Chapter 2

2005 Geologic Assessment of Undiscovered Oil and Gas Resources, Hanna, Laramie, and Shirley Basins Province, Wyoming and Colorado

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Volume Title Page

By Thaddeus S. Dyman and Steven M. Condon

Chapter 2 of

Petroleum Systems and Geologic Assessment of Undiscovered Oil and Gas, Hanna, Laramie, and Shirley Basins Province, Wyoming and Colorado

By U.S. Geological Survey Hanna, Laramie, and Shirley Basins Province Assessment Team

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Abbreviations Used in This Report

AU	assessment unit
BCFG	billion cubic feet of natural gas
BWPD	barrels of water per day
CFGPD	cubic feet of gas per day
MMBNGL	million barrels of natural gas liquids
MMBO	million barrels of oil
MMBOE	million barrels of oil equivalent
R_o	vitrinite reflectance
TPS	total petroleum system
USGS	U.S. Geological Survey
ft	foot, feet
Ga	Giga-annum; billions of years ago
Ma	Mega-annum; millions of years ago
mi	mile, miles
m.y.	millions of years

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2005 Geologic Assessment of Undiscovered Oil and Gas Resources, Hanna, Laramie, and Shirley Basins Province, Wyoming and Colorado

By Thaddeus S. Dyman and Steven M. Condon

Abstract

Undiscovered oil and gas resources of the Hanna, Laramie, and Shirley Basins Province, Wyoming and Colorado, were assessed in 2005 as part of the U.S. Geological Survey National Oil and Gas Assessment Project. The province contains five total petroleum systems: Phosphoria, Mowry-Hanna Composite, Niobrara, Niobrara Biogenic Gas, and Hanna-Mesaverde Coalbed Gas. Reservoirs as old as the Pennsylvanian Tensleep Sandstone and as young as the Paleocene-Eocene Hanna Formation compose the stratigraphic sequence.

Within these total petroleum systems, primary source rocks are (1) phosphatic shales of the Permian Phosphoria Formation; (2) shales and calcareous mudstones of the Cretaceous Thermopolis and Mowry Shales, Frontier and Niobrara Formations, and Steele Shale; and (3) coals and mudstones of the Upper Cretaceous Mesaverde Group and Medicine Bow Formation, Upper Cretaceous and Paleocene Ferris Formation, and Paleocene and Eocene Hanna Formation. Lacustrine mudstones of the Ferris and Hanna Formations may be minor source rocks in the central part of the Hanna Basin.

Oil and gas were generated in economic quantities in different parts of the province at different times, primarily relating to variations in depth of burial. Data for the Thermopolis-Mowry interval indicate that (1) in the Hanna Basin center, peak oil generation occurred about 68 million years ago (Ma) and oil-to-gas cracking occurred about 60 Ma; (2) along the south margin of the Hanna Basin, peak oil generation also occurred at about 68 Ma, but no appreciable oil-to-gas cracking has occurred to date; and (3) in the Laramie and Shirley Basins, source rocks did not reach thermal maturities necessary for significant oil and gas generation. Most of the oil and gas currently trapped in fields in the Laramie Basin migrated into local reservoirs from the Hanna Basin prior to Laramide structural partitioning.

Oil and gas migrated from source rocks into reservoirs through a system of faults and fractures that are pervasive throughout the area and updip along bedding planes and within sandstone units. Trapping mechanisms include structures formed initially in association with the late Paleozoic Ancestral Rocky Mountains and later during the Late Cretaceous to early Tertiary Laramide orogeny. Structures may be thrust faults, faulted anticlines, triangle zones, or pop-up structures. Stratigraphic pinchouts and combination stratigraphic-structural traps are also common, especially where sedimentary facies change in reservoir rocks. Seals consist of interbedded shales and mudstones and diagenetic cements. In some instances oil from older late Paleozoic structural traps remigrated into younger Laramide traps.

Seven assessment units were identified for the Hanna, Laramie, and Shirley Basins Province: (1) Tensleep-Casper Conventional Oil and Gas (50300101), (2) Mesozoic-Cenozoic Conventional Oil and Gas (50300201), (3) Hanna Basin Continuous Gas (50300261), (4) Niobrara Continuous Oil (50300361), (5) Niobrara Biogenic Gas (50300461), (6) Medicine Bow-Ferris-Hanna Coalbed Gas (50300581), and (7) Mesaverde Coalbed Gas (50300582). Only three of these assessment units (Tensleep-Casper Conventional Oil and Gas, Mesozoic-Cenozoic Conventional Oil and Gas, and Niobrara Continuous Oil) were quantitatively assessed; lack of data precluded assessment of the others.

Total mean estimated undiscovered conventional and continuous resources in these three assessment units are 94 million barrels of oil, 298 billion cubic feet of natural gas, and 14 million barrels of natural gas liquids.

Introduction

Purpose and Scope

The purpose of this report is to present the results of a U.S. Geological Survey (USGS) assessment of undiscovered oil and gas resources in the Hanna, Laramie, and Shirley Basins Province of south-central Wyoming and northern Colorado (fig. 1). The province was affected by two major crustal processes: by the development of an early Mesozoic foreland basin that produced a large, asymmetric depositional trough in the Western Interior of the United States and Canada and by the Late Cretaceous to early Tertiary Laramide orogeny that broke up the intracontinental depositional basin and formed a variety of discrete structural basins and bordering uplifts. The province contains the Hanna, Laramie, and Shirley Laramide structural basins (fig. 1).

The Hanna, Laramie, and Shirley Basins Province extends from the Rawlins uplift eastward through the Hanna, Laramie, and Shirley Basins to the Laramie Mountains. On the north and northwest, it is bounded by the Sweetwater uplift and the Wind River Basin; on the south, it is bounded by the Medicine Bow Mountains and Sierra Madre uplift (fig. 1). Surrounding petroleum provinces have also been assessed for oil and gas—the Wind River Basin Province to the northwest, the Southwestern Wyoming Province to the west, and the Park Basins Province to the south (fig. 1). This province includes most of Carbon and Albany Counties, Wyoming, and the northernmost part of Larimer County, Colorado. Its area encompasses more than 4 million square miles. Subbasin names, such as Pass Creek, Kindt, Carbon, and Cooper Lake, are commonly used to identify specific geologic areas within the province (fig. 1).

Various oil- and gas-producing regions of the United States are being reevaluated as a follow up to the USGS's 1995 National Assessment of United States Oil and Gas Resources (Gautier and others, 1996); the results of these studies are available at http://energy.cr.usgs.gov/oilgas/noga/. In the 1995 national assessment, the Hanna, Laramie, and Shirley Basins Province was combined with the Southwest Wyoming Province (Gautier and others, 1996; Law, 1996). Because the Hanna, Laramie, and Shirley Basins Province had not been previously assessed separately by the USGS, estimates of undiscovered resources from the current assessment cannot be directly compared with those of previous USGS estimates. Law (1996) identified and assessed plays that lay in all or part of the combined Green River, Hanna, Laramie, and Shirley Basins. A new assessment of the Greater Green River Basin was recently completed by the USGS (U.S. Geological Survey Southwestern Wyoming Assessment Team, 2005).

Another difference between the U.S. Geological Survey's 1995 national assessment and this assessment is the use of the petroleum system model (Magoon and Dow, 1994). A total petroleum system (TPS) is defined as "all genetically related petroleum that occurs, or is estimated to occur, in shows and accumulations, both discovered and undiscovered, which have been generated by a pod or by closely related pods of mature source rock," and it consists of "essential geologic elements [that] control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum within the total petroleum system" (Klett, 2004). It consists of all areas to which hydrocarbons from related source rocks potentially migrated after generation and expulsion, and it is commonly defined by the geographic extent of source and reservoir rocks. A composite total petroleum system is a mappable entity that is used when more than one source rock has charged the accumulations (Klett, 2004).

Assessment units (AUs) have replaced plays as the basic unit of assessment. Plays were identified primarily by using similarities in petroleum reservoirs, and source rocks were not emphasized. An assessment unit is "a mappable part of a total petroleum system in which discovered and undiscovered oil and gas accumulations constitute a single relatively homogeneous population such that the methodology of resource assessment is applicable" (Klett, 2004). It is a three-dimensional entity, consisting of a contiguous geographic area and one or more geologic formations. The use of AUs rather than plays does not necessarily result in differences in assessed volumes of undiscovered resources, but applying the concept of the total petroleum system provides a unifying framework for identifying and analyzing accumulations (Klett, 2004).

As one aspect of our study of the Hanna, Laramie, and Shirley Basins province, we looked at the characteristics of known and potential oil or gas accumulations to determine if they are discrete (conventional) or continuous (unconventional) as classified by Schmoker (1996), a distinction that is based on geologic parameters rather than on government regulations relating to reservoir classification. It is important to distinguish between the two types of accumulation because different methods are used for each type to estimate undiscovered resources. Several features distinguish the end-member accumulation types, although a probable continuum between the types can in some cases make classification difficult. Two lists of such distinguishing features (table 1), were drawn mainly from Spencer (1989), Schmoker (1996), Wilson and others (2001), and Law (2002).

Oil and gas fields in the Hanna, Laramie, and Shirley Basins Province were evaluated with respect to the characteristics listed in table 1. Most existing fields, which lie on the margins of the Laramie and Hanna Basins, have characteristics that clearly classify them as conventional. Two small Niobrara oil fields on the south flank of the Hanna Basin were modeled after continuous Niobrara oil fields in the Southwestern Wyoming Province, and a continuous assessment unit was defined and quantitatively assessed for Niobrara oil. Gas fields have not yet been discovered in the deep central Hanna Basin, and few deep wells have been drilled there. As a result, a deep (>20,000 foot (ft)) basin-center gas AU was defined in the Hanna Basin but was not assessed. An evaluation of the few deep wells in the Hanna Basin was based on data from Wilson and others (2001).

The geochemistry of oil samples collected from Pennsylvanian, Jurassic, and Cretaceous reservoirs in the Laramie Basin indicates that the source of some fields was the Permian Phosphoria Formation, and the source of others was marine shales of Cretaceous and lower Tertiary formations (fig. 2) (M.D. Lewan and P.G. Lillis, USGS, written commun., 2004). Rock-Eval pyrolysis data indicate source-rock potential

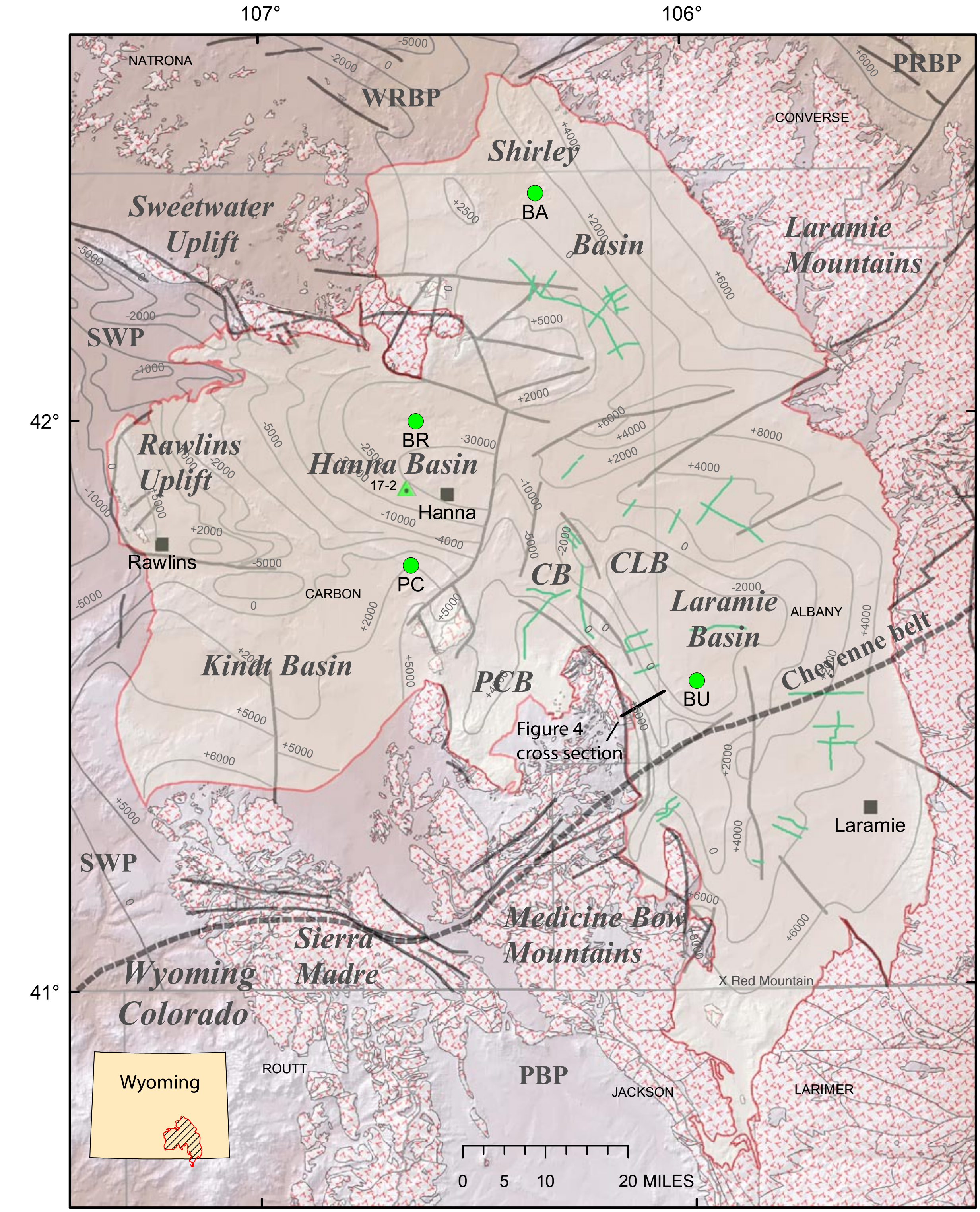

Figure 1. Hanna, Laramie, and Shirley Basins Province (outlined in red), major topographic and geologic features, subbasins, and bordering petroleum provinces. Contours are drawn on the top of Precambrian basement in feet relative to sea level (modified from Blackstone, 1989). Thick gray lines are major faults. Red patterned areas are outcrops of Precambrian rocks from Green (1992) and Green and Drouillard (1994). Green lines are seismic profiles used to interpret subsurface structure for this assessment. CB, Carbon Basin; CLB, Cooper Lake Basin; PBP, Park Basins Province; PCB, Pass Creek Basin; PRBP, Powder River Basin Province; SWP, Southwestern Wyoming Province; WRBP, Wind River Basin Province. Green triangle—Anadarko Durante 17–2 well. Green filled circles—BA, Coastal Bates Creek Cattle 1–18–28–79 well; BR, Brinkerhoff Hanna Unit No. 1 well; BU, Buttes Federal 1–18 well; PC, Humble Pass Creek Ridge No. 1 well. Location of the Cheyenne belt from Stone (1995).

Table 1. Characteristics of discrete and continuous oil and gas accumulations.

[Distinguishing features from Spencer (1989), Schmoker (1996), Wilson and others (2001), and Law (2002)]

Characteristic	*Type of accumulation*	
	Discrete (conventional)	*Continuous (unconventional)*
Source rocks	Potentially distant from reservoirs	Source rocks near reservoirs; migration distances commonly short
Maturity	Accumulations can occur in immature rocks because of migration	Tops of accumulations commonly within a narrow vitrinite reflectance (Ro) range of 0.75–0.9 percent
Reservoir rocks		
Seals or traps	Well-defined stratigraphic and structural traps	Lack traditional seals or traps
Porosity	Good reservoir porosity	Low reservoir porosity, commonly less than 13 percent
Permeability	Good reservoir permeability	Low reservoir permeability (<0.1 millidarcies) reduces ability of gas to migrate by buoyancy; natural or induced fractures important for production
The producing field		
Extent	Field delimited by water-saturated rocks	Large geographic extent, commonly in the deeper central parts of basins
Reservoir pressure	Normally pressured reservoirs	Abnormal pressures (usually underpressured or overpressured); thick sequences of reservoirs are gas-saturated
Hydrocarbon production rate	Initially high production rates that decline as the wells mature	Large in-place resources, but low well recoveries and production rates
Hydrocarbon-water contact	Distinct hydrocarbon-water contacts	Lack of hydrocarbon-water contacts
Water production rate	Variable water production; water production can be high and commonly increases as wells mature	Little or no water production; accumulations occur downdip from water-saturated rocks and conventional fields

for Lower Cretaceous marine rocks of the Thermopolis and Mowry Shales and for Upper Cretaceous to Eocene marine and lacustrine rocks of the Steele and Lewis Shales and of the Medicine Bow, Ferris, and Hanna Formations.

As a result of our analysis of source rocks, oils, and biogenic gas generation, we identified five total petroleum systems: (1) Phosphoria, (2) Mowry-Hanna Composite, (3) Niobrara, (4) Niobrara Biogenic Gas, and (5) Hanna-Mesaverde Coalbed Gas. Detailed descriptions of these petroleum systems are presented in this report. Within these TPSs, seven AUs were defined: (1) Tensleep-Casper Conventional Oil and Gas, (2) Mesozoic-Cenozoic Conventional Oil and Gas, (3) Hanna Basin Continuous Gas, (4) Niobrara Continuous Oil, (5) Niobrara Biogenic Gas, (6) Medicine Bow–Ferris–Hanna Coalbed Gas, and (7) Mesaverde Coalbed Gas (table 2). Three of these (Tensleep-Casper Conventional Oil and Gas, Mesozoic-Cenozoic Conventional Oil and Gas, and Niobrara Continuous Oil) were quantitatively assessed.

The estimated mean volumes of undiscovered resources are 94 million barrels of oil (MMBO), 298 billion cubic feet of natural gas (BCFG), and 14 million barrels (MMBNGL) of natural gas liquids (table 2). Total cumulative production to date from the assessed formations in 12 of the larger fields is some 77 MMBO and 24 BCFG (table 3).

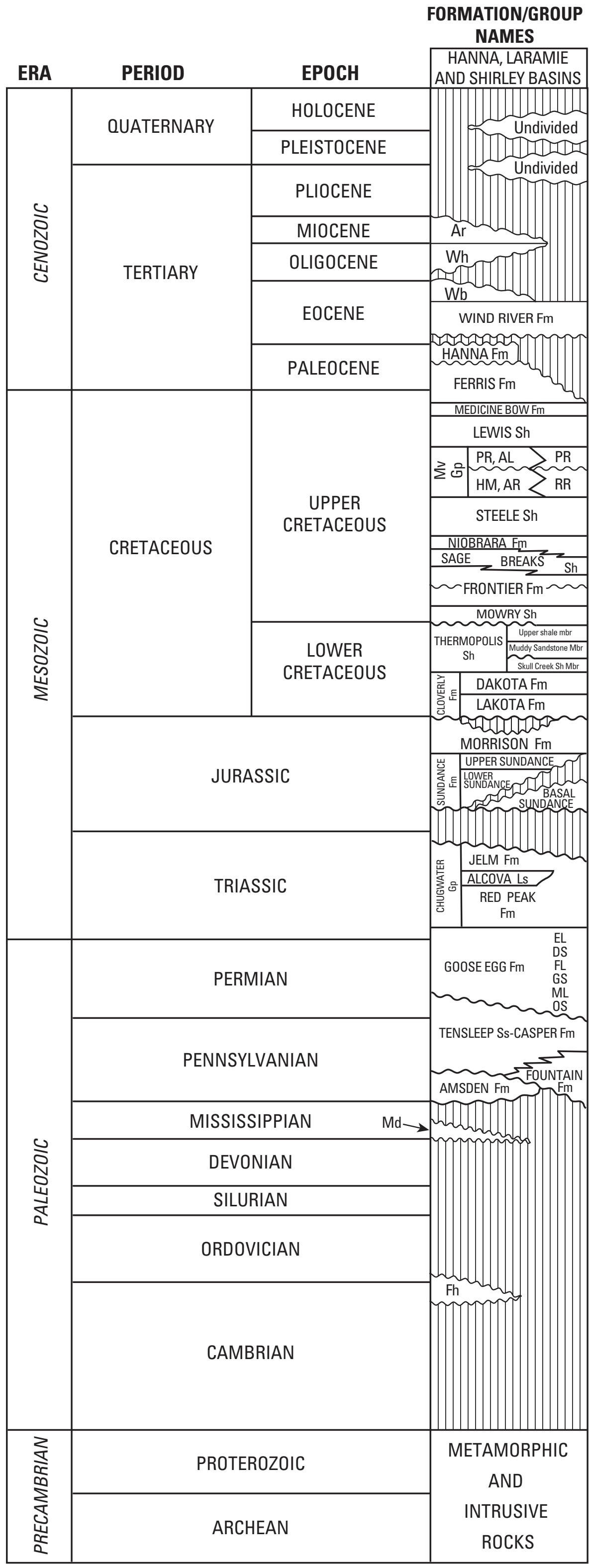

Figure 2. Columnar section of stratigraphic units in the Hanna, Laramie, and Shirley Basins Province (modified from Harshman, 1972; Love and others, 1987; and Stone, 1995). Fm, Formation; Gp, Group; Ls, Limestone; Mbr, Member; Sh, Shale; Ss, Sandsonte. Fh, Flathead Sandstone; Md, Madison Limestone; OS, Opeche Shale Member; ML, Minnekahta Limestone Member; GS, Glendo Shale Member; FL, Forelle Limestone Member; DS, Difficulty Shale Member; EL, Ervay Limestone Member; MV Gp, Mesaverde Group; HM, Haystack Mountains Formation; AR, Allen Ridge Formation; PR, Pine Ridge Sandstone; AL, Almond Formation; RR, Rock River Formation; Wb, Wagon Bed Formation; Wh, White River Group; Ar, Arikaree Formation.

Table 2. Hanna, Laramie, and Shirley Basins Province assessment results.

[MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MBNGL, thousand barrels of natural gas liquids; MAS, minimum accumulation size assessed (MMBO for oil accumulations, BCFG for gas accumulations); Prob., probability (including both geologic and accessibility probabilities) of at least one accumulation equal to or greater than the MAS or, for continuous-type resources, at least one additional cell equal to or greater than the minimum estimated ultimate recovery; Accums., accumulations. Results shown are fully risked estimates. For gas accumulations, all liquids are included as NGL (natural gas liquids). F95 represents a 95 percent chance of at least the amount tabulated; other fractiles are defined similarly. A single major commodity and its coproducts were assessed for continuous-type assessment units. Fractiles are additive under the assumption of perfect positive correlation. Resource totals may not be equal to the sums of the fractiles or means because numbers have been independently rounded. Totals reflect rounding to nearest whole number. Shading indicates not applicable]

Total petroleum system (TPS) and assessment unit (AU)	MAS	Prob. (0-1)	Total undiscovered resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Conventional oil and gas resources														
Phosphoria TPS														
Tensleep–Casper Conventional Oil and Gas AU														
Oil accums.	0.5	1	6	19	39	20	6	18	42	20	190	650	1,590	740
Gas accums.	3.0						16	47	101	52	460	1,380	3,220	1,550
Total		1	6	19	39	20	22	66	143	72	650	2,030	4,810	2,290
Mowry–Hanna Composite TPS														
Mesozoic–Cenozoic Conventional Oil and Gas AU														
Oil accums.	0.5	1	7	31	79	36	17	75	208	89	1,620	7,320	21,610	8,910
Gas accums.	3.0						25	99	278	118	460	1,920	5,770	2,360
Total		1	7	31	79	36	42	174	486	207	2,080	9,240	27,380	11,270
Total undiscovered conventional oil and gas resources														
Oil accums.			13	50	119	56	23	94	250	110	1,810	7,970	23,200	9,650
Gas accums.							42	146	379	170	920	3,300	8,990	3,910
Total			**13**	**50**	**119**	**56**	**64**	**240**	**629**	**279**	**2,730**	**11,270**	**32,190**	**13,560**
Continuous oil and gas resources														
Mowry-Hanna Composite TPS														
Hanna Basin Continuous Gas AU—Not quantitatively assessed														
Niobrara TPS														
Niobrara Continuous Oil AU														
Oil accums.	0.5	1	14	33	76	38	6	16	43	19	0	0	0	0
Gas accums.	3.0													
Total		1	14	33	76	38	6	16	43	19	0	0	0	0
Niobrara Biogenic Gas TPS														
Niobrara Biogenic Gas AU—Not quantitatively assessed														
Mesaverde–Hanna Coalbed Gas TPS														
Medicine Bow–Ferris–Hanna Coalbed Gas AU—Not quantitatively assessed														
Mesaverde Coalbed Gas AU—Not quantitatively assessed														
Total undiscovered continuous oil and gas resources														
Oil accums.			14	33	76	38	6	16	43	19	0	0	0	0
Gas accums.														
Total			**14**	**33**	**76**	**38**	**6**	**16**	**43**	**19**	**0**	**0**	**0**	**0**
Total undiscovered oil and gas resources														
Oil accums.			28	83	195	94	29	110	292	129	1,810	7,970	23,200	9,650
Gas accums.							42	146	379	170	920	3,300	8,990	3,910
Total			**28**	**83**	**195**	**94**	**70**	**256**	**671**	**298**	**2,730**	**11,270**	**32,190**	**13,560**

Table 3. Oil and gas production from formations that compose assessment units for significant fields in this study. Data from Hollis and Potter (1984) and IHS Energy Group (2004a).

[Mean depth, average depth of perforations for the reservoir in the listed field (*, perforation data not available; average total depth calculated); MMBO, millions of barrels of oil; BCFG, billions of cubic feet of gas (gas volumes less than 0.1 BCFG rounded to zero)]

Primary reservoir	Field name	Discovery year	Mean depth (ft)	Oil (MMBO)	Gas (BCFG)
Tensleep-Casper Conventional Oil and Gas Assessment Unit (50300101)					
Tensleep	Allen Lake East	1950	3,944	0.6	0
Tensleep	Big Medicine Bow	1948	*6,838	0.2	0.1
Tensleep	Herrick (Dome)	1947	3,654	1.1	0.1
Tensleep	Little Laramie	1948	3,740	1.3	0.1
Tensleep	Quealy (Dome)	1947	5,414	5.3	0
Mesozoic-Cenozoic Conventional Oil and Gas Assessment Unit (50300201)					
Sundance, Dakota	Big Medicine Bow	1935	5,019	7.5	11.1
Dakota, Muddy, Shannon	Cooper Cove	1944	4,793	1.9	0.7
Lakota, Dakota, Muddy	Diamond Ranch	1957	5,410	1.1	0.2
Muddy, Shannon	Dutton Creek	1926	4,775	0.3	0.2
Sundance	Elk Mountain	1957	6,520	0.9	0
Sundance, Dakota	Quealy (Dome)	1934	3,324	5.3	0
Lakota-Dakota, Muddy, Shannon.	Rex Lake	1923	2,726	1.0	0
Sundance through Frontier	Rock River	1918	3,021	50.0	11.5
Lakota, Muddy	Seven Mile	1947	5,957	0.6	0
TOTAL PRODUCTION				77.1	24.0

Data Sources

Primary data sources for our assessment are commercial databases from IHS Energy Group (2004a,b). Well production and completion data are current as of February and April 2004, respectively. Production and completion data are available for nearly 600 leases for the units assessed in the province, and data such as formation tops, drill-stem tests, and initial production tests for some 1,350 wells have been reported.

Another primary source of gas and oil field and reservoir data was NRG Associates (2003), which provided information on the dates of discovery and sizes of gas and oil fields, trends of increasing or decreasing field volumes, gas-oil ratios, and API oil-gravity values (see chapter by Klett and Le (2007) (this CD-ROM). Many published papers on the structure, stratigraphy, and petroleum geology of the region, as well as discussions with petroleum industry personnel, also provided important information.

Acknowledgments

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Structural Setting

The Hanna, Laramie, and Shirley Basins Province experienced a complex structural history highlighted by major tectonic events in the Precambrian, late Paleozoic, and Late Cretaceous to early Tertiary. These tectonic events and structural styles have been described in detail by many investigators, such as Blackstone (1953, 1965, 1975, 1983, 1991, 1993, 1994, 1996), McGookey and others (1972), Stone (1984, 1995, 2002, 2005), Kaplan and Skeen (1985), Merewether and Cobban (1985), Hansen (1986), LeFebre (1988), Lillegraven and Snoke (1996), Perry and Flores (1997), Secord (1998), Wroblewski (2003), and Lillegraven and others (2004). A brief summary of the structural history of the region is presented here, drawn largely from these papers and others that are cited below.

Regional structures that were created within and adjacent to the province in Precambrian time also influenced later tectonics. The Cheyenne belt of Stone (1995), also known as the Wyoming lineament (Ransome, 1915; Blackstone, 1953) or the Sybille lineament (Maughan and Perry, 1983), trends from the Sierra Madre and Medicine Bow Mountains northeastward through the Laramie Mountains (fig. 1). The feature has been interpreted as a suture zone of mylonitic and cataclastic rocks that separates the Wyoming and Colorado basement crustal terranes. Rocks north of this boundary are Archean in age (greater than 1.8 billion years old (Ga)), whereas rocks south of the boundary are Proterozoic in age (less than 1.8 Ga) (Sims and others, 2005). This suture zone is evidence of a collision between the paleo-Proterozoic arc terrane of the Colorado province with Archean cratonic rocks of the Wyoming province. The collision occurred about 1.8 Ga and deformed and metamorphosed rocks on both sides of the suture (Sims and others, 2005). The presence of numerous folds and faults in younger rocks within the area of the Cheyenne belt indicates recurrent structural activity during the Phanerozoic. Within the Laramie Basin in particular, later Laramide deformation follows the established northeast-directed trend of the earlier Precambrian structures.

Maughan and Perry (1983) described a system of linear structural elements in the northern Rocky Mountain region that can be identified in the Hanna, Laramie, and Shirley Basins Province. The province lies at the intersection of six of these features that may have had their origins in the Precambrian; these features affected sedimentary depositional patterns and facies development during the Paleozoic and early Mesozoic (Blackstone, 1993).

A second episode of regional deformation occurred during the late Paleozoic. The supercontinent Pangea coalesced during the Pennsylvanian and Permian Periods and caused a collision between the African, South American, and North American plates. This collision deformed Paleozoic rocks of the Ouachita orogenic belt and caused cratonic deformation as far north as Colorado and Wyoming that culminated in development of the Ancestral Rocky Mountains (Kluth, 1986).

The axis of the Ancestral Rocky Mountains extended northwestward from the Denver, Colo., area into south-central Wyoming oblique to the north-south axis of the present-day Front Range of Colorado and Wyoming. The ancestral feature was composed of a series of tilted and rotated fault blocks that stepped downward along its northeast margin into a broad depositional trough of marine and nonmarine sediments in southeastern Wyoming (Maughan and Ahlbrandt, 1985). This deformation is reflected in the Permian thrust-fold complex, a rotated block of north- to northeast-trending thrust-faulted anticlines lying north of the Cheyenne belt (Stone, 1995). Some of these anticlines are associated with oil fields in the Laramie Basin and have been well documented on seismic profiles. Seismic data show that thrust faults terminate in the Permian Goose Egg Formation, which was deposited during development of the thrust faults (Stone, 1995).

The third and most prominent deformation episode is the Laramide orogeny of Late Cretaceous to early Tertiary age (Dickinson and Snyder, 1978; Dickinson and others, 1988). Commonly, Laramide structures so thoroughly overprinted earlier structures that many became hidden or difficult to recognize. Today, the Hanna, Laramie, and Shirley Basins are distinct structural basins. Prior to the Laramide, however, they were part of a broad foreland basin that included the entire Hanna, Laramie, and Shirley Basins Province and had contiguous eastward-flowing fluvial systems. The structural basins were formed in the late Paleocene in conjunction with the development of basement-cored uplifts to the west (Rawlins uplift) and east (Flat Top and Simpson Ridge anticlines, fig. 3) (Lillegraven and others, 2004). According to Wroblewski (2003), the Hanna and Laramie Basins tectonically separated during the middle Paleocene (about 58 Ma), an event associated with tectonic uplift along the northwest margin of the Laramie Basin. Damming of through-flowing streams resulted in a widespread lacustrine facies in the upper part of the Ferris Formation in the Hanna Basin.

The modern Hanna Basin is one of the smallest Laramide structural basins in the Rocky Mountain region but it is also the deepest; its more than 40,000 ft of basin fill includes more than 15,000 ft of Upper Cretaceous and lower Tertiary synorogenic sedimentary rocks (fig. 2). The basin is structurally complex and possesses numerous Laramide structures that were formed during a time span of about 15 m.y. The Laramie Basin, larger but not as deep as the Hanna Basin, is also structurally complex, particularly along its west margin. Historically, the Laramie Basin has produced the most oil and gas in the Hanna, Laramie, and Shirley Basins Province.

The Shirley Basin is a broad, southward-plunging syncline bounded on the west and southwest by the Shirley, Seminoe, and Freezeout Mountains, on the east and northeast by the Laramie Mountains, and on the south by structures at the north end of the Laramie Basin such as Como Bluff and Flat Top anticlines (fig. 3). In this basin, post-Laramide Tertiary sediments were deposited on an eroded surface of Upper Cretaceous strata. Laramide-age normal faults displace rocks as young as Late Cretaceous, but large-displacement thrust faults are rare.

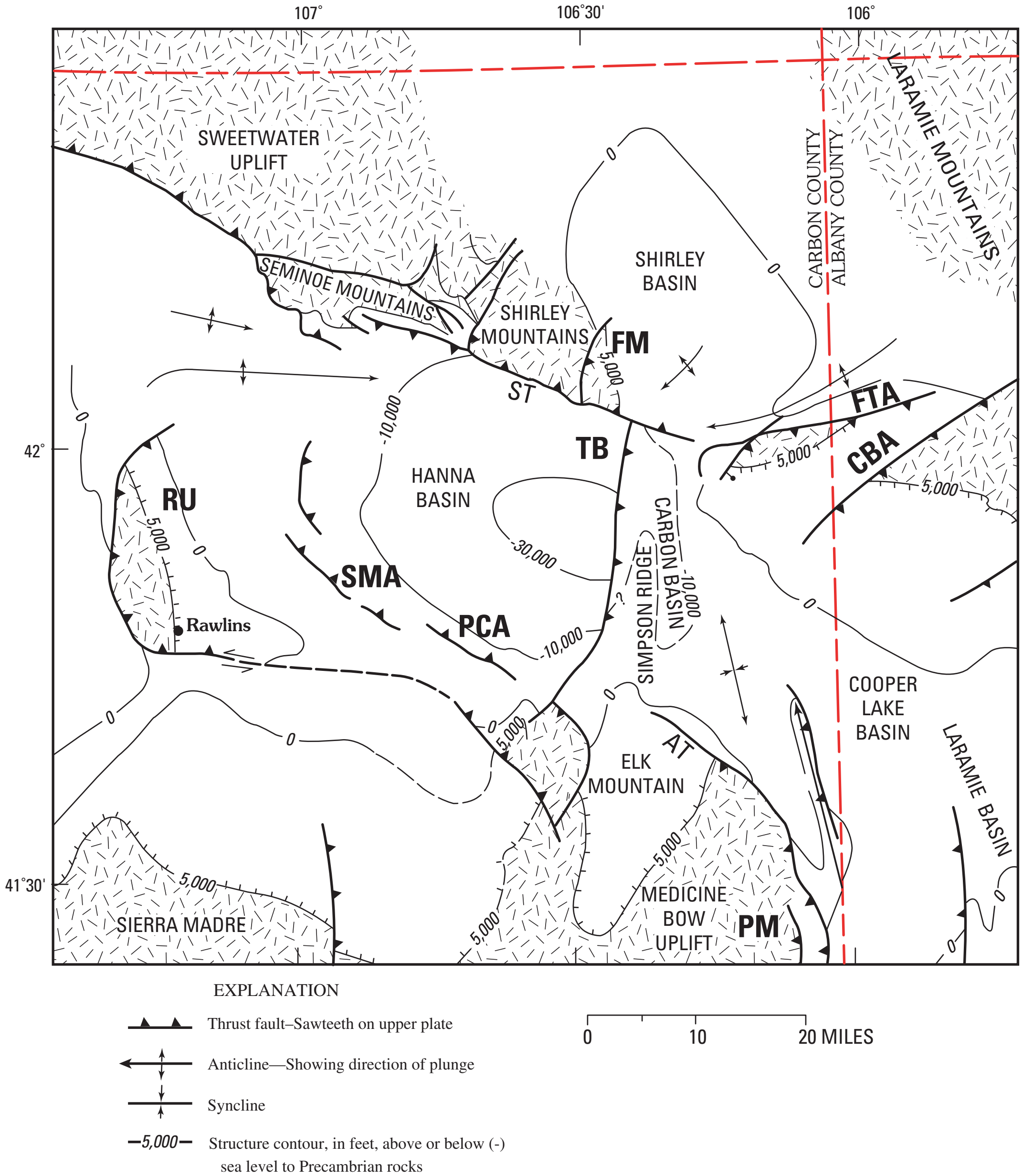

Figure 3. Part of the Hanna, Laramie, and Shirley Basins Province showing major tectonic features (modified from Perry and Flores, 1997). AT, Arlington thrust fault; CBA, Como Bluff anticline; FM, Freezeout Mountains; FTA, Flat Top anticline; PCA, Pass Creek anticline; PM, Pennock Mountain; RU, Rawlins uplift; SMA, St. Mary's anticline; ST, Shirley thrust fault; TB, The Breaks.

Gries (1983a) related the timing and direction of regional deformation events in the Laramide orogeny to continental-scale plate tectonic events. She showed that the orientation of Laramide uplifts changed through time owing to changes in the regional stress field, such that Late Cretaceous structures trend north-south, Paleocene structures trend northwest-southeast, and Eocene structures trend east-west.

In the Hanna, Laramie, and Shirley Basins Province, Laramide structures typically are Precambrian-cored uplifts with bounding thrust systems where mountain-front thrust faults overrode basin margins, or they are thrust-faulted anticlines with both into-basin– and out-of-basin–directed thrust faults that formed pop-up structures or triangle zones (Mount and others, 2004). In addition, some Laramide faults have a considerable strike-slip component because the province has undergone rotation (Stone, 1995).

The Rocky Mountain region has numerous examples of Precambrian-cored uplifts that overrode the margins of deep structural basins along thrust faults with thousands of feet of displacement. Thick subthrust rock sequences have the potential for undiscovered oil and gas accumulations (Gries, 1983b). The Shirley thrust, at the north margin of the Hanna Basin, and the Arlington thrust (figs. 3, 4), along the west margin of the Laramie Basin, comprise extensive subthrust (footwall) wedges of sedimentary rocks beneath shallow (hanging-wall) Precambrian rocks. The Shirley and

Arlington thrusts have long and complex Laramide histories of development (Stone, 1995; Lillegraven and others, 2004).

Laramide deformation in the Hanna and Laramie Basins also involved thin-skinned, out-of-basin thrusts that placed younger rocks over Precambrian basement and older sedimentary rocks and formed triangle zones (fig. 5) (Erslev, 1991; Lillegraven and others, 2004). These out-of-basin thrust systems are associated with folding of the thick (>15,000 ft) Upper Cretaceous and lower Tertiary basin fill. Out-of-basin blind thrusts disappear into Cretaceous shales in many places, such as the Pass Creek, St. Mary's, and Simpson Ridge anticlines in the southern part of the Hanna Basin, and "The Breaks" at the north end of the basin (fig. 3; Hitchens, 1999). Early Laramide syntectonic sediments were involved in later Laramide deformation, creating a complex depositional pattern (Blackstone, 1993).

Precambrian-cored satellite uplifts border the south end of the Hanna Basin just north of the Medicine Bow uplift (Blackstone, 1993). These asymmetric structures are bounded by thrust faults and were formed by uplift of Precambrian cores and concurrent folding of the less brittle sedimentary cover rocks (McClurg and Matthews, 1978).

Stratigraphy

North of the Cheyenne belt (fig. 1), the Precambrian basement is an Archean microplate of metasedimentary gneiss and schist and granitic rocks, older than 2.5 Ga, that underlies most of the Hanna, Laramie, and Shirley Basins Province. These rocks are exposed in the northern Sierra Madre, Medicine Bow Mountains, Laramie Mountains, and Sweetwater uplift (fig. 3). South of the Cheyenne belt, the Precambrian basement rocks consist of a 1.8-Ga metamorphic terrane intruded by 1.5- to 1.4-Ga granitic rocks (Peterman and others, 1968). Metasedimentary and metavolcanic gneisses and calc-alkalic plutonic igneous rocks are exposed in portions of the southern Medicine Bow and Sierra Madre uplifts (Houston, 1968; Sims and others, 2005). Precambrian plutonic and metamorphic rocks are overlain by an unconformity by Cambrian and younger sedimentary rocks.

Cambrian sedimentary rocks are absent throughout much of the province but are exposed on the east flank of the Rawlins uplift (fig. 1), where they are 450 ft thick (Lovering, 1929). In the Cambrian Flathead Sandstone (fig. 2), a basal conglomeratic sandstone is overlain by quartzose sandstone or quartzite and by reddish-brown glauconitic sandstone and shale. The formation thins to the east and is entirely absent at the west end of the Laramie Basin and in the Shirley Basin (Harshman, 1972). Rocks of Ordovician, Silurian, and Devonian age are absent in the province.

On the Rawlins uplift, the Mississippian Madison Limestone unconformably overlies Cambrian strata (fig. 2). Eastward, where the Flathead is absent, the Madison rests unconformably on Precambrian rocks. Along the Rawlins uplift, the Madison is a gray to red limestone or cherty limestone; a karst surface is well developed in the upper part of the unit. The Madison averages 100 ft thick on the Rawlins uplift (Lovering, 1929) and 150 ft thick in the Shirley Basin (Harshman, 1972), but it is thin or absent in the Laramie Basin. Lillegraven and Snoke (1996) identified 98 ft of Madison Limestone in the northern Hanna Basin.

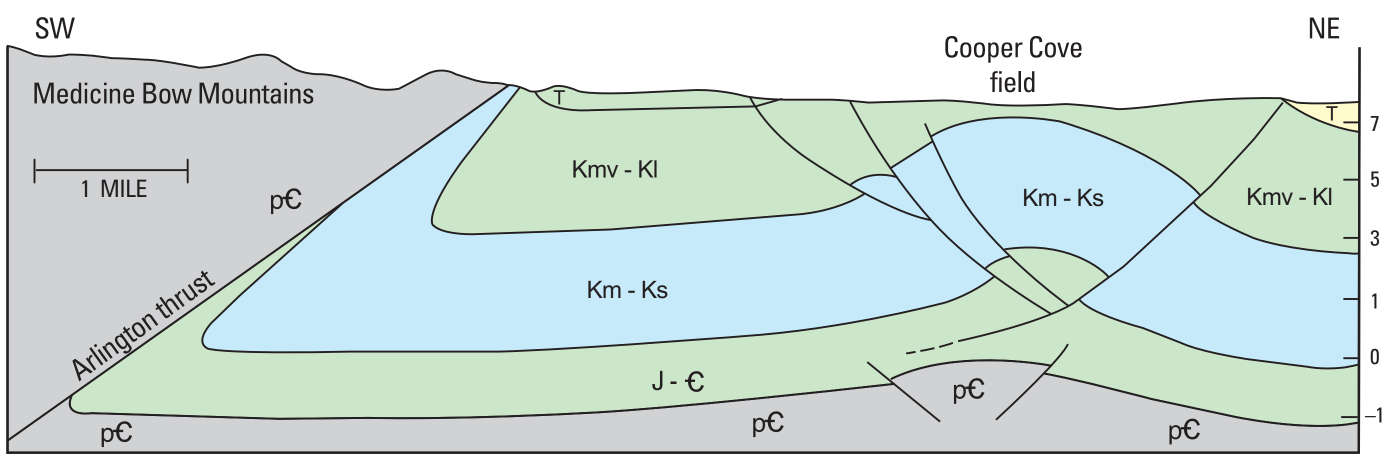

Figure 4. Generalized southwest-northeast cross section showing the Arlington thrust fault and the Cooper Cove field in the western Laramie Basin. Simplified from Stone (2005). Location of cross section shown on figure 1. p€, Precambrian; J-€, Jurassic through Cambrian ; Km-Ks, Cretaceous Muddy Sandstone Member through Cretaceous Steele Shale; Kmv-Kl, Cretaceous Mesaverde Group through Cretaceous Lewis Shale; T, Tertiary rocks undifferentiated. Vertical scale in thousands of feet. No vertical exaggeration.

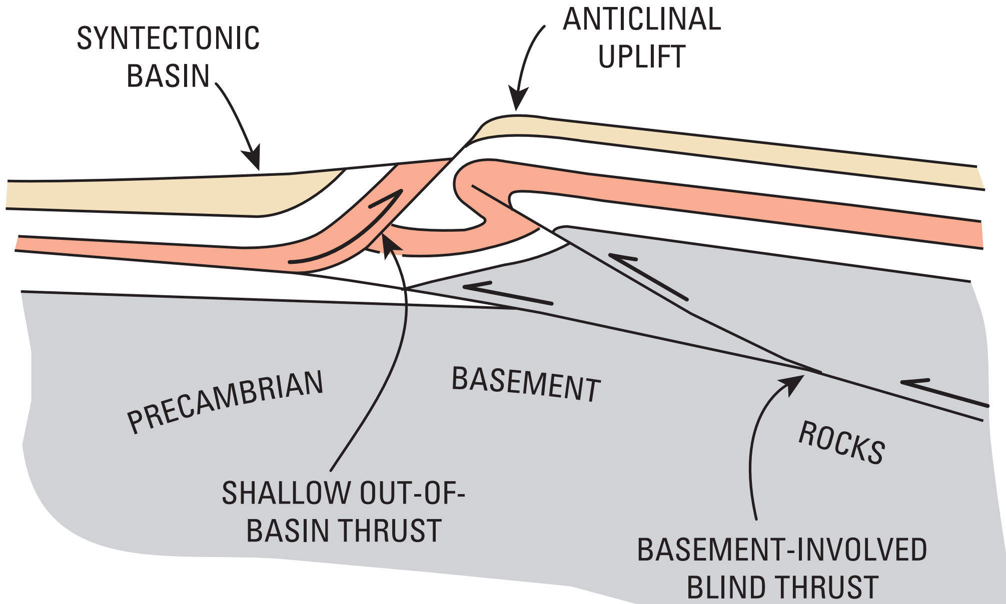

Figure 5. Generalized cross section showing triangle zone development as described by Lillegraven and others (2004) for structures in the Hanna and Laramie Basins.

Where present, the Pennsylvanian Amsden Formation unconformably overlies the Madison Limestone (fig. 2). The Amsden's sandstone, reddish mudstone, and cherty limestone (Lovering, 1929) averages 200 ft thick on the Rawlins uplift. It thins to 140 ft in the southern part of the Hanna Basin. Harshman (1972) did not recognize Amsden in the Shirley Basin but identified a distinctive solution breccia and karst zone with reddish shale and sandstone that he placed in the upper part of the Madison. Hausel and Jones (1984) did not recognize the Amsden Formation in the Laramie Basin, but time-equivalent rocks of the Fountain Formation crop out in the southern part of the basin near the Wyoming-Colorado state line (fig. 2).

The Pennsylvanian Tensleep Sandstone unconformably overlies the Amsden Formation and averages 300–400 ft thick in the Hanna Basin, where it is described as a medium-grained, crossbedded, quartzose sandstone and limestone unit (Mitchell, 1961; Stone, 1966; figs. 2, 6). The equivalent Casper Formation averages 500 ft thick in the Laramie Basin and is 650 ft thick in the Shirley Basin, where some rocks in the lower part are correlative with the Amsden Formation to the west (Harshman, 1972). The Casper becomes more arkosic southeastward in the Laramie Basin and is in part equivalent to the Fountain Formation. Fusilinid data indicate that lithic units in the Tensleep-Casper depositional system are time transgressive. In the Hanna Basin, the Tensleep is primarily Desmoinesian in age, whereas the top of the Casper in the Laramie Basin is Wolfcampian (Mitchell, 1961). The Tensleep is important to the petroleum geology of the province because it is a regional reservoir rock, particularly where the eolian sandstone facies is well developed.

The Permian and Triassic Goose Egg Formation unconformably overlies the Tensleep Sandstone and Casper

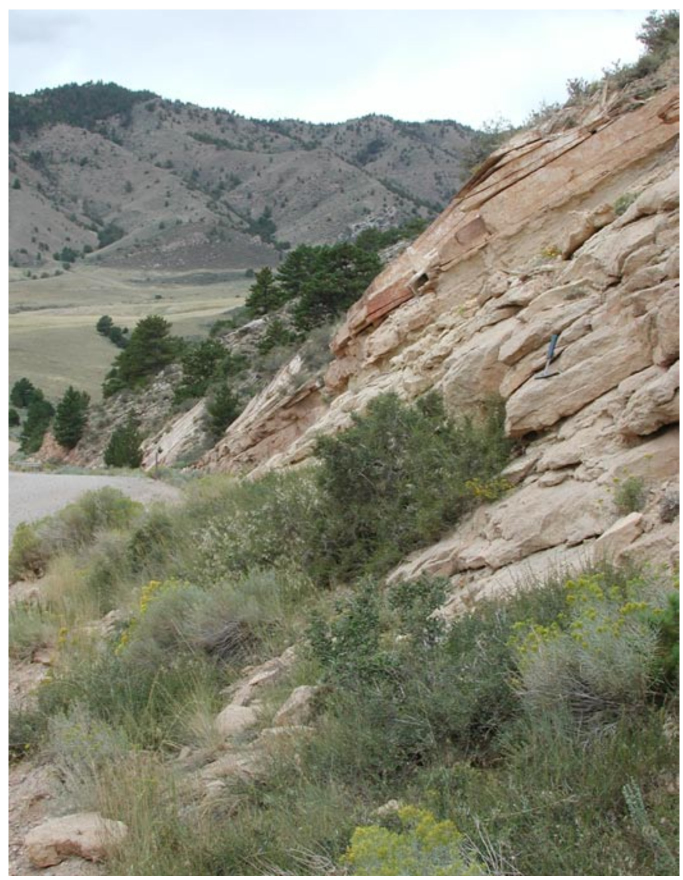

Figure 6. Tensleep Sandstone outcrop along west side of Seminoe Reservoir (T. 24 N., R. 84 W.) in northern part of Hanna Basin. Sandstones are fine-grained and cross-bedded sublitharenites typical of the Tensleep in the region. Younger Jurassic rocks in background. Hammer for scale in right center of photograph.

Formation (fig. 2). In the Hanna Basin, the Goose Egg averages 250 ft thick and is composed of reddish-brown calcareous sandstone, dolomitic limestone, siltstone, and anhydrite (fig. 7). It averages 400 ft thick in the Shirley Basin. Named members are, in ascending order, the Opeche Shale, Minnekahta Limestone, Glendo Shale, Forelle Limestone, Difficulty Shale, and Ervay Limestone Members (Harshman, 1972; Piper and Link, 2002). The Goose Egg is time equivalent to the Phosphoria Formation in western Wyoming (Cheney and Sheldon, 1959) and represents an eastern evaporite facies of the Phosphoria that was deposited in the Goose Egg embayment (see fig. 21) of the Phosphoria sea (Piper and Link, 2002). The Goose Egg is important to the petroleum geology of the province because it forms a regional seal to the eastward migration of oil generated from Phosphoria source rocks in western Wyoming and southeastern Idaho (see later discussion).

Formations in the Triassic Chugwater Group (fig. 2) are, in ascending order, the Red Peak Formation, Alcova Limestone, and Jelm Formation. In the Hanna and Carbon Basins, the Chugwater Group averages 1,300 ft thick and consists of coastal and shallow marine limestone, mudstone, sandstone, and gypsum (Dobbin and others, 1929). The Chugwater is characteristically red but also contains shades of green, purple, and brown. It is conformable with the underlying Goose Egg Formation in the northern part of the Hanna Basin (Lillegraven and Snoke, 1996). The Alcova Limestone is a thin (10–15 ft thick) discontinuous unit of hard, sandy limestone that locally forms ridges. The Chugwater is about 1,100 ft thick at Red Mountain at the south end of the Laramie Basin (Darton and Siebenthal, 1909) and is about 725 ft thick in the Shirley Basin (Harshman, 1972). The Chugwater is important to the petroleum geology of the province because it forms a regional seal for petroleum traps. Locally, Jelm Formation sandstones form reservoirs for oil and gas in the Laramie Basin (Mitchell, 1961).

The Jurassic Sundance Formation unconformably overlies the Chugwater Group in much of the province (fig. 2). The underlying Jurassic Nugget Sandstone (not shown on fig. 2) has been identified in the westernmost Hanna Basin, but it pinches out to the east in the central Hanna Basin (Mitchell, 1961). The Sundance Formation consists of gray-

Figure 7. Goose Egg Formation outcrop along west side of Seminoe Reservoir (T. 24 N., R. 84 W.) in northern part of Hanna Basin. Red mudrocks interbedded with tan evaporites. Note vertical faults in central part of photograph. Field of view is approximately 30 ft across.

green marine shale, fossiliferous limestone, and glauconitic sandstone (Mitchell, 1961; Harshman, 1972). Dobbin and others (1929) measured 350 ft of Sundance along Como Ridge in the northern Laramie Basin (CBA of fig. 3), about 50 percent of which is sandstone. Lillegraven and Snoke (1996) identified more than 400 ft of Sundance in the northern Hanna Basin, and Harshman (1972) reported an average thickness of 240 ft in the Shirley Basin. The Sundance Formation is composed of a basal chert-pebble conglomerate and sandstone unit ("basal Sundance" of fig. 2) and at least two distinct sandstone units identified as "upper Sundance" and "lower Sundance." The "upper," or younger, sandstone unit is areally restricted to the Hanna and Laramie Basins, whereas the "lower," or older, sandstone is more widespread (Stone, 1966). The Jurassic Morrison Formation conformably overlies the Sundance. Sundance sandstone reservoirs produce both gas and oil in the Laramie Basin.

The Upper Jurassic Morrison Formation ranges from 150 to 300 ft thick in the province and thickens southward into Colorado. It is characterized by gray, green, and maroon nonmarine shales and mudstones, lithic-rich sandstones and conglomeratic sandstones, and rare limestones. The lower part of the Morrison is primarily sandstone, and in the Laramie Basin this unit is 140 ft thick. In the Shirley Basin, however, the lower sandstone of the formation is only about 20 ft thick (Harshman, 1972). It is not a significant oil and gas reservoir in the province.

The Lower Cretaceous Cloverly Formation unconformably overlies Jurassic rocks in the Hanna, Laramie, and Shirley Basins Province. The name Cloverly is used for rocks equivalent to the Lower Cretaceous Dakota Formation, Fuson Shale, and Lakota Formation of the Black Hills; but because each of these units is not continuous and consistently recognizable in the province, they are combined (fig. 2; Stone, 1966). Bowen (1917) identified an average thickness of 231 ft for the Cloverly Formation in the Hanna Basin. At Oil Springs field (fig. 20) in the northern part of the Laramie Basin, the Cloverly includes a basal 10-ft-thick nonmarine unit of chert-pebble conglomerate and conglomeratic sandstone (fig. 8), a 33-ft-thick middle unit of gray to green carbonaceous shale, and an upper 85-ft-thick unit of marine sandstone (Dobbin and others, 1929). The Cloverly thins to the south and is less than 100 ft thick in the southern part of the Laramie Basin (Stone, 1966). It is as much as 200 ft thick in the Shirley Basin where the thickening is due primarily to development of the upper sandstone unit (Harshman, 1972). Both sandstone-rich units are known oil and gas reservoirs in the Laramie Basin.

Figure 8. Basal Cloverly Formation conglomerate along west side of Seminoe reservoir (T. 24 N., R. 84 W.) in northern part of Hanna Basin. Clasts are dominantly quartzite and chert. Maximum clast diameter approximately 8 in. Hammer for scale in left center of photograph.

The Lower Cretaceous Thermopolis Shale is present throughout the province (figs. 2, 9). It ranges in thickness from 200 ft in the northern Laramie and Hanna Basins (Dobbin and others, 1929) to 185 ft in the Shirley Basin (Harshman, 1972) and to 50 ft in the southern Laramie Basin (Mitchell, 1966). It is primarily dark-gray marine shale with a variably developed sandstone unit called the Muddy Sandstone Member in the middle (Eicher, 1960). The lower shale unit, commonly referred to as the Skull Creek Shale (Burtner and Warner, 1984), is Albian in age and is associated with the initial Cretaceous marine transgression. The Muddy Sandstone Member is a composite unit of foreshore to shoreface regressive sandstones that are incised in places by fine- to coarse-grained valley-fill deposits of sandstone and shale that are, in turn, overlain by transgressive marine sandstones (Dolson and others, 1991). Owing to its lithologic heterogeneity, the Muddy is an important petroleum reservoir in some parts of the province but is a poor reservoir or may even be absent in other parts (Stone, 1966). The upper part of the Thermopolis contains an unnamed dark-gray shale that is equivalent to the informally named “Shell Creek shale” member of the Thermopolis Shale in northern and eastern Wyoming and central Montana (Eicher, 1962; Dyman and others, 1994; Porter and Wilde, 2001).

The Mowry Shale (figs. 2, 10) is a sequence of dark-gray to black siliceous marine shale with interbedded porcellanite and bentonite. In the Hanna and Laramie Basins, it ranges in thickness from more than 200 ft in the north to 150 ft in the south (Dobbin and others, 1929). Mitchell (1961) identified 400 ft of Mowry in the Laramie Basin, but he may have included the informal “Shell Creek shale” unit. Harshman (1972) recognized an average Mowry thickness of 110 ft in the Shirley Basin. The top of the Mowry is identified by a regional bentonite bed of Cenomanian age, the Clay Spur Bentonite Bed (Burtner and Warner, 1984; Davis and others, 1989; Obradovich, 1993). Byers and Larson (1979), Burtner and Warner (1984), Davis and others (1986), and Davis and Byers (1989) identified regional lithofacies within the Mowry and designated it a major source rock for petroleum in the northern Rocky Mountain region. We discuss the Mowry-Hanna Composite TPS in a later section of this report.

The Frontier Formation (figs. 2, 11) consists of a lower unit of dark-gray carbonaceous shale, the Belle Fourche Shale Member, and an upper unit of sandstone and interbedded shale, the Wall Creek Sandstone Member. The formation averages about 700–900 ft thick in the province (Stone, 1966; Harshman, 1972; Mieras, 1992; Lillegraven and Snoke, 1996); it is Late Cretaceous (Cenomanian-Turonian) in age. The Belle Fourche represents regressive marine deposition and contains less sandstone eastward in the Laramie Basin. Transgressive marine sandstones of the Wall Creek Sandstone Member average 10–40 ft thick (fig. 11) and are fine-grained and glauconitic. The unit is 110 ft thick in the Shirley Basin (Harshman, 1972). Wall Creek sandstones, which are petroleum reservoirs in the province, are discussed in a later section of this report.

In the Hanna Basin, rocks immediately above the Frontier are called the Sage Breaks Shale (fig. 2; Merewether, 1990) or Niobrara Formation (Lillegraven and Snoke, 1996). Dobbin and others (1929) identified 450 ft of dark-gray concretionary shale as equivalent to the Sage Breaks Member of the Carlile Shale of the Black Hills. Mitchell (1961) identified about 1,200 ft of Niobrara (including the Sage Breaks Shale) in the Hanna Basin and about 600 ft in the southern Laramie Basin. The Sage Breaks Shale contains ammonites of Late Cretaceous (Turonian) age (Stone, 1966). Niobrara rocks above the Sage Breaks Shale are calcareous shales, limestones, and chalky limestones (fig. 12). The Niobrara is concretionary and contains ledge-forming coquina beds. Harshman (1972) measured about 900 ft of Niobrara (including the Sage Breaks Shale) in the Shirley Basin. Limestones and chalks in the Niobrara give off a strong petroliferous odor and form the Niobrara TPS discussed later in this report.

The Steele Shale conformably overlies the Niobrara Formation (figs. 2, 13). It is dark-gray marine shale and minor interbedded sandstone, siltstone, and bentonite of early Campanian age. A persistent 5-ft-thick bentonite in the upper part of the Steele in the northwestern Laramie Basin is equivalent to the Ardmore Bentonite Bed of the Black Hills region (Gill and others, 1970; Obradovich, 1993). The Steele ranges in thickness from 3,500 ft in the northern Hanna and Laramie Basins to 2,400 ft in the western Hanna Basin and to 2,300 ft in the southern Laramie Basin (Gill and others, 1970). Lillegraven and Snoke (1996) recognized 5,500 ft of Steele strata in the northern Hanna Basin. Thin discontinuous sandstones, referred to informally as “Shannon” sandstones, are gas reservoirs in the Hanna and Laramie Basins. The Steele contains locally continuous sandstones at or near the top that are equivalent to basal sandstones of the Mesaverde Group farther west. In the Shirley Basin, Harshman (1972) estimated the Steele to be 1,500–2,000 ft thick, but there it has been partly eroded and all younger Cretaceous strata have been entirely removed by erosion. The Steele Shale is part of the Mowry-Hanna Composite TPS discussed later in this report.

The overlying Mesaverde Group is conformable with both the Steele Shale and the overlying Lewis Shale in the Hanna, Laramie, and Shirley Basins Province. It is divided into four formations in the Hanna Basin—in ascending order, the Haystack Mountains Formation, Allen Ridge Formation, Pine Ridge Sandstone, and Almond Formation (fig. 2; Gill and others, 1970). In the Laramie Basin, the Mesaverde consists of the Rock River Formation and overlying Pine Ridge Sandstone owing to an eastward facies change from sandstone to shale. The Rock River Formation is largely the time equivalent of the Allen Ridge Formation. The Haystack Mountains Formation consists of 1,700–2,550 ft of interbedded marine sandstone and shale (fig. 14). The lithologically diverse Allen Ridge Formation contains a unit of nonmarine sandstone and carbonaceous shale 700–1,200 ft thick which, in the eastern Hanna Basin, is underlain and overlain locally by 350–700 ft of marine to brackish-water sandstone and shale (Gill and

Figure 9. Muddy Sandstone Member of Thermopolis Shale and the Cloverly Formation; view looking southwest near Rendle Hill, approximately 15 mi north of Rawlins, Wyo. (T. 24 N., R. 88 W.), in western part of Hanna Basin. Muddy Sandstone Member in lower left, Thermopolis Shale in dark gray middle area, and Cloverly Formation in light gray background forming dip slope. Foreground distance approximately 20 ft across

Figure 10. Mowry Shale near Rendle Hill, approximately 15 mi north of Rawlins, Wyo. (T. 24 N., R. 88 W.), in western part of Hanna Basin. Hammer for scale near center of photograph.

Figure 11. Frontier Formation along Union Pacific Railroad tracks near Como, Wyo. (T. 22 N., R. 78 W.), in central part of Hanna Basin. Upper part of outcrop is sandstone of Wall Creek Sandstone Member. Foreground distance approximately 150 ft across.

Figure 12. Niobrara Formation at Separation Flats, approximately 8 mi northeast of Rawlins, Wyo. (T. 22 N., R. 86 W.), in western part of Hanna Basin. Younger rocks are to left. Foreground distance approximately 30 ft across. Steele Shale and Mesaverde Group form gray hills on horizon at far left.

Figure 13. Steele Shale at Separation Flats, approximately 10 mi northeast of Rawlins, Wyo. (T. 22 N., R. 86 W.), in western part of Hanna Basin. Looking upsection at concretionary zones that form "knobby" ridges in middle part of Steele, top center of photograph. Foreground distance approximately 10 ft across.

others, 1970). The Pine Ridge Sandstone unconformably overlies the Allen Ridge. Martinsen and others (1993) suggested that this unconformity separates different sequences derived from different directions and was related to early Laramide uplift north of the Hanna Basin. In the Hanna Basin, the formation is a 100–250-ft-thick unit of nonmarine sandstone, siltstone, carbonaceous shale, and impure coal (fig. 15). The Almond Formation is a marine and nonmarine coastal sequence of sandstone, shale, and coal ranging in thickness from 450 to 600 ft. In the western Hanna Basin, fluvial sandstone, shale, and coal in the nonmarine lower part of the Almond are about 180 ft thick. It contains as many as seven coal beds greater than 5 ft thick. The Mesaverde Group is both a source and reservoir rock in the province and is discussed as part of coalbed gas and continuous gas total petroleum systems later in this report.

The Maastrichtian Lewis Shale (fig. 2) was deposited during the final transgressive-regressive phase of the Western Interior seaway and during the early part of the Laramide orogeny (Perman, 1990). It is a thick (2,200–2,600 ft) sequence of gray marine shale, fine- to medium-grained sandstone, and siltstone. In the western part of the Hanna Basin, it forms coarsening-upward parasequences of shale and sandstone that are as much as a few hundred feet thick (fig. 16). The 600-ft-thick Dad Sandstone Member of the Lewis separates lower and upper shale-rich intervals of the Lewis. Numerous sandstone bodies in the upper part of the formation in the eastern part of the Southwestern Wyoming Province to the west and in the western Hanna Basin are laterally equivalent to the Fox Hills Sandstone, and that name is used in some places (Gill and others, 1970; Fox, 1971). Sandstones and shales of the Lewis contain marine megafauna of Maastrichtian age from *Baculites eliasi* through *B. clinolobatus* (Gill and others, 1970). The Lewis is a known source and reservoir rock in the region. It is part of the Mowry-Hanna Composite TPS discussed later in this report.

The Medicine Bow, Ferris, and Hanna Formations are syntectonic sedimentary units associated with the Laramide orogeny. They are primarily restricted to the Hanna Basin and northern part of the Laramie Basin where they record a history of periodic uplift of surrounding Laramide structures, sea level fluctuations, and subsidence (Knight, 1951; W.R. Keefer, written commun., 1999; Wroblewski, 2003). These formations are important to our study because they contain numerous coal beds and lacustrine mudstones that are hydrocarbon sources. In the deeper parts of the Hanna Basin, fluvial sandstone reservoirs may contain gas accumulations.

The Medicine Bow Formation (fig. 2) was deposited during the final withdrawal of the Maastrichtian sea from the Hanna, Laramie, and Shirley Basins Province during early stages of the Laramide orogeny. It is a thick (about 6,200 ft) nonmarine sequence of fluvial to estuarine sandstone, carbonaceous shale, and coal (fig. 17; Landon and Heller, 2000). High-volatile A or B bituminous coals are especially abundant in the lower part of the formation, and in the Hanna coal field in the central Hanna Basin as many as 30 individual coal beds have been identified (fig. 1). However, only three of these coal beds exceed 5 ft in thickness (Glass and Roberts, 1980). The Medicine Bow Formation is conformably overlain by the Ferris Formation (figs. 2, 18) or is locally in angular discordance with the Hanna Formation in the eastern Hanna and Laramie Basins (Gill and others, 1970).

The Upper Cretaceous to lower Paleocene Ferris Formation is more than 6,000 ft thick at its type locality in the Hanna Basin, where it is entirely nonmarine. It can be divided into two lithic units: a lower 1,100-ft-thick Upper Cretaceous unit composed of conglomeratic sandstone, sandstone, and shale and an upper 5,400-ft-thick Paleocene unit of sandstone and coal (Gill and others, 1970). Glass and Roberts (1980) identified 28 coal beds in the central Hanna Basin ranging in thickness from 4.5 to 25 ft.

The Paleocene and Eocene Hanna Formation may be as thick as 13,000 ft in the northern part of the Hanna Basin, but it is generally much thinner. It is a fluvial-lacustrine cyclic sequence of conglomerate, sandstone, mudstone, shale, and coal (figs. 2, 19). Depositional cycles are defined by the

Figure 14. Haystack Mountains Formation along North Platte River, approximately 10 mi north of Sinclair, Wyo. (T. 22 N., R. 85 W.), in western part of Hanna Basin, showing coarsening-upward parasequences in upper part of formation. Approximately 700 ft of formation exposed.

Figure 15. Pine Ridge Sandstone along North Platte River, approximately 10 mi north of Sinclair, Wyo. (T. 22 N., R. 85 W.), in western part of Hanna Basin, showing sandstone, mudstone, and coal interbedded in middle part of formation. Coal bed in middle part of photograph approximately 18 in. thick.

Figure 16. Lewis Shale, approximately 12 mi north of Sinclair, Wyo. (T. 22 N., R. 85 W.), in western part of Hanna Basin, showing coarsening-upward parasequence of shale and sandstone in lower part of formation. Person for scale at left center.

Figure 17. Sandstone bed in the Medicine Bow Formation on Snyder Ridge (T. 24 N., R. 83 W.) in northern part of Hanna Basin. Staff in left center portion of photograph is 5 ft tall.

Figure 18. Ferris Formation, approximately 3 mi west of Hanna, Wyo. (T. 22 N., R. 82 W.), along U.S. Highways 30 and 287 in central part of Hanna Basin, showing interbedded carbonaceous shale, coal, and sandstone. Middle-ground distance approximately 125 ft across.

sedimentary response to uplift and subsidence during the main phase of the Laramide orogeny. The Hanna contains more than 30 individual coal beds at least 5 ft thick of high-volatile C bituminous rank that are distributed throughout the formation (Glass and Roberts, 1980). The formation unconformably overlies the Ferris Formation in the central Hanna Basin, but it rests on older rocks along the northeast margin of the basin (Gill and others, 1970).

Upper Eocene and younger rocks are limited mainly to the Shirley Basin. The Eocene Wind River Formation, the oldest unit, consists of a basal conglomerate and arkosic sandstone overlain by interbedded coarse- to medium-grained sandstone, siltstone, claystone, and minor lignite beds; maximum thickness is about 500 ft (Harshman, 1972). The Wind River unconformably overlies the Steele Shale in the Shirley Basin. The Wagon Bed Formation is also Eocene in age and conformably overlies the Wind River Formation (fig. 2). It is composed of interbedded coarse-grained sandstone and claystone that reach a maximum thickness of about 150 ft (Harshman, 1972).

The Oligocene White River Formation unconformably overlies the Wagon Bed or older rocks in the Shirley Basin. In many places it consists of a basal conglomerate, overlain by tuffaceous siltstone, sandstone, and limestone beds and local interbedded conglomerates. The White River has been divided into a lower member that is as much as 400 ft thick and an upper member that is as much as 350 ft thick (Harshman, 1972).

The Miocene Arikaree Formation conformably overlies the White River Formation in the Shirley Basin. It consists of fine- to medium-grained tuffaceous sandstone, conglomerate, and limestone with a maximum thickness of about 180 ft (Harshman, 1972). In the Hanna Basin Miocene rocks are locally present. They unconformably overlie the Hanna Formation and are assigned to the Browns Park Formation (Blackstone, 1993). None of the Tertiary formations younger than the Hanna is thought to have hydrocarbon potential.

Production Characteristics

Twelve significant fields (cumulative production greater than 0.5 million barrels of oil equivalent) have been discovered in the Hanna, Laramie, and Shirley Basins Province; all are located along the west margin of the Laramie Basin (fig. 20), where they produce from 7 different reservoirs. Table 3 shows the assessment unit number and name, primary reservoirs, field name, discovery year, mean depth of producing interval, commodity, and cumulative production for these fields, as compiled from Hollis and Potter (1984) and IHS Energy Group (2004a). The 12 fields are found in 2 TPSs that are discussed in the following sections of this report. As shown in table 3, production from these fields has been more than 77 million barrels of oil (MMBO) and 24 billion cubic feet of gas (BCFG) from a total of about 79 MMBO and 31.8 BCFG

Figure 19. Hanna Formation, approximately 2 mi west of Hanna, Wyo. (T. 22 N., R. 82 W.), in a road cut along U.S. Highways 30 and 287 in central part of Hanna Basin, showing interbedded carbonaceous shale, coal, and sandstone. Person (E.A. Merewether) for scale.

from all fields in the province. Nearly 65 percent of that oil has been produced from Jurassic and Cretaceous reservoirs at Rock River field in the northwestern part of the Laramie Basin (fig. 20). Three fields (Rock River, Quealy, and Big Medicine Bow) account for more than 85 percent of the oil produced in the province. Only 2 of the 12 fields have appreciable gas reservoirs (Big Medicine Bow and Rock River); their total cumulative production is 22.6 BCFG (table 3). All other fields produce considerably less gas.

The Hanna Basin hosts only three fields, none of which is significant. Hugus and Overland are both Niobrara oil fields, and Cedar Ridge has produced gas from “Shannon” sandstones (stray sandstones in the Steele Shale). In addition, two coalbed gas pilot projects are underway in the northern part of the Hanna Basin—the Seminoe Road Pilot Project (Mesaverde Group coals) and the Hanna Draw Pilot Project (Hanna Formation coals) (Debruin, 2003b; fig. 20). Cretaceous rocks in the Hanna Basin center have only recently been penetrated but are not yet economically productive (DeBruin, 2003a,b). Several deep wells have been drilled in the central part of the Hanna Basin and are discussed in a separate section.

Production is primarily from structural traps, but there is a potential for traps formed by facies variations. Structural traps may be thrust-faulted anticlines, triangle zones, and combination (structural-stratigraphic) traps in which facies variations control the sandstone distribution across structures. In some structures, trapping mechanisms are complex owing to remigration of oil from late Paleozoic (Ancestral Rocky Mountains) traps to Laramide traps; for example, at Quealy field Phosphoria-derived Tensleep-Casper oil accumulated in this manner (Stone, 1995).

Five of the 12 significant fields, the Allen Lake East, Big Medicine Bow, Herrick, Little Laramie, and Quealy fields in the western Laramie Basin, produce oil from reservoirs in the Tensleep Sandstone and Casper Formation. These fields, which were discovered in the late 1940s to 1950, have a total cumulative production of 8.5 MMBO (table 3).

The exploration history of the Hanna, Laramie, and Shirley Basins Province can be divided into early, middle, and late stages. During the early stage, from 1918 to the early 1940s, field discoveries were based primarily on surface mapping of structures such as at Rock River and Rex Lake (Stone, 2002). During the middle phase, in the 1950s, fields were discovered using seismic exploration methods, such as at Diamond Lake and Elk Mountain. Cretaceous reservoirs at Quealy were the first seismic discovery in the Rocky Mountain region, in 1934 (table 3). The latest stage of exploration (since the 1970s) has been dominated by deep drilling using improved technology, but no significant fields have been discovered.

The lack of discovered oil or gas accumulations in the Shirley Basin is enigmatic. The area has been moderately explored, and some 80 wells (all dry and abandoned) were drilled, most of which were located in three areas (fig. 1): (1) east of the +2000 ft contour on Precambrian basement on the east side of the basin, (2) on the anticline in the northwestern part of the basin, and (3) within the faulted Shirley Mountains area in the southwestern part of the basin (fig. 3). Many of these wells penetrated Paleozoic strata, and some reached Precambrian basement. There have been about 40 drill-stem tests in formations ranging from the Muddy Sandstone Member of the Thermopolis Shale to the Tensleep Sandstone (fig. 2), but none reported shows of oil or gas (IHS Energy Group, 2004b). This lack of hydrocarbons in the Shirley Basin is difficult to explain, because Phosphoria oil should have been able to migrate into the Shirley Basin from the west in a manner similar to that elsewhere in the province (see the discussion of the Phosphoria TPS later in this report). Barriers could possibly have formed between this basin and the Hanna and Laramie Basins to prevent such migration, but direct evidence is lacking and the question remains unresolved.

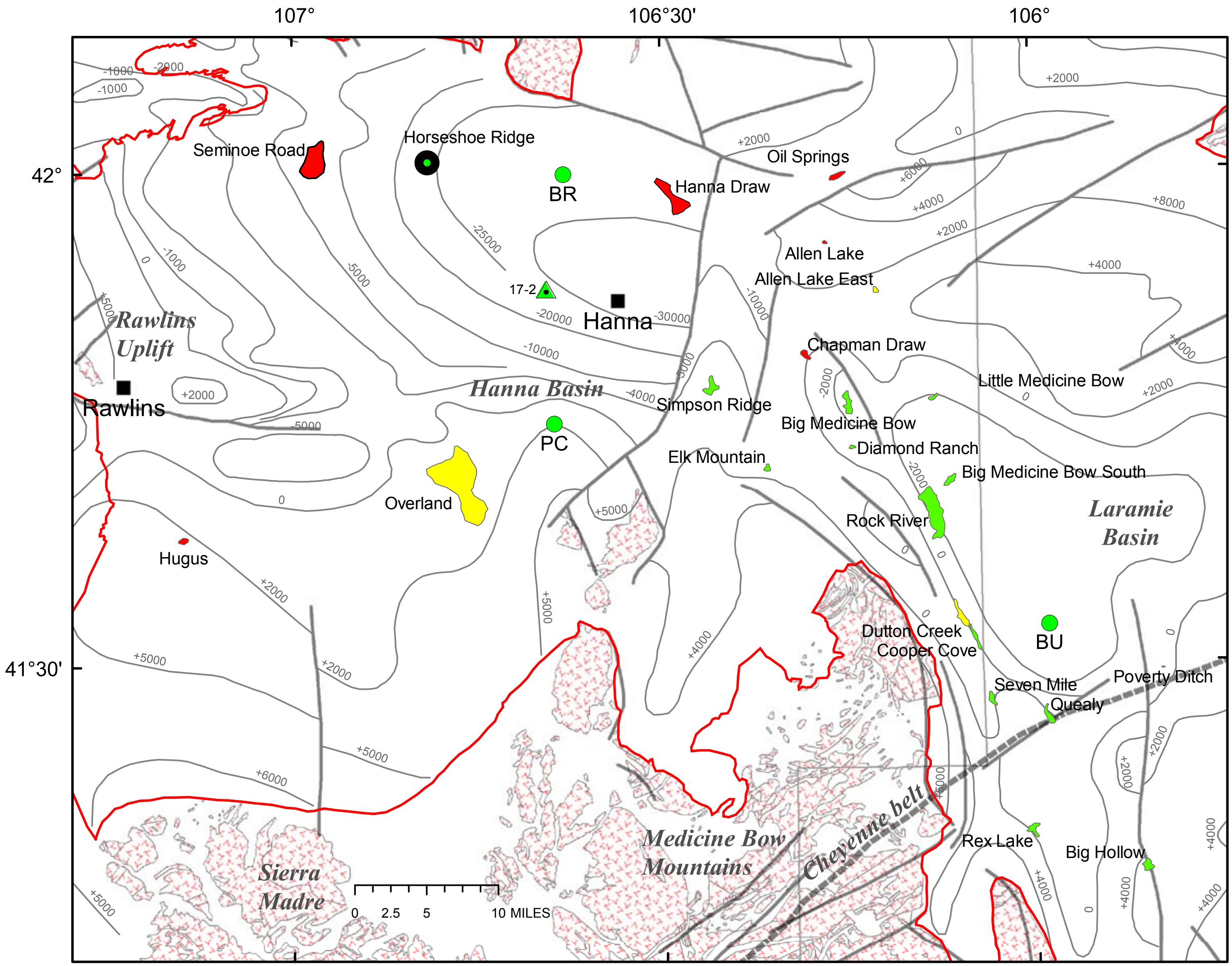

Figure 20. Southwestern part of the Hanna, Laramie, and Shirley Basins Province showing locations of oil (green), gas (red), and oil and gas (yellow) fields, wells used to model thermal history of the southern part of province (green filled circles), locations of the Hanna Draw and Seminoe Road coalbed gas pilot projects (red tracts), and Anadarko Durante 17-2 well (green triangle). Contours drawn on top of Precambrian basement in feet relative to sea level (modified from Blackstone, 1989). Heavy gray lines are major faults. Red patterned areas are outcrops of Precambrian rocks from Green (1992) and Green and Drouillard (1994). Location of Cheyenne belt from Stone (1995). BR, Brinkerhoff Hanna Unit No. 1 well; BU, Buttes Federal 1–18 well. PC, Humble Pass Creek Ridge No. 1 well.

Assessment of Oil and Gas Resources

System for Numbering Assessed Resources

In the Hanna, Laramie, and Shirley Basins Province we assessed the 5 TPSs and 7 AUs listed below. They are numbered according to a system established by the USGS to facilitate petroleum resource assessment (U.S. Geological Survey, 2000): the first digit (5) refers to the region, the next three (030) to the province, the next two (01, 02, and so on) to the TPS, and the last two digits to the assessment unit.

503001	**Phosphoria TPS**
50300101	Tensleep-Casper Conventional Oil and Gas AU
503002	**Mowry-Hanna Composite TPS**
50300201	Mesozoic-Cenozoic Conventional Oil and Gas AU
50300261	Hanna Basin Continuous Gas AU (not quantitatively assessed)
503003	**Niobrara TPS**
50300361	Niobrara Continuous Oil AU
503004	**Niobrara Biogenic Gas TPS**
50300461	Niobrara Biogenic Gas AU (not quantitatively assessed)
503005	**Hanna-Mesaverde Coalbed Gas TPS**
50300581	Medicine Bow–Ferris–Hanna Coalbed Gas AU (not quantitatively assessed)
50300582	Mesaverde Coalbed Gas AU (not quantitatively assessed)

Each AU was defined on the basis of geologic characteristics and conditions favorable for hydrocarbon generation and accumulation—such as source, reservoir, and seal rocks; burial, thermal, and migration histories; and trapping mechanisms—that combine to distinguish it from other AUs. [Note: Hanna Basin Continuous Gas, Niobrara Biogenic Gas, Medicine Bow–Ferris–Hanna Coalbed Gas, and Mesaverde Coalbed Gas AUs were not assessed owing to a lack of geologic data and inadequate production data.]

A thorough analysis of all available geologic data, as well as petroleum exploration and development information, was presented to a review panel for a final determination of the criteria and boundaries to be used for each AU. In addition, estimates of the sizes and numbers of undiscovered conventional oil and gas accumulations, based on a tabulation of existing field and well records provided by Klett and Le (2007) (this CD-ROM), were presented on data input forms to the review panel. These input-data forms (see Klett and Le, 2007, this CD-ROM) constitute the basis for estimating hydrocarbon resources in the AUs.

The default minimum accumulation size that has potential for additions to reserves for conventional accumulations is 0.5 million barrels of oil equivalent (MMBOE). The Niobrara Continuous Oil AU was assessed using the methodology described by Schmoker (1996), wherein the number of untested cells with potential for additions to reserves and total recovery per cell were estimated. For that AU, the minimum recovery is 1,000 barrels of oil per cell. Other data were compiled or calculated for each AU to aid in the final estimate of undiscovered resources: gas-oil ratio, natural gas liquids to gas ratio, API gravity, sulfur content, and drilling depth. Additionally, allocations of undiscovered resources were calculated for Federal, State, and private lands and for various ecosystem regions. Data are available on the completed data input forms for the three assessed AUs in Klett and Le (2007) (this CD-ROM).

The “wells” shown on the AU maps in this report are generalized locations of wells called “cells.” Cell maps for each oil and gas assessment unit were created by the USGS to illustrate the degree of exploration, type of production, and distribution of production in an AU or province. Each cell represents a quarter-mile square of the land surface, and the cells are coded to represent whether the wells located within the cell are predominantly oil-producing, gas-producing, both oil- and gas-producing, dry, or of unknown production type. The well information was initially retrieved from the IHS Energy Group, PI/Dwights PLUS Well Data on CD-ROM (IHS Energy Group, 2004b). Cells were developed as a graphic solution to overcome the problem of displaying proprietary PI/Dwights PLUS Well Data. Consequently, proprietary data are not displayed on or used in the cell maps.

For this study, we defined dry holes for each AU as wells that reached total depth in or through the assessed formations and moreover were classified as dry and abandoned in the well database for formations in that AU. Dry holes are distributed relatively evenly in the Laramie Basin but have not penetrated the deepest part of the Hanna Basin. The following sections describe the characteristics of the TPSs and the quantitatively assessed AUs within the respective TPSs.

Links to Data Input Forms and Graphical Data

Klett and Le (2007) (this CD-ROM) provide files of input forms and graphical data that were used in the assessment of the Hanna, Laramie, and Shirley Basins Province. Two sets of exploration-activity and discovery-history graphs are provided for each of the AUs, one set showing known field sizes (cumulative production plus remaining reserves) and another set showing field sizes that were adjusted to compensate for potential reserve growth in the next 30 years (labeled "grown"). Within each set of graphs, oil fields and gas fields are shown separately. The links, below, directly access the material in Klett and Le's chapter of this report.

Data Input Forms:

Tensleep-Casper Conventional Oil and Gas AU (50300101)
Mesozoic-Cenozoic Conventional Oil and Gas AU (50300201)
Niobrara Continuous Oil AU (50300361)

Graphs of Exploration and Discovery Data for Conventional Assessment Units

Tensleep-Casper Conventional Oil and Gas AU (known field sizes)
Tensleep-Casper Conventional Oil and Gas AU (grown field sizes)
Mesozoic-Cenozoic Conventional Oil and Gas AU (known field sizes)
Mesozoic-Cenozoic Conventional Oil and Gas AU (grown field sizes)

Phosphoria Total Petroleum System

The geographic extents of both source and reservoir rocks that constitute the Phosphoria TPS are shown in figure 21. The TPS extends eastward and incorporates virtually all of the Hanna, Laramie, and Shirley Basins Province, but because Phosphoria source rocks do not extend into the province, the concept of long-distance migration of oil is important to our understanding of this TPS.

Key elements of the Phosphoria TPS:

- Source rocks of appropriate organic content and sufficient thermal maturity to generate hydrocarbons, such as the Meade Peak and Retort Phosphatic Shale Members of the Phosphoria Formation.
- Long-distance migration pathways, such as vertical paths through faults and fractures, and lateral (updip) paths along bedding planes and disconformities.
- Reservoir rocks, in this case the sandstones of the Pennsylvanian Tensleep Sandstone and Casper Formation.
- Traps, such as thrust-faulted anticlines, complex triangle zones, sedimentary pinchouts, and combinations of these features, along with enclosing shale, mudstone, and evaporite units and other tightly cemented beds that act as seals.

Figure 22 is a total petroleum system events chart for the Phosphoria TPS and the Tensleep-Casper Conventional Oil and Gas AU. This chart summarizes the relative ages of source and reservoir rocks; seals; overburden; trap formation; generation, migration, and accumulation of oil and gas; and the critical moment (time of maximum burial depth), as discussed in detail below.

Source Rocks

Lillis and others (2003) identified several oil types in Paleozoic, Cretaceous, and Tertiary strata in the Uinta and Piceance Basins of northeastern Utah and northwestern Colorado on the basis of geochemical composition of sampled oil. Their Phosphoria oil type is widely distributed in Pennsylvanian through Jurassic reservoirs in the Uinta-Piceance and Southwestern Wyoming Provinces. Johnson (2003) recognized Phosphoria oil in the Pennsylvanian-Permian Weber Sandstone at Rangely field in northwestern Colorado; that report also identifies 65 oil and gas fields in the Southwestern Wyoming Province that produce Phosphoria oil from 18 pre-Cretaceous reservoirs in the TPS.

Regionally, the Phosphoria oil type is characterized by high sulfur content (0.5–1.4 wt percent sulfur) and pristane-phytane values of less than 1.0 (Lillis and others, 2003). For the current assessment, samples were analyzed from Casper Formation reservoirs at Herrick, Little Laramie, Allen Lake East, and Quealy fields in the Laramie Basin. Sulfur values for these fields ranged from 2.5 to 3.5 wt percent (fig. 23). Two Tensleep oil samples having moderate to high API gravity and low sulfur are at O'Brien Springs and Big Medicine Bow fields (fig. 23). The regional difference in weight percent sulfur may be due to variations in Phosphoria source rock facies and kerogen composition, the mixing of oils from other source rocks with the Phosphoria, or differences in thermal history (Paul Lillis, USGS, oral commun., 2005). Low sulfur oils in Jurassic Sundance Formation reservoirs (fig. 23) in the Laramie Basin at Elk Mountain, Rock River, Quealy, and Little Medicine Bow fields are interpreted as derived from Mowry oils of the Mowry-Hanna Composite TPS rather than from Phosphoria oils.

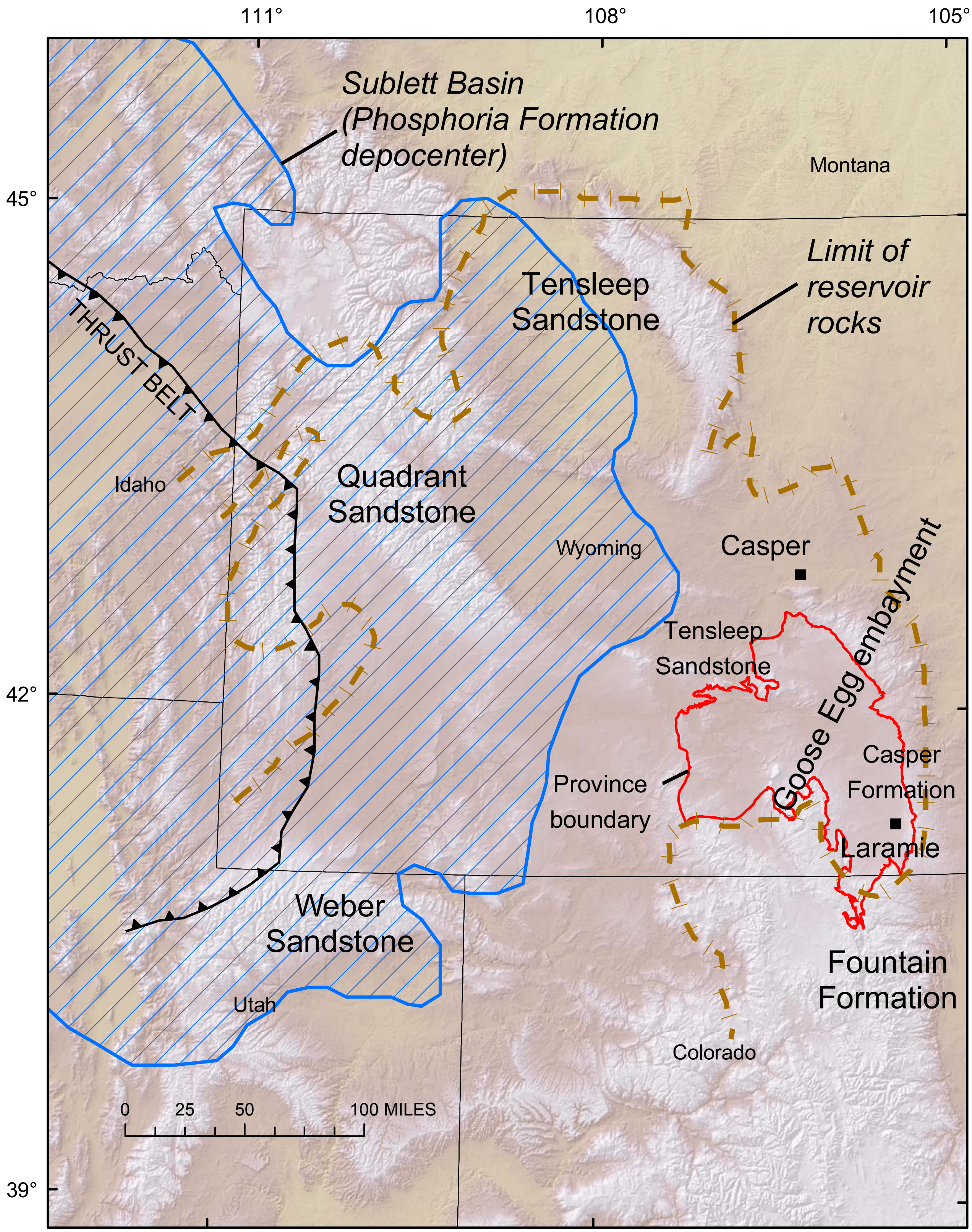

Figure 21. Pennsylvanian and Permian source and reservoir rocks in western Wyoming and adjacent areas and the Phosphoria Total Petroleum System in the Hanna, Laramie, and Shirley Basins Province (outlined in red), showing the distribution of Phosphoria source rocks (Sublett Basin, within blue crosshatched area) and a portion of the Thrust belt (modified from Maughan, 1984). Tensleep, Casper, and equivalent potential reservoir rocks (inside dashed brown line) modified from Mallory (1972). [Note: the GIS layer for the Phosphoria TPS shows only that part of the TPS within the Hanna, Laramie, and Shirley Basins Province.]

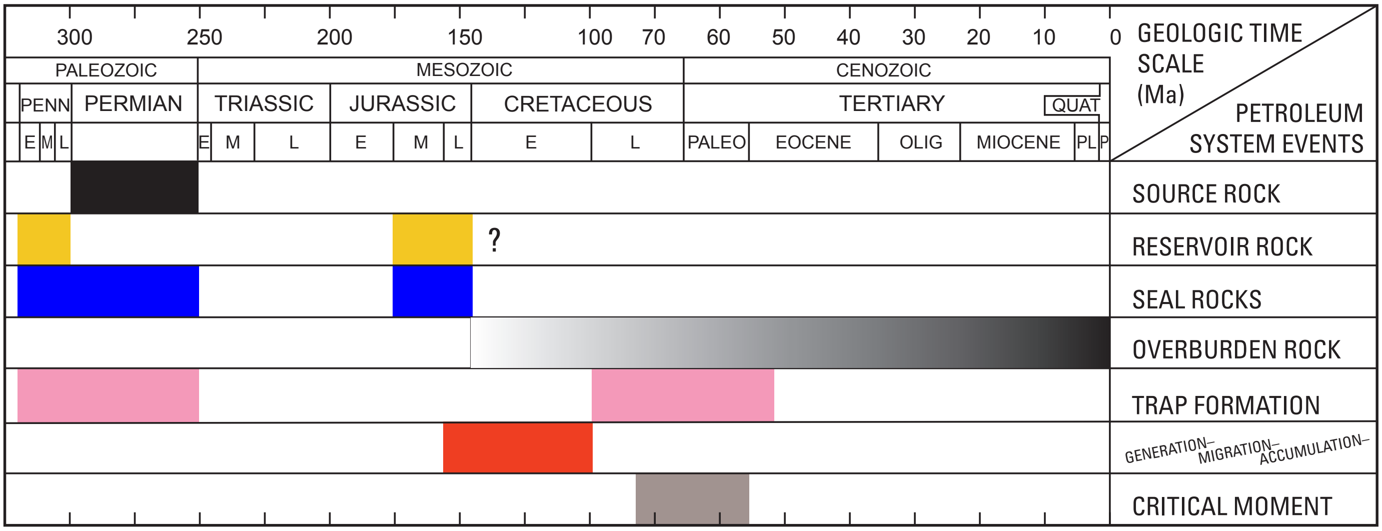

Figure 22. Events chart for the Phosphoria Total Petroleum System in the Hanna, Laramie, and Shirley Basins Province. PENN, Pennsylvanian; QUAT, Quaternary; PALEO, Paleocene; OLIG, Oligocene; PL, Pliocene; P, Pleistocene; E, Early; M, Middle; L, Late.

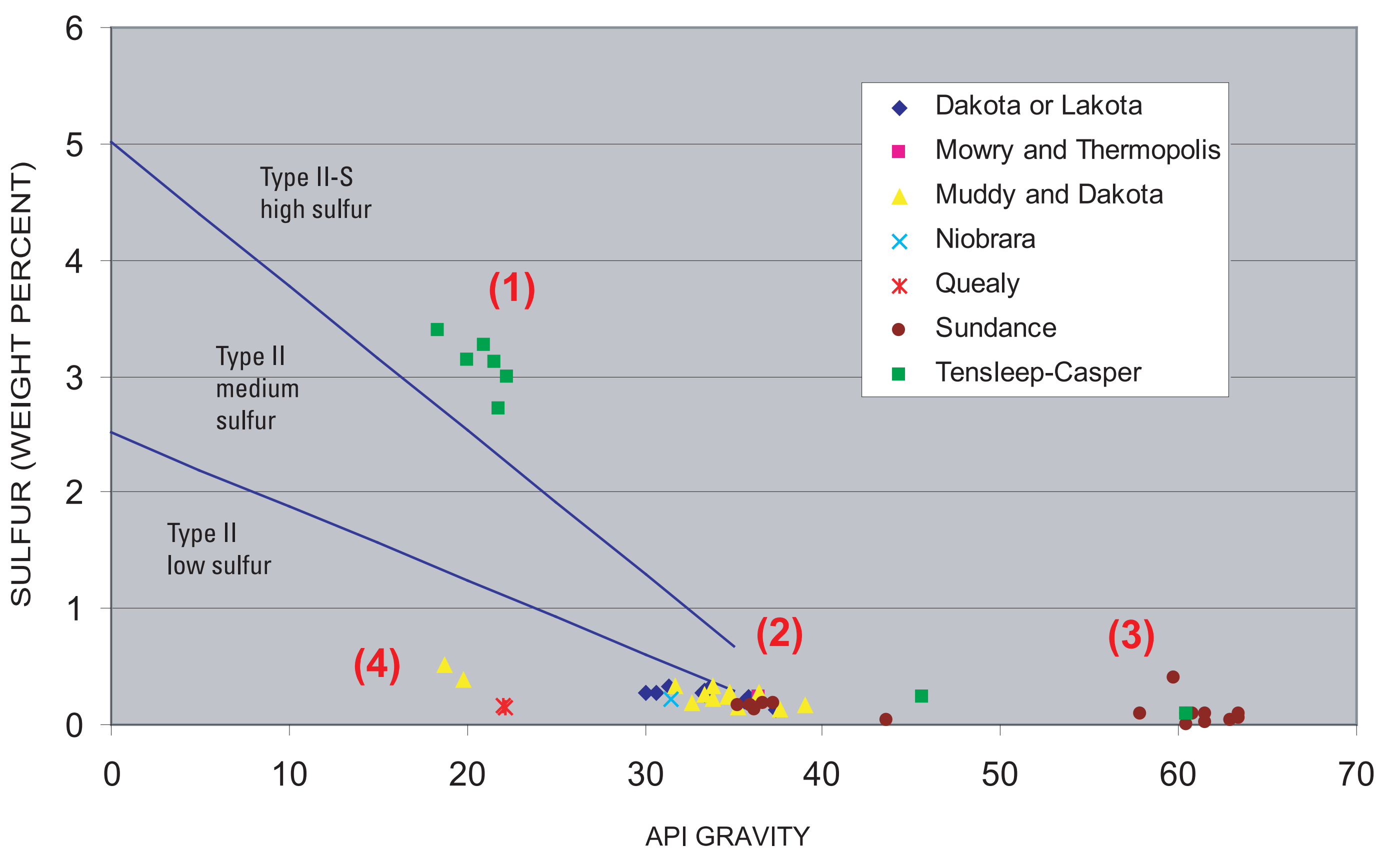

Figure 23. Weight percent sulfur versus API gravity for oil samples in the Hanna, Laramie, and Shirley Basins Province. Data were obtained from the U.S. Department of Energy crude oil analysis database (COADB) and are separated by lines representing variations in Type-II organic matter: (1) high sulfur–low API gravity oil is derived from the Phosphoria Formation; (2) low sulfur–moderate API gravity oil is derived from Cretaceous rocks; (3) low sulfur condensate of Sundance reservoirs; (4) low sulfur–low API gravity degraded oils. The COADB is available from the U.S. Department of Energy, National Energy Technology Laboratory. (http://www.netl.doe.gov/technologies/oil-gas/Software/database.html, last accessed 9/27/2007).

In the Hanna, Laramie, and Shirley Basins Province, high sulfur, low API gravity oil in Tensleep-Casper reservoirs is interpreted as migrated Phosphoria oil owing to (1) its geochemical similarity to other identified Phosphoria oils (Lillis and others, 2003) and to (2) the lack of local source rocks containing this type of oil. Stone (1966) suggested that organic-rich carbonate facies of the Pennsylvanian and Permian Minnelusa Formation of the Powder River Basin could be a possible secondary source for Casper Formation oil in the Laramie Basin, but we believe that the Phosphoria is a more likely source because (1) Minnelusa oil from the Powder River Basin and Tensleep oil from the Bighorn Basin differ in composition (Clayton and Ryder, 1984); (2) sulfur content in Minnelusa oil is generally less than 2 wt percent (Clayton and Ryder, 1984), whereas it is 2.5–3.5 wt percent in sampled Laramie Basin oil (which is comparable to the average sulfur content of 2.71 wt percent in three large Tensleep fields in the Bighorn Basin (Stone, 1967)); (3) differences in depositional facies assemblages and in diagenesis between Tensleep and Minnelusa sandstones (Patterson and others, 1986; Schenk and others, 1986) indicate that the Tensleep is better suited as a carrier bed for long-distance migration of oil; and (4) a structurally high area in east-central Wyoming in Pennsylvanian and early Permian time (Kluth, 1986) was a barrier between the Hanna, Laramie, and Shirley Basins Province and the Powder River Basin, thus hindering migration of oil from the northeast.

During Permian (Wolfcampian-Leonardian) time, the Phosphoria Formation was deposited in the Sublett Basin, an extensive foreland basin located in southeastern Idaho, southwestern Montana, northern Utah, and western Wyoming (Maughan, 1984; fig. 21). The basin is underlain by an area of organic-rich phosphatic shale of the Phosphoria Formation centered in western Wyoming and adjacent areas to the west and bordered on the east by shelf carbonate rocks of the equivalent Park City Formation (Johnson, 2003, 2005). Terrigineous sediment came from highlands surrounding the basin (Piper and Link, 2002). Transgressions and regressions owing to sea level fluctuations resulted in interfingering of Park City carbonate and Phosphoria phosphatic shale facies. Among the several named members in the Phosphoria (Maughan, 1984) are the primary source rock units—the Meade Peak and Retort Phosphatic Shale Members.

The Hanna, Laramie, and Shirley Basins Province lies east of the locus of Phosphoria–Park City deposition in an area called the Goose Egg embayment (fig. 21). There, shallow marine and sabkha evaporites and carbonate rocks of the Goose Egg Formation were deposited contemporaneously with the Phosphoria in a setting where evaporation exceeded freshwater input to the basin (Piper and Link, 2002).

Conditions were favorable for the accumulation and preservation of organic matter in the Phosphoria anoxic organic-rich facies (Piper and Link, 2002). The regional average total organic carbon (TOC) content of the Meade Peak Member is 2.4 wt percent (n = 285); highest average and maximum wt percent values are 9.0 and 30.0, respectively, in southeastern Idaho. The regional TOC of the Retort Member averages 4.9 wt percent (n = 82); the highest TOC is 10 wt percent in southwest Montana (Maughan, 1984).

Source Rock Thermal Maturity

The Phosphoria is inferred to have generated and expelled hydrocarbons as it reached burial depths greater than 6,560 ft. It continued to generate oil as it passed through the oil window until it reached a depth of about 16,400 ft in the Sublett Basin (Claypool and others, 1978). Below 16,400 ft, oil-to-gas cracking may have resulted in the generation of thermogenic gas. Maughan (1984) suggested that burial depths required for significant oil generation might have been reached in the Late Triassic in the central part of the Sublett Basin, and that most oil generation took place before the end of the Cretaceous. Johnson (2003) suggested that maximum oil generation occurred during the Late Jurassic and Early Cretaceous. At modeled locations in the Southwestern Wyoming Province, Roberts and others (2005) identified peak oil generation in the Late Cretaceous (80–73 Ma) and peak oil-to-gas cracking during late Paleocene (57 Ma). This timing would allow for significant oil migration (but not gas migration) prior to Laramide basin partitioning in the Hanna, Laramie, and Shirley Basins Province. Vitrinite reflectance data from organic-rich mudstones in the Meade Peak Member throughout the area of its deposition indicate that thermal maturity was high enough in that unit to generate economic quantities of oil in most of the Sublett Basin. However, the Retort is considered thermally immature in southwestern Montana owing to shallow burial depths (Johnson, 2003).

Additional burial occurred during thrusting in the Wyoming part of the thrust belt (fig. 21) during the Late Cretaceous, but Maughan (1984) believed that most oil generation took place prior to thrusting. Using conodont alteration indices for Phosphoria source rocks in northern Utah, Wardlaw and others (1979) suggested that thermal maturities were high enough in that area to generate significant quantities of oil. Data and conclusions from Britt and Howard (1982) and Huntoon and others (1999) support a Jurassic-Cretaceous window for oil generation from the Phosphoria Formation in the region.

The Phosphoria is thus thought to be a potential source rock for oil everywhere within the province where favorable structural development and facies are present in combined carrier and reservoir beds in the Casper Formation or Tensleep Sandstone. Claypool and others (1978) estimated that the Phosphoria Formation might have generated as much as 225 billion barrels of oil in the region.

Hydrocarbon Migration

Most workers support a Late Jurassic to mid-Cretaceous migration history for Phosphoria-derived oil (for example, Sheldon, 1966; Stone, 1966; Claypool and others, 1978; Britt and Howard, 1982; Fryberger and Koelmel, 1986; Johnson, 2003, 2005). Weber, Park City, Quadrant, Tensleep, and Casper sandstones and carbonate rocks formed a regional hydrostratigraphic unit and are considered to be the major carrier beds for Phosphoria-derived oil in the region until fluid-flow barriers developed during Laramide structural partitioning in the early Tertiary. Fluid movement resulted in updip migration from deeper parts of the Mesozoic foreland basin to the basin margins. Inasmuch as the Hanna, Laramie, and Shirley Basins were part of the larger foreland basin until at least the middle to late Paleocene, adequate time was available to migrate oil into traps. Sequence-boundary disconformities, bedding planes, permeable sandstones, faults, and fractures within the reservoirs were probable migration pathways.

Most natural gas is thought to have been generated primarily through the cracking of Phosphoria oil, not by primary generation from source rocks (Lewan and Henry, 2001). Migration distances for gas were probably less than for oil. Little gas has been produced from Tensleep-Casper reservoirs in the Hanna, Laramie, and Shirley Basins Province, and the full extent of Phosphoria oil-to-gas cracking is unknown.

Vertical remigration of oil from Tensleep-Casper reservoirs into Jurassic-Cretaceous reservoirs during the Laramide required continuous fault and fracture pathways. Thick Cretaceous shales would have inhibited propagation of continuous fractures through the entire sedimentary section. Thus, larger features such as faults would seem to be necessary to permit vertical remigration.

Reservoir Rocks

In the adjacent Southwestern Wyoming Province, the Phosphoria TPS contains 18 different reservoirs ranging in age from Precambrian crystalline rocks to the Jurassic Morrison Formation (Johnson, 2005). In contrast, the Tensleep Sandstone and Casper Formation are the primary reservoirs for Phosphoria oil in the Hanna, Laramie, and Shirley Basins Province. Reservoir properties of these formations vary greatly with geographic location and depositional environment. At Lost Soldier field in the adjacent northeastern part of the Southwestern Wyoming Province, the Tensleep includes fine-grained quartz-rich sandstone and thin interbedded dolomite and dolomitic limestone deposited in eolian dune, interdune, and sabkha environments. At the south end of the Laramie Basin, the Casper Formation grades into arkosic sandstone, red shale, and limestone deposited primarily in fluvial and coastal sabkha environments. Maughan and Ahlbrandt (1985) correlated the middle member of the Casper Formation in the Laramie Basin with the upper member of the Fountain Formation of Colorado.

In known fields of the Laramie Basin, Casper Formation porosity ranges from 10 to 23 percent, and permeability ranges from 10 to 400 millidarcies (mD) (Hollis and Potter, 1984). Porosity, permeability and, ultimately, reservoir quality are believed to be determined by the combined effects of depositional environment and diagenesis, the latter being an important factor in porosity reduction. Mou and Brenner (1981) identified diagenetic facies at Lost Soldier field that are associated with variations in sabkha and eolian dune facies. James (1992) identified four important porosity reducing cements in Quadrant and Tensleep Sandstones in the northern Rocky Mountain region—from earliest to latest, anhydrite, dolomite, quartz, and calcite—and noted that the type and intensity of cementation are related to depositional environment and vertical position with respect to bounding units between sandstone beds.

The best Tensleep-Casper reservoirs in the region are cross-stratified eolian sandstones, consisting of well-rounded and well-sorted quartz-rich grain assemblages. The sandstones are fine grained to very fine grained and range from tabular planar to trough cross-stratified in dune areas and to planar bedded and wavy bedded in interdune areas (Ciftci and others, 2004).

Traps and Seals

Hydrocarbon traps in the Phosphoria TPS are primarily structural or a combination of structural and stratigraphic traps. Stratigraphic traps, although less common, are formed by pinchouts of reservoir sandstones into finer grained mudrocks, by truncation beneath disconformities, and by bounding surfaces in eolian dune and sabkha facies.

In the Phosphoria TPS, trapping mechanisms include late Paleozoic deformation in the Laramie Basin where basement-involved thrusts formed duplex structures (localized features characterized by stacked imbricate faults) having both strike-slip and dip-slip components (Stone, 1995). Stone (2005) documented the presence of a Paleozoic duplex beneath Laramide structures at Cooper Cove and Dutton Creek oil fields in the western Laramie Basin (figs. 4, 20). At both fields, production is from Cretaceous reservoirs in Laramide traps. At Cooper Cove deeper Permian thrust faults die out within the Goose Egg Formation; these faults form duplex structures not yet tested for oil in Tensleep-Casper reservoirs. The diversity of structural traps in the province is due to the development of different deformation styles that accompanied long-term changes in stress fields of the Laramide orogeny. Stone (1995) described the fault kinematics and deformation style at Quealy field just south of the Cooper Cove structural trend (fig. 20), where Tensleep-Casper production is from a complex Paleozoic structure that was later reactivated during the Laramide.

The Quealy, Dutton Creek, and Cooper Cove structures are close to and structurally related to the Arlington thrust fault (Stone, 1995) that trends north-south and northwest-southeast along the west margin of the Laramie Basin (figs. 3, 4). It is one of many Rocky Mountain basin-margin thrusts that placed Precambrian crystalline basement over thick sedimentary sections (Gries, 1983a) in which Laramide traps may have formed.

Several structures in the Hanna Basin contain shallow out-of-basin thrusts rooted in the sedimentary section (generally Cretaceous shales) and oppositely directed, basement-involved thrust faults. Episodic deformation along these faults formed triangle zones of opposing fault geometries (Erslev, 1991; Lillegraven and others, 2004). Brown (1984) discussed the origin of these basin-margin structures as volumetric adjustments. Blackstone (1993) referred to them as representing “flexural slip deformation” of a thick sedimentary section around the Hanna Basin margin and identified several examples—Pass Creek Ridge, St. Mary’s Ridge, and Simpson Ridge anticlines (fig. 3). Subsidiary faulting in the triangle zones may have resulted in complex trapping mechanisms.

Ciftci and others (2004) described a regional example of stratigraphic control on the trapping of hydrocarbons in the Tensleep Sandstone in the Bighorn Basin. They identified (1) small-scale reservoir heterogeneity that is caused by variations in the eolian dune facies and (2) large-scale heterogeneity that is a result of interbedding of the eolian dune facies with fine-grained sabkha and marine carbonate facies. Permeability is reduced across internal bounding surfaces in the dune facies and between lithologic variations in the different depositional facies, which increases the potential for reservoir compartmentalization in the Tensleep.

Primary seals of the Phosphoria TPS are shallow marine and evaporitic sabkha deposits of the Goose Egg Formation. Lithologies of the Goose Egg include fine-grained redbed siltstones, carbonate rocks, and gypsum (Harshman, 1972; Piper and Link, 2002). The Goose Egg directly overlies the Tensleep and Casper throughout the province and acts as a seal in both structural and stratigraphic traps. In some areas, diagenesis of the Tensleep-Casper reservoirs produced tightly cemented zones that may also act as local seals. Structural seals are also important in the Phosphoria TPS where fault movements placed impermeable rocks in contact with reservoirs. In these traps, siltstones and carbonate rocks of the Triassic Chugwater Group may also act as seals.

Tensleep-Casper Conventional Oil and Gas Assessment Unit (50300101)

The Tensleep-Casper Conventional Oil and Gas AU occupies an irregularly shaped area covering most of the Hanna, Laramie, and Shirley Basins Province. The areal extent is based on the distribution of Tensleep and Casper reservoir rocks and contains approximately 3.9 million acres (fig. 24). It includes both late Paleozoic and Late Cretaceous to early Tertiary Laramide structures that trapped migrating Phosphoria oil. Earliest noteworthy oil production from Tensleep-Casper reservoirs was at Herrick and Quealy fields in the Laramie Basin in 1947. Three other fields with Tensleep reservoirs—Allen Lake East, Big Medicine Bow, and Little Laramie—were discovered in the 1940s to 1950 and continue to produce today (table 3; fig. 20). The AU is considered mature with respect to drilling for oil and gas resources.

Production from Tensleep-Casper reservoirs is limited to the Laramie Basin (fig. 24); drilling depths to the tops of the producing units range from 126 to 16,380 ft (table 4). To date, 8.5 MMBO and 0.3 BCFG have been produced (table 3; IHS Energy Group, 2004a); most wells are classified as oil, but many have minor amounts of associated gas.

Estimated Resources

The Tensleep-Casper Conventional Oil and Gas AU is considered frontier on the basis of the small number of discovered fields (5 oil, 0 gas) that equal or exceed the minimum accumulation size of 0.5 MMBOE (see Klett and Le, 2007 (this CD-ROM)). The median sizes of previously discovered accumulations, when divided into halves (by initial date of production) is 1.5 and 2 MMBO (Klett and Le, 2007, (this CD-ROM)), indicating a slight increase in discovered accumulation size through time. Conditions are deemed favorable for the AU to contain one or more undiscovered hydrocarbon accumulations equal to or greater than the minimum field size, as indicated below.

In this AU, we estimate the number of undiscovered oil accumulations to be a minimum of 1 and a maximum of 25; the most likely number is 7. All five of the discovered fields having production above the minimum of 0.5 MMBOE were discovered prior to 1950, but we believe the potential exists for at least one more oil field discovery above the minimum size, given the number and complexity of late Paleozoic and Laramide structures. At the maximum, we allowed for the possibility of 25 more discoveries, on the basis of finding and drilling many of these structures. We selected a mode of seven undiscovered fields because this area is moderately explored.

In terms of the sizes of undiscovered oil accumulations, we estimate (1) a minimum size of 0.5 MMBO on the basis of the minimum allowed at the current cutoff; (2) a maximum size of 12 MMBO, allowing for the possibility that a future field discovery could be twice the size of the largest discovered field (Quealy); and (3) a median size of 1.5 MMBO, which reflects a decrease from the 2 MMBO reported for the second half of the discovery history. As indicated by the trend of halves, which is based on only five fields, the size of discovered fields is small and has been relatively constant since the last discovery more than 50 years ago. Future discoveries will likely be small.

Mean estimates of undiscovered resources for the Tensleep-Casper Conventional Oil and Gas AU are 20 MMBO, 72 BCFG, and 2 million barrels of natural gas liquids (MMBNGL) (table 2). Table 2 also shows a resource breakdown into the F95, F50, and F5 fractiles. The potential for future discoveries is considered to be low in the Laramie and Shirley Basins, on the basis of the maturity of exploration and the lack of recent new discoveries. Future resource

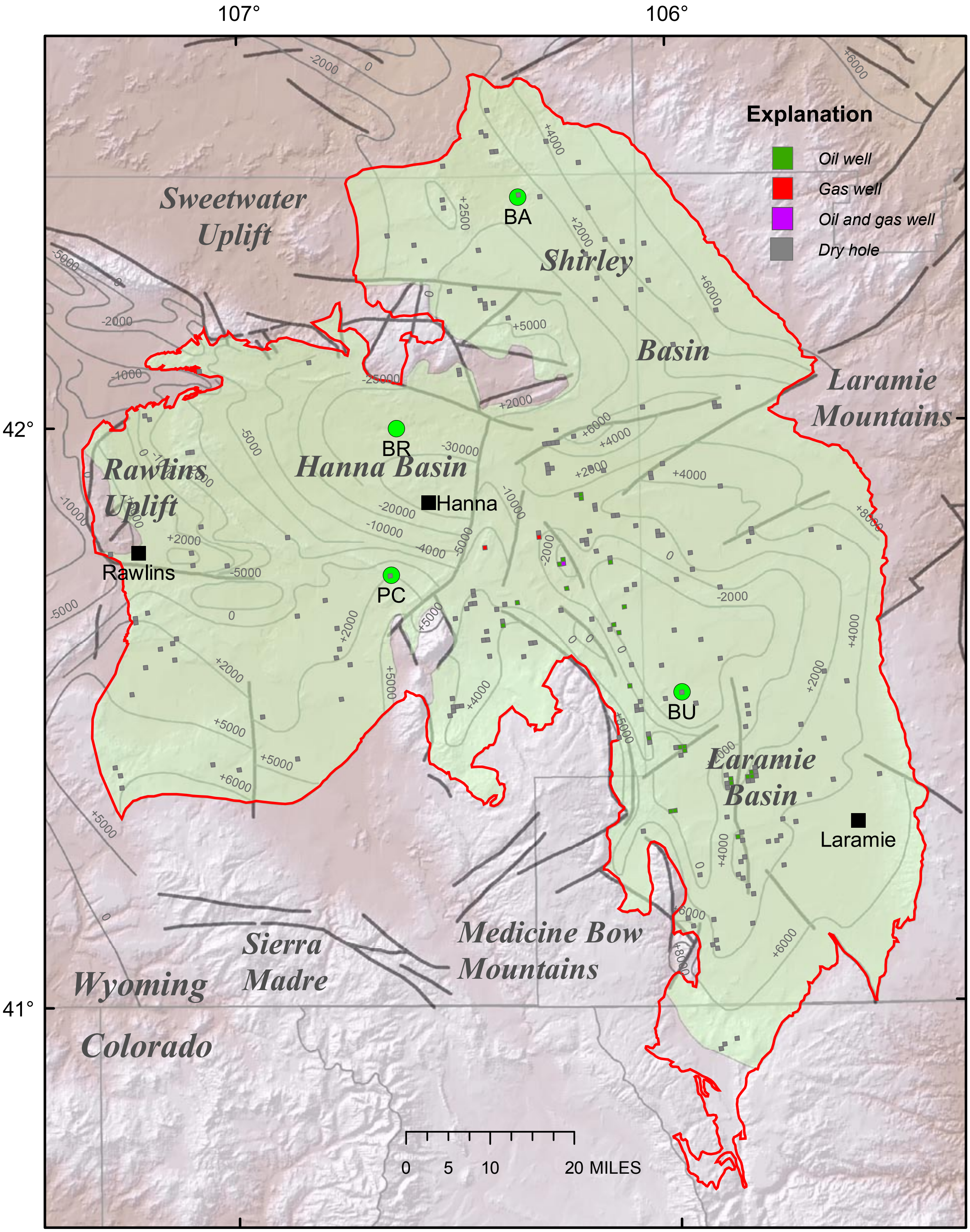

Figure 24. Extent of the Tensleep-Casper Conventional Oil and Gas Assessment Unit (shaded green) in the Hanna, Laramie, and Shirley Basins Province (red outline). Contours drawn on top of Precambrian basement in feet relative to sea level (modified from Blackstone, 1989). Heavy gray lines are major faults. Small colored squares are generalized locations of wells in the AU that penetrate the Tensleep or Casper formations. BA, Coastal Bates Creek Cattle 1–18–28–79 well; BR, Brinkerhoff Hanna Unit No. 1 well; BU, Buttes Federal 1–18 well; PC, Humble Pass Creek Ridge No. 1 well.

Table 4. Range of depths to formation tops in the Hanna, Laramie, and Shirley Basins Province as reported by oil and gas exploration companies. The deepest part of the Hanna Basin has not been drilled, so these reported depths are subject to change with additional deep drilling.

Formation, Group, or geologic time interval	Reported depths to formation top	
	Shallowest (ft)	Deepest (ft)
Hanna Formation	12	4,235
Ferris Formation	370	7,650
Medicine Bow Formation	2,026	9,226
Fox Hills Sandstone	750	8,466
Lewis Shale	270	8,970
Mesaverde Group	60	11,503
Almond Formation	224	9,045
Allen Ridge Formation	1,148	12,530
Pine Ridge Sandstone	832	11,887
Steele Shale	125	7,520
Niobrara Formation	310	10,198
Sage Breaks Shale	3,408	9,988
Wall Creek Member	138	4,830
Frontier Formation	16	13,620
Mowry Shale	188	14,250
Muddy Sandstone Member	142	12,650
Thermopolis Shale	102	11,650
Skull Creek Shale Member	850	9,096
Cloverly Formation	204	9,011
Morrison Formation	45	14,700
Sundance Formation	150	15,012
Chugwater Group	155	15,327
Goose Egg Formation	962	16,047
Tensleep Sandstone/ Casper Formation	126	16,380
Fountain Formation	710	9,578
Amsden Formation	448	16,775
Madison Limestone	622	15,410
Cambrian	740	5,330
Precambrian	710	7,838

development in these reservoirs in the Laramie Basin will likely be the result of reserve growth from previously discovered fields. The best areas for new discoveries are in undrilled and sparsely drilled structures in the Hanna Basin.

Mowry-Hanna Composite Total Petroleum System

The geographic extent of the Mowry-Hanna Composite TPS is shown in figure 25. It encompasses the entire province, based mainly on the distribution of potential source and reservoir rocks, especially the widespread distribution of marine shales of Cretaceous age. The TPS has the potential for continuous basin-center gas within deep source and reservoir rocks in the central Hanna Basin, although geologic data were lacking for a quantitative assessment.

Key elements of the Mowry-Hanna Composite TPS:

- Source rocks of appropriate organic content and sufficient thermal maturity to generate hydrocarbons, such as the Thermopolis and Mowry Shales, Frontier Formation, Steele and Lewis Shales, Mesaverde Group, Medicine Bow, Ferris, and Hanna Formations.
- Short- to moderate-distance migration pathways, such as vertical migration through faults and fractures, and lateral (updip) migration along bedding planes and disconformities. Migration from the deep central Hanna Basin to the basin margins and into the Laramie Basin occurred prior to structural basin partitioning in the late Laramide.
- Reservoir rocks, consisting of Jurassic Sundance and Cretaceous Cloverly, Muddy, Frontier, Steele, Mesaverde, Lewis, Medicine Bow, Ferris, and Hanna sandstones. The Ferris and Hanna Formations are present in the structurally deepest parts of the Hanna and Laramie Basins; they are absent in the Shirley Basin.
- Traps, such as thrust-faulted anticlines, complex triangle zones, sedimentary pinchouts, and combinations of these features, along with enclosing shale, mudstone, and evaporite units and other tightly cemented beds that act as seals.

Figure 26 is the events chart for the Mowry-Hanna Composite TPS and the Mesozoic-Cenozoic Conventional Oil and Gas AU. This chart summarizes the relative ages of source and reservoir rocks, seals, overburden, and trap formation; the generation, migration, and accumulation of oil and gas; and the critical moment.

Source Rocks

The Mowry Shale is considered to be the primary source rock for oil in Cretaceous reservoirs in much of Wyoming (Kirschbaum and Roberts, 2005). It is an organic-rich siliceous shale and mudstone unit consisting of laminated and bioturbated facies. Sediments were deposited on an anoxic substrate during a period of increased volcanic activity associated with development of the Idaho and other satellite batholiths to the west of the Hanna, Laramie, and Shirley Basins Province (Burtner and Warner, 1984; Davis and others, 1986). Mowry shales and mudstones have TOC contents ranging from 0.7 to 4.1 wt percent across the Western Interior (fig. 27). Within the Hanna, Laramie, and Shirley Basins

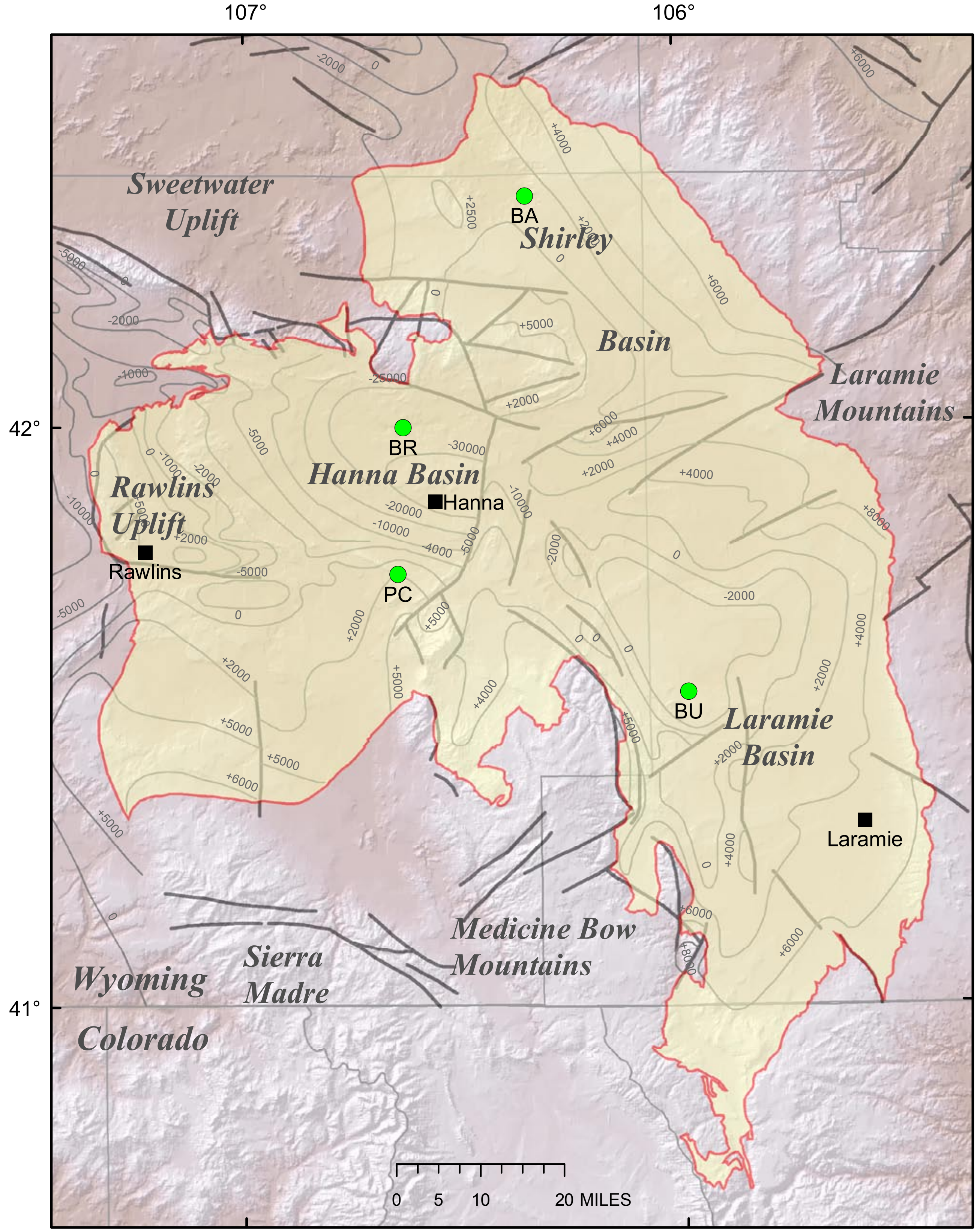

Figure 25. Mowry-Hanna Composite Total Petroleum System (tan shaded area) showing the distribution of Mowry through Hanna source and reservoir rocks in the Hanna, Laramie, and Shirley Basins Province (red outline). Contours drawn on top of Precambrian basement in feet relative to sea level (modified from Blackstone, 1989). Heavy gray lines are major faults. BA, Coastal Bates Creek Cattle 1–18–28–79 well; BR, Brinkerhoff Hanna Unit No. 1 well; BU, Buttes Federal 1–18 well; PC, Humble Pass Creek Ridge No. 1 well.

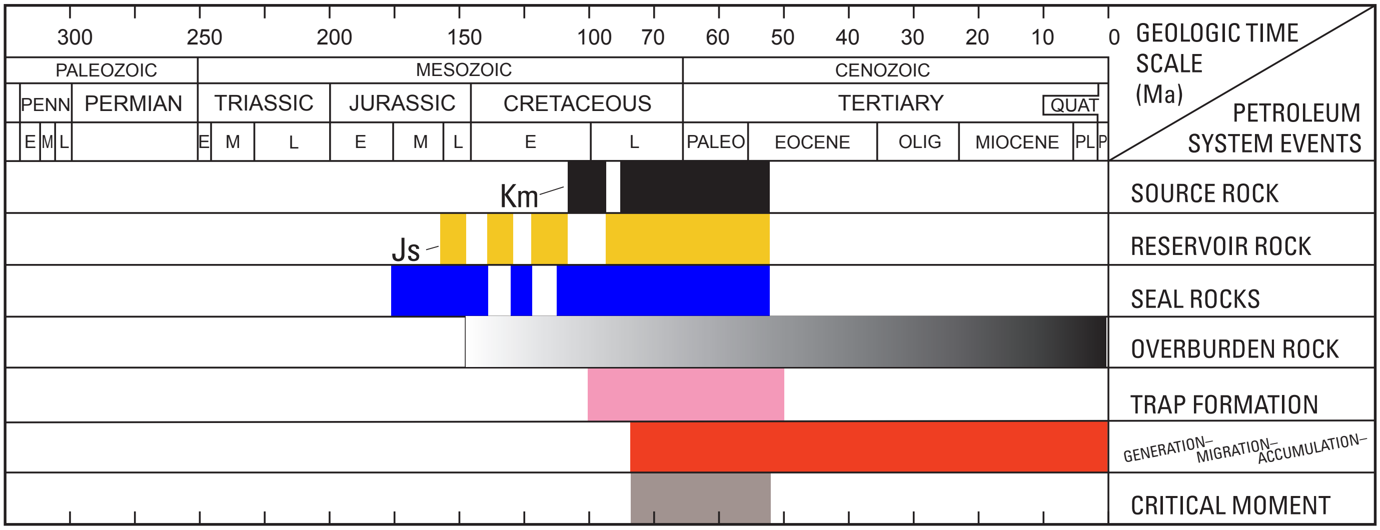

Figure 26. Events chart for the Mowry-Hanna Composite Total Petroleum System in the Hanna, Laramie, and Shirley Basins Province. PENN, Pennsylvanian; QUAT, Quaternary; PALEO, Paleocene; OLIG, Oligocene; PL, Pliocene; P, Pleistocene; E, Early; M, Middle; L, Late; Km, Mowry Shale; Js, Sundance Formation.

Province, which lies near the geographic axis of the Mowry sea, three Mowry samples collected in the Hanna Basin show TOC values ranging from 1.01 to 2.66 wt percent and indicate a mixed Type II and Type III source on the basis of their ratio of hydrogen to oxygen indices (fig. 28). The Mowry becomes a Type III source farther to the west where terrestrial organic matter increases in abundance (Burtner and Warner, 1984). Mowry oils from southwestern Wyoming have sulfur values less than 0.5 wt percent and pristane-phytane values between 1.8 and 2.1, indicating that the source rock is marine (Paul Lillis, oral commun., 2005). In the Hanna, Laramie, and Shirley Basins Province, low sulfur, moderate API gravity oils in Sundance through Muddy reservoirs were interpreted as Cretaceous oils (fig. 23). Analyses of oil samples from Jurassic Sundance and Cretaceous reservoirs in the Rock River, Big Medicine Bow, Diamond Ranch, and Quealy fields (fig. 20) show that sulfur values average less than 0.5 wt percent and that oil gravity ranges from about 30 to 40 degrees API. Figure 28 shows the hydrogen index plotted against the oxygen index for various source rock samples; data is in table 5.

The Lower Cretaceous Thermopolis Shale and Upper Cretaceous Frontier Formation and Carlile Shale are considered minor marine source rocks in the Mowry-Hanna Composite TPS. Carbonaceous marine shales and mudstones are mixed Type II and Type III and have TOC values ranging from 0.86 to 2.52 wt percent (table 5; fig. 28). Bierei (1987) analyzed 13 Frontier Formation samples from the Hanna Basin that show a TOC range of 0.4 to 1.4 wt percent.

Lillis and others (2003) identified a Mancos oil type in Jurassic through Upper Cretaceous sandstone reservoirs in the Uinta and Piceance Basins of northwestern Colorado and eastern Utah, and Finn and Johnson (2005) defined a Hilliard-Baxter-Mancos TPS in the Southwestern Wyoming Province—the Mancos, Hilliard, and Baxter Shales are equivalent in part to the Steele Shale of the Hanna, Laramie, and Shirley Basins Province. These thick shale units represent a lower Campanian sea level highstand in the Western Interior basin (Finn and Johnson, 2005). Mancos oils are characterized by low sulfur and medium API gravity. Bierei (1987) analyzed 34 Steele Shale source rock samples collected in the Hanna Basin; their TOC range was 0.9 to 1.7 wt percent. We analyzed two additional Steele Shale samples that showed 0.69 and 0.91 wt percent TOC (table 5).

Additional potential sources are gas-prone coal and carbonaceous shale in the Mesaverde Group and Medicine Bow, Ferris, and Hanna Formations. The Pine Ridge and Almond Formations of the Mesaverde Group, the lower part of the Medicine Bow Formation, the upper part of the Ferris Formation, and most of the Hanna Formation are coal rich (Gill and others, 1970). Seven persistent coal beds greater than 5 ft thick have been mapped in the Almond Formation in the Hanna Coal Field in the central Hanna Basin (Merewether, 1973). Johnson and others (2005) defined a Mesaverde TPS in the Southwestern Wyoming Province and indicated that coals and organic-rich shales provided both Type II and Type III organic matter and generated both oil and gas. Average TOC values for Mesaverde coals and carbonaceous shales range from 1.3 to 4.9 wt percent from Bierei's (1987) analyses, and from 1.42 to more than 50 wt percent from our analyses (table 5). Mesaverde source rocks are typically gas-prone (Type III) but are also Type II and produce some oil in the region (fig. 28; Johnson and others, 2005).

Medicine Bow coals are limited to the lower 2,600 ft of the formation, and persistent coal beds are less common there than in the other coal-rich formations (Glass and Roberts, 1980). The upper part of the Ferris Formation contains at least 28 persistent coal beds, some of which reach a maximum thickness of 40 ft (Glass and Roberts, 1980). Coal beds are

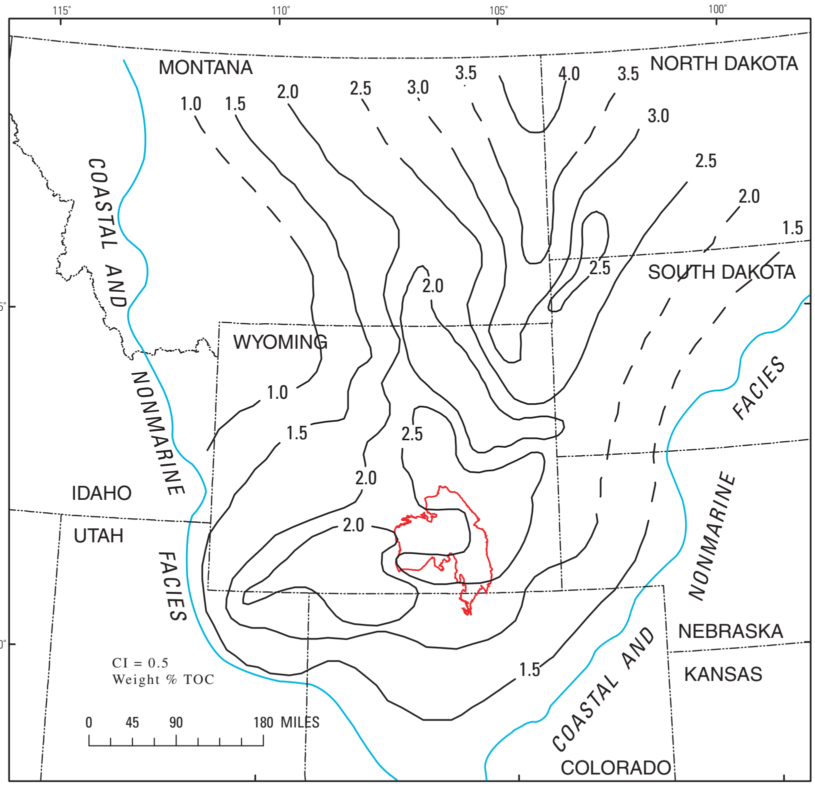

Figure 27. Regional distribution of total organic carbon in the Mowry Shale in the northern Rocky Mountains and Great Plains. CI, contour interval. Simplified from Burtner and Warner (1984). Red outline, Hanna, Laramie, and Shirley Basins Province. Blue line separates coastal and nonmarine facies from marine facies.

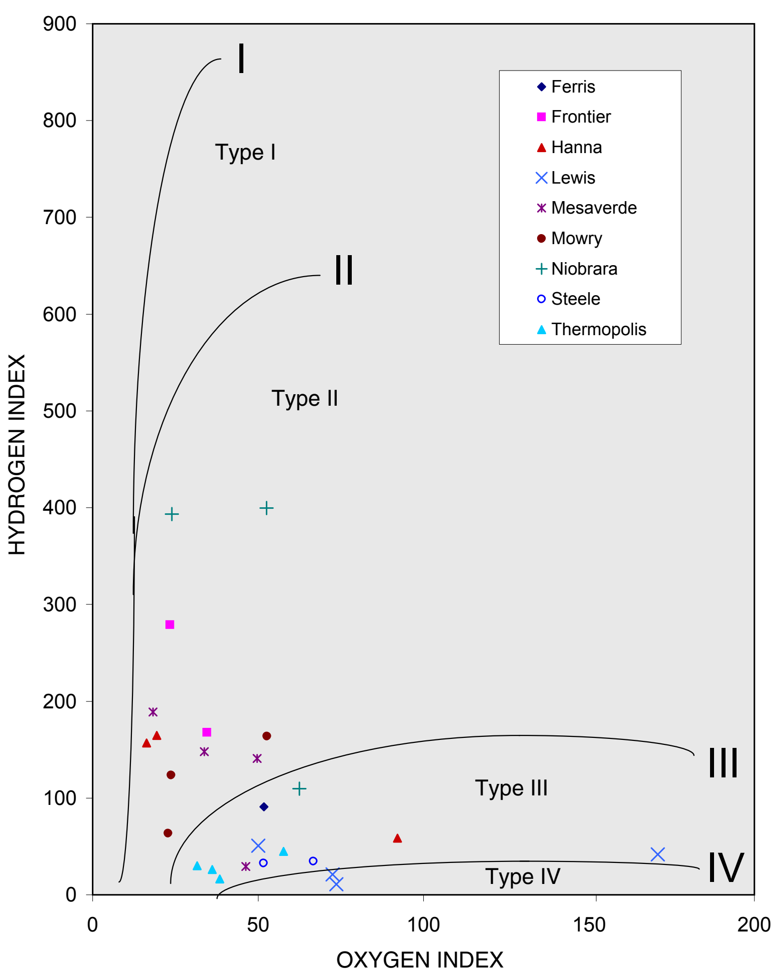

Figure 28. Van Krevelen diagram showing oxygen index versus hydrogen index for samples collected in the Hanna, Laramie, and Shirley Basins Province. Kerogen Type-I and Type-II will generate oil, and Type-III will generate gas; Type-IV will not generate appreciable hydrocarbons. See table 5 for data.

Table 5. Rock-Eval pyrolysis data for samples collected in the Hanna, Laramie, and Shirley Basins Province.

[Rock-Eval analyses of samples were performed by DGSI Laboratories of Houston, Texas. R_O, vitrinite reflectance, in percent; TOC, total organic carbon, in wt percent; S1, free hydrocarbons liberated by volatization at 25°C, in mg hydrocarbon/g rock; S2, hydrocarbons produced by cracking of kerogen, in mg hydrocarbon/g rock; S3, amount of CO_2 produced during pyrolysis up to 390°C, in mg CO_2/g rock; Tmax, maximum temperature of S2 peak; HI, hydrogen index; OI, oxygen index; S1/TOC, in mg HC/g rock; PI, production index; GS, gas source; IM, immature; M, mature, NS, nonsource; OS, oil source]

Sample ID	Formation or Group	R_o, comments	TOC (wt %)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax (°C)	HI	OI	S1/TOC	PI
04035-002	Hanna	IM, NS	5.08	0.16	2.98	4.68	434	59	92	3	0.05
04035-008	Hanna	0.34%, GS	63.03	16.75	98.99	10.28	383	157	16	27	0.14
04035-025	Hanna	0.40%, GS	65.82	9.49	108.41	12.73	397	165	19	14	0.08
04035-007	Ferris	0.46%, GS	43.23	1.76	39.31	22.39	421	91	52	4	0.04
04035-012	Lewis	IM, NS	1.48	0.02	0.16	1.09	431	11	74	1	0.11
04035-013	Lewis	IM, NS	1.09	0.04	0.23	0.79	471	21	72	4	0.15
04035-014	Lewis	GS	17.50	0.25	8.90	8.76	428	51	50	1	0.03
04035-016	Lewis	NS	0.24	0.04	0.10	0.41	488	42	171	17	0.29
04035-001	Mesaverde	0.59%, GS	12.18	1.29	17.18	6.06	425	141	50	11	0.07
04035-009	Mesaverde	IM, GS	1.42	0.13	2.10	0.48	428	148	34	9	0.06
04035-010	Mesaverde	IM, GS	2.25	0.14	4.25	0.41	434	189	18	6	0.03
04035-011	Mesaverde	0.56%, GS	57.13	0.53	16.79	26.47	421	29	46	1	0.03
04035-023	Steele	IM, GS	0.91	0.05	0.30	0.47	439	33	52	5	0.14
04035-024	Steele	IM, GS	0.69	0.03	0.24	0.46	435	35	67	4	0.11
04035-005	Niobrara	IM, GS	1.76	0.05	1.93	1.10	425	110	63	3	0.03
04035-006	Niobrara	IM, OS	2.49	0.20	9.95	1.31	413	400	53	8	0.02
04035-022	Niobrara	0.70%, IM, OS	2.42	1.52	9.52	0.58	432	393	24	63	0.14
04035-003	Frontier	IM, GS	2.52	0.29	7.03	0.59	417	279	23	11	0.04
04035-004	Frontier	IM, GS	1.33	0.11	2.23	0.46	419	168	35	8	0.05
04035-015	Mowry	0.76%, GS	2.66	0.24	4.36	1.40	429	164	53	9	0.05
04035-020	Mowry	M, GS, OS	1.40	0.18	0.89	0.32	440	64	23	13	0.17
04035-021	Mowry	M, GS, OS	1.01	0.39	1.25	0.24	441	124	24	39	0.24
04035-017	Thermopolis	M, GS, OS	1.17	0.05	0.35	0.37	442	30	32	4	0.13
04035-018	Thermopolis	M, GS, OS	1.19	0.06	0.31	0.43	440	26	36	5	0.16
04035-019	Thermopolis	M, NS	0.86	0.01	0.14	0.33	486	16	38	1	0.07
04035-026	Thermopolis	IM, NS	1.23	0.04	0.55	0.71	436	45	58	3	0.07

thickest and most numerous in the Hanna Formation; at least 32 individual beds greater than 5 ft thick have been recognized in the formation in the central part of the Hanna Basin (Glass and Roberts, 1980). Mean TOC values for the Medicine Bow, Ferris, and Hanna (primarily from coal beds) in the Hanna Basin range from 2.4 to 4.2 wt percent; maximum values are as high as 35.6 wt percent (Bierei, 1987). Our Ferris-Hanna samples (n=3) ranged from 5.08 to more than 60 wt percent (table 5).

The Hanna and Ferris Formations contain cyclic sequences of lacustrine and fluvial rocks, individual cycles of which range from 30 to 50 ft thick. Complete cycles contain basal lacustrine mudstones overlain by interbedded coals and fluvial sandstones (Dobbin and others, 1929). Five samples of lacustrine mudstone from the Ferris and Hanna Formations range from 0.95 to 1.75 wt percent TOC (R.M. Matson, unpub. data, 2003).

Source Rock Thermal Maturity

Bierei (1987) calculated thermal maturity models for the Hanna Basin using (1) time-temperature index of maturity (TTI) as described by Lopatin (1971) and Waples (1980), and (2) transformation ratio (TR) after Tissot and Welte (1978). Bierei selected key wells in the central and marginal areas of the Hanna Basin to constrain his models, measured vitrinite reflectance of samples collected in each well, and modeled TTI and TR using selected input parameters. The TTI model calculates the effects of time and temperature on the maturity of organic matter, whereas in the TR model the ratio of hydrocarbons already generated to hydrocarbons still present in the rock is used to interpret the timing and rate of hydrocarbon generation.

The results of Bierei's (1987) TTI basin-center model indicated that (1) the Medicine Bow Formation and older rocks in the Hanna Basin have passed through the oil generation window and are currently overmature with respect to oil generation, and (2) the onset of oil generation in the central part of the basin occurred about 80 Ma for the base of the Cretaceous and that window currently lies in the Ferris Formation. Bierei postulated that large quantities of natural gas have been generated in the deep central Hanna Basin on the basis of this model.

Bierei (1987) constructed his Hanna basin-margin TTI model using a higher geothermal gradient than for his basin-center model, resulting in an interpretation that Cretaceous source rocks in the Steele Shale and Niobrara and Frontier Formations remained in the oil generation window for a much longer time. In his basin-margin model, the Steele Shale has remained in the window for the last 70 m.y. but, in the basin-center model, it passed through the window relatively quickly (74–68 Ma). The Niobrara Formation was in the oil generation window from 78 to 58 Ma on the basin margin and 78–72 Ma in the basin center, and the Frontier was in the window from 82 to 64 Ma on the basin margin and 80 to 73 Ma in the basin center.

Bierei's (1987) basin-center TR model indicated that the Frontier through Steele interval reached maximum oil generation (TR= 0.5) rapidly from about 83 to 74 Ma, the Lewis Shale from about 70 to 69 Ma, and the Ferris Formation from about 57 to 54 Ma (fig. 29*A*). The Hanna Formation, however, has taken about 60 m.y. to reach a transformation ratio of 0.22 in the Hanna Basin center and has not generated significant volumes of oil. This model predicts that the oil generation window is below the base of the Hanna Formation, similar to the prediction of the TTI model for the basin center.

The basin-margin TR model indicates that the maturity of the Lewis Shale in that area is similar to the maturity of the Hanna Formation in the basin center (fig. 29*A*). The Lewis Shale has not had the temperature exposure to form significant volumes of hydrocarbons on the basin margin. However, comparison of figure 29*A*,*B* shows that the Frontier and Niobrara Formations have similar maturation trends in both the basin center and basin margin areas. This model predicts that the oil generation window is below the base of the Lewis Shale and above the base of the Steele Shale, which is also similar to the results of the TTI model for the basin margin (Bierei, 1987).

We compiled one-dimensional burial history models for four wells in the Hanna, Laramie, and Shirley Basins Province (fig. 1) using PetroMod80 1-D Express of Integrated Exploration Systems GmbH (IES) Germany. The wells are presumed to represent the range of thermal variability in the province. The Brinkerhoff Hanna Unit No. 1 and Humble Pass Creek Ridge No. 1 wells were chosen to represent the Hanna Basin center and margin respectively. The Buttes Federal 1–18 and Coastal Bates Creek Cattle 1–18–28–79 wells were chosen because they were drilled in the deepest portions of the Laramie and Shirley Basins and offer the best data from among the few deep wells drilled in these areas. Formation tops were interpreted using published data and well logs, and seismic data were analyzed to estimate formation tops below total depths of these wells. Ages of stratigraphic units were taken from the literature using the 1999 geologic time scale (Obradovich; 1993; Geological Society of America, 1999). Unconformities were also identified from the published literature and verified in the field where recognizable. Thicknesses of eroded rocks were tabulated using our interpretations of times of erosion and erosion rates. The Medicine Bow, Ferris, and Hanna Formations have a combined thickness of thousands of feet. They exhibit considerable facies and thickness differences over distances of only a few miles, their lithologic characteristics are difficult to extrapolate areally and, as a result, their thermal maturity differs from place to place. Data from Meissner (1978), Bierei (1987), IHS (2004b), and Roberts and others (2005) were used to calibrate vitrinite reflectance and heat flow values for the thermal models.

PetroMod results for our study are illustrated in figures 30–33, and input data files are presented in table 6 for the four selected wells listed above. The plots show (1) burial history curves for all four wells, (2) colored overlays of transformation ratios for oil generation for these wells, and (3) a colored overlay of oil-to-gas cracking for the Brinkerhoff well in the Hanna Basin center. In the Brinkerhoff well (fig. 30), Mowry-Thermopolis source rocks reached a TR of 0.5 (50 percent) for oil generation by about 68 Ma; currently, the lower part of the Hanna Formation has a TR of 50 percent and is actively generating oil. Significant oil-to-gas cracking occurred in the Steele Shale by 60 Ma (fig. 31). Currently, the Medicine Bow is actively generating gas from the cracking of oil. In the Pass Creek well on the south Hanna Basin margin (fig. 32), Mowry-Thermopolis source rocks also reached a TR of 50 percent for oil generation by about 68 Ma. Currently, the Steele Shale has a TR of 50 percent and is actively generating oil; no significant gas generation has occurred from the cracking of oil. According to our burial history models, the Laramie and Shirley Basins have not reached the thermal maturity levels required for the generation of significant volumes of oil and gas from any source rock (fig. 33*A*,*B*).

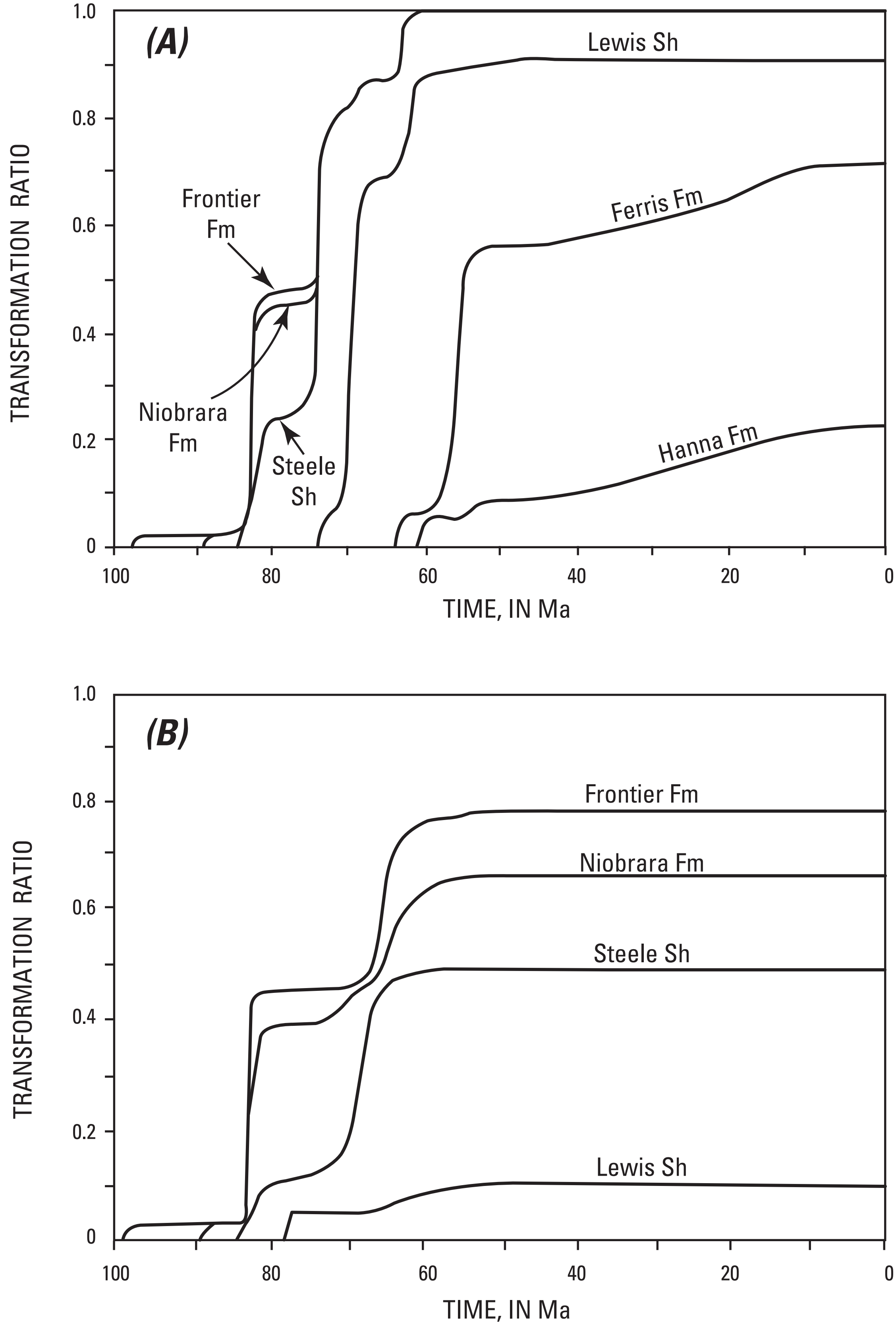

Figure 29. Transformation ratio versus time for the Frontier through Hanna Formations in the Hanna Basin. Data are based on transformation ratio models for Hanna Basin center (*A*) and Hanna Basin margin (*B*) from Bierei (1987). Ma, millions of years before present.

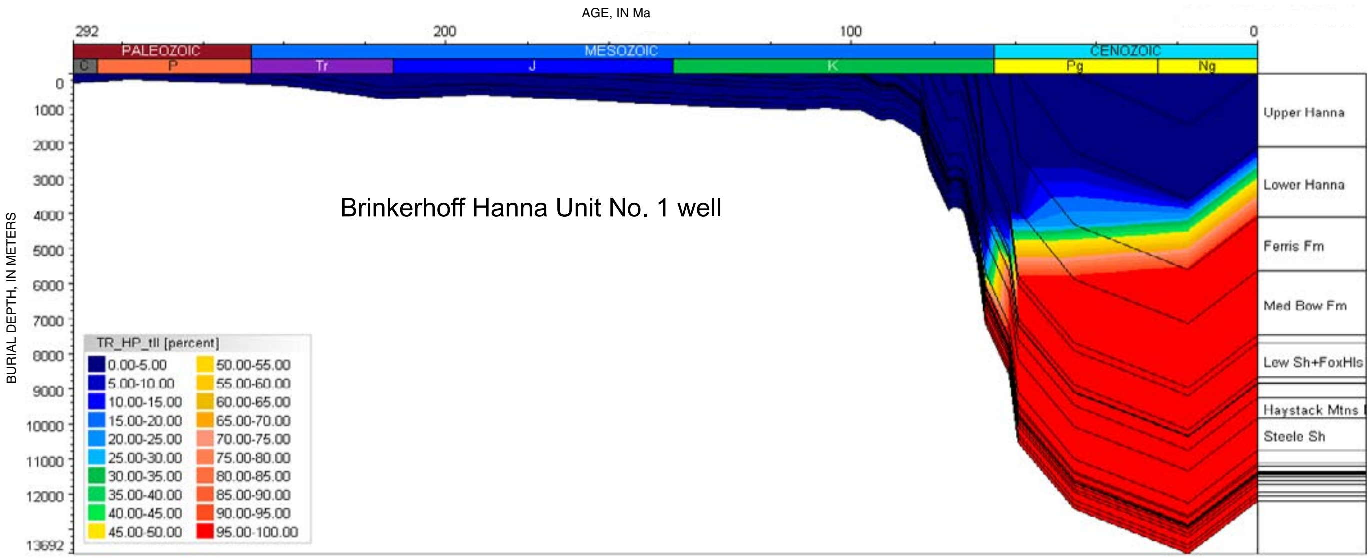

Figure 30. One-dimensional burial history model showing transformation ratio overlay in percent for the generation of oil for the Brinkerhoff Hanna Unit No. 1 well near the Hanna Basin center (see fig. 1 for well location) using PetroMod80 1-D Express of Integrated Exploration Systems GmbH (IES) Germany. Vitrinite reflectance data taken from surface exposures near well site and from Bierei (1987). C, Carboniferous; P, Pennsylvanian-Permian; Tr, Triassic; J, Jurassic; K, Cretaceous; Pg, Paleogene; Ng, Neogene; Fm, formation; Med Bow, Medicine Bow; Lew Sh + Fox Hls, Lewis Shale and Fox Hills; Mtns, Mountains; Sh, Shale; TR_HP_tII (percent), Transformation Ratio in percent, Hydrous pyrolysis kinetics, Type II kerogen.

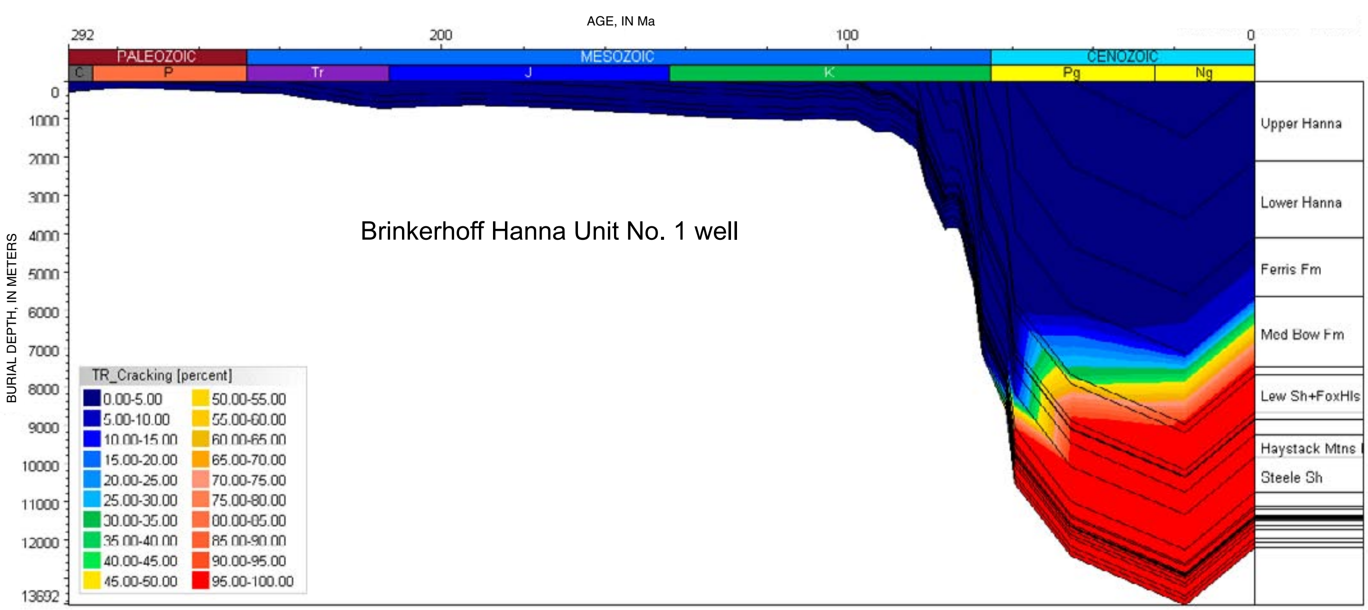

Figure 31. One-dimensional burial history model showing transformation ratio overlay in percent for oil-to-gas cracking for the Brinkerhoff Hanna Unit No. 1 well near the Hanna Basin center (see fig. 1 for well location) using PetroMod80 1-D Express of Integrated Exploration Systems GmbH (IES) Germany. Vitrinite reflectance data taken from surface exposures near well site and from Bierei (1987). C, Carboniferous; P, Pennsylvanian-Permian; Tr, Triassic; J, Jurassic; K, Cretaceous; Pg, Paleogene; Ng, Neogene; Fm, formation; Med Bow, Medicine Bow; Lew Sh + Fox Hls, Lewis Shale and Fox Hills; Mtns, Mountains; Sh, Shale; TR_Cracking (percent), Transformation Ratio, in percent, Cracking of oil to gas.

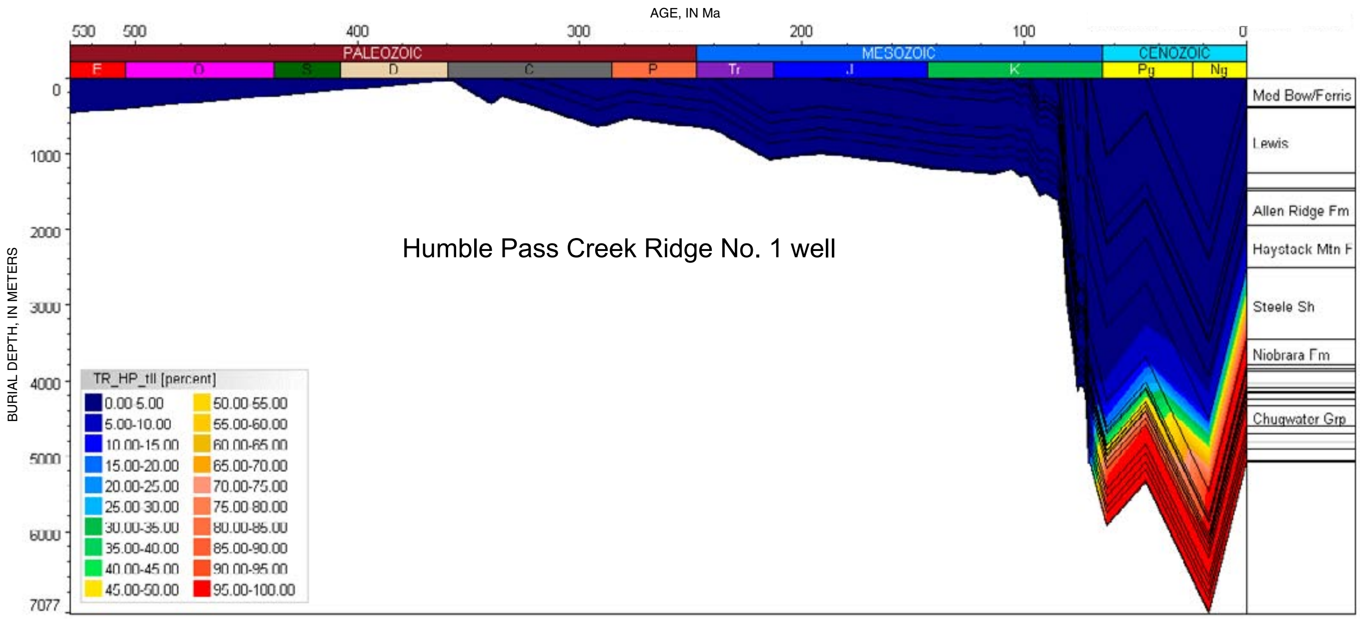

Figure 32. One-dimensional burial history model showing transformation ratio overlay in percent for the generation of oil for the Humble Pass Creek Ridge No. 1 well along the southern margin of Hanna Basin (see fig. 1 for well location) using PetroMod80 1-D Express of Integrated Exploration Systems GmbH (IES) Germany. Vitrinite reflectance data taken from surface exposures near well site and from Bierei (1987). E, Cambrian; O, Ordovician; S, Silurian; D, Devonian; C, Carboniferous; P, Pennsylvanian-Permian; Tr, Triassic; J, Jurassic; K, Cretaceous; Pg, Paleogene; Ng, Neogene; F, formation; Fm, formation; Med Bow, Medicine Bow; Lewis, Lewis Shale; Mtn, Mountains; Sh, Shale, Grp, Group; TR_HP_tII (percent), Transformation Ratio in percent, Hydrous pyrolysis kinetics, Type II kerogen.

A

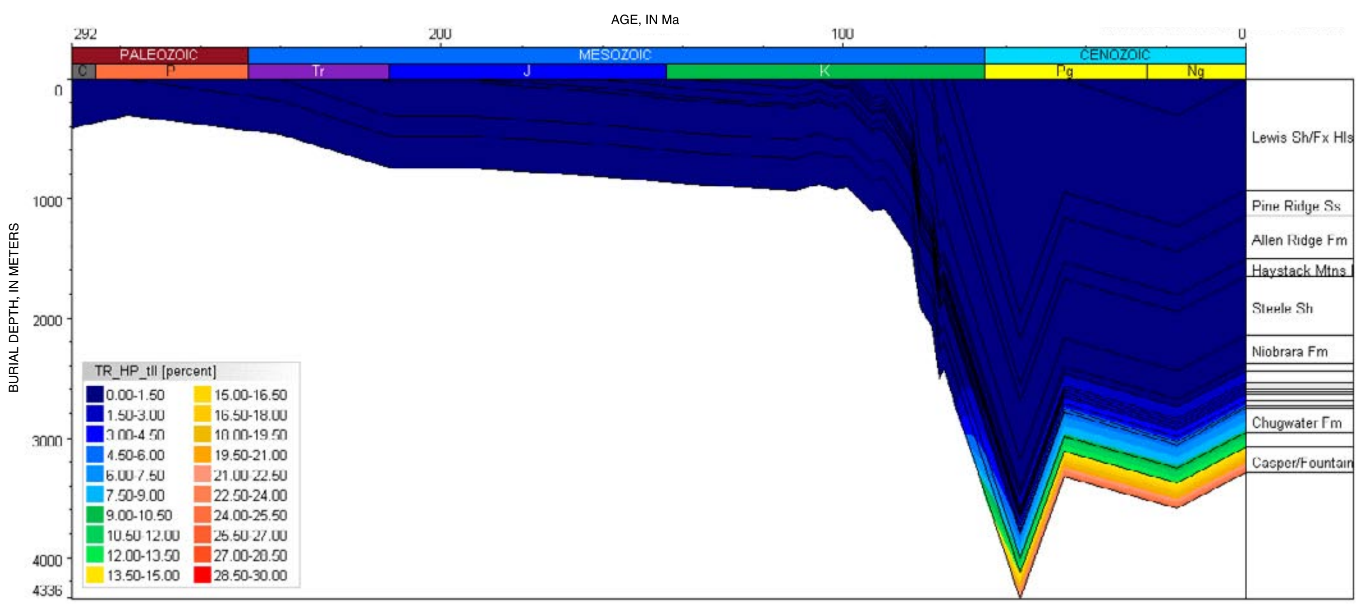

Figure 33 *A*. One-dimensional burial history model showing transformation ratio overlay in percent for the generation of oil using PetroMod80 1-D Express of Integrated Exploration Systems GmbH (IES) Germany. Vitrinite reflectance data taken from Bierei (1987) for south margin of Hanna Basin. *A,* Buttes Federal 1–18 well, Laramie Basin center. See figure 1 for well locations. C, Carboniferous; P, Pennsylvanian-Permian; Tr, Triassic; J, Jurassic; K, Cretaceous; Pg, Paleogene; Ng, Neogene; Lewis Sh/Fx Hls, Lewis Shale and Fox Hills; Ss, Sandstone; Fm, Formation; Mtns, Mountains; Sh, Shale; ChugWtr, Chugwater.

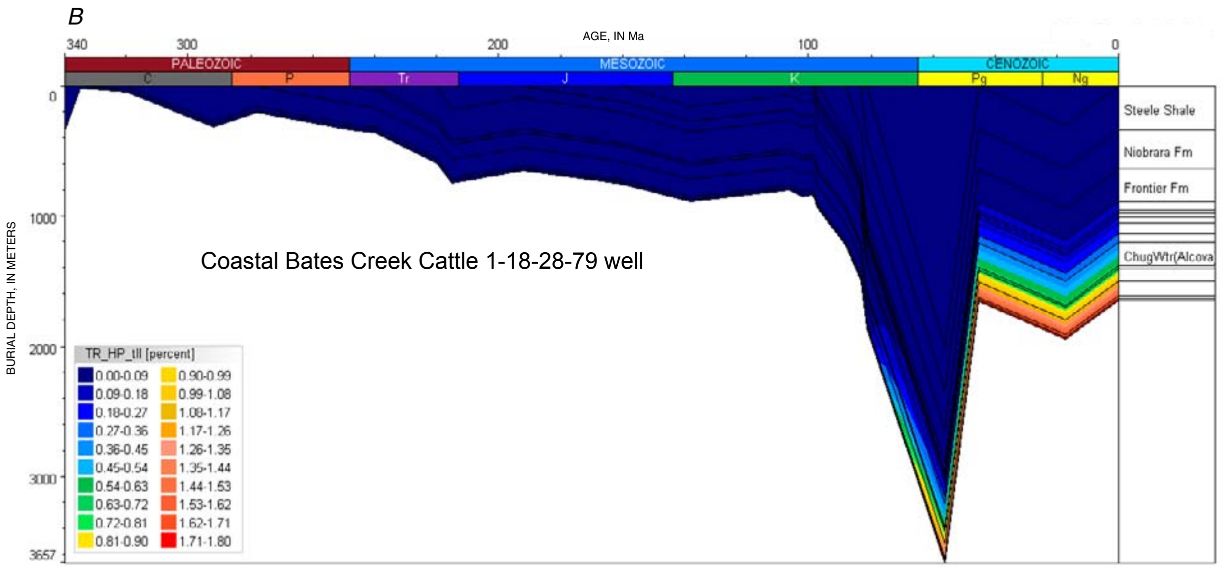

Figure 33 *B*. One-dimensional burial history model showing transformation ratio overlay in percent for the generation of oil using PetroMod80 1-D Express of Integrated Exploration Systems GmbH (IES) Germany. Vitrinite reflectance data taken from Bierei (1987) for south margin of Hanna Basin. *B,* Coastal Bates Creek Cattle 1–18–28–79 well, Shirley Basin center. See figure 1 for well locations. C, Carboniferous; P, Pennsylvanian-Permian; Tr, Triassic; J, Jurassic; K, Cretaceous; Pg, Paleogene; Ng, Neogene; Lewis Sh/Fx Hls, Lewis Shale and Fox Hills; Ss, Sandstone; Fm, Formation; Mtns, Mountains; Sh, Shale; ChugWtr, Chugwater.

Table 6. Burial history of four wells in the Hanna, Laramie, and Shirley Basins Province; data input into the software program PetroMod80 1-D Express of Integrated Exploration Systems GmbH (IES) Germany. Well locations shown on figure 1.

[Formation tops data interpreted from well logs and from seismic data below well total depth. Heat flow constant at 45 milliwatts per m^2. Temperature of sediment-water interface 7°C since 45 Ma and 20°C for 320–45 Ma. Base, base of rock unit; Top, top of rock unit; m, meters; Ma, millions of years before present; Lithology, dominant lithology of rock unit interval; Fm., Formation]

Well name and rock unit	Present depth (m)		Deposited thickness (m)	Eroded thickness (m)	Deposition age (Ma)		Erosion age (Ma)		Lithology
	Base	Top			From	To	From	To	
Brinkerhoff Hanna Unit No. 1 well									
Tertiary rocks	0	0	0	1,500	45	17	17	0	Siltstone.
Upper Hanna Formation	0	2,105	2,105	-	59	45	-	-	Siltstone/shale.
Lower Hanna Formation	2,105	4,117	2,012	-	61	59	-	-	Siltstone.
Ferris Formation	4,117	5,647	1,530	-	67	61	-	-	Siltstone.
Medicine Bow Formation	5,647	7,475	1,828	-	69	67	-	-	Sandstone.
Fox Hills Sandstone	7,475	7,689	214	-	70	69	-	-	Sandstone.
Lewis Shale + Fox Hills Sandstone	7,689	8,665	976	-	72	70	-	-	Shale/sandstone.
Almond Formation	8,665	8,847	182	-	73	72	-	-	Siltstone.
Pine Ridge Sandstone	8,847	8,873	26	-	75	73	-	-	Sandstone.
Allen Ridge Formation	8,873	9,244	371	61	78	76	76	75	Sandstone.
Haystack Mountains Fm.	9,244	9,848	604	-	81	78	-	-	Sandstone.
Steele Shale	9,848	10,763	915	-	83	81	-	-	Shale.
Niobrara Formation	10,763	11,129	366	-	88	83	-	-	Shale.
Upper Frontier Formation	11,129	11,190	61	-	90	88	-	-	Sandstone.
Lower Frontier Formation	11,190	11,372	182	15	97	93	93	90	Sandstone.
Mowry Shale	11,372	11,409	37	-	98	97	-	-	Shale.
Muddy Sandstone	11,409	11,427	18	-	99	98	-	-	Sandstone.
Lower Thermopolis Shale	11,427	11,453	26	9	106	102	102	99	Siltstone.
Cloverly Sandstone	11,453	11,514	61	30	138	113	113	106	Sandstone.
Morrison Formation	11,514	11,628	114	-	160	138	-	-	Sandstone.
Sundance Formation	11,628	11,735	107	-	192	160	-	-	Sandstone.
Chugwater Group	11,735	11,948	213	61	240	215	215	192	Sandstone.
Goose Egg Formation	11,948	12,070	122	-	278	240	-	-	Sandstone.
Tensleep Sandstone	12,070	12,192	122	76	320	292	292	278	Sandstone.

Table 6. Burial history of four wells in the Hanna, Laramie, and Shirley Basins Province; data input into the software program Petro-Mod80 1-D Express of Integrated Exploration Systems GmbH (IES) Germany. Well locations shown on figure 1.—Continued

[Formation tops data interpreted from well logs and from seismic data below well total depth. Heat flow constant at 45 milliwatts per m^2. Temperature of sediment-water interface 7°C since 45 Ma and 20°C for 320–45 Ma. Base, base of rock unit; Top, top of rock unit; m, meters; Ma, millions of years before present; Lithology, dominant lithology of rock unit interval; Fm., Formation]

Well name and rock unit	Present depth (m)		Deposited thickness (m)	Eroded thickness (m)	Deposition age (Ma)		Erosion age (Ma)		Lithology
	Base	Top			From	To	From	To	
Humble Pass Creek Ridge No. 1 well									
Tertiary rocks	0	0	0	2,000	45	17	17	0	Siltstone.
Medicine Bow Formation/ Ferris Formation	0	376	376	500	70	63	63	45	Siltstone.
Fox Hills Sandstone	376	400	24	-	71	70	-	-	Siltstone.
Lewis Shale	400	1,258	858	-	72	71	-	-	Shale.
Almond Formation	1,258	1,453	195	-	73	72	-	-	Sandstone.
Pine Ridge Sandstone	1,453	1,483	30	-	75	73	-	-	Sandstone.
Allen Ridge Formation	1,483	1,952	469	61	78	76	76	75	Sandstone.
Haystack Mountains Fm.	1,952	2,506	554	-	81	78	-	-	Sandstone.
Steele Shale	2,506	3,457	951	-	83	81	-	-	Shale.
Niobrara Formation	3,457	3,784	327	-	85	83	-	-	Sandstone.
Carlile Shale	3,784	3,848	64	-	88	85	-	-	Shale.
Upper Frontier Formation	3,848	3,877	29	-	90	88	-	-	Siltstone.
Lower Frontier Formation	3,877	4,031	154	15	97	93	93	90	Siltstone.
Mowry Shale	4,031	4,088	57	-	98	97	-	-	Shale.
Muddy Sandstone	4,088	4,098	10	-	99	98	-	-	Sandstone.
Thermopolis Shale	4,098	4,149	51	9	106	102	102	99	Shale.
Dakota Sandstone	4,149	4,169	20	30	138	113	113	106	Sandstone.
Morrison Formation	4,169	4,248	79	-	160	138	-	-	Siltstone.
Sundance Formation	4,248	4,331	83	-	192	160	-	-	Sandstone.
Chugwater Group	4,331	4,591	260	61	240	215	215	192	Sandstone.
Goose Egg Formation	4,591	4,693	102	-	278	240	-	-	Sandstone.
Tensleep Sandstone	4,693	4,813	120	76	320	292	292	278	Sandstone.
Amsden Formation	4,813	4,904	91	-	335	320	-	-	Sandstone.
Madison Formation	4,904	5,057	153	61	358	340	340	335	Sandstone.
Flathead Formation	5,057	5,077	20	305	540	530	530	358	Sandstone.

Well name and rock unit	Present depth (m)		Deposited thickness (m)	Eroded thickness (m)	Deposition age (Ma)		Erosion age (Ma)		Lithology
	Base	Top			From	To	From	To	
Buttes Federal No. 1–18 well									
Tertiary rocks	0	0	0	300	45	17	17	0	Siltstone.
Lewis Shale/ Fox Hills Sandstone.	0	930	930	1,000	73	56	56	45	Shale.
Pine Ridge Sandstone	930	1,138	208	-	75	73	-	-	Sandstone.
Allen Ridge Formation	1,138	1,504	366	61	78	76	76	75	Siltstone.
Haystack Mountains Fm.	1,504	1,646	142	-	81	78	-	-	Siltstone.
Steele Shale	1,646	2,134	488	-	83	81	-	-	Shale.
Niobrara Formation	2,134	2,377	243	-	88	83	-	-	Siltstone.
Upper Frontier Formation	2,377	2,438	61	-	90	88	-	-	Siltstone.
Lower Frontier Formation	2,438	2,530	92	15	97	93	93	90	Siltstone.
Mowry Shale	2,530	2,560	30	-	98	97	-	-	Shale.
Muddy Sandstone	2,560	2,585	25	-	99	98	-	-	Sandstone.
Dakota Formation	2,585	2,615	30	9	106	102	102	99	Sandstone.
Cloverly Formation	2,615	2,627	12	30	138	112	112	106	Siltstone.
Morrison Formation	2,627	2,682	55	-	160	138	-	-	Shale.
Sundance Formation	2,682	2,728	46	-	192	160	-	-	Siltstone.
Nugget Sandstone/Jelm Fm.	2,728	2,749	21	-	215	212	212	192	Sandstone.
Chugwater Formation	2,749	2,950	201	-	240	215	-	-	Sandstone.
Goose Egg Formation	2,950	3,072	122	-	278	240	-	-	Sandstone.
Casper Formation/ Fountain Formation.	3,072	3,286	214	76	320	292	292	278	Sandstone.

Table 6. Burial history of four wells in the Hanna, Laramie, and Shirley Basins Province; data input into the software program PetroMod80 1-D Express of Integrated Exploration Systems GmbH (IES) Germany. Well locations shown on figure 1.—Continued

[Formation tops data interpreted from well logs and from seismic data below well total depth. Heat flow constant at 45 milliwatts per m^2. Temperature of sediment-water interface 7°C since 45 Ma and 20°C for 320–45 Ma. Base, base of rock unit; Top, top of rock unit; m, meters; Ma, millions of years before present; Lithology, dominant lithology of rock unit interval; Fm., Formation]

Well name and rock unit	Present depth (m)		Deposited thickness (m)	Eroded thickness (m)	Deposition age (Ma)		Erosion age (Ma)		Lithology
	Base	Top			From	To	From	To	
Buttes Federal No. 1–18 well									
Tertiary rocks	0	0	0	300	45	17	17	0	Siltstone.
Mesaverde Group/ Hanna Formation.	0	0	0	2,000	81	56	56	45	Siltstone.
Steele Shale	0	335	335	-	83	81	-	-	Shale.
Niobrara Formation	335	639	304	-	88	83	-	-	Limestone.
Frontier Formation	639	889	250	-	97	88	-	-	Siltstone.
Mowry Shale	889	952	63	-	98	97	-	-	Shale.
Muddy Sandstone	952	979	27	-	99	98	-	-	Sandstone.
Thermopolis Shale	979	1,007	28	9	106	102	102	99	Shale.
Morrison Formation	1,007	1,052	45	61	160	138	138	106	Siltstone.
Sundance Formation	1,052	1,137	85	-	192	160	-	-	Sandstone.
Jelm Formation	1,137	1,199	62	61	220	215	215	192	Siltstone.
Chugwater Group	1,199	1,380	181	-	240	220	-	-	Sandstone.
Dinwoody Formation	1,380	1,401	21	-	248	240	-	-	Sandstone.
Phosphoria Formation	1,401	1,496	95	-	278	248	-	-	Shale.
Tensleep Sandstone	1,496	1,609	113	76	320	292	292	278	Sandstone.
Amsden Formation	1,609	1,628	19	-	330	320	-	-	Sandstone.
Madison Formation	1,628	1,643	15	274	358	340	340	335	Limestone.

Hydrocarbon Migration

We support a primarily Paleocene age for migration of Cretaceous-derived oil. On the basis of the results of burial history analyses, oil and gas migrated into Jurassic-Cretaceous reservoirs in the Laramie Basin from the Hanna Basin prior to Laramide basin partitioning in the latest Paleocene to early Eocene (55 Ma) when fluid-flow barriers developed. Sandstones of the Cloverly, Muddy (Thermopolis), Wall Creek (Frontier), Mesaverde, Lewis, and Medicine Bow are considered the major carrier beds for Cretaceous-derived oil in the province. Fluid movement resulted in updip migration from the deeper parts to the margins of the Hanna Basin and into the Laramie Basin. Because the Hanna and Laramie Basins were not separated structurally until the late Paleocene, adequate time was available for oil to migrate from the Hanna into the Laramie Basin. Sequence-boundary disconformities, bedding planes, permeable sandstones, faults, and fractures within the reservoirs were potential migration pathways.

Natural gas is thought to have been generated primarily by the cracking of Cretaceous oil in the Hanna Basin center, but only two small gas fields, Oil Springs and Allen Lake East in the northern part of the Laramie Basin (fig. 20), have been discovered. A possible explanation for the occurrence of gas only in that area may be that basin partitioning started in the south and migrated northward during Laramide deformation.

Some oil might have initially accumulated in stratigraphic traps formed by updip facies pinchouts prior to Laramide structural development. Facies variations in Muddy, Mesaverde, Medicine Bow, and Ferris reservoirs resulted in some early potential stratigraphic traps. Later remigration may have taken place during the Laramide orogeny in some structurally trapped fields such as Rock River and Rex Lake where facies control has been identified in traps. For continuous basin-center gas in the central Hanna Basin, migration distances were short. Remigration of oil during the Laramide required at least some fault pathways, as opposed to fractures alone, because thick Cretaceous shales would have inhibited propagation of fractures through the entire sedimentary section.

Reservoir Rocks

Sundance Formation

The Sundance Formation produces oil and gas from two separate sandstone reservoirs termed “first” and “second” sandstones in at least eight fields in the Laramie Basin (Hollis and Potter, 1984). Facies variations and reservoir quality vary greatly within the Hanna, Laramie and Shirley Basins. The “first” sandstone or “upper Sundance” (fig. 2) is developed only locally in the northern part of the Laramie Basin, where it has been identified at Big Medicine Bow field. There, the unit is fine grained, interbedded with greenish-gray shale, and about 50 ft thick; it grades laterally into a green calcareous shale elsewhere in the basin (Stone, 1966). The “second” sandstone or “lower Sundance” (fig. 2) is more widely distributed than the “first” sandstone, is relatively uniform in thickness, and averages about 50 ft thick. In the Shirley Basin, the Sundance is about 250 ft thick and includes three mappable sandstone units (Harshman, 1972), none of which is currently productive.

Favorable porosity and permeability from field measurements indicates that reservoir sandstones underwent dissolution late in their burial history, thus improving reservoir quality. In known fields of the Laramie Basin, Sundance Formation porosities reach 24 percent and permeabilities reach 800 mD (Hollis and Potter, 1984).

Cloverly Formation

The Cloverly Formation in the Hanna, Laramie, and Shirley Basins Province can be locally subdivided into lower and upper sandstone units and a middle shale; these correlate with the Lakota Formation, Fall River Sandstone, and Fuson Shale, respectively, in the Black Hills region of northeastern Wyoming (Montana Geological Society, 1969). In much of the Laramie Basin, however, these units are not easily subdivided on geophysical logs (Stone, 1966). The lower and upper sandstone units are calcareous, locally conglomeratic, and are each about 75 ft thick (Dobbin and others, 1929). At Oil Springs field in the northern part of the Laramie Basin, three separate sandstone units were identified by Stone (1966): (1) a basal fluvial channel-fill sandstone that unconformably overlies the Morrison Formation, (2) a middle sandstone (undescribed), and (3) an upper sandstone deposited as a shallow marine transgressive deposit. In the Shirley Basin, the typical three-part Cloverly subdivision (sandstone, shale, sandstone) can be identified; total sandstone thickness is 130 ft (Harshman, 1972).

Interpretations of porosity and permeability data from field measurements indicate that lower Cloverly sandstones exhibit higher average porosity than upper sandstones (Stone, 1966). In known fields of the Laramie Basin, Cloverly Formation porosities average 15 percent and permeabilities average 90 mD (Hollis and Potter, 1984).

Muddy Sandstone Member of Thermopolis Shale

The Muddy Sandstone Member produces in Rock River, Dutton Creek, Cooper Cove, Diamond Ranch, and Seven Mile fields in the western part of the Laramie Basin (fig. 20; Stone, 1966). The Muddy depositional system is complex, consisting of (1) a basal unit of regressive marine sandstones, (2) variable valley-fill sequences of fluvial to marine sandstones and shale, and (3) an upper unit of transgressive marine sandstones (Dolson and others, 1991). A relative sea-level lowstand during the Albian created an incised drainage system at the top of the basal regressive sandstones. Later, a rise in sea level resulted in back filling of the incised valleys and deposition of the valley-fill sequences. Continued sea level rise resulted in deposition of the upper transgressive sandstones (Dolson and others, 1991). Within the Laramie Basin, the middle valley-fill sequence trends southeastward in a zone not exceeding 0.5 mi in width. In the eastern part of the basin, the Muddy averages 35 ft thick. At Big Medicine Bow South field in the northernmost part of the basin (fig. 20), subsurface data suggests that the Muddy may be as much as 50 ft thick; Hollis and Potter (1984) described a 10-ft-thick pay zone there. In the Shirley Basin, the Muddy is a 14-ft-thick unit of thin-bedded silty sandstone (Harshman, 1972), but in other areas of the province sandstone development in the member is not well defined owing to a lack of well control.

Interpretations of porosity and permeability data from field measurements indicate that the best reservoir sandstones are found where fluvial channel systems are best developed. Diagenesis of Muddy sandstones in the form of authigenic clay pore fillings and secondary cements probably plays an important role in reservoir quality, but data are sparse. In known fields of the Laramie Basin, Muddy Sandstone Member porosities average 16 percent and permeabilities average 26 mD (Hollis and Potter, 1984).

Frontier Formation

The Frontier Formation is a progradational clastic wedge of Cenomanian and Turonian age enclosed between a thick package of marine shales of the underlying Mowry Shale and overlying Steele Shale (Bhattacharya and Willis, 2001). In the Hanna, Laramie, and Shirley Basins Province, Frontier sandstone reservoirs are, from oldest to youngest, the Belle Fourche, Emigrant Gap, and Wall Creek Sandstone Members (Merewether and Cobban, 1972), all bounded by unconformities and deposited in marine environments. Regionally, oil and gas reservoirs include the upper Belle Fourche and Wall Creek Sandstone Members (Bhattacharya and Willis, 2001). At Rock River and Big Medicine Bow fields in the northern part of the Laramie Basin, Frontier Formation production is limited to reservoirs in the Wall Creek Sandstone Member (Stone, 1966), which are fine to very fine grained, silty, shaly, and irregularly bedded. In the Shirley Basin, Harshman (1972) described the Wall Creek Sandstone Member as a 110-ft-thick unit of fine- to coarse-grained, well-cemented sandstone.

At Rock River field, the average net pay thickness of the Wall Creek is 10 ft (Hollis and Potter, 1984). Along the Rawlins uplift in the western part of the Hanna Basin, the member is 350 ft thick and averages about 63 percent sandstone, 23 percent siltstone, and 14 percent shale (Barlow, 1959; Merewether and Cobban, 1972). The Wall Creek thins to the east and south in the province.

In the best reservoir sandstones, burrowing has not disrupted the original bedding; within intervals of extensive bioturbation, sandstones are tight and of poor reservoir quality. Diagenesis of Frontier sandstones—such as authigenic clay pore fillings and secondary cements—probably also plays an important role in reservoir development, although limited data are available. Wall Creek sandstone porosity averages 12 percent at Rock River field; permeability data are unavailable (Hollis and Potter, 1984).

Mesaverde Group

The Mesaverde Group was deposited in two distinct depositional sequences associated with transgressive-regressive cycles during the Campanian (Martinsen and others, 1993). In the Hanna, Laramie, and Shirley Basins Province, Mesaverde strata are primarily marine and are subdivided into four formations, from oldest to youngest the Haystack Mountains Formation, the Allen Ridge Formation, the Pine Ridge Sandstone, and the Almond Formation (Martinsen and others, 1993). All contain potential reservoirs, but the Haystack Mountains and Almond Formations have the greatest potential.

In the Hanna Basin, the Haystack Mountains Formation is lithologically diverse and contains marine sandstones and minor interbedded shales separated into eight sandstone-rich members. The sandstones are fine to very fine grained, silty, shaly, and irregularly bedded (Gill and others, 1970). Individual units thin to the east in the Laramie Basin and grade into the Steele Shale. The name “Shannon” is used for sandstones in the upper part of the Steele Shale in the Laramie Basin that are time-equivalent to the Haystack Mountains Formation of the Hanna Basin (Stone, 1966); the name “Quealy sand” has also been used in the western Laramie Basin for productive Steele reservoirs. These sandstones may be offshore bars encased in marine shales or may be channeled delta-front sandstones associated with eastward-thinning transgressive-regressive wedges derived from the west (Stone, 1966).

Sandstone reservoirs of the Haystack Mountains Formation have been identified at Simpson Ridge, Diamond Dome, and Medicine Bow fields in the Laramie Basin, and at Horseshoe Ridge field in the northern part of the Hanna Basin (fig. 20; Hollis and Potter, 1984). At Diamond Dome field, the average net pay thickness of the Shannon sandstone is 33 ft and the porosity and permeability average 21 percent and 70 mD, respectively. At Simpson Ridge field, porosity and permeability of the Quealy sand are characterized as “low” (Hollis and Potter, 1984). At Horseshoe Ridge, drill-stem test data indicate gas shows in the Hatfield Sandstone Member of the Haystack Mountains Formation, in the Almond Formation, and in the overlying Lewis Shale, although Horseshoe Ridge field has no history of sustained production (R.M. Matson, unpub. data, 2003).

Almond sandstones are productive in the Southwestern Wyoming Province to the west (Johnson and others, 2005), but they have no history of sustained production in the Hanna Basin. Almond sandstones were deposited in a progradational fluvial to shallow marine depositional environment as fluvial channels and barrier bars (Gill and others, 1970). Net sandstone thickness increases upward in the Almond in the Hanna Basin; the Almond is not recognized in the Laramie Basin. R.M. Matson, (unpub. data, 2003) reported gas shows in the upper Mesaverde Group, including the Almond interval, on the basis of well-log shows in the 11,000- to 12,000-ft interval at the Internorth 1–25 Seminoe Unit well at Horseshoe Ridge in the northern Hanna Basin (fig. 20). Anadarko Petroleum drilled a Mesaverde exploratory well in the central Hanna Basin in 2004 (fig. 20), the Durante 17–2 well, which was abandoned at 19,700 ft in the Mesaverde. This well had gas shows in the Almond and Allen Ridge Formations (Thomas Griffith, Anadarko Petroleum, written commun., 2005).

Lewis Shale

The Lewis Shale was deposited in marine shelf, delta front, and basin-floor fan environments that were associated with regional tectonics during the Maastrichtian Bearpaw transgressive-regressive cycle (Gill and others, 1970; Asquith, 1974; Winn and others, 1987; Hettinger and Roberts, 2005; Pasternack, 2005). In the Hanna and Laramie Basins, the Lewis is primarily marine and is subdivided into lower and upper shaly units and a middle unit of sandstone called the Dad Sandstone Member (Gill and others, 1970). Most petroleum reservoirs in the Lewis in the Southwestern Wyoming Province are in the Dad Sandstone Member (Law, 1996; Hettinger and Roberts, 2005). In the Hanna, Laramie, and Shirley Basins Province the Dad Sandstone Member contains interbedded sandstone and shale and ranges in thickness from 300 to 700 ft. It represents sediment influx associated with uplift in central Wyoming (Gill and others, 1970; Hettinger and Roberts, 2005).

Sandstones throughout the Lewis Shale are potential reservoirs in the Hanna and Laramie Basins, but no sustained production has been identified in the province. Sandstone cumulative thickness in the Southwestern Wyoming Province ranges from 200 to 600 ft (Law and others, 1989). Steinhoff and others (2001) recognized more than 20 parasequences and 50 to 60 individual sandstone lobes in the Lewis–Fox Hills depositional system in the Greater Green River Basin. In the Hanna and Laramie Basins, Lewis sandstones are fine to medium grained and are interbedded with shale and siltstone. Sandstones are burrowed in many places with *Ophiomorpha*, are thin bedded to massive (Gill and others, 1970), and form coarsening-upward parasequences a few hundreds of feet thick (fig. 16).

Sandstone reservoirs of the lower Lewis were targeted by two wells drilled in the early 1980s in the northern part of the Hanna Basin at Horseshoe Ridge by HBV Associates (fig. 20; R.M. Matson, unpub. data, 2003). Both wells flowed gas at commercial rates within the 10,000- to 13,000-ft interval.

One of the wells (Internorth 1–30 Seminoe Unit) flowed gas at 1.2–3.2 MMCF per day from an overpressured sandstone interval at a depth of about 11,800 ft.

Medicine Bow, Ferris, and Hanna Formations

The Medicine Bow, Ferris, and Hanna Formations were deposited in a rapidly subsiding structural basin during and after the final withdrawal of the Western Interior Cretaceous seaway in south-central Wyoming. The Hanna Basin acted as a sediment trap during the latest Cretaceous and Paleocene, resulting in a maximum combined thickness of more than 20,000 ft for the three formations. The sequence consists of clastic rocks—sandstone, conglomerate, shale, mudstone, and coal—deposited in fluvial-deltaic, lacustrine, and coastal environments (Wroblewski, 2002). On the basis of sedimentologic and biostratigraphic work by Wroblewski (2002, 2003) and Lillegraven and others (2004), the Hanna, Laramie, and Shirley Basins were not partitioned into separate structural basins and separated from the Green River Basin until latest Paleocene or early Eocene time. The Ferris and Hanna Formations are dominated by 30- to 50-ft thick fluvial-lacustrine cycles having oil-prone source rocks and sandstone reservoirs (R.M. Matson, unpub. data, 2003). The greatest reservoir potential lies in the deep northern part of the Hanna Basin where thermally mature coaly source rocks and fluvial-lacustrine reservoir rocks are in proximity.

In the Hanna Basin, the Ferris-Hanna depositional system is represented by a through-flowing eastward-directed paleodrainage system of primarily fine-grained strata. Tributary streams flowed from source areas north and south of the province into the trough of the depositional basin and then eastward. Sandstone reservoirs are laterally discontinuous and encased in lacustrine shales and mudstones. The sandstones are sedimentologically heterogeneous and exhibit variable sedimentary structures. They have erosive bases, are conglomeratic in many places, grade from coarse to fine upward, and are massively bedded to crossbedded.

Traps and Seals

Hydrocarbon traps in the Mowry-Hanna Composite TPS are stratigraphic, structural, and combination structural-stratigraphic traps. Stratigraphic traps formed from lateral pinchouts of reservoir sandstones into finer grained mudrocks, by truncation of reservoirs beneath disconformities, and by the interbedding of shallow marine sandstones with mudrocks. Stratigraphic traps are especially important in laterally discontinuous sandstones of the upper Sundance Formation, Muddy Sandstone Member of the Thermopolis Shale, Mesaverde Group, and Medicine Bow, Ferris, and Hanna Formations. Lewis basin-floor turbidite sandstones are encased in marine shales. Many traps were originally stratigraphic prior to Laramide deformation, and they later became structural traps because of migration of oil or gas into newly formed structures in the latest Cretaceous and Paleocene. For Paleocene fluvial sandstone reservoirs in the Ferris and Hanna Formations, Laramide structural traps developed prior to oil maturation.

Dolson and others (1991) described a regional example of stratigraphic control on trapping mechanisms for the Muddy Sandstone Member in the Rocky Mountain region. They identified Muddy depositional trends typical of reservoir facies, such as paleohills of older marine sandstones, younger valley fills, and associated fluvial channel sandstones. Lithologic changes related to variations in fluvial facies, which strongly influence the permeability of reservoirs and affect fluid flow, increase the potential for reservoir compartmentalization in the Muddy, particularly where traps are enhanced by structure. Muddy production is restricted to the western part of the Laramie Basin in a north-south area of favorable Muddy sandstone development (Stone, 1966).

Stratigraphic traps may be significant in overlying marine sandstones of the Frontier Formation, Steele Shale, Mesaverde Group, and Lewis Shale. Marine-shelf, basin-floor, and deltaic sandstones are characterized by lateral facies changes and reservoir compartmentalization, especially where structures play a subordinate role in trapping. Reservoir development was influenced by tectonics in sandstones of the Lewis Shale, as early Laramide uplifts contributed clastic sediments to the marine shelf, and variable subsidence rates affected the distribution of facies (Winn and others, 1987).

Stone (2005) documented the geologic complexity of Cooper Cove and Dutton Creek oil fields in the western Laramie Basin. Several structures in the Hanna Basin include shallow out-of-basin thrusts rooted within the sedimentary section in Cretaceous shales, and basin-directed basement thrust faults. Episodic movement along these faults created triangle zones of opposing fault geometries (Erslev, 1991; Lillegraven and others, 2004). Brown (1984) discussed the origin of these basin-margin structures as volumetric adjustments. Blackstone (1993) described this as “flexural slip deformation” of a thick sedimentary section around the Hanna Basin margin and identified several examples at Pass Creek Ridge, St. Mary’s Ridge, and Simpson Ridge anticlines (fig. 3).

Reservoir seals in the Mowry-Hanna Composite TPS consist of levee and overbank mudrocks, marginal-marine swamp and lagoon fine-grained strata, evaporites, and marine shales. Thick marine shales are interbedded with reservoirs, so that vertical sequences of stacked reservoirs, traps, and seals were formed. Marine shale seals are especially important where thick shales have isolated shelf and basin-floor sandstones. Lacustrine mudstones may form major seals associated with fluvial sandstone reservoirs in the Ferris and Hanna Formations. In some areas, diagenesis of Jurassic-Cretaceous reservoir rocks resulted in tightly cemented zones that may also act as local seals. Structural seals are important in the Mowry-Hanna Composite TPS where fault movements place impermeable rocks in contact with reservoirs.

Mesozoic-Cenozoic Conventional Oil and Gas Assessment Unit (50300201)

The Mesozoic-Cenozoic Conventional Oil and Gas AU occupies an irregularly shaped area that encompasses most of the Hanna, Laramie, and Shirley Basins Province. The AU boundary is based on the distribution of Sundance through Hanna source and reservoir rocks and contains approximately 3 million acres (fig. 34). It contains Laramide structural features that have become traps for locally derived oil. The deep interior portion of the Hanna Basin lies within the AU. Although the deeper reservoirs of Jurassic and Early Cretaceous age may be thermally overmature, Upper Cretaceous and Tertiary Hanna Formation reservoirs are currently in the oil and gas generation windows. Earliest significant oil production in the province was from Sundance through Frontier reservoirs at Rock River field, discovered in the Laramie Basin in 1918 (table 3). Four other fields with Sundance through Frontier reservoirs—Dutton Creek, Big Medicine Bow, Quealy, and Rex Lake—were discovered prior to the mid-1930s and continue to produce today. The AU is considered mature with respect to drilling for oil and gas.

Production in the AU is limited to the Laramie Basin. Drilling depths to formation tops range from 150 to more than 15,000 ft for the Sundance Formation and from 12 to more than 4,200 ft for the Hanna Formation (table 4). To date, there have been more than 68 MMBO and nearly 24 BCFG produced from Jurassic and Cretaceous reservoirs in the AU (table 3; IHS Energy Group, 2004a). Most wells are classified as oil and produce only minor amounts of associated gas.

Estimated Resources

The Mesozoic-Cenozoic Conventional Oil and Gas AU is considered frontier on the basis of the small number of field discoveries (9 oil and 2 gas) that equal or exceed the minimum accumulation size of 0.5 MMBOE (see Klett and Le, 2007 (this CD-ROM)). The median size of previously discovered oil and gas accumulations, when divided into halves (by initial date of production) is 5.2 and 1.0 MMBO and 5.1 and 15.2 BCFG (Klett and Le, 2007 (this CD-ROM)), indicating a decrease in discovered oil accumulation size and an increase in gas accumulation size through time. Conditions were deemed favorable for the AU to contain one or more undiscovered hydrocarbon accumulations equal to or greater than the minimum field size of 0.5 MMBOE, as indicated below.

In this AU, we estimate the number of undiscovered oil accumulations to be a minimum of 1 and a maximum of 30; the most likely number is 7. All nine of the discovered oil fields having production above the minimum of 0.5 MMBOE were discovered before 1958. The area is in a mature stage of exploration, but we believe there is potential for the discovery of at least one more oil field and one more gas field above the minimum size, given the number and complexity of potential stratigraphic traps and Laramide structural traps. At the maximum, we allowed for the possibility of 30 more oil discoveries and 15 more gas discoveries, but we selected a mode of 7 undiscovered oil fields and 5 undiscovered gas fields because this is a maturely explored area.

In terms of the sizes of undiscovered oil and gas accumulations, we estimate (1) a minimum size of 0.5 MMBO and 3 BCFG on the basis of the minimum allowed at the current cutoff; (2) a maximum size of 12 MMBO and 360 BCFG, allowing for the possibility that a future field discovery could equal 25 percent of the size of the largest discovered field (Rock River); and (3) a median size of 1.5 MMBO and 9 BCFG, which reflects a slight increase from the 1 MMBO reported for the second half for oil and a slight decrease from the 15.2 BCFG reported for the second half for gas. As indicated by the trend of halves, which is based on only 9 oil and 2 gas fields, the size of discovered fields is small and has been relatively constant since the last discovery more than 50 years ago. We therefore expect future discoveries to be small in size.

Mean estimates of undiscovered resources for the Mesozoic-Cenozoic Conventional Oil and Gas AU are 36 MMBO, 207 BCFG, and 11 MMBNGL (table 2). Table 2 also shows a resource breakdown into the F95, F50, and F5 fractiles. The potential for future discoveries is considered to be low in the Laramie and Shirley Basins, on the basis of the maturity of exploration and the lack of recent new discoveries. Future resource development in these reservoirs in the Laramie Basin will likely be the result of reserve growth in previously discovered fields. The best areas for new discoveries will most likely be in undrilled and sparsely drilled structures in the Hanna Basin.

Hanna Basin Continuous Gas Assessment Unit (50300261)

The Hanna Basin Continuous Gas AU was not assessed quantitatively because geologic and production data were lacking.

Niobrara Total Petroleum System

The geographic extent of the Niobrara TPS is shown in figure 35. The boundary, which encompasses the entire Hanna, Laramie, and Shirley Basins Province, is based mainly on the distribution of potential source and reservoir rocks within the Niobrara Formation and the concept that reservoirs are self sourced and continuous (Schmoker, 1996).

Key elements of the Niobrara TPS:

- Source rocks of appropriate organic carbon content and sufficient thermal maturity to generate hydrocarbons, primarily the Smoky Hill Member of the Niobrara,

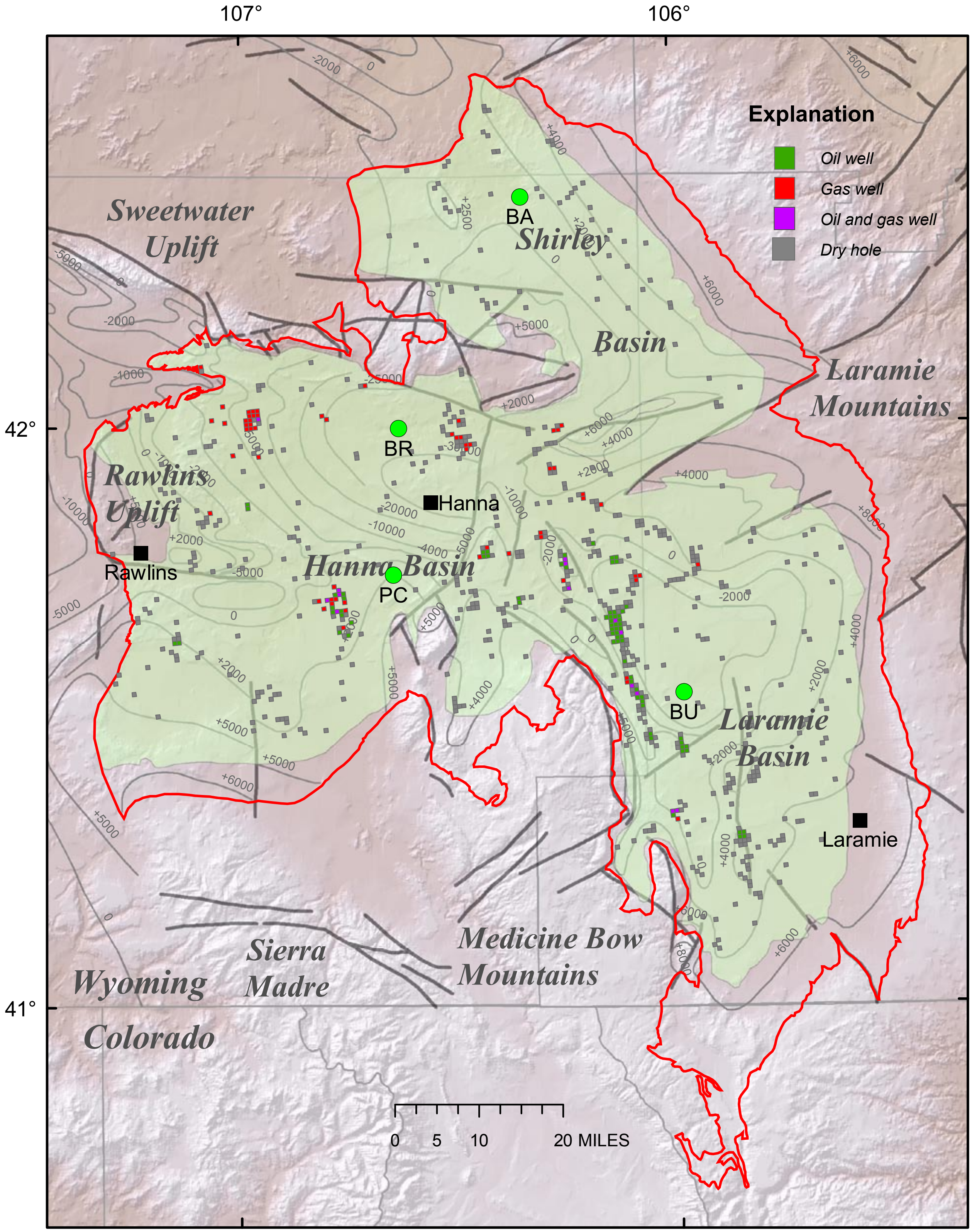

Figure 34. Mesozoic-Cenozoic Conventional Oil and Gas Assessment Unit (shaded green) in the Hanna, Laramie, and Shirley Basins Province (red outline). Contours drawn on top of Precambrian basement in feet relative to sea level (modified from Blackstone, 1989). Heavy gray lines are major faults. Small colored squares are generalized locations of wells in the AU that penetrate Hanna through Sundance Formations. BR, Brinkerhoff Hanna Unit No. 1 well; PC, Humble Pass Creek Ridge No. 1 well; BU, Buttes Federal 1–18 well; BA, Coastal Bates Creek Cattle 1–18–28–79 well.

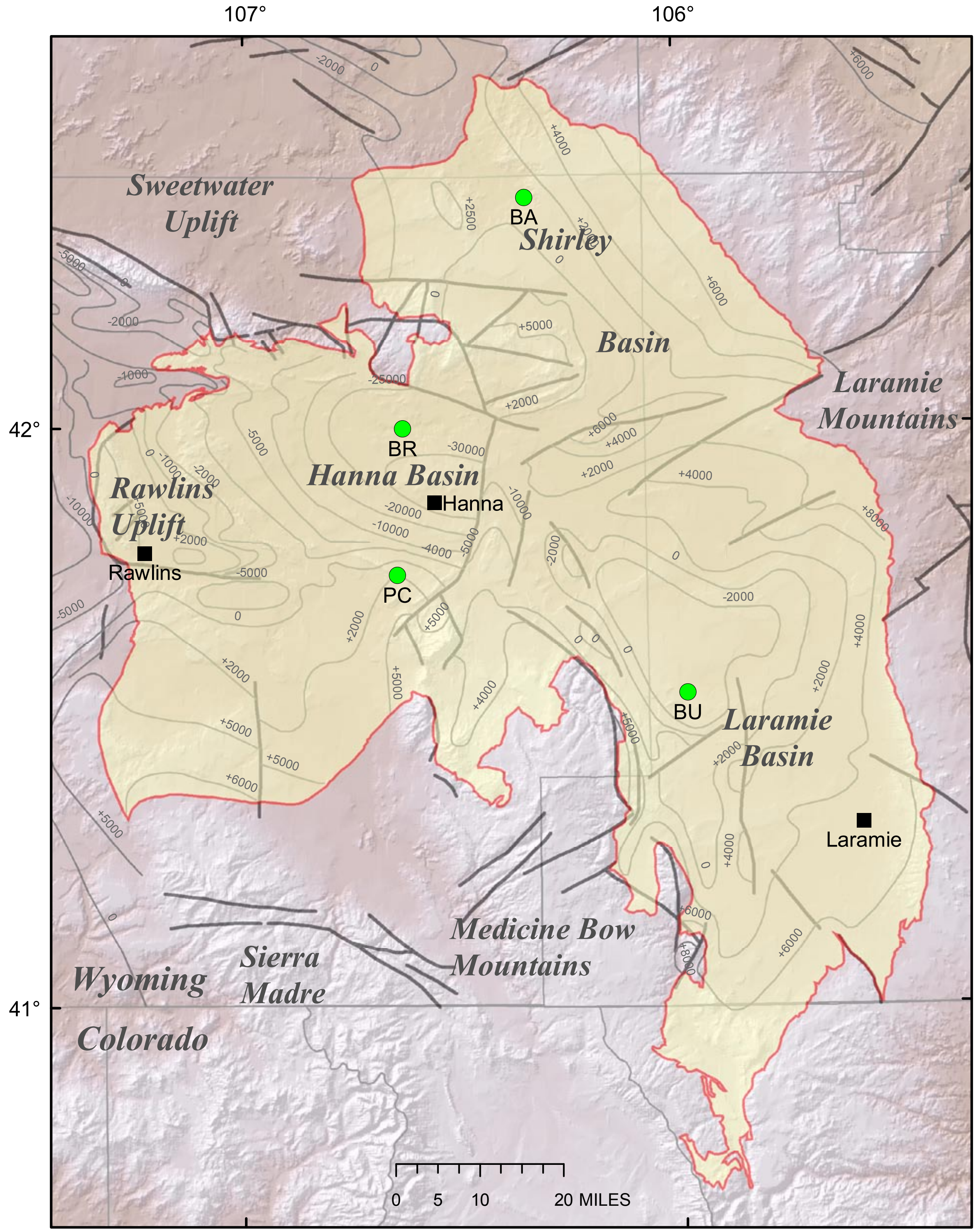

Figure 35. Niobrara Total Petroleum System (shaded brown) showing the distribution of Niobrara Formation source and reservoir rocks in the Hanna, Laramie, and Shirley Basins Province (red outline). Contours drawn on Precambrian basement in feet relative to sea level (modified from Blackstone, 1989). Heavy gray lines are major faults. BR, Brinkerhoff Hanna Unit No. 1 well; PC, Humble Pass Creek Ridge No. 1 well; BU, Buttes Federal 1–18 well; BA, Coastal Bates Creek Cattle 1–18–28–79 well.

which was deposited in anoxic bottom conditions favorable for the preservation of organic matter.

- Short-distance migration pathways—fractures, bed ding planes, and disconformities within the Niobrara Formation.
- Reservoir rocks consisting of fractured, laminated, and chalky units in otherwise low-porosity strata.
- Traps, such as facies variations resulting in sedimen tary pinchouts with laminated and marly zones within the Niobrara, changes in fracture intensity, direction and magnitude enhanced by structural features, along with enclosing shale and mudstone and other tightly cemented beds that act as seals.

Figure 36 is a total petroleum system events chart for the Niobrara TPS and the Niobrara Continuous Oil AU. This chart summarizes the relative age of source and reservoir rocks, seals, overburden, trap formation, the generation, migration, and accumulation of oil and gas, and the critical moment.

Source Rocks

Lillis and others (2003) identified several oil types in the Uinta-Piceance Basin, Colorado and Utah, on the basis of geochemical composition of sampled oil. Their Mancos-Niobrara oil group is widely distributed in Niobrara reservoirs. On the basis of stable carbon isotope analysis, Lillis and others (2003) characterized Niobrara oils as marine-derived nonwaxy oils typical of those that have produced at Rangely field in northwestern Colorado since the early 1900s. Roberts and others (2005) described the Niobrara in the Southwestern Wyoming Province as an oil-prone source rock that typically generates low-sulfur oil. In the Hanna, Laramie, and Shirley Basins Province, only two currently shut-in fields (Hugus and Overland) have produced oil (composition not known) from the Niobrara; both are located along the south margin of the Hanna Basin (fig. 20).

The Niobrara has been subdivided into a lower Fort Hays Limestone Member composed of limestone, shale, and minor sandstone and siltstone and an upper Smoky Hill Shale Member that is chalky and marly. The best Niobrara source rocks are the Smoky Hill marls, which were deposited on an anoxic substrate in areas largely devoid of clastic sediments in the central part of the Western Interior seaway (Longman and others, 1998; Landon and others, 2001; Finn and Johnson, 2005). Within the Western Interior Basin, Niobrara TOC ranges from 0.2 to 7.6 wt percent; the best values lie east of the Hanna, Laramie, and Shirley Basins Province in the area of Silo field in Laramie County, Wyoming, in the northern Denver Basin (Landon and others, 2001). There is a general increase in siliciclastic material in the Niobrara in the western part of the Western Interior seaway, and source rock quality decreases. Average TOC for the Hanna Basin is 2.14 wt percent, and the high percentage of chalk in the Niobrara indicates minor clastic dilution from western sources (Landon and others, 2001). TOC ranges from 0.85 to 2.75 wt percent in 28 samples from equivalent strata in the Southwestern Wyoming Province, the majority of which contain Type II oil-prone kerogen with some mixing from Type III gas-prone kerogen, especially in the western part of that province (Finn and Johnson, 2005). Bierei (1987) analyzed 16 Niobrara samples from the Hanna Basin for organic richness and identified a TOC range of 1.2 to 2.8 wt percent and an average of 2.0 wt percent. He recognized mixed Type II and Type III kerogen. Three additional Niobrara samples were processed for this study (TOC range, 1.76–2.42 wt percent; table 5);

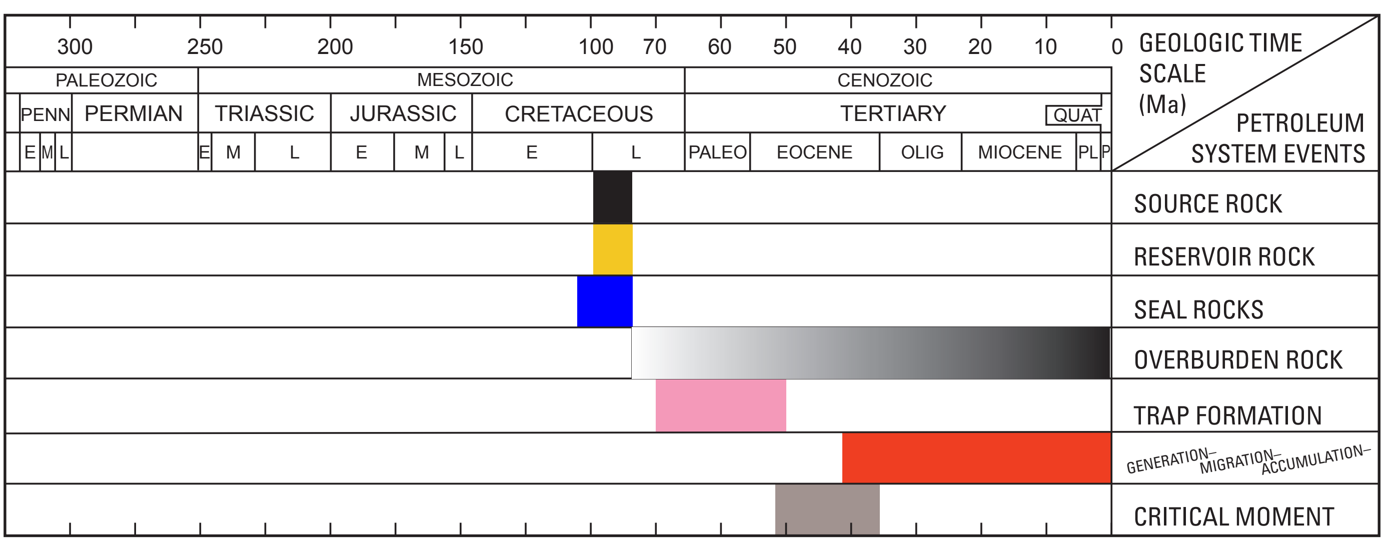

Figure 36. Events chart for the Niobrara Total Petroleum System in the Hanna, Laramie, and Shirley Basins Province. PENN, Pennsylvanian; QUAT, Quaternary; PALEO, Paleocene; OLIG, Oligocene; PL, Pliocene; P, Pleistocene; E, Early; M, Middle; L, Late.

pyrolysis results indicate mixing of Type II and Type III kerogen (fig. 28).

Source Rock Thermal Maturity

Bierei's (1987) TR-based thermal maturity models for the Hanna Basin were constructed to identify the maturation history of the Niobrara TPS. Bierei (1987) calculated that the Niobrara Formation reached a TR value of 0.5 (50 percent) at 75 Ma and is currently overmature (TR at or near 100 percent) with respect to oil generation in the central Hanna Basin (fig. 29*A*). He showed that the Niobrara reached maximum oil generation (TR=50 percent) rapidly from about 83 to 74 Ma in the basin center. Bierei's (1987) Hanna basin-margin model (fig. 29*B*) used a higher geothermal gradient than his basin-center model, resulting in an interpretation that Steele, Niobrara, and Frontier source rocks remained in the oil generation window for a much longer time. On the basin margin the Niobrara passed through a TR of 50 percent at about 66 Ma, and leveled off at about 65 percent from about 56 Ma to the present, indicating that the Niobrara is also overmature with respect to oil generation on the basin margin.

Analysis of the Brinkerhoff well in the central Hanna Basin with PetroMod80 1-D Express indicated that Niobrara source rocks rapidly reached a TR of 50 percent for oil generation by about 68 Ma (fig. 30); currently, the lower part of the Hanna Formation has a TR of 50 percent and is actively generating oil. Significant oil-to-gas cracking occurred in the Niobrara by 60 Ma (fig. 31); currently, the Niobrara is overmature with respect to both oil generation and oil-to-gas cracking. The Medicine Bow Formation is actively generating gas from the cracking of oil.

In the Pass Creek well on the Hanna Basin margin, Niobrara source rocks reached a TR of 50 percent for oil generation by about 38 Ma (fig. 32). Currently, the Niobrara is overmature with respect to oil generation but the Steele Shale, with a TR of 50 percent, is currently generating oil. No significant gas generation has occurred from the cracking of oil on the Hanna Basin margin. According to our burial history models, the Laramie and Shirley Basins have not reached the thermal maturity levels necessary for the generation of oil and gas in the Niobrara (fig. 33*A,B*).

Hydrocarbon Migration

We support an interpretation of limited migration for Niobrara-derived oil and consider potential oil accumulations in the Niobrara to be continuous-type accumulations. Landon and others (2001) considered the formation's generally low effective matrix porosity and permeability to have limited migration within the Niobrara. The presence of oil, therefore, is based primarily on thermal maturity rather than on migration pathways. Minimal updip migration occurred from deeper parts of the Hanna Basin into the basin margins. Fractures within the reservoirs served as local migration pathways. Overland and Hugus fields are located on structures, and production may have been enhanced owing to local migration into structures (fig. 20). Migration may have been more effective where siliciclastic content in the Niobrara is high and fracturing is more prevalent (Landon and others, 2001).

Reservoir Rocks

Niobrara lithologies are generally fine grained, and effective matrix porosity and permeability are low. Reservoir quality is good where fracture systems are well connected, such as possibly along Laramide anticlinal trends similar to the carbonate-rich brittle and fractured zones within the Niobrara serving as good reservoirs in northwestern Colorado that were described by Vincelette and Foster (1992). They illustrated that vein-filling minerals reduced porosity and permeability in Niobrara reservoirs, and they identified the best porosity and permeability in areas subjected to post-Laramide extensional fracturing. Pollastro (1992) identified similar trends in Niobrara reservoirs at Berthoud field in the Denver Basin of Colorado.

Reservoir zones within the Niobrara average 50–200 ft thick in the Southwestern Wyoming Province (Finn and Johnson, 2005). The Niobrara reservoir at Overland field in the Hanna Basin (fig. 20) is 200 ft thick, but the field is considered marginally productive and all wells are currently shut in (Hollis and Potter, 1984). Production at Overland field was from two well-developed chalk benches in the middle part of the Niobrara.

Traps and Seals

Hydrocarbon traps in the Niobrara TPS are considered unconventional in that they are defined by changing patterns in fracture development. More effective stratigraphic traps may develop where facies change laterally (such as chalk facies laterally grading into shales or mudstones), where interbedded mudrocks provide bounding surfaces, or by truncation beneath disconformities. At Overland field, the Niobrara is truncated by an unconformity at the south end of the structural closure that may have improved trapping conditions. For the Niobrara TPS, trapping mechanisms may have involved an early phase of Laramide fracture development and subsequent post-Laramide fracture enhancement where early vein fillings were reopened with post-Laramide extension (Vincelette and Foster, 1992). The unnamed structures at Overland and Hugus fields along the south margin of the Hanna Basin provide similar traps.

Reservoir seals in the Niobrara TPS consist of mudrocks—marine shales and mudstones of the overlying Steel Shale and underlying Carlile Shale. Fracture systems in the brittle chalk facies of the Niobrara typically do not extend into the thick marine shales of the Steele. Commonly, the fractured chalk facies is interbedded with less brittle shaly facies that form intraformational seals. At Overland field, two separate perforated chalky intervals are separated by more shaly units within the Niobrara. In some areas, diagenesis of Niobrara reservoirs produced tightly cemented zones that may also act as local seals, and structural seals may be important where fault movements place impermeable rocks in contact with reservoirs.

Niobrara Continuous Oil Assessment Unit (50300361)

The Niobrara Continuous Oil AU occupies most of the Hanna Basin portion of the Hanna, Laramie, and Shirley Basins Province (fig. 37); the boundary is based on the distribution of potential Niobrara reservoir rocks and thermal maturity required to generate oil. The central deep portion of the basin is not included in the AU because the Niobrara there is thermally overmature, and although the Niobrara is present in the Laramie and Shirley Basins, the AU does not extend into those areas because the source rocks are thermally immature. Additionally, the Laramie and Shirley Basins are thought to be outside the areas where oil could have migrated from the central Hanna Basin. Its area ranges from a minimum of 799,000 acres to a maximum of 883,000 acres and has a mean size of 841,000 acres. The range of area values is based on the uncertainty in the location of the –20,000 ft basement structure contour line that defines the downdip limit of the AU, owing to a lack of subsurface data. It contains Laramide structural features, facies pinchouts, and fracture systems that are potential traps for locally derived oil. Significant oil production (ultimate production greater than 0.5 million barrels of oil) has not occurred in this AU in the province.

Drilling depths to the top of the Niobrara range from 310 to 10,198 ft in the province (table 4). To date, nearly 130,000 barrels of oil and 11.0 MMCFG have been produced from Niobrara reservoirs at the Hugus and Overland fields (IHS Energy Group, 2004a). Most wells are classified as oil but produce minor amounts of associated gas.

Estimated Resources

The methodology of assessing undiscovered continuous oil and gas accumulations differs from the process used for conventional accumulations, as indicated in table 1. A significant difference is that conventional accumulations commonly display a downdip hydrocarbon-water contact. In contrast, continuous accumulations lack traditional traps or seals and commonly lack the water contact. Continuous accumulations have lower recoveries per well, on average, but the hydrocarbons are present throughout a large volume of closely associated source and reservoir rocks.

Because of the large, diffuse nature of continuous accumulations, a cell-based assessment methodology was developed (Schmoker, 1996). Cells are variously sized land tracts that represent the drainage area of wells using different geologic scenarios in an AU. Minimum, maximum, mode, and mean values of cell areas (in acres) are all used in the methodology; they are shown on the input data form for this unit (Klett and Le, 2007 (this CD-ROM)). An AU is divided into tested cells that have been drilled and untested cells that lack drilling. In this unit, the calculated mean area per untested cell having the potential for additions to reserves is 173 acres. The calculated mean percentage of the assessment unit area that is untested is 98.4 percent, and the calculated mean percentage of untested area that has the potential for additions to reserves is 10 percent. This percentage is based on our interpretation of the sizes and distribution of structures within the AUs area and on past and estimated future drilling success ratios.

Total recovery per cell (MMBO for oil and BCFG for gas) is an essential part of assessing a continuous accumulation. In this AU, the maximum, median, and minimum recoveries per untested cell having the potential for additions to reserves are 1.6, 0.04, and 0.001 MMBO respectively. These cell recovery estimates are based on characteristics of the Niobrara Formation that were used in assessing a similar AU in the adjacent Southwestern Wyoming Province (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005). The Niobrara Continuous Oil AU is a frontier assessment unit, because it has only 76 tested cells and contains no producing fields. Conditions are favorable for it to contain one or more undiscovered hydrocarbon accumulations with recovery from individual cells equal to or greater than the minimum cell recovery of 0.001 MMBO.

Mean estimates of undiscovered resources for the Niobrara Continuous Oil AU are 38 MMBO and 19 BCFG (table 2). Table 2 also shows a resource breakdown into the F95, F50, and F5 fractiles. The potential for future discoveries is considered moderate on the basis of the lack of systematic exploration in much of the Hanna Basin. The best areas for new discoveries will most likely be “sweet spots” where fracturing on structures has enhanced permeability.

Niobrara Biogenic Gas Total Petroleum System

The Niobrara Biogenic Gas TPS was defined for the Hanna, Laramie, and Shirley Basins Province on the basis of the potential that a biogenic gas resource exists in strata of the Niobrara Formation in the Laramie and Shirley Basins (fig. 38). These two basins were included in the TPS and the Hanna Basin excluded because (1) the Niobrara is mature for oil generation in the Hanna Basin, and therefore it was placed in the Niobrara TPS (and Niobrara Continuous Oil

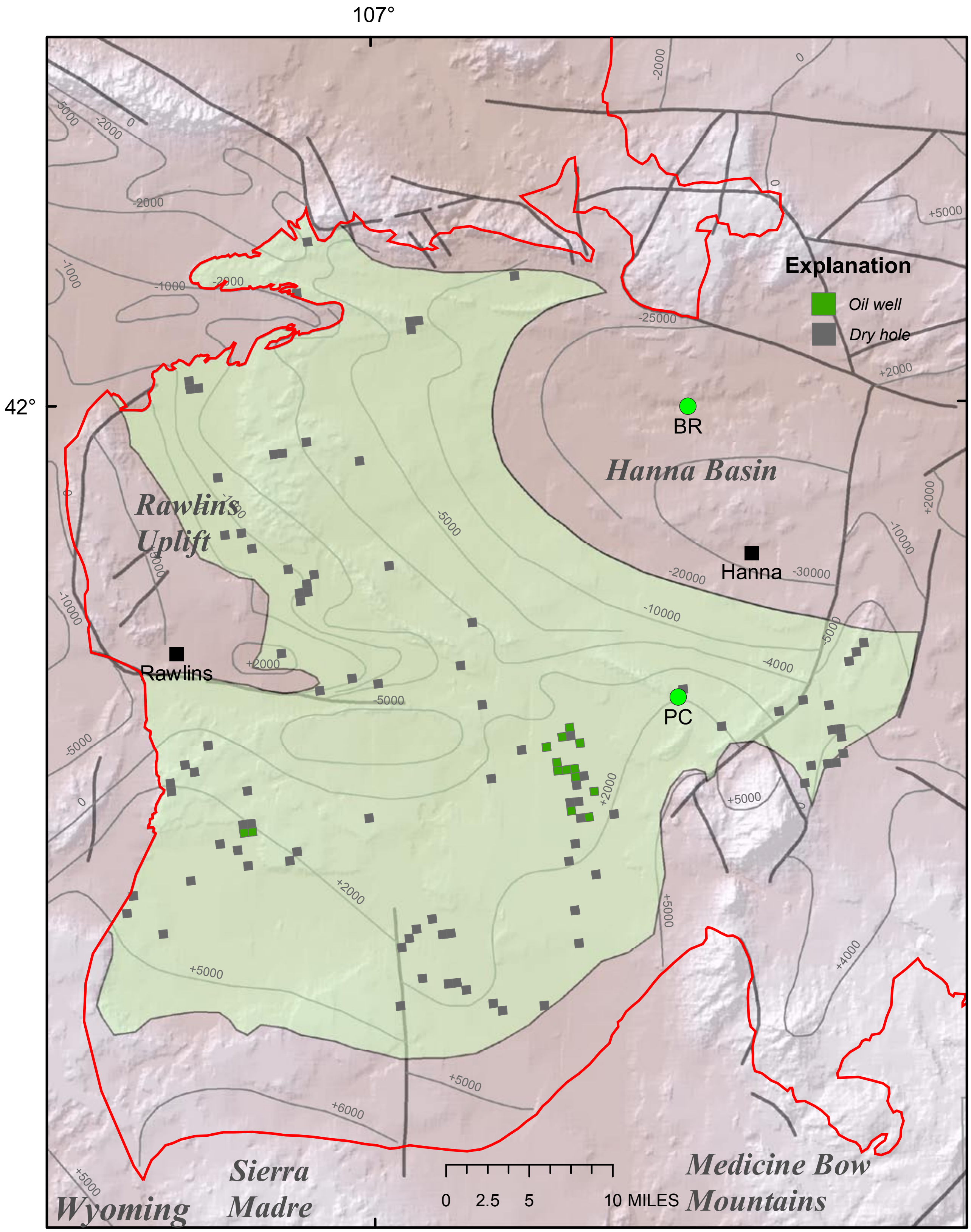

Figure 37. Niobrara Continuous Oil Assessment Unit (shaded green) in the western part of the Hanna, Laramie, and Shirley Basins Province (red outline). Contours drawn on the top of Precambrian basement in feet relative to sea level (modified from Blackstone, 1989). Heavy gray lines are major faults. Small colored squares are generalized locations of wells in the AU that penetrate the Niobrara Formation. BR, Brinkerhoff Hanna Unit No. 1 well; PC, Humble Pass Creek Ridge No. 1 well.

AU) discussed earlier; and (2) the Niobrara in the Laramie and Shirley Basins is immature for oil (and associated gas), so that the rare gas shows detected in these areas can be attributed to the generation of biogenic gas. The distribution of the Niobrara Formation in the Laramie and Shirley Basins is shown in figure 38, but whether geologic conditions were favorable for the generation of biogenic gas could not be determined from the sparse information that is available. As mentioned above, there have been a few gas shows to indicate a potential, but no commercial production has been reported. For these reasons, an events chart was not compiled for the TPS and the Niobrara Biogenic Gas AU was not assessed.

Niobrara Biogenic Gas Assessment Unit (50300461)

The Niobrara Biogenic Gas AU was not quantitatively assessed because of a lack of geologic and production data.

Hanna-Mesaverde Coalbed Gas Total Petroleum System

The Hanna-Mesaverde Coalbed Gas TPS has coal beds within the Mesaverde, Medicine Bow, Ferris, and Hanna Formations. The distribution of the various formations is shown in figure 39, but the TPS boundary is not drawn because data are insufficient to identify areas where coalbed gas-generating potential exists. Coals extend from the deep northern part of the Hanna Basin southward to an outcrop edge in the central basin south of Hanna, Wyoming, and also in the Carbon Basin and northern Laramie Basin. The TPS contains coal beds less than 7,000 ft deep in the central part of the Hanna and Laramie Basins. To date, only small volumes of gas have been produced from two coalbed gas pilot projects in the northern part of the Hanna Basin.

Key elements of the Hanna-Mesaverde Coalbed Gas TPS:

- Coal-rich source rocks of thickness appropriate for generating biogenic and minor amounts of thermal gas, such as the Almond Formation of the Mesaverde Group, and the Medicine Bow, Ferris, and Hanna Formations, which were deposited in coastal and nonmarine environments. Uncertainty exists regarding the role of hydrostatic pressure and early episodes of flushing by groundwater systems.
- Short-distance migration pathways through fractures and updip along bedding planes and disconformities at depths ranging from a few hundred to 7,000 feet.
- Reservoir rocks consisting of coal units within the Mesaverde Group, and Medicine Bow, Ferris, and Hanna Formations.
- Traps such as facies variations resulting in sedimentary pinchouts within the units and changes in fracture intensity by structural features.
- Seals formed by interbedded shale and mudstone and by tightly cemented beds.

An events chart for the Hanna-Mesaverde Coalbed Gas TPS was not compiled because the TPS is based primarily on a biogenic gas model. The geologic framework and geologic history of the TPS are briefly discussed below. The Medicine Bow-Ferris-Hanna Coalbed Gas and Mesaverde Coalbed Gas AUs were not assessed owing to a lack of geologic and drilling data.

Source Rocks

Glass and Roberts (1980) recognized that the most numerous coal beds are in the upper 12,000 ft of the Hanna Formation and in the upper part of the Ferris Formation in the northern part of the Hanna Basin. Individual coal beds in the Hanna are thicker, on average, than those of the Ferris Formation; cumulative coal bed thicknesses range from 30 to 375 ft and 125 to 305 ft, respectively. Hanna Formation coal beds are not well correlated between the Hanna Basin and the Carbon Basin (a synclinal area between the Hanna and Laramie Basins, fig. 3), and separate bed names are used (Glass and Roberts, 1980). Medicine Bow coals are generally restricted to the lower part of the formation and are not as laterally persistent as those of the Hanna and Ferris Formations (Merewether, 1971, 1972, 1973; Glass and Roberts, 1980). For the deeper Almond coals, seven laterally persistent coal beds greater than 5 ft thick have been described, and cumulative coal thickness ranges from 10 to 40 ft. In the northern part of the Hanna Basin, Mesaverde coals are deep, and steep dips and faults are encountered in wells. The Mesaverde was not reached at 19,600 ft in the Anadarko Petroleum Durante 11–2 well (fig. 20). At such extreme depths, thermal gas would be expected from gas-prone coaly source rocks.

Source Rock Thermal Maturity

According to Glass and Roberts (1980, 1984), Hanna Formation coals in the Hanna Coal Field north of Hanna, Wyoming, are high-volatile C bituminous. Ferris Formation coals in the Seminoe Road Mining District west of Hanna are subbituminous A and are suspected to be high-volatile C bituminous underlying the Hanna Formation at Hanna. Medicine Bow and Almond coals in the central Hanna Basin are expected to be high-volatile A or B bituminous coals. Vitrinite reflectance (R_o) values of sampled Hanna coals ranges from 0.45 to 0.54 percent and of Ferris coals from 0.48 to 0.53 percent. In the Carbon Basin, R_o values for Hanna coals ranges from 0.51 to 0.54 percent (Flores and others, 1999a,b).

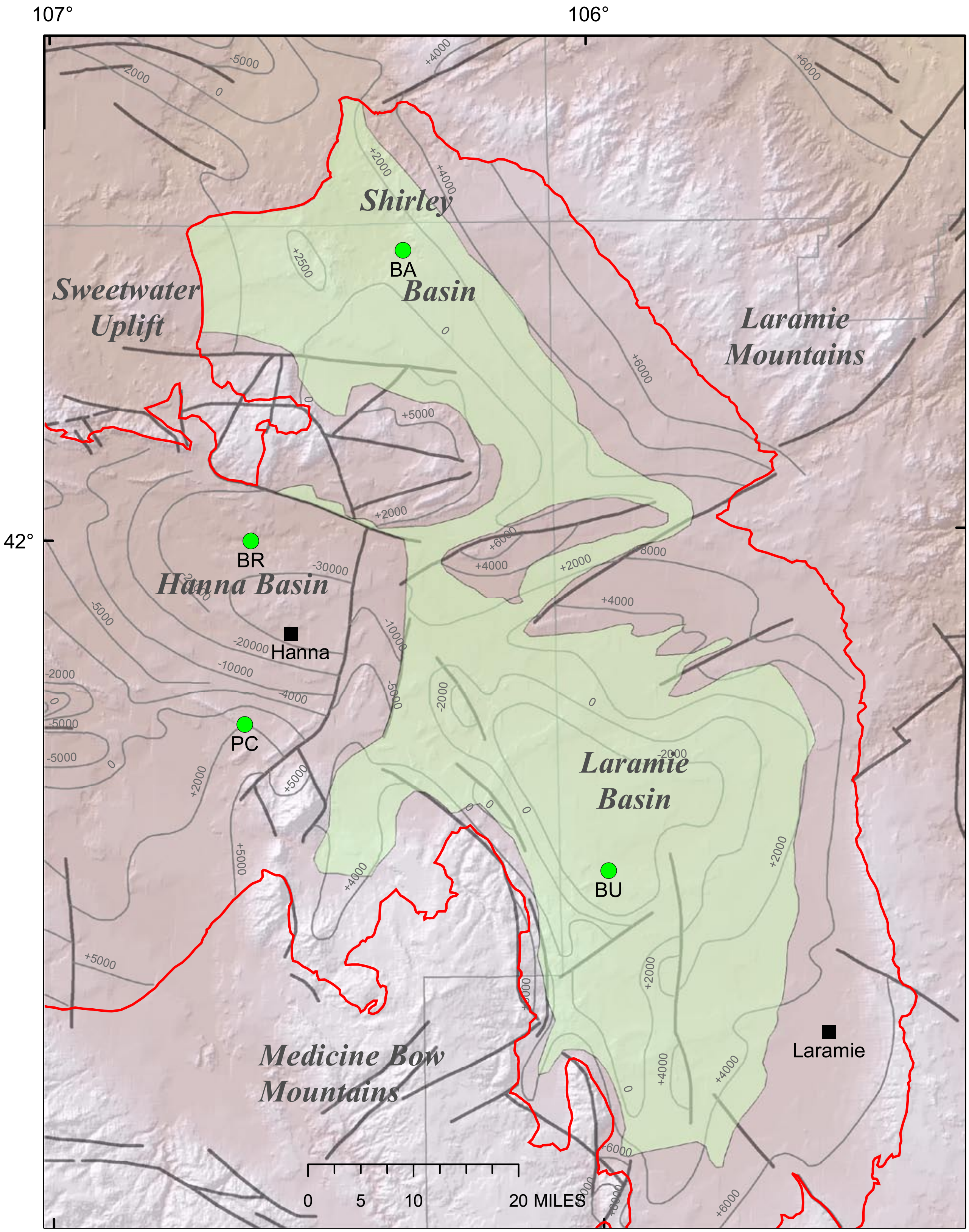

Figure 38. Niobrara Formation in the Shirley and Laramie Basins (shaded green) where the potential exists for biogenic gas accumulations. Contours drawn on top of Precambrian basement in feet relative to sea level (modified from Blackstone, 1989). Heavy gray lines are major faults. Red line is boundary of Hanna, Laramie, and Shirley Basins Province. BR, Brinkerhoff Hanna Unit No. 1 well; PC, Humble Pass Creek Ridge No. 1 well; BU, Buttes Federal 1–18 well; BA, Coastal Bates Creek Cattle 1–18–28–79 well.

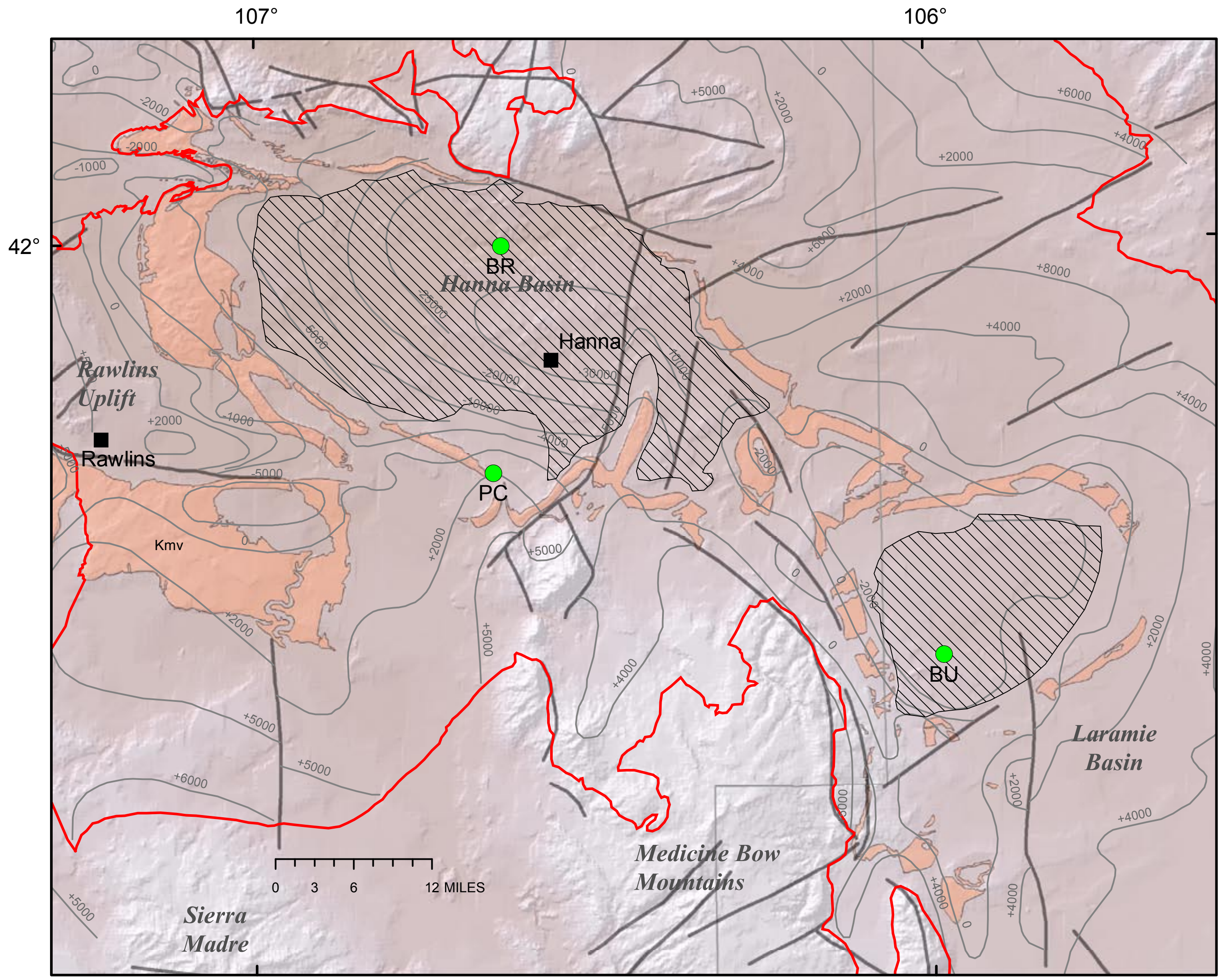

Figure 39. Outcrops of Mesaverde Group (shaded orange) and extent of the Medicine Bow Formation at the surface and in the subsurface (patterned area). Ferris and Hanna Formations are present within patterned area of Medicine Bow. Contours drawn on Precambrian basement in feet relative to sea level (modified from Blackstone, 1989). Thick gray lines are major faults. Red line is province boundary. BR, Brinkerhoff Hanna Unit No. 1 well; PC, Humble Pass Creek Ridge No. 1 well; BU, Buttes Federal 1–18 well.

Most of the undiscovered gas potential for the Hanna-Mesaverde Coalbed Gas TPS is expected to be biogenic. On the basis of Bierei's (1987) TR-based thermal maturity models and our PetroMod models for the Hanna Basin, the Hanna and Ferris Formations are thermally immature for petroleum generation except at great depths in the Hanna Basin (fig. 29*A*). The Medicine Bow and Almond Formations may contain more thermal gas where thick overburden has been removed by erosion. On the basis of our one-dimensional burial history models for the Hanna Basin center, oil-to-gas cracking occurred in the Mesaverde-Lewis interval by 55 Ma (fig. 31). The Medicine Bow Formation is now actively generating gas from the cracking of oil. Some of this thermal gas may have migrated updip and filled shallow reservoirs.

Hydrocarbon Migration

We support an interpretation of limited migration of Hanna-Mesaverde coalbed gas from the deeper parts of the Hanna Basin updip into the basin margins, and fractures within the reservoirs serve as local migration pathways. At both the Seminoe Road and Hanna Draw coalbed gas pilot projects (fig. 20), steep dips and faults were encountered during drilling. These pilot projects are located on structures, and traps may have been enhanced owing to local migration into structures.

Reservoir Rocks

Reservoirs are coals within the Almond, Medicine Bow, Ferris, and Hanna Formations. Typically, the best reservoirs are those where adsorbed gas from coals can be released to fractures as water is withdrawn to reduce hydrostatic pressure. At the Seminoe Road coalbed gas pilot project operated by Dudley and Associates (fig. 20), 16 producing gas wells average 1,400 cubic feet of gas per day (CFGPD) and 900 barrels of water per day (BWPD) from a 75-ft-thick coal zone in the Almond Formation at an average depth of about 5,000 ft (David Dudley, Dudley and Associates , oral commun., 2004). The reservoirs are steeply dipping and faulted. At the Hanna Draw coalbed gas pilot project operated by Anadarko Petroleum (fig. 20), nine active wells are currently averaging less than 1,000 CFGPD and about 285 BWPD from a 40- to 80-ft thick coal zone in the upper Hanna Formation at an average depth of about 4,000 ft (Thomas Griffith, Anadarko Petroleum, oral commun., 2005). Gas production at both projects is limited, as drilling is still in its early stages. Whether economically viable production will result from these projects is yet to be determined.

Traps and Seals

Hydrocarbon accumulations in the Hanna-Mesaverde Coalbed Gas TPS are considered unconventional and continuous; traps are stratigraphic, structural, or combined structural-stratigraphic. More effective stratigraphic traps may develop where coals grade into shales or mudstones, are with interbedded mudrocks, or are truncated beneath disconformities. For the Hanna-Mesaverde Coalbed Gas TPS, some potential traps are associated with an early phase of Laramide fracture development and subsequent post-Laramide fracture enhancement where early vein fillings were reopened during post-Laramide extension in a manner similar to that described for the Niobrara (Vincelette and Foster, 1992).

Medicine Bow-Ferris-Hanna Coalbed Gas Assessment Unit (50300581)

The Medicine Bow-Ferris-Hanna Coalbed Gas AU was not quantitatively assessed because of a lack of geologic and production data. Current production for producing cells is less than the minimum recovery per cell required for assessment.

Mesaverde Coalbed Gas Assessment Unit (50300582)

The Mesaverde Coalbed Gas AU was not quantitatively assessed because of a lack of geologic and production data. Current production for producing cells is less than the minimum recovery per cell required for assessment.

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