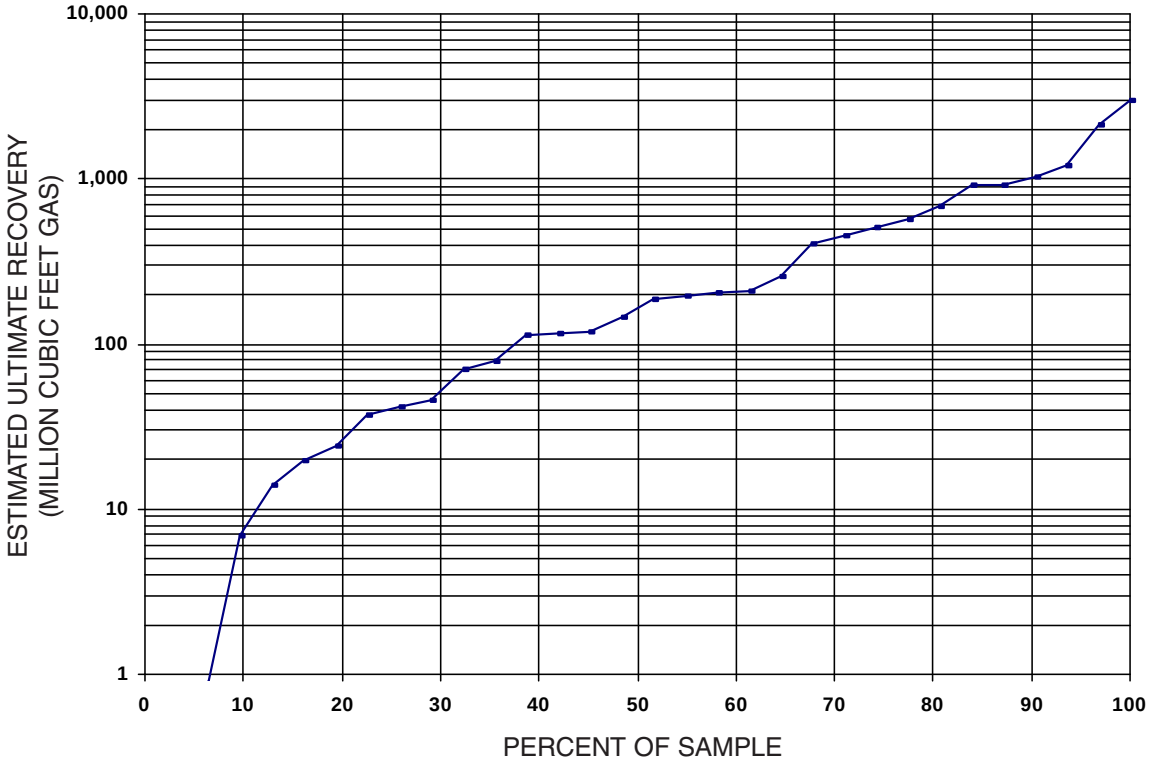

Figure 57. Distribution of estimated ultimate recoveries (EURs) for gas wells from within the Lance-Fort Union Sandstone Gas Assessment Unit, Wind River Basin (WRB) Province, Wyoming, but from outside the Madden and Frenchie Draw fields.

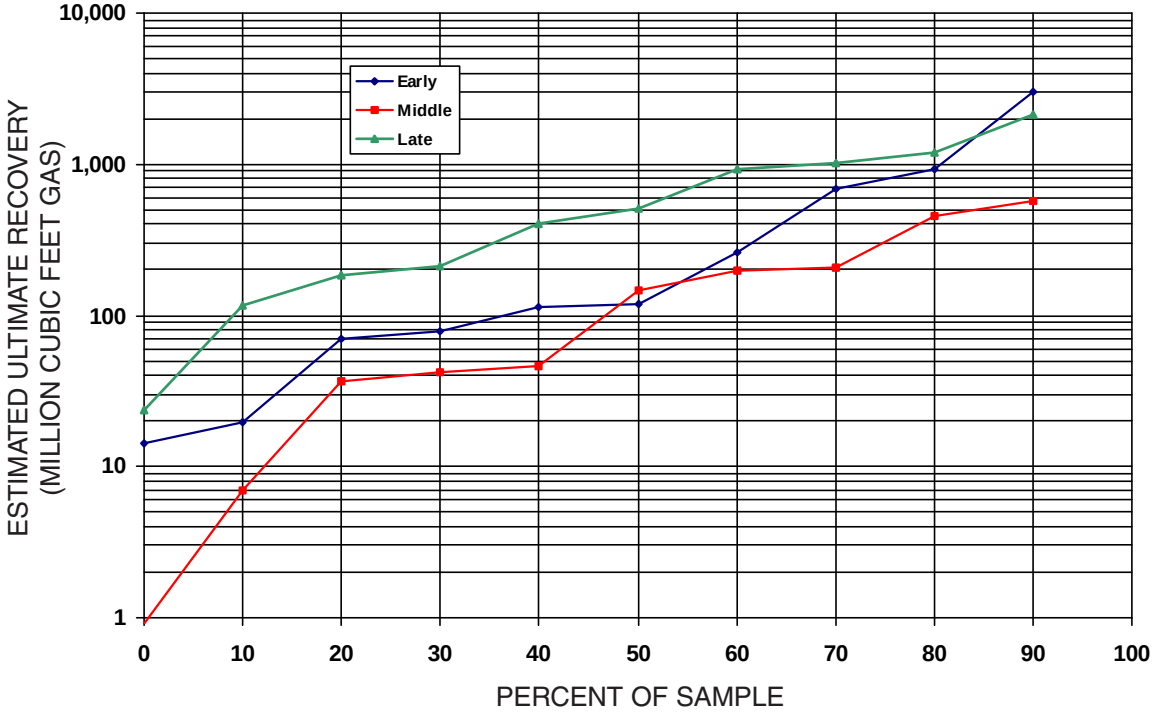

Figure 58. Distribution of estimated ultimate recoveries (EURs) by "thirds": for gas wells from within the Lance-Fort Union Sandstone Gas Assessment Unit, but from outside of Madden and Frenchie Draw fields. "Thirds" refers to the division into three parts of the number of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third "third" of the wells drilled to determine changes in EURs with time.

The average size of sweet spots discovered to date in the basin is about 5,000 acres. The minimum assumes that only the undrilled sites at Madden anticline and one sweet spot of about 5,000 acres have potential for additions to reserves. The mode assumes that, in addition to the undrilled sites on Madden anticline, five sweet spots of about 5,000 acres each will have potential for additions to reserve. The maximum area could only be achieved if a large number of sweet spots were discovered, or if future discoveries cover larger areas than those of the past.

Minimum, median, and maximum total recovery per cell for untested cells having potential for additions to reserves are 0.02, 1, and 50 BCFG (Appendix D). These numbers assume that future discoveries will be significantly more productive than the last "third" of existing Fort Union and Lance wells. Many of these recent wells are completed in only a small percentage of the total sandstones in the Fort Union and Lance interval, and the EURs may be higher if all the potentially productive sandstones in the interval were perforated. The mean estimate of undiscovered resources that have the potential for additions to reserves in the Lance-Fort Union Sandstone Gas AU is 711 BCFG (table 1).

Mesaverde Coalbed Gas Assessment Unit (AU 50350281)

The Mesaverde Coalbed Gas AU, defined as that area where the Mesaverde Formation lies at a depth 6,000 ft or less (fig. 59), covers a miniumum, mode, and maximum area of 584,000, 649,000, and 713,000 acres, respectively (Appendix E). The AU is informally subdivided into high potential and low potential areas (fig. 59). The high potential area covers 378,742 acres and is defined as that area where the Mesaverde contains 20 ft or more of total coal; whereas, the low potential area covers 319,766 acres encompassing the area where the Mesaverde contains less than 20 ft of coal (fig. 59). The high potential area is in the western part of the basin, on the Wind River Indian Reservation and to the south where total coal ranges from 20 ft to over 100 ft thick (fig. 18). Thermal maturities are low, varying from less than 0.6 percent R_o to just over 0.73 percent (fig. 59).

To date, attempts to complete Mesaverde coalbed gas wells in the AU have met with little success, despite the presence of significant in-place gas. Johnson and others (1993) cored and desorbed Mesaverde coal beds at eight locations on the Wind River Indian Reservation along the southwest flank of the basin, and measured methane contents in coals from five of the drill holes ranging from 0.40 to 3.6 cc/gm (12.8 to 115 cubic ft/ton). Little methane was recorded in coals from the remaining three holes. Johnson and others (1993) estimated 2.6 trillion cubic feet of gas (TCFG) in place in Mesaverde coals at depths of less that 6,000 ft on the Wind River Indian Reservation. Gases desorbed from these shallow core holes appear to be mixtures of biogenic gas originating in the coal and thermogenic gas that migrated from deeper, more mature source rocks (Johnson and Rice, 1993).

In late 1990, ARCO Oil and Gas Company (ARCO) recompleted an old well, the ARCO Tribal No. 15 well, in Mesaverde coals, at Riverton Dome in the southeast corner of the Wind River Indian Reservation (fig. 59). Initial production in December 1990 was 233.4 thousand cubic feet of gas per day (MCFGD) and 214.3 barrels of water per day, but production was irregular and the well was shut in during 1992 after producing 41.3 million cubic feet of gas (MMCFG) and 43,214 barrels of water (data from Wyoming Oil and Gas Conservation Commission). This is the only Mesaverde coalbed methane test in the Wind River Basin that produced more than the minimum of 0.02 required to be considered a successful test. Gas from this well appears to be of thermogenic origin and probably migrated from deeper, mature source rocks (Johnson and Rice, 1993).

In 2001, Devon Energy completed six Mesaverde coalbed methane tests at Beaver Creek field (fig. 59), just south of the southeast corner of the Wind River Indian Reservation in the area where more than 120 ft of total coal is present in the formation. The six wells were tested for about a year and produced little gas, from 0 to 4.1 MCFG per well, and large amounts of water, from 482,027 to 946,920 barrels (bbls) (data from Wyoming Oil and Gas Conservation Commission). Coals in this thick buildup are interbedded with persistent, blanket-like marginal marine sandstones that crop out in recharge areas along the south and southwest margins of the basin, and these sandstones appear to be water-wet for a considerable distance into the basin (Johnson and others, 1996a). It is possible that much of the water produced from these wells came from these sandstone aquifers. In late 2004, Wolverine Energy began drilling Mesaverde coalbed methane tests along the southeast margin of the Wind River Indian Reservation, just east of the USGS coreholes CBM-2 and CBM-9 in T. 2 S., R. 3 E. (fig. 59). There is a great deal of uncertainty in the values for the parameters required for the assessment listed below because of the lack of successful commercial coalbed methane production. The Mesaverde Group Coalbed Methane AU (AU 50200282) in the Piceance Basin of western Colorado and eastern Utah (Johnson and Roberts, 2003) was used as an analog.

Minimum, mode, and maximum area per cell for untested cells within the Mesaverde Coalbed Gas AU having potential for additions to reserves are 40, 120, and 280 acres, respectively, with a calculated mean of 147 acres (Appendix E). These cell sizes also were used in the Mesaverde Group Coalbed Methane AU (AU 50200282) in the Piceance Basin of western Colorado and eastern Utah (Johnson and Roberts, 2003), the analog for this AU.

The AU is virtually untested, with one successful well (> 20 MMCFG) in seven tests. Minimum, mode, and maximum percentages of total untested area within the AU are 99.7, 99.9, and 100 percent, respectively (Appendix E).

Minimum, mode, and maximum percentage of untested area that has potential for additions to reserves are 1, 7, and 27 percent, with a calculated mean of 11.7 percent (Appendix

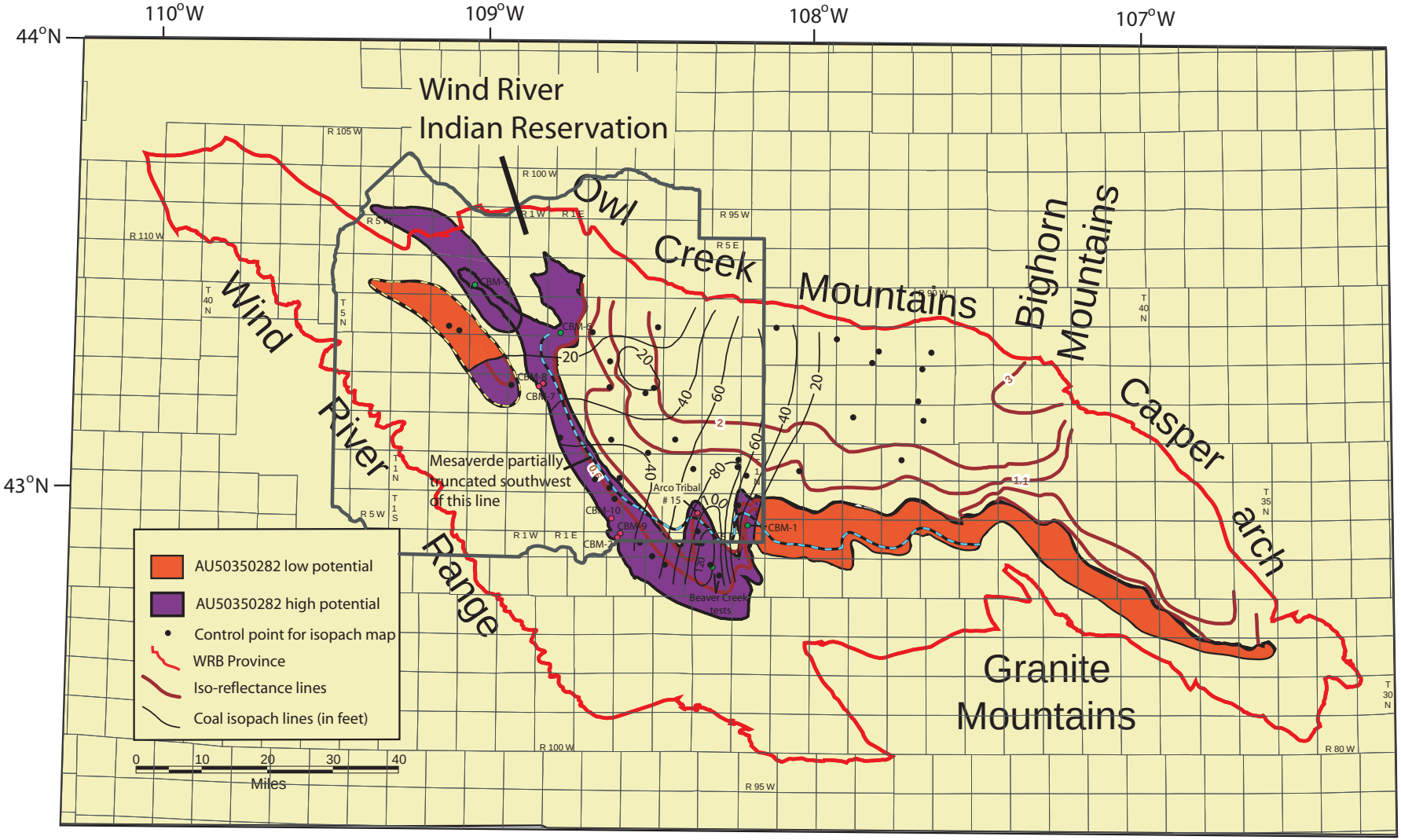

Figure 59. Extent of the Mesaverde Coalbed Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province (WRB), Wyoming. Isopach map is total coal in the Mesaverde Formation (modified from Johnson and others, 1996b). Contour interval is 20 feet. Variations in vitrinite reflectance at base of the Mesaverde Formation shown with dark red lines. Wells and core holes that tested coal beds in the Mesavede and Meeteetse Formation are shown. Coalbed methane core hole data are from Johnson and others (1993). The AU is subdivided into a high-potential area (reddish purple) and low-potential are (purple) based on total coal thickness.

E). The minimum of 1 percent assumes that only about 3,500 acres near Pilot Butte and 3,000 acres near Hudson will be productive, which are tracts where Mesaverde coals contain significant in-place gas (Johnson and others, 1993). The mode of 7 percent assumes that about 10 percent of the high potential area will be productive and the maximum of 27 percent assumes that 40 percent of the high potential area combined with a minor amount of the low potential area will be productive.

Minimum, median, and maximum total recovery per cell for untested cells having potential for additions to reserves are 0.02, 0.1, and 5 BCFG, with a calculated mean of 0.22 percent (Appendix E). These values are similar to the analog AU, the Mesaverde Group Coalbed Methane AU in the Piceance Basin. The mean estimate of undiscovered resources that have the potential for additions to reserves in the Mesaverde Coalbed Gas AU is 107 BCFG (table 1).

Meeteetse Coalbed Gas Assessment Unit (AU 50350282)

The Meeteetse Coalbed Gas AU is defined as that area where the Meeteetse Formation is at depths of 6,000 ft or less (fig. 60). The Meeteetse Formation, which was deposited in a poorly drained coastal plain and marginal marine setting, appears to include some coal throughout the extent; total coal within the AU boundaries ranges in thickness from less than 10 ft to more than 40 ft (fig. 60). The AU covers a minimum, mode, and maximum areas of 338,000, 367,000, and 414,000 acres, respectively, (Appendix F). There are no known tests of Meeteetse coal beds, thus 100 percent of the AU is untested. Johnson and others (1993) cored and desorbed a Meeteetse coal near an abandoned open-pit mine in the northern part of the Wind River Indian Reservation (CBM-6, fig. 59), but no coal gas was detected.

Because of the lack of successful tests in the AU, the the Mesaverde Group Coalbed Methane AU (AU 50200282) in the Piceance Basin of western Colorado and eastern Utah (Johnson and Roberts, 2003) was used as an analog. Minimum, mode, and maximum areas per untested cells having potential for additions to reserves are 40, 120, and 280 acres, which are the same as those used in the Piceance Basin analog.

Minimum, mode, and maximum percentage of untested assessment-unit area having potential for additions to reserves are 1, 3, and 15 percent, respectively (Appendix F). Minimum, median, and maximum total recovery per cell for untested cells having potential for additions to reserves are 0.2, 0.8, and 2 BCFG (Appendix F). These percentages are less than those for the Mesaverde Coalbed Gas AU because there is significantly less coal in the Meeteetse Formation than in the Mesaverde Formation. The mean estimate of undiscovered resources that have the potential for additions to reserves in the Meeteetse Coalbed Gas AU is 21 BCFG (table 1).

Fort Union Coalbed Gas Assessment Unit (AU 50350283)

The Fort Union Coalbed Gas AU is defined as that area where the lower member of the Fort Union Formation lies at depths of 6,000 ft or less (fig. 61). The AU covers much of the southern part of the basin as well as a small area on the crest of Madden anticline, with minimum, mode, and maximum areas of 1,277,000, 1,419,000, and 1,561,000, respectively, (Appendix G). An isopach map of total coal in the Fort Union Formation is shown in figure 20. The AU is subdivided into a high-potential area of 518,728 acres, where isopachs indicate coal to be present, and a low-potential area covering 837,622 acres, where no coal has been identified (fig. 61). It is possible that significant coal beds have been missed in marginal areas of the Wind River Basin where drilling is sparse. Lenticular coal beds as much as 26 ft thick were described in the Fort Union Formation by Roberts and Stanton (1994) along the southern margin of the Bighorn Basin, north of the Wind River Basin (fig. 3).

Thermal maturities are low in Fort Union coal beds, with a maximum R_o of slightly more than R_o 0.60 percent at the top of the lower member (fig. 24). It is likely that any gas present in these coal beds is either of biogenic origin or is migrated thermogenic gas.

There appears to be only two tests of Fort Union coal beds in the AU, with one a marginally successful gas well on Madden anticline. This well, the Burlington Resources No. 41 Madden Deep Unit in sec. 32, T. 39 N., R. 90 W. (fig. 61), is reported by the Wyoming Oil and Gas Conservation Commission to be completed in Fort Union and Lance coals at depths of 5,750 to 5,925 ft and 7,110 to 7,484 ft, respectively. It has produced 30 MCFG and 1,450 barrels of water since 2001, and thus is just above the minimum of 20 MCFG to be considered a successful test. The other test was the Tom Brown LD Tribal 3-30 well drilled in sec. 3, T. 2 N., R. 1 E. (fig. 61) to a depth of 5,324 ft in the thick coal accumulation in the syncline south of Little Dome anticline. The coals were tight, producing little gas, and the well was abandoned.

Because there are only two tests, the percentage of total area of the AU that is untested is virtually 100 percent (Appendix G). Minimum, mode, and maximum areas per cell of untested cells having potential for additions to reserves are 40, 80, and 140 acres, with a calculated mean of 87 acres (Appendix G). Minimum, mode, and maximum percentages of untested area that has potential for additions to reserves are 0.5, 3, and 13 percent respectively, with a calculated mean of 5.5 percent. Minimum, median, and maximum total recovery

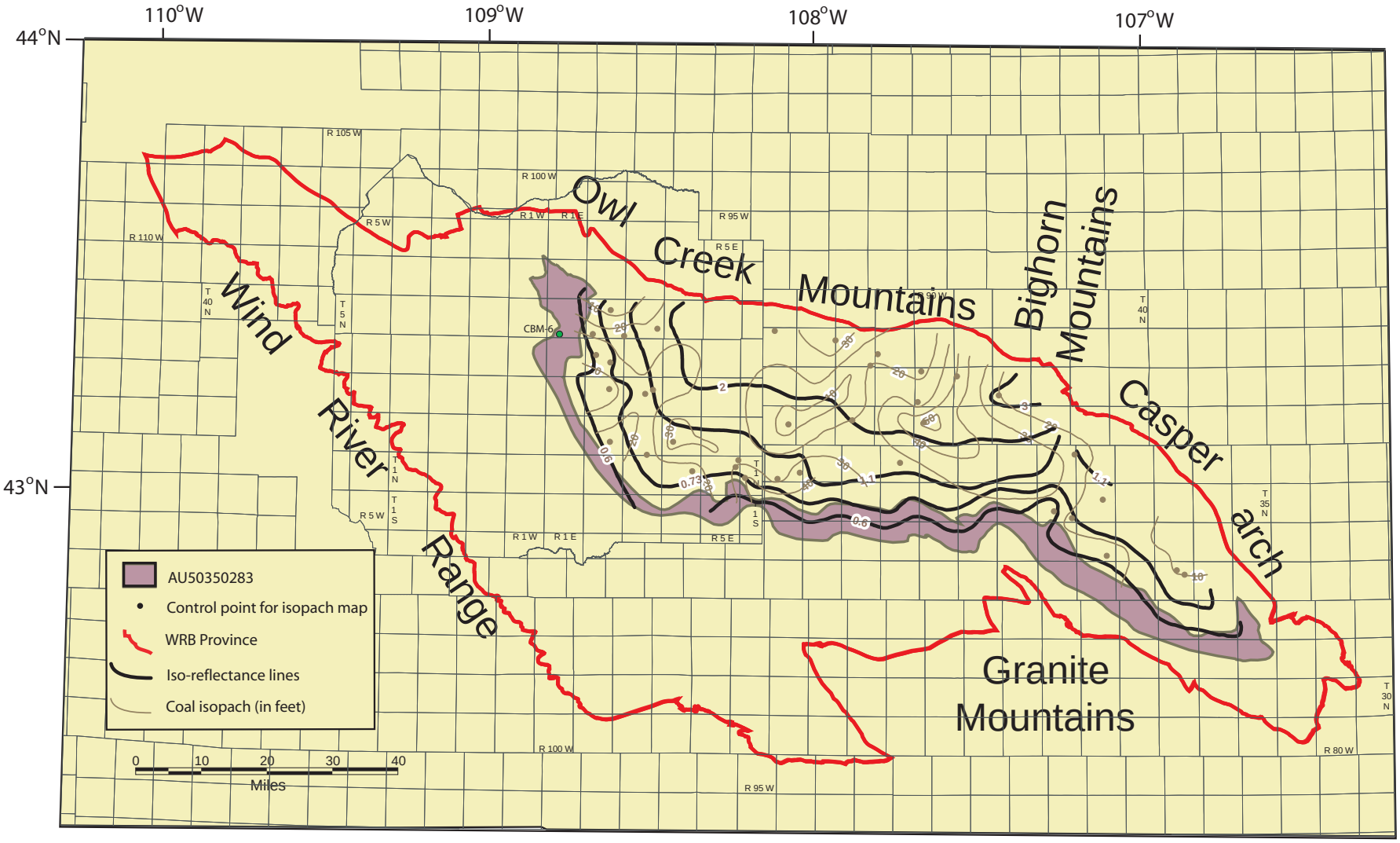

Figure 60. Extent of the Meeteetse Coalbed Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province (WRB), Wyoming. Isopach map is total coal in the Meeteetse Formation (modified from Johnson and others, 1996b). Contour interval is 10 feet. Variations in vitrinite reflectance at the base of Meeteetse Formation shown with heavy black lines. CBM-6 core hole tested Meeteetse coals and is from Johnson and others (1993).

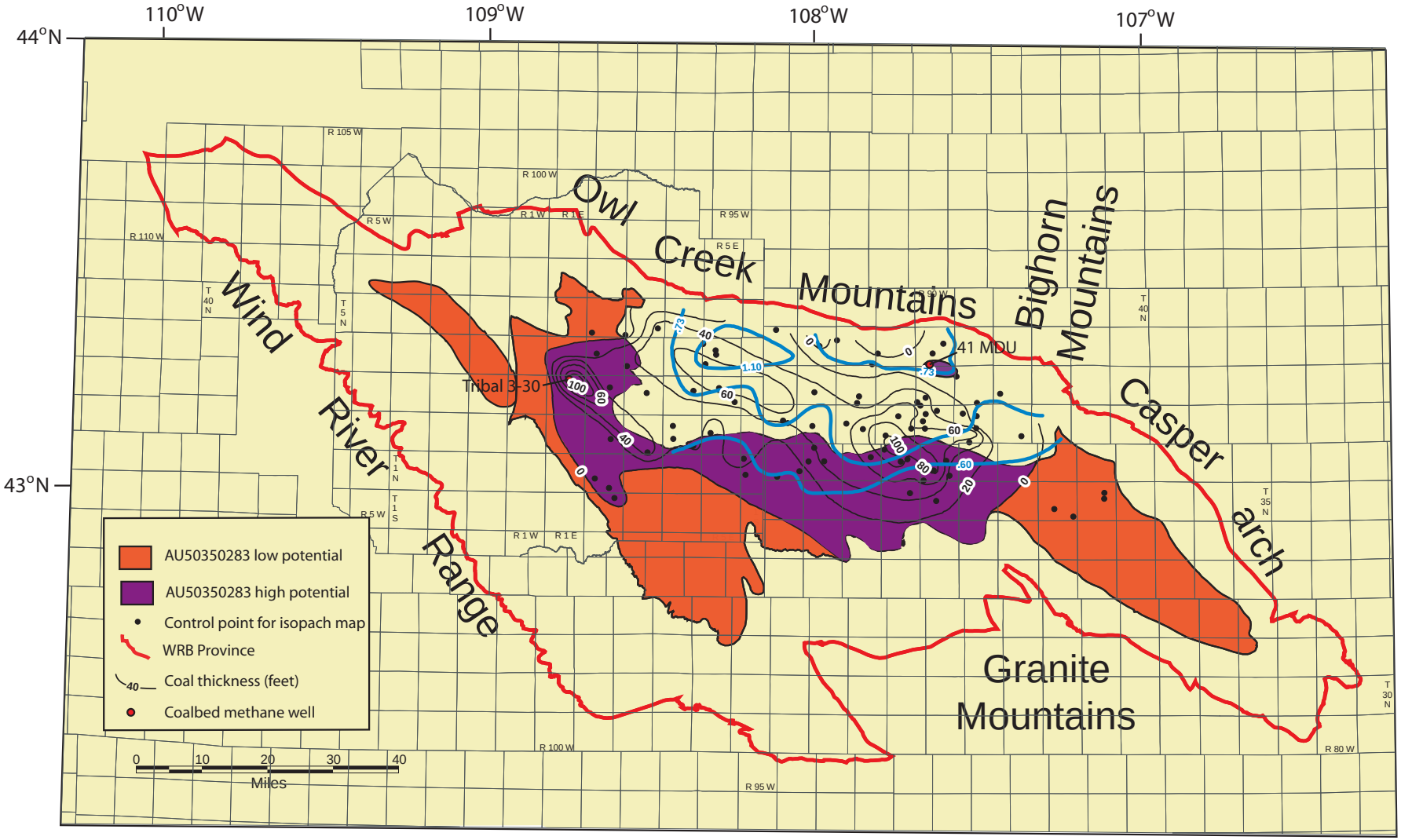

Figure 61. Extent of the Fort Union Coalbed Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province (WRB), Wyoming. Isopach map is total coal in the Fort Union Formation (modified from Johnson and others, 1996b). Contour interval is 20 feet. Variations in vitrinite reflectance at the base of the Waltman Shale Member shown with heavy blue lines (modified from Johnson and others, 1996a).

per untested cell having potential for additions to reserves are 0.02, 0.08, and 2 , with a calculated mean of 0.13 . Mean estimate of undiscovered resources that have the potential for additions to reserves in the Fort Union Coalbed Gas AU is 118 BCFG (table 1).

Cretaceous-Tertiary Conventional Oil and Gas Assessment Unit (AU 50350201)

The Cretaceous-Lower Tertiary Conventional Oil and Gas AU covers the entire area of the Cretaceous-Tertiary TPS (fig. 62) and where the Waltman Shale Member is absent, the AU includes all conventional Cretaceous and lower Tertiary production from the base of the Lower Cretaceous Cloverly Formation to the top of the Eocene Wind River Formation that is sourced by Cretaceous and Tertiary (excluding Waltman) source rocks. All production from the base of the Cloverly Formation to the base of the Mowry Shale is included in this conventional AU, as production from these units is considered to be conventional everywhere, even in the deeper parts of the basin where the AU lies beneath the Frontier-Muddy Continuous AU (fig. 63). The Cretaceous-Tertiary Conventional Oil and Gas AU overlaps areally with the Waltman Shale TPS, which is shown in purple in figure 63; in the overlapped area, the AU includes only production that is stratigraphically below the Waltman, as this thick shale unit is believed to act as a seal, separating Waltman-sourced hydrocarbons from those sourced from Cretaceous and lower Tertiary source rocks below the Waltman. Locally, near the Frenchie Draw field (fig. 62), minor Waltman-sourced oil is produced from the uppermost part of the lower member of the Fort Union, and this production is included in the Waltman Shale TPS. The AU is above and marginal to the continuous assessment units (figs. 27 and 63), and, at Madden anticline, the AU extends stratigraphically downward to include the Mississippian Madison Limestone, which is believed to be charged with Cretaceous gas (Schelling and Wavrek, 1999).

The Cretaceous-Tertiary Conventional Oil and Gas AU contains 12 oil and 17 gas fields exceeding the minimum size of 0.5 million barrels of oil equivalent (MMBOE) grown field size (Appendix H) (grown field size is an estimate of ultimate recovery from that field using data from NRG Associates, 2005). Figures 64 and 65 are graphs showing the sizes and discovery years for these oil and gas fields. Some fields, such as Muddy Ridge also produce gas from continuous AUs within the Cretaceous-Lower Tertiary Composite TPS; whereas, others produce oil from either the Waltman Shale TPS or the Phosphoria TPS (not included in figures 64 and 65). Grown field (pool) sizes for the first and second half of oil fields discovered are 1.54 and 1.62 MMBO respectively (Appendix H). The last oil field discovered was the Saddle Rock field in 1989, a small field producing from the Muddy Sandstone; thus, there have been no new oil field discoveries exceeding the minimum for 17 years. During this period, 105 wildcat wells were drilled in the AU. Grown field sizes for the first, second, and third “third” of gas fields discovered are 32.5, 85.3, and 72.0 BCFG (Appendix H) using data from NRG Associates (2005), with the last gas pool discovered that exceeded the minimum of 3 BCFG being the Madison pool at Madden anticline in 1985.

Minimum, mode, and maximum number of oil fields that will be discovered are estimated at 1, 3, and 15 respectively (Appendix H). Most of these yet-to-be discovered fields will produce from the Muddy Sandstone, as have all five oil fields discovered since 1964. Minimum, median, and maximum sizes of undiscovered accumulations are estimated at 0.5, 1.5, and 10 MMBO. These modest numbers reflect the relatively small size of Muddy fields discovered in the past.

Minimum, mode, and maximum numbers of gas fields that will be discovered are estimated at 1, 5, and 20, respectively. Because most anticlinal structures in the basin have already been explored, most of these fields are expected to be stratigraphic traps in updip pinchouts along the basin flanks. Most of these are likely to be of modest size, as most large stratigraphic traps would have been discovered with the present-day density of drilling; accordingly, minimum, median, and maximum sizes of these undiscovered accumulations are estimated to be 3, 10, and 50 BCFG (Appendix H). The mean estimates of undiscovered resources that have the potential for additions to reserves are 98.94 BCFG and 11.33 MMBO (table 1).

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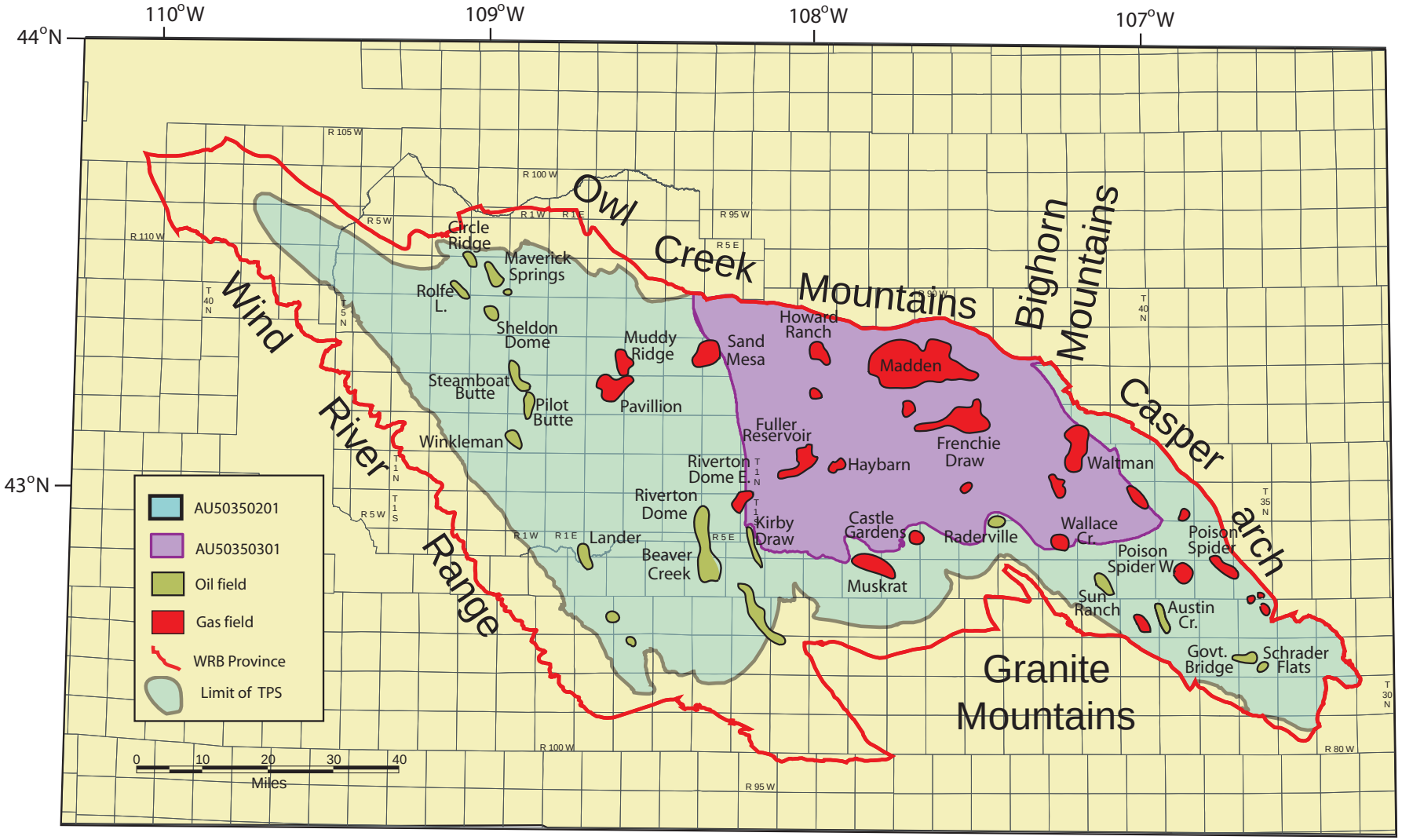

Figure 62. Extent of the Cretaceous-Tertiary Conventional Oil and Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin (WRB) Province, Wyoming, and locations of oil and gas fields.

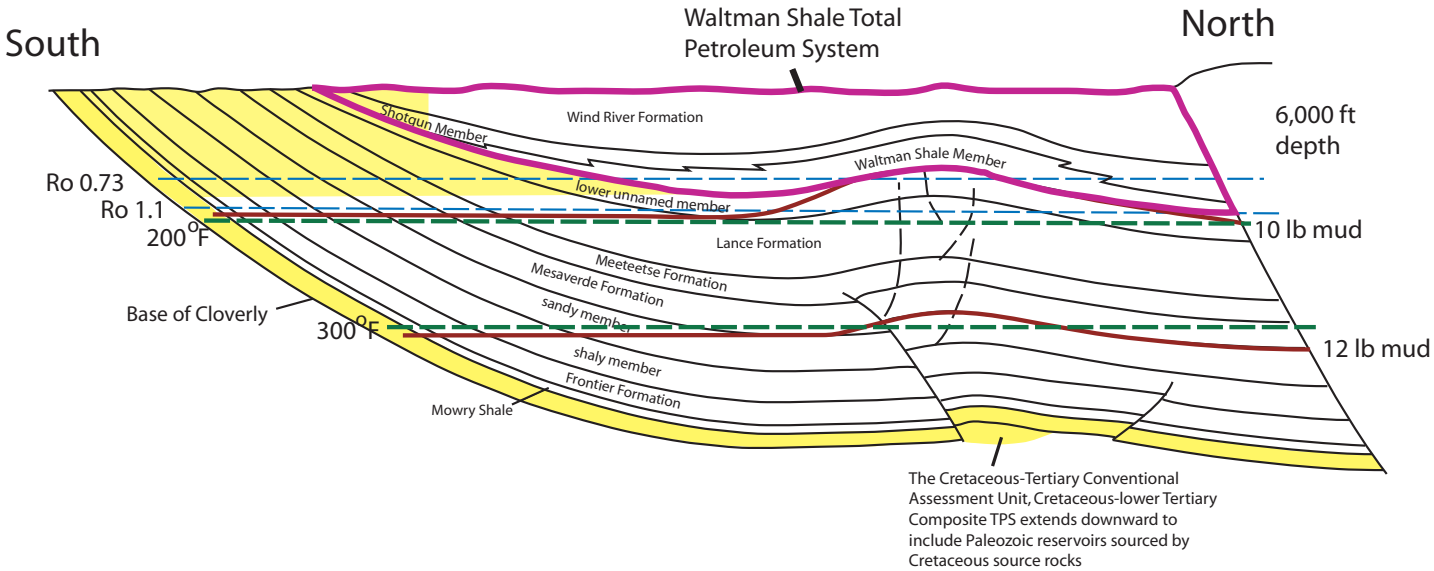

Figure 63. Schematic cross section showing extent of the Cretaceous-Tertiary Conventional Oil and Gas Assessment Unit (yellow), Cretaceous-Lower Tertiary Composite Total Petroleum System (TPS) Wind River Basin (WRB) Province, Wyoming. Variations in thermal maturity using vitrinite reflectance (R_o), depths where 10-pound (lb) mud and 12-lb mud were used while drilling, and the 200° F and 300° F isotherms are from Johnson and others (1996a, fig. 6). The Waltman Shale TPS (Roberts and others, Chapter 5, this CD-ROM) is outlined in purple.

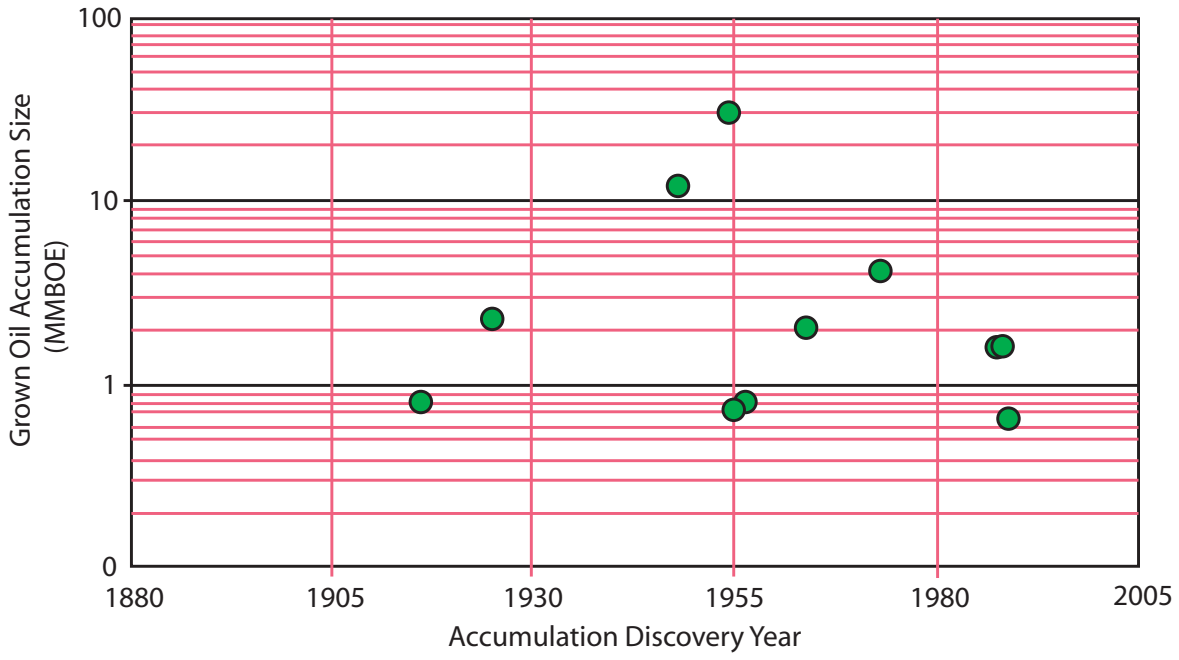

Figure 64. Grown field sizes and discovery year for oil pools in the Cretaceous-Tertiary Conventional Oil and Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming. MMBOE, million barrels of oil equivalent.

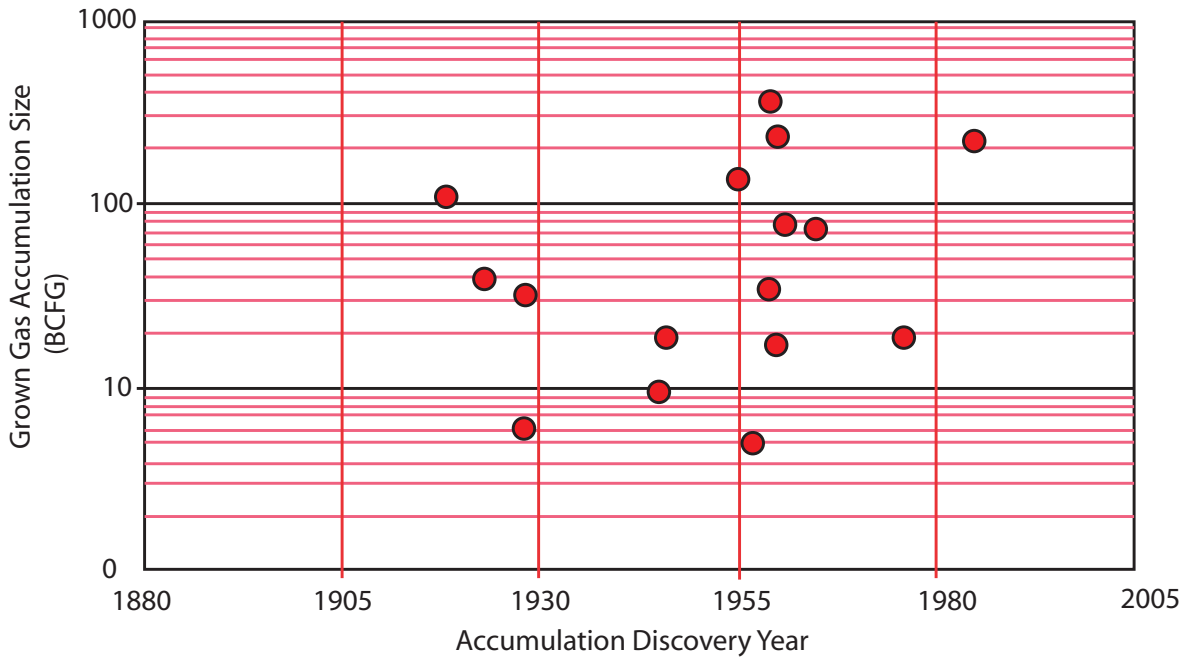

Figure 65. Grown field sizes and discovery year for gas pools in the Cretaceous-Tertiary Conventional Oil and Gas Assessment Unit, Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province, Wyoming. BCFG, billions of cubic feet of gas.

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Appendix A. Input parameters for the Frontier-Muddy Continuous Gas Assessment Unit (AU 50350261), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 9, 2-10-03)

IDENTIFICATION INFORMATION

Assessment Geologist:	M.A. Kirschbaum	Date:	9/20/2005
Region:	North America	Number:	5
Province:	Wind River Basin	Number:	5035
Total Petroleum System:	Cretaceous-Lower Tertiary Composite	Number:	503502
Assessment Unit:	Frontier-Muddy Continuous Gas	Number:	50350261
Based on Data as of:	IHS Energy (2002, production data 2005), Wyoming Geological Association (1989), Wyoming Oil and Gas Conservation Commission (2005)		
Notes from Assessor:	SW Wyoming Province assessment unit Mowry Continuous Gas (50370261) used as partial analog.		

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additions: 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: 51

Number of tested cells with total recovery per cell ≥ minimum: 21

Established (discovered cells): X Hypothetical (no cells): _____

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

1st 3rd discovered: 3 2nd 3rd: 4 3rd 3rd: 2.2

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

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

1. Total assessment-unit area (acres): (uncertainty of a fixed value)

   calculated mean 1,750,000 minimum 1,575,000 mode 1,750,000 maximum 1,925,000

2. Area per cell of untested cells having potential for additions to reserves (acres): (values are inherently variable)

   calculated mean 153 minimum 40 mode 120 maximum 300

   uncertainty of mean: minimum 120 maximum 185

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

   calculated mean 99.6 minimum 99.5 mode 99.6 maximum 99.7

Appendix A. Input parameters for the Frontier-Muddy Continuous Gas Assessment Unit (AU 50350261), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Frontier-Muddy Continuous Gas, 50350261

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES (Continued)

4. Percentage of untested assessment-unit area that has potential for additions to reserves (%):
(a necessary criterion is that total recovery per cell ≥ minimum; uncertainty of a fixed value)

calculated mean 3.8 minimum 0.7 mode 1.6 maximum 9

Geologic evidence for estimates: Based on locations of faults, fractures, and existing sweet spots. Minimum reflects infill around existing established production and recompletions of deep wells. Maximum reflects areas of structure that should enhance permeability.

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves:
(values are inherently variable; mmbo for oil A.U.; bcfg for gas A.U.)

calculated mean 1.14 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	mode	maximum
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	0.5	2

Appendix A. Input parameters for the Frontier-Muddy Continuous Gas Assessment Unit (AU 50350261), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Frontier-Muddy Continuous Gas, 50350261

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

Oil assessment unit:	minimum	mode	maximum
API gravity of oil (degrees)			
Sulfur content of oil (%)			
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum

Gas assessment unit:	minimum	mode	maximum
Inert-gas content (%)	0.00	0.50	2.00
CO_2 content (%)	0.00	3.00	5.00
Hydrogen sulfide content (%)	0.00	0.00	0.00
Heating value (BTU)	950	1000	1100
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum
2400	4614	6400	6234	7300

Success ratios:	calculated mean	minimum	mode	maximum
Future success ratio (%)	48.33	30	40	75

Historic success ratio, tested cells (%) 39

Completion practices:

1. Typical well-completion practices (conventional, open hole, open cavity, other) conventional
2. Fraction of wells drilled that are typically stimulated 1
3. Predominant type of stimulation (none, frac, acid, other) hydrofrac
4. Fraction of wells drilled that are horizontal 0

Appendix B. Input parameters for the Cody Sandstone Continuous Gas Assessment Unit (AU 50350262), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 9, 2-10-03)

IDENTIFICATION INFORMATION

Assessment Geologist:	T.M. Finn	Date:	9/20/2005
Region:	North America	Number:	5
Province:	Wind River Basin	Number:	5035
Total Petroleum System:	Cretaceous-Lower Tertiary Composite	Number:	503502
Assessment Unit:	Cody Sandstone Continuous Gas	Number:	50350262
Based on Data as of:	IHS Energy (2002, production data 2005), NRG Associates (2004, data current 2002)		
	Wyoming Oil and Gas Conservation Commission (2005)		
Notes from Assessor:			

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additions: 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: 83

Number of tested cells with total recovery per cell ≥ minimum: 35

Established (discovered cells): X Hypothetical (no cells): _____

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

1st 3rd discovered 1.2 2nd 3rd 7.5 3rd 3rd 0.59

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

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

1. Total assessment-unit area (acres): (uncertainty of a fixed value)

   calculated mean 1,134,000 minimum 1,077,000 mode 1,134,000 maximum 1,191,000

2. Area per cell of untested cells having potential for additions to reserves (acres): (values are inherently variable)

   calculated mean 280 minimum 40 mode 160 maximum 640

   uncertainty of mean: minimum 160 maximum 400

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

   calculated mean 98 minimum 97.1 mode 98 maximum 98.8

Appendix B. Input parameters for the Cody Sandstone Continuous Gas Assessment Unit (AU 50350262), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Cody Sandstone Continuous Gas, 50350262

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES (Continued)

4. Percentage of untested assessment-unit area that has potential for additions to reserves (%):
(a necessary criterion is that total recovery per cell ≥ minimum; uncertainty of a fixed value)

calculated mean 3.4 minimum 0.8 mode 1.4 maximum 8

Geologic evidence for estimates:

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves:
(values are inherently variable; mmbo for oil A.U.; bcfg for gas A.U.)

calculated mean 0.88 minimum 0.02 median 0.4 maximum 20

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

Oil assessment unit:	minimum	mode	maximum
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	0.015	1

Appendix B. Input parameters for the Cody Sandstone Continuous Gas Assessment Unit (AU 50350262), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Cody Sandstone Continuous Gas, 50350262

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

Oil assessment unit:	minimum	mode	maximum
API gravity of oil (degrees)			
Sulfur content of oil (%)			
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum

Gas assessment unit:	minimum	mode	maximum
Inert-gas content (%)	0.00	0.50	2.00
CO_2 content (%)	0.00	3.00	5.00
Hydrogen sulfide content (%)	0.00	0.00	0.00
Heating value (BTU)	950	1050	1100
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum
2438	4087	5181	5302	6400

Success ratios:	calculated mean	minimum	mode	maximum
Future success ratio (%)	40	20	40	60

Historic success ratio, tested cells (%) 42

Completion practices:

1. Typical well-completion practices (conventional, open hole, open cavity, other) conventional
2. Fraction of wells drilled that are typically stimulated 100
3. Predominant type of stimulation (none, frac, acid, other) water, acid
4. Fraction of wells drilled that are horizontal 0

Appendix C. Input parameters for the Mesaverde-Meeteetse Sandstone Gas Assessment Unit (AU 50350264), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 9, 2-10-03)

IDENTIFICATION INFORMATION

Assessment Geologist:	R.C. Johnson	Date:	9/19/2005
Region:	North America	Number:	5
Province:	Wind River Basin	Number:	5035
Total Petroleum System:	Cretaceous-Lower Tertiary Composite	Number:	503502
Assessment Unit:	Mesaverde-Meeteetse Sandstone Gas	Number:	50350264
Based on Data as of:	tested cells based on IHS Energy Data 2002, EUR based on first quarter 2005		
Notes from Assessor:			

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additions: 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: 157

Number of tested cells with total recovery per cell ≥ minimum: 34

Established (discovered cells): X Hypothetical (no cells):

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

1st 3rd discovered 1.8 2nd 3rd 2 3rd 3rd 1.1

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

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

1. Total assessment-unit area (acres): (uncertainty of a fixed value)

   calculated mean 1,204,000 minimum 1,088,000 mode 1,204,000 maximum 1,325,000

2. Area per cell of untested cells having potential for additions to reserves (acres): (values are inherently variable)

   calculated mean 83.3 minimum 20 mode 50 maximum 180

   uncertainty of mean: minimum 70 maximum 100

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

   calculated mean 99 minimum 98.5 mode 99.1 maximum 99.4

Appendix C. Input parameters for the Mesaverde-Meeteetse Sandstone Gas Assessment Unit (AU 50350264), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Mesaverde-Meeteetse Sandstone Gas, 50350264

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES (Continued)

4. Percentage of untested assessment-unit area that has potential for additions to reserves (%):
(a necessary criterion is that total recovery per cell ≥ minimum; uncertainty of a fixed value)

calculated mean 3 minimum 0.5 mode 1.5 maximum 7

Geologic evidence for estimates: At minimum, Madden plus at least one more sweet spot of 5000 acres;
at mode, about 5 more sweet spots;
at maximum, about 20 more sweet spots

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves:
(values are inherently variable; mmbo for oil A.U.; bcfg for gas A.U.)

calculated mean 0.91 minimum 0.02 median 0.5 maximum 15

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

Oil assessment unit:	minimum	mode	maximum
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	3	6

Appendix C. Input parameters for the Mesaverde-Meeteetse Sandstone Gas Assessment Unit (AU 50350264), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Mesaverde-Meeteetse Sandstone Gas, 50350264

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

Oil assessment unit:	minimum	mode	maximum
API gravity of oil (degrees)			
Sulfur content of oil (%)			
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum

Gas assessment unit:	minimum	mode	maximum
Inert-gas content (%)	0.10	3.00	7.00
CO_2 content (%)	0.50	3.00	7.00
Hydrogen sulfide content (%)	0.00	0.00	0.00
Heating value (BTU)	900	1000	1200
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum
1800	3496	4300	4846	6400

Success ratios:	calculated mean	minimum	mode	maximum
Future success ratio (%)	30	20	30	40

Historic success ratio, tested cells (%) 22

Completion practices:

1. Typical well-completion practices (conventional, open hole, open cavity, other)	conventional
2. Fraction of wells drilled that are typically stimulated	1
3. Predominant type of stimulation (none, frac, acid, other)	hydro/foam
4. Fraction of wells drilled that are horizontal	0

Appendix D. Input parameters for the Lance-Fort Union Sandstone Gas Assessment Unit (AU 50350265), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 9, 2-10-03)

IDENTIFICATION INFORMATION

Assessment Geologist:	R.C. Johnson	Date:	9/19/2005
Region:	North America	Number:	5
Province:	Wind River Basin	Number:	5035
Total Petroleum System:	Cretaceous-Lower Tertiary Composite	Number:	503502
Assessment Unit:	Lance-Fort Union Sandstone Gas	Number:	50350265
Based on Data as of:	tested cells based on IHS Energy Data 2002, EUR based on first quarter 2005		
Notes from Assessor:			

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additions: 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: 346

Number of tested cells with total recovery per cell ≥ minimum: 216

Established (discovered cells): X Hypothetical (no cells): _____

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

1st 3rd discovered 0.9 2nd 3rd 1.9 3rd 3rd 0.4

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

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

1. Total assessment-unit area (acres): (uncertainty of a fixed value)

   calculated mean 887,000 minimum 798,000 mode 887,000 maximum 976,000

2. Area per cell of untested cells having potential for additions to reserves (acres): (values are inherently variable)

   calculated mean 80 minimum 20 mode 60 maximum 160

   uncertainty of mean: minimum 40 maximum 100

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

   calculated mean 96.3 minimum 95 mode 96.6 maximum 97.4

Appendix D. Input parameters for the Lance-Fort Union Sandstone Gas Assessment Unit (AU 50350265), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Lance-Fort Union Sandstone Gas, 50350265

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES (Continued)

4. Percentage of untested assessment-unit area that has potential for additions to reserves (%):
(a necessary criterion is that total recovery per cell ≥ minimum; uncertainty of a fixed value)

calculated mean 6 minimum 2 mode 4 maximum 12

Geologic evidence for estimates: At minimum at least one more sweet spot of 5000 acres,
at mode about 5 more sweet spots,
at maximum include some non-structurally controlled sweet spots

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves:
(values are inherently variable; mmbo for oil A.U.; bcfg for gas A.U.)

calculated mean 1.14 minimum 0.02 median 0.6 maximum 20

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

	minimum	mode	maximum
Oil assessment unit:			
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	5	35

Appendix D. Input parameters for the Lance-Fort Union Sandstone Gas Assessment Unit (AU 50350265), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Lance-Fort Union Sandstone Gas, 50350265

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

Oil assessment unit:	minimum	mode	maximum
API gravity of oil (degrees)			
Sulfur content of oil (%)			
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum

Gas assessment unit:	minimum	mode	maximum
Inert-gas content (%)	0.10	1.00	2.00
CO_2 content (%)	0.50	3.00	7.00
Hydrogen sulfide content (%)	0.00	0.00	0.00
Heating value (BTU)	900	1000	1125
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum
1500	3021	4000	4146	5200

Success ratios:	calculated mean	minimum	mode	maximum
Future success ratio (%)	48.3	30	50	65

Historic success ratio, tested cells (%) 62

Completion practices:

1. Typical well-completion practices (conventional, open hole, open cavity, other) conventional
2. Fraction of wells drilled that are typically stimulated 1
3. Predominant type of stimulation (none, frac, acid, other) hydro/foam
4. Fraction of wells drilled that are horizontal 0

Appendix E. Input parameters for the Mesaverde Coalbed Gas Assessment Unit (AU 50350281), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 9, 2-10-03)

IDENTIFICATION INFORMATION

Assessment Geologist:	R.C. Johnson	Date:	9/19/2005
Region:	North America	Number:	5
Province:	Wind River Basin	Number:	5035
Total Petroleum System:	Cretaceous-Lower Tertiary Composite	Number:	503502
Assessment Unit:	Mesaverde Coalbed Gas	Number:	50350281
Based on Data as of:	tested cells based on IHS Energy Data 2002, EUR based Wyoming Oil and Gas Conservation Commission data		
Notes from Assessor:	analogs: Powder River Basin and Piceance Basin (50200282) and Southwestern Wyoming (50370681)		

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additions 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: 7

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

Established (discovered cells): X Hypothetical (no cells): _____

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

1st 3rd discovered _____ 2nd 3rd _____ 3rd 3rd _____

Assessment-Unit Probabilities:

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

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

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

1. Total assessment-unit area (acres): (uncertainty of a fixed value)

   calculated mean 649,000 minimum 584,000 mode 649,000 maximum 713,000

2. Area per cell of untested cells having potential for additions to reserves (acres): (values are inherently variable)

   calculated mean 146.7 minimum 40 mode 120 maximum 280

   uncertainty of mean: minimum 100 maximum 190

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

   calculated mean 99.9 minimum 99.7 mode 99.9 maximum 100

Appendix E. Input parameters for the Mesaverde Coalbed Gas Assessment Unit (AU 50350281), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Mesaverde Coalbed Gas, 50350281

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES (Continued)

4. Percentage of untested assessment-unit area that has potential for additions to reserves (%):
(a necessary criterion is that total recovery per cell ≥ minimum; uncertainty of a fixed value)

calculated mean 11.7 minimum 1 mode 7 maximum 27

Geologic evidence for estimates: At minimum, minimal development areas around USGS pilot areas;
at mode, 10% of high potential area;
at maximum, about 40% of the high potential area plus a minor amount of the low potential area

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves:
(values are inherently variable; mmbo for oil A.U.; bcfg for gas A.U.)

calculated mean 0.22 minimum 0.02 median 0.1 maximum 5

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

	minimum	mode	maximum
Oil assessment unit:			
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	2	5

Appendix E. Input parameters for the Mesaverde Coalbed Gas Assessment Unit (AU 50350281), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Mesaverde Coalbed Gas, 50350281

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

Oil assessment unit:	minimum	mode	maximum
API gravity of oil (degrees)			
Sulfur content of oil (%)			
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum

Gas assessment unit:	minimum	mode	maximum
Inert-gas content (%)	0.10	0.30	1.00
CO_2 content (%)	0.50	1.80	20.00
Hydrogen sulfide content (%)	0.00	0.00	0.00
Heating value (BTU)	850	950	1050
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum
90	779	1200	1294	1800

Success ratios:	calculated mean	minimum	mode	maximum
Future success ratio (%)	41.7	10	50	65

Historic success ratio, tested cells (%) 14

Completion practices:

1. Typical well-completion practices (conventional, open hole, open cavity, other)	conventional
2. Fraction of wells drilled that are typically stimulated	1
3. Predominant type of stimulation (none, frac, acid, other)	hydro
4. Fraction of wells drilled that are horizontal	0

Appendix F. Input parameters for the Meeteetse Coalbed Gas Assessment Unit (AU 50350282), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 9, 2-10-03)

IDENTIFICATION INFORMATION

Assessment Geologist:	R.C. Johnson	Date:	9/19/2005
Region:	North America	Number:	5
Province:	Wind River Basin	Number:	5035
Total Petroleum System:	Cretaceous-Lower Tertiary Composite	Number:	503502
Assessment Unit:	Meeteetse Coalbed Gas	Number:	50350282
Based on Data as of:	untested		
Notes from Assessor:	analogs: Piceance Basin (50200282) and Southwestern Wyoming (50370581)		

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additions: Gas

What is the minimum total recovery per cell? 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)

Number of tested cells: 0

Number of tested cells with total recovery per cell ≥ minimum: 0

Established (discovered cells): _____ Hypothetical (no cells): X

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

1st 3rd discovered _____ 2nd 3rd _____ 3rd 3rd _____

Assessment-Unit Probabilities:

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

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

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

1. Total assessment-unit area (acres): (uncertainty of a fixed value)

   calculated mean 376,000 minimum 338,000 mode 376,000 maximum 414,000

2. Area per cell of untested cells having potential for additions to reserves (acres): (values are inherently variable)

   calculated mean 146.7 minimum 40 mode 120 maximum 280

   uncertainty of mean: minimum 100 maximum 190

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

   calculated mean 100 minimum 100 mode 100 maximum 100

Appendix F. Input parameters for the Meeteetse Coalbed Gas Assessment Unit (AU 50350282), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Meeteetse Coalbed Gas, 50350282

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES (Continued)

4. Percentage of untested assessment-unit area that has potential for additions to reserves (%):
(a necessary criterion is that total recovery per cell ≥ minimum; uncertainty of a fixed value)

calculated mean 6.3 minimum 1 mode 3 maximum 15

Geologic evidence for estimates: At minimum, thickest coals with best permeability;
at mode, 20% of 75,000 acres high potential area with 75% success ratio;
at maximum, about 75,000 acres of high potential with 75% success ratio

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves:
(values are inherently variable; mmbo for oil A.U.; bcfg for gas A.U.)

calculated mean 0.13 minimum 0.02 median 0.08 maximum 2

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

Oil assessment unit:	minimum	mode	maximum
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	2	5

Appendix F. Input parameters for the Meeteetse Coalbed Gas Assessment Unit (AU 50350282), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Meeteetse Coalbed Gas, 50350282

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

Oil assessment unit:	minimum	mode	maximum
API gravity of oil (degrees)			
Sulfur content of oil (%)			
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum

Gas assessment unit:	minimum	mode	maximum
Inert-gas content (%)	0.10	0.30	1.00
CO_2 content (%)	0.50	1.80	20.00
Hydrogen sulfide content (%)	0.00	0.00	0.00
Heating value (BTU)	850	950	1050
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum
90	678	900	1180	1800

Success ratios:	calculated mean	minimum	mode	maximum
Future success ratio (%)	35	5	40	60

Historic success ratio, tested cells (%) _____

Completion practices:

1. Typical well-completion practices (conventional, open hole, open cavity, other)	conventional
2. Fraction of wells drilled that are typically stimulated	1
3. Predominant type of stimulation (none, frac, acid, other)	hydro
4. Fraction of wells drilled that are horizontal	0

Appendix G. Input parameters for the Fort Union Coalbed Gas Assessment Unit (AU 50350283), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 9, 2-10-03)

IDENTIFICATION INFORMATION

Assessment Geologist:	R.C. Johnson	Date:	9/20/2005
Region:	North America	Number:	5
Province:	Wind River Basin	Number:	5035
Total Petroleum System:	Cretaceous-Lower Tertiary Composite	Number:	503502
Assessment Unit:	Fort Union Coalbed Gas	Number:	50350283
Based on Data as of:	Wyoming Oil and Gas Conservation Commission (2005)		

Notes from Assessor: Powder River Basin Lower Fort Union-Lance Formations (50330183) and Upper Fort Union Formation (50330182); Wind River Mesaverde Coalbed Gas (50350281); and Piceance Basin assessment unit (50200282) as analogs.

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additions: 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: 2

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

Established (discovered cells): X Hypothetical (no cells): _____

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

1st 3rd discovered _____ 2nd 3rd _____ 3rd 3rd _____

Assessment-Unit Probabilities:

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

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

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

1. Total assessment-unit area (acres): (uncertainty of a fixed value)

   calculated mean 1,419,000 minimum 1,277,000 mode 1,419,000 maximum 1,561,000

2. Area per cell of untested cells having potential for additions to reserves (acres): (values are inherently variable)

   calculated mean 87 minimum 40 mode 80 maximum 140

   uncertainty of mean: minimum 50 maximum 120

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

   calculated mean 100 minimum 100 mode 100 maximum 100

Appendix G. Input parameters for the Fort Union Coalbed Gas Assessment Unit (AU 50350283), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Fort Union Coalbed Gas (50350283)

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES (Continued)

4. Percentage of untested assessment-unit area that has potential for additions to reserves (%):
(a necessary criterion is that total recovery per cell ≥ minimum; uncertainty of a fixed value)

calculated mean 5.5 minimum 0.5 mode 3 maximum 13

Geologic evidence for estimates: Area with coal is 40% of assessment unit area, coals greater than 20 ft thick account for 20% of the assessment unit area. Line 4 numbers reflect those percentages with respective success ratios are imposed.

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves:
(values are inherently variable; mmbo for oil A.U.; bcfg for gas A.U.)

calculated mean 0.13 minimum 0.02 median 0.08 maximum 2

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

	minimum	mode	maximum
Oil assessment unit:			
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	0.25	0.5

Appendix G. Input parameters for the Fort Union Coalbed Gas Assessment Unit (AU 50350283), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Fort Union Coalbed Gas (50350283)

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

Oil assessment unit:	minimum	mode	maximum
API gravity of oil (degrees)			
Sulfur content of oil (%)			
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum

Gas assessment unit:	minimum	mode	maximum
Inert-gas content (%)	0.10	0.30	1.00
CO_2 content (%)	0.50	1.80	20.00
Hydrogen sulfide content (%)	0.00	0.00	0.00
Heating value (BTU)	850	950	1050
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum
90	791	1220	1315	1830

Success ratios:	calculated mean	minimum	mode	maximum
Future success ratio (%)	41.7	10	50	65

Historic success ratio, tested cells (%) 50

Completion practices:

1. Typical well-completion practices (conventional, open hole, open cavity, other)	conventional
2. Fraction of wells drilled that are typically stimulated	1
3. Predominant type of stimulation (none, frac, acid, other)	hydro
4. Fraction of wells drilled that are horizontal	0

Appendix H. Input parameters for the Cretaceous-Tertiary Conventional Oil and Gas Assessment Unit (AU 50350201), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.

SEVENTH APPROXIMATION
DATA FORM FOR CONVENTIONAL ASSESSMENT UNITS (Version 6, 9 April 2003)

IDENTIFICATION INFORMATION

Assessment Geologist:	R.C. Johnson, M.A. Kirschbaum, and T.M. Finn	Date:	9/21/2005
Region:	North America	Number:	5
Province:	Wind River Basin	Number:	5035
Total Petroleum System:	Cretaceous-Lower Tertiary Composite	Number:	503502
Assessment Unit:	Cretaceous-Tertiary Conventional Oil and Gas	Number:	50350201
Based on Data as of:	IHS Energy (2005), Wyoming Oil and Gas Conservation Commision (2005)		
Notes from Assessor:	NRG Associates (2005, data current through 2003), Wyoming Geological Association (1989); Mowry (50370201), Hilliard-Baxter-Mancos (50370401), and Mesaverde (50370501) assessment units as partial analogs.		

CHARACTERISTICS OF ASSESSMENT UNIT

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

What is the minimum accumulation size? 0.5 mmboe grown
(the smallest accumulation that has potential to be added to reserves)

No. of discovered accumulations exceeding minimum size: Oil: 12 Gas: 17
Established (>13 accums.) X Frontier (1-13 accums.) ____ Hypothetical (no accums.) ____

Median size (grown) of discovered oil accumulations (mmbo):
1st 3rd 1.54 2nd 3rd 1.62 3rd 3rd ____
Median size (grown) of discovered gas accumulations (bcfg):
1st 3rd 32.5 2nd 3rd 85.3 3rd 3rd 72

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 siz	1.0

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): 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:	minimum (>0) 1	mode 3	maximum 15
Gas Accumulations:	minimum (>0) 1	mode 5	maximum 20

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):	minimum 0.5	median 1.5	maximum 10
Gas in Gas Accumulations (bcfg):	minimum 3	median 10	maximum 50

Appendix H. Input parameters for the Cretaceous-Tertiary Conventional Oil and Gas Assessment Unit (AU 50350201), Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin Province.—Continued

Assessment Unit (name, no.)
Cretaceous-Tertiary Conventional, 50350201

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

Oil Accumulations:	minimum	mode	maximum
Gas/oil ratio (cfg/bo)	1750	3500	5250
NGL/gas ratio (bngl/mmcfg)	12	24	36

Gas Accumulations:	minimum	mode	maximum
Liquids/gas ratio (bliq/mmcfg)	4	8	12
Oil/gas ratio (bo/mmcfg)			

SELECTED ANCILLARY DATA FOR UNDISCOVERED ACCUMULATIONS
(variations in the properties of undiscovered accumulations)

Oil Accumulations:	minimum	mode	maximum
API gravity (degrees)	30	40	50
Sulfur content of oil (%)	0	0.1	0.5
Depth (m) of water (if applicable)			

	minimum	F75	mode	F25	maximum
Drilling Depth (m)	150	1424	2000	2453	3660

Gas Accumulations:	minimum	mode	maximum
Inert gas content (%)	0	0.5	15
CO_2 content (%)	0	0.5	2
Hydrogen-sulfide content (%)	0	0	0
Depth (m) of water (if applicable)			

	minimum	F75	mode	F25	maximum
Drilling Depth (m)	460	1605	2100	2543	3660

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