Chapter 4

New Source Rock Data for the Thermopolis and Mowry Shales in the Wyoming Part of the Bighorn Basin

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By Thomas M. Finn

Chapter 4 of

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New Source Rock Data for the Thermopolis and Mowry Shales in the Wyoming Part of the Bighorn Basin

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Abstract

Thirty samples of well cuttings, collected from marine shales from the Cretaceous Thermopolis and Mowry Shales in the Bighorn Basin, were analyzed using Rock-Eval and total organic carbon analysis to determine their source rock potential. The samples were collected from wells located near the outcrop belt along the margins of the basin and are generally immature with respect to hydrocarbon generation. Results for the Thermopolis Shale indicate that it is composed of mainly Type-III gas-prone kerogen, however S_2/S_3 ratios indicate that the Thermopolis is capable of generating both oil and gas. Organic richness levels for the Thermopolis Shale are considered poor to fair. Results indicate that the Mowry Shale has a generative potential based on organic richness that is considered to be poor to very good, and hydrogen indices and S_2/S_3 ratios indicate it is capable of generating both oil and gas.

Introduction

The Bighorn Basin is one of many structural and sedimentary basins that formed in the Rocky Mountain foreland during the Laramide orogeny (Late Cretaceous through early Eocene). The basin is nearly 180 mi long, 100 mi wide, and encompasses about 10,400 mi^2 in north-central Wyoming and south-central Montana (fig. 1). The basin is structurally bounded on the northeast by the Pryor Mountains, on the east by the Bighorn Mountains, and on the south by the Owl Creek Mountains. The north boundary as defined in this report includes a zone of faulting and folding referred to as the Nye-Bowler lineament (Wilson, 1936). The northwest and west margins are formed by the Beartooth Mountains and Absaroka Range, respectively (fig. 2).

The first commercial hydrocarbon production from Cretaceous reservoirs in the basin was established at Garland and Greybull fields in 1906 and 1907, respectively (Fox and Dolton, 1996) (fig. 2). Since then cumulative production from Cretaceous and Tertiary reservoirs is about 94 million barrels of oil and 830 billion cubic feet of gas (IHS Energy Group, 2007). In addition, a potential unconventional basin-centered gas accumulation may be present in Cretaceous reservoirs (Surdam and others, 1997; Johnson and Finn, 1998; Johnson and others, 1999; Finn and others, Chapter 3, this CD–ROM). It has been suggested that various Cretaceous marine shales are the principal hydrocarbon source rocks for these accumulations in the Bighorn Basin (Burtner and Warner, 1984; Hagen and Surdam, 1984; Meissner and others, 1984).

The purpose of this report is to present new data from results of Rock-Eval and total organic carbon (TOC) analysis for samples collected from immature Thermopolis and Mowry Shales in the Bighorn Basin and characterize their source rock potential. These new data supplement previously published reports by Schrayer and Zarrella (1963, 1966, 1968), Nixon (1973), Burtner and Warner (1984), Hagen and Surdam (1984), Hagen (1986), Davis (1986), and Davis and others (1989). This study was conducted to support the U.S. Geological Survey's assessment of undiscovered oil and gas resources in the Bighorn Basin in 2007–08.

Acknowledgments

The author thanks Paul Lillis and Mike Pribil for numerous helpful discussions regarding organic geochemistry and source rocks, and for their assistance in interpreting the Rock-Eval and TOC data presented in this report. Important geologic input was provided by Mark Kirschbaum and Tom Judkins. The manuscript benefited from reviews by Larry Anna, Paul Lillis, Dick Keefer, Doug Nichols, and Gayle Dumonceaux and their suggestions and comments are greatly appreciated.

Depositional Setting

During much of Cretaceous time, the part of central Wyoming that is now the Bighorn Basin was located near the west edge of the Rocky Mountain foreland basin, an elongate north-south structural depression that developed to the east of the tectonically active Western Cordilleran highlands prior to the Laramide orogeny. Throughout much of its history the foreland basin was flooded by a broad epicontinental sea, referred to as the Western Interior Seaway (WIS) that developed in response to foreland basin subsidence and eustatic sea-level rise (Steidtmann, 1993). At its maximum extent, the WIS extended for more than 3,000 mi from the Arctic Ocean

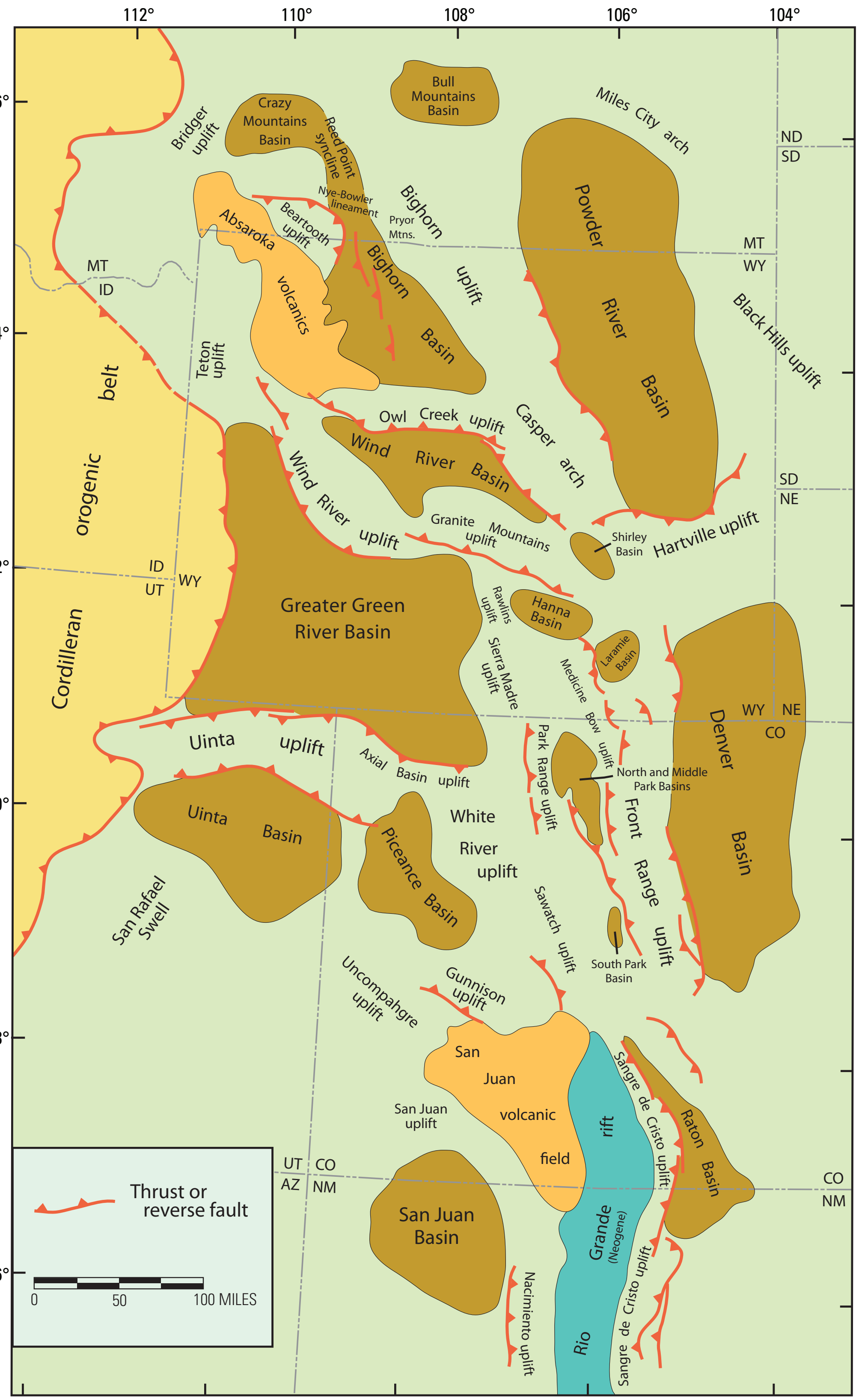

Figure 1. Rocky Mountain region extending from southern Montana to northern New Mexico showing locations of Laramide sedimentary and structural basins and intervening uplifts. Modified from Dickinson and others (1988).

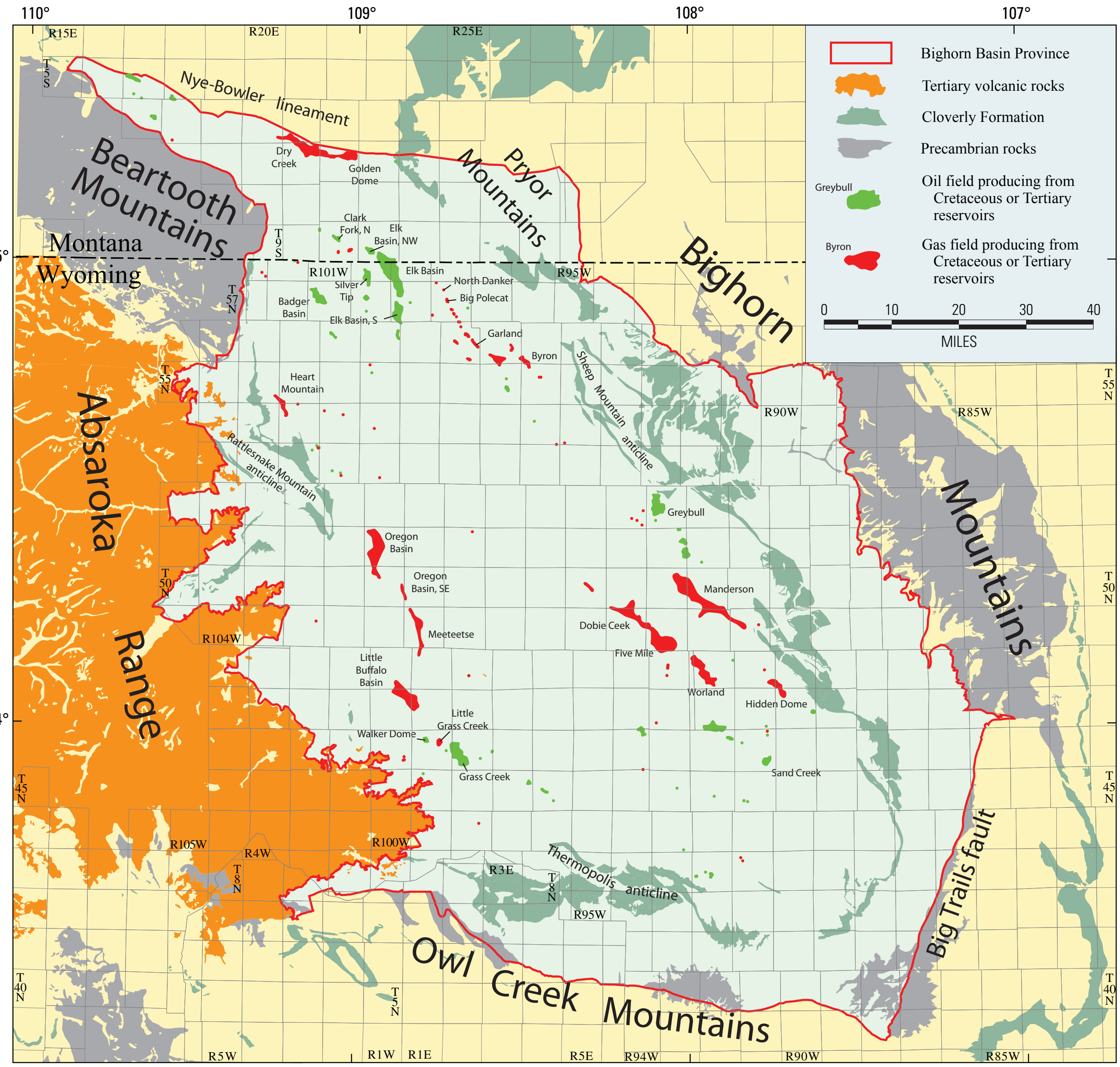

Figure 2. Index map showing the location of the Bighorn Basin Province, major structural elements, and oil and gas fields that produce from Cretaceous or Tertiary reservoirs.

to the Gulf of Mexico (fig. 3) (Kauffman, 1977). Erosion of the Western Cordilleran highlands supplied sediment to the basin by eastward-flowing streams, whereas the eastern shore was part of the stable craton that was topographically low and supplied little sediment westward into the seaway (Molenaar and Rice, 1988). During much of Cretaceous time, sediments accumulated in or adjacent to the WIS as the western shoreline repeatedly advanced and retreated across the western part of the basin resulting in a complex pattern of intertonguing marine and nonmarine deposits (fig. 4). The marine deposits are represented by westward-thinning tongues of marine shale, siltstone, limestone, and marine sandstone. The nonmarine deposits are represented by eastward-thinning wedges of marginal marine and nonmarine sandstone, siltstone, shale, carbonaceous shale, and coal. The marine sediments were deposited during widespread marine transgressions creating highstand conditions that resulted in deepening of the seaway, limiting clastic input, and forming anoxic bottom conditions favorable for the preservation of organic matter (Meissner and others, 1984; Gries and others, 1992). Figure 5 is a generalized

Figure 3. Extent of the Cretaceous Western Interior seaway during Campanian time. Brown areas show the approximate geographic distribution of land areas. Modified from Gill and Cobban (1973).

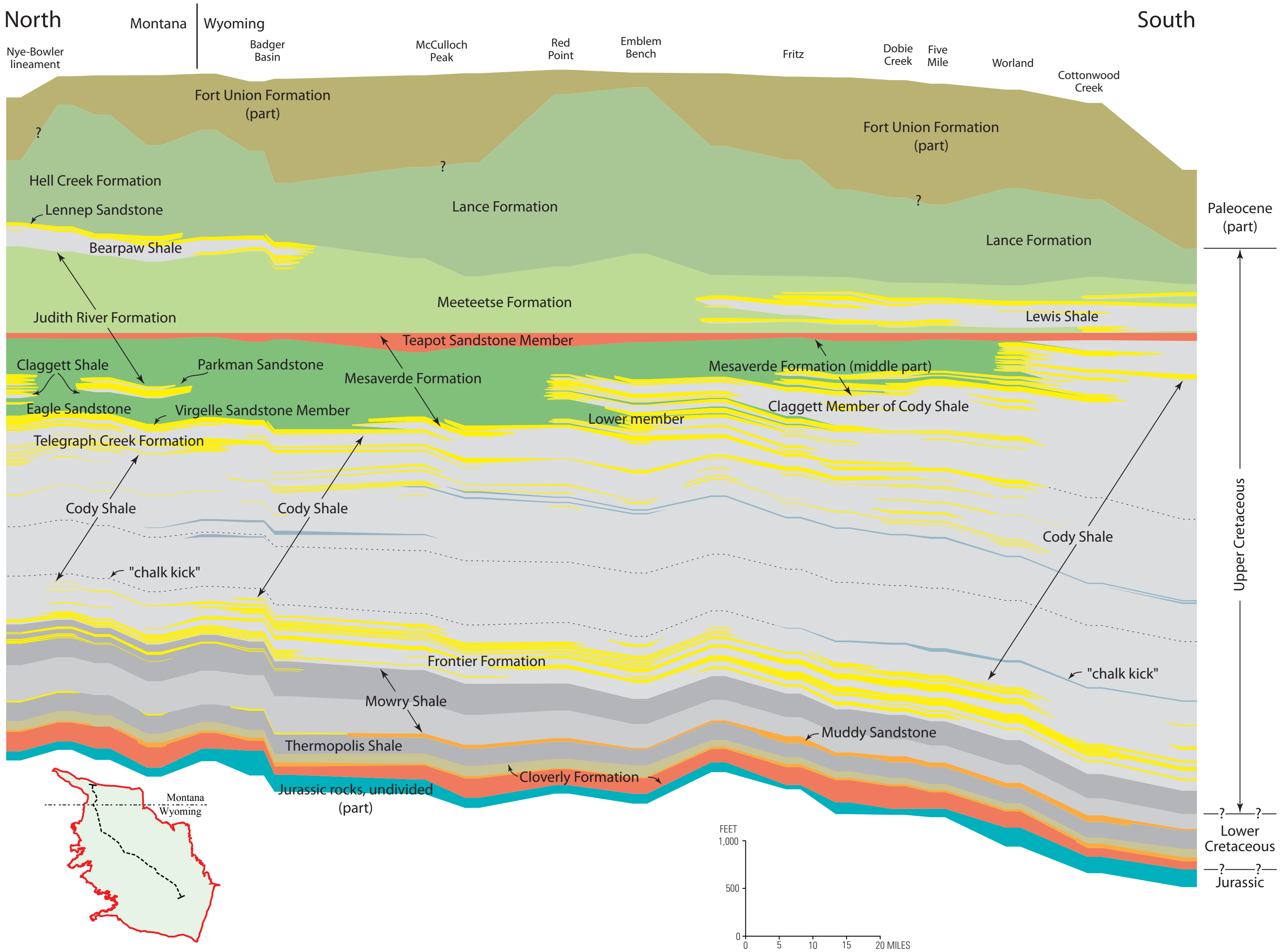

Figure 4. Regional northwest-southeast stratigraphic cross section of Cretaceous and Paleocene (part) rocks, Bighorn Basin, Wyoming and Montana. Colors represent different lithologies and environments of deposition: red, fluvial sandstone and conglomerate; yellow, marine and marginal marine sandstone and siltstone; orange, fluvial and estuarine sandstone; tan, tidal sandstone, siltstone, and shale; various shades of gray are marine shales; various shades of green are coastal plain and floodplain sandstones, shales, and coals; brown, sandstone, siltstone, shale, coal, and conglomerate of continental origin; blue, undifferentiated sedimentary deposits.

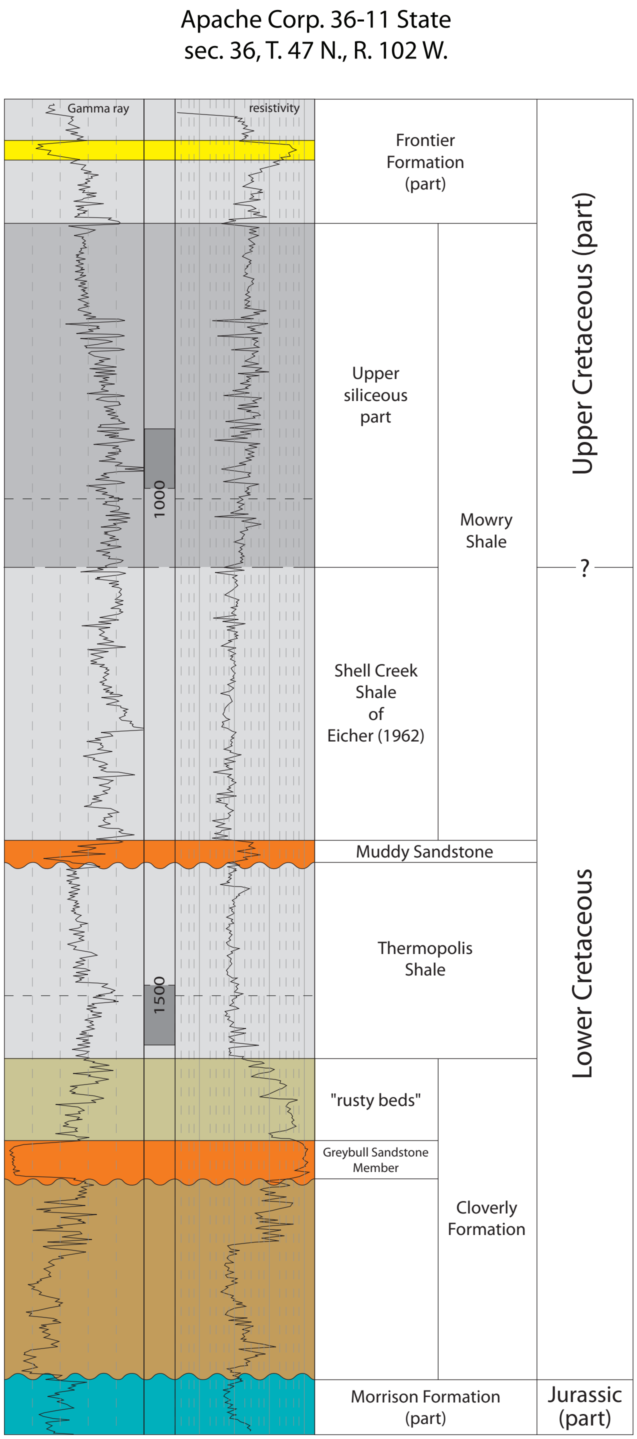

Figure 5. Type log of Lower and lowermost Upper Cretaceous rocks in the Bighorn Basin showing the stratigraphic nomenclature used in this report. Floodplain deposits are shown in brown; marine and marginal marine sandstones, yellow; marine shales, various shades of gray; estuarine and fluvial sandstones shown in orange, tidal deposits are shown in tan, and undifferentiated deposits shown in blue. Sample interval, dark gray. Location shown in figure 6.

stratigraphic chart and type log of the Lower Cretaceous and lowermost Upper Cretaceous rocks in the Bighorn Basin.

Stratigraphy

Thermopolis Shale

The Thermopolis Shale (known as the Skull Creek Shale in some other Rocky Mountain basins) as used in this report refers to lower Thermopolis Shale of Lupton (1916), Mills (1956), and Haun and Barlow (1962), which overlies the “rusty beds” of the Cloverly Formation, and underlies the Muddy Sandstone (fig. 5 and plate 1). The Thermopolis consists of 125 to 230 ft of marine shales and siltstones and represents a continuation of marine deposition that began with the “rusty beds” during sea-level rise in Albian time (Burtner and Warner, 1984; Hagen and Surdam, 1984). The shales are dark gray to black, contain thin layers of siltstone, sandy claystone, and bentonite. The basal contact is gradational with the underlying “rusty beds” of the Cloverly Formation; the upper contact may be sharp and locally unconformable or gradational with the overlying Muddy Sandstone.

Muddy Sandstone

The Muddy Sandstone is composed of very fine to medium-grained sandstone interbedded with minor amounts of shale, siltstone, carbonaceous shale, and coal of latest Albian age (Paull, 1962). The formation was deposited in fluvial, marginal marine, and estuarine environments and ranges in thickness from 7 to 125 ft. The thickest accumulations are associated with an incised valley-fill complex that developed on the exposed surface of the Thermopolis Shale during sea-level lowstand (Dolson and others, 1991).

Mowry Shale

According to Keefer and others (1998), the Mowry Shale in the Bighorn Basin consists of two distinct units (fig. 5 and plate 1). The lower part consists of about 160 to 400 ft of soft, fissile clay-rich shale similar to the Thermopolis Shale and is referred to as the upper Thermopolis Shale by several authors including Mills (1956) and Haun and Barlow (1962), and as the Shell Creek Shale by Eicher (1962) (fig. 5). The upper part consists of about 240 to 400 ft of hard, brittle siliceous shale. Numerous gray to tan bentonite beds are common throughout both parts and range in thickness from a fraction of an inch to about 7 ft (Byers and Larson, 1979). The siliceous shales are dark brown to black, organic-rich, and contain an abundance of fish scales (Burtner and Warner, 1984). Locally, thin fine-grained sandstones occur in the middle to upper part of the siliceous part of the Mowry. These units, referred to informally as the “Kimball” and “Octh Louie” sands have produced oil from fields on the east side of the basin (Pierce, 1948; Mills, 1956; Cardinal and others, 1989). The Mowry Shale is marine in origin with a combined thickness for the lower and upper parts ranging from about 400 ft in the southeastern part of the basin to more than 800 ft near the Beartooth uplift (Finn and others, Chapter 3, this CD–ROM). Paleontologic evidence and radiometric dating indicate that the upper siliceous part of the Mowry is largely early Cenomanian in age (Cobban and Kennedy, 1989; Obradovich and others, 1996), however, radiometric dates for bentonite beds in the basal Mowry (Shell Creek equivalent) indicate an Albian (Early Cretaceous) age (Obradovich and others, 1996).

Methods

Thirty samples from 15 wells were collected from well cuttings of Thermopolis and Mowry Shales stored at the U.S. Geological Survey (USGS) Core Research Center in Lakewood, Colorado. The selected wells are located near the outcrop belt along the shallow margins of the basin in order to obtain samples that were not subjected to the effects of deep burial and therefore are immature with respect to hydrocarbon maturation (figs. 6, 7). Fifteen samples are from the Thermopolis Shale and 15 from the Mowry Shale. The 15 samples from the Mowry were collected from the lower 200 ft of the upper siliceous part, with the exception of the sample at location two that includes some of the upper part of the Shell Creek Shale interval of Eicher (1962) (plate 1). The 15 samples from the Thermopolis were collected from the middle to lower part of the unit (plate 1). Sample intervals were determined by examining a gamma-ray log, if available, and the interval(s) with higher gamma-ray intensities were selected, based on work by numerous authors who described a close association of gamma-ray intensity with higher TOC content (for example, Schmoker, 1981; Zelt, 1985; Hester and others, 1990; Herron, 1991; Pratt and others, 1993; Dean and Arthur, 1998; Pasternack, 2005; and Rigoris and others, 2005). This relation, according to Hunt (1996), is a result of organic matter (OM) concentrating uranium from seawater.

The cuttings were examined under a binocular microscope and the darkest chips were selected for analysis based on observations by Hosterman and Whitlow (1981), Charpentier and Schmoker (1982), Hunt (1996), and Landon and others (2001), all of whom suggested that TOC content generally increases as color goes from gray to black and therefore is a rough (although not always reliable) indicator of organic richness. If a gamma-ray log was not available or there was insufficient cuttings material present from a high gamma interval then sample intervals were determined strictly by color. The cuttings were composited into one sample from thickness intervals that were generally 30 to 50 ft thick, but ranged from 10 to 80 ft depending on how much material was available for a proper analysis (table 1).

The whole-rock samples were ground to a fine powder and splits were sent along with an internal USGS laboratory standard to an outside geochemical laboratory for analysis. Total organic carbon (TOC) content was determined using the Leco combustion method described by Jarvie (1991), and the pyrolysis analysis was done using a Rock-Eval 2 pyroanalyzer (Espitalie and others, 1977; Tissot and Welte, 1978; Peters, 1986; and Hunt, 1996, contain detailed discussions of the pyrolysis method).

Results

Quantity of Organic Matter

According to Jarvie (1991), the quantity of organic matter in a formation measured as weight percent (TOC) is an indicator of the organic richness and generative potential. Rocks with less than 0.5 weight percent TOC have poor generative potential, rocks with 0.5 to 1 weight percent TOC are considered fair, rocks with 1–2 weight percent TOC are considered good, rocks with 2–4 weight percent TOC are considered very good, and rocks with greater than 4 weight percent TOC are considered to have excellent generative potential (Peters and Casa, 1994). Table 1 and figure 8*A* show the results of TOC analyses of Cretaceous marine shales in the Bighorn Basin.

The results of TOC analyses of the 15 samples collected from the Thermopolis Shale show values ranging from 1.04 to 1.91 percent, with an average of 1.5 percent indicating good generative potential (fig. 8*A*). The 15 samples collected from the Mowry Shale have TOC contents that range from 1.11 to 2.65 percent, with an average of 1.8 percent. Most of the samples fall in the 1 to 2 percent range indicating good generative potential, but a few samples fall into the 2 to 4 percent range indicating very good generative potential (fig. 8*A*).

Peters and Cassa (1994) pointed out that TOC is not always a good indicator of source rock potential because measurements may include inert carbon that has little or no generating potential. They (Peters and Cassa, 1994) stated that the S_2 measurement derived from pyrolysis analysis is a better indicator of generative potential of source rocks. The value S_2, expressed as milligrams of hydrocarbons per gram of rock, represents the fraction of original kerogen in a source rock capable of generating hydrocarbons that have not yet been converted to oil or gas or both (Tissot and Welte, 1978). According to Peters and Cassa (1994), rocks with S_2 values less than 2.5 have poor generative potential, rocks with S_2 values between 2.5 and 5 have fair generative potential, rocks with S_2 values ranging from 5 to 10 have good generative potential, rocks with S_2 values from 10 to 20 are considered to have very good generative potential, and rocks with S_2 values greater than 20 have excellent generative potential.

S_2 measurements for the Thermopolis and Mowry Shales are presented in table 1 and on figure 8*B*. The 15 samples from the Thermopolis Shale show a range of S_2 values from 0.82 to 3.49, indicating that it is a poor to fair source rock (fig. 8*B*). Six of the 15 samples from the Mowry Shale have S_2 values

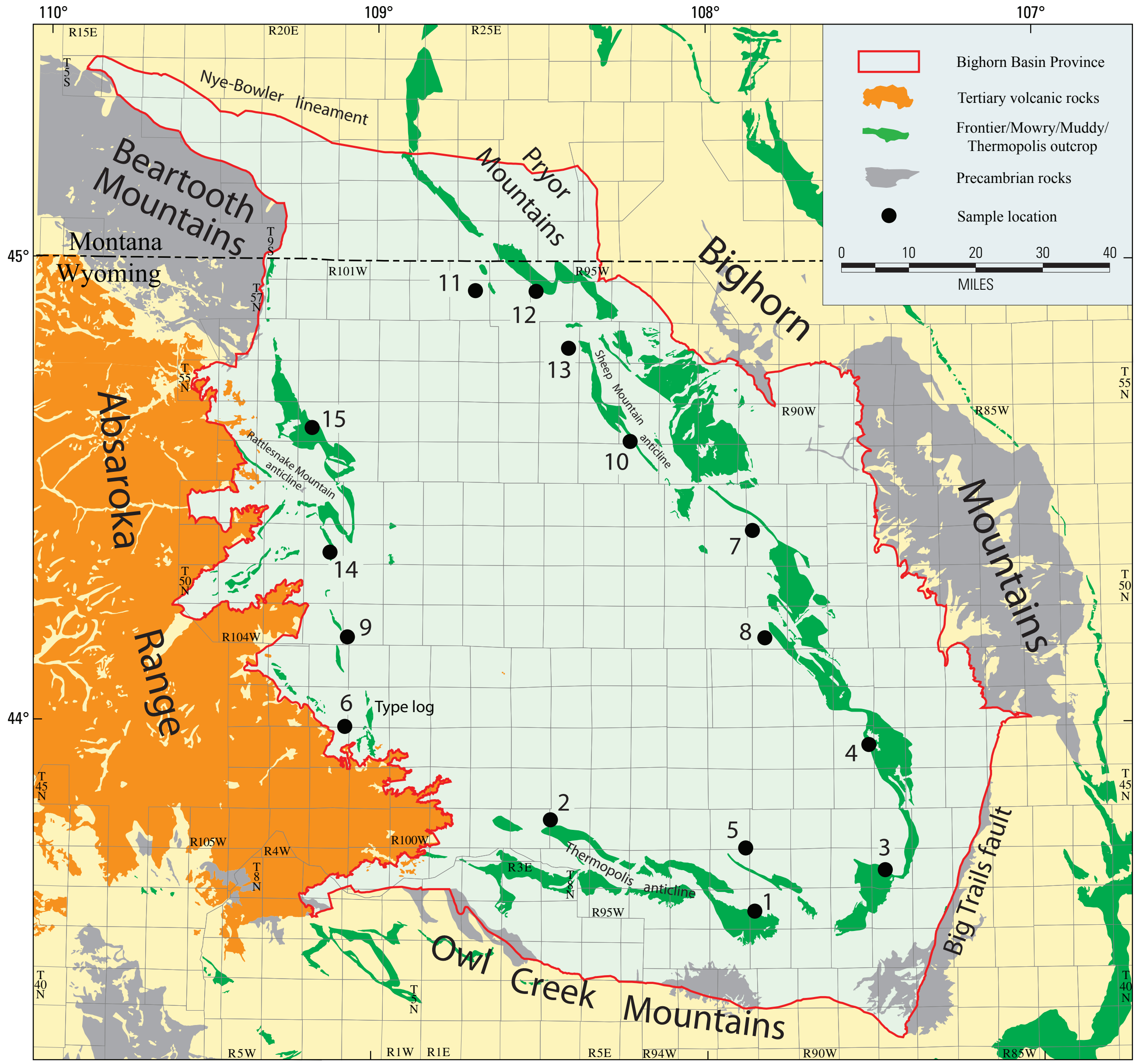

Figure 6. Index map of the Bighorn Basin showing sample localities.

less than 2.5, indicating poor generative potential (fig. 8*B*). Of the remaining samples, seven are in the fair range, and two fall in the good range, indicating the Mowry is generally a fair source rock.

Types of Organic Matter

According to Jacobson (1991) and Peters and Cassa (1994), there are four types of kerogen in sedimentary rocks: Type-I, composed of oil-prone hydrogen-rich organic matter generally in lacustrine and some marine sediments; Type-II, also composed of oil-prone hydrogen-rich organic matter mainly in marine sediments, Type-III composed of terrestrial organic matter derived mainly from woody plant material that is low in hydrogen content and generates mainly gas, and Type-IV composed of dead or inert carbon that has little or no generating capacity. Even though oil is the main product of Type-II kerogen, it actually produces more gas than Type-III kerogen (Hunt, 1996). Using the results of pyrolysis analysis, the type of kerogen present in a source rock can be determined by the hydrogen index (HI) and the oxygen index (OI), defined as $(S_2/TOC) \times 100$, and $(S_3/TOC) \times 100$, respectively (Espitalie and others, 1977; Tissot and Welte, 1978; and Hunt,

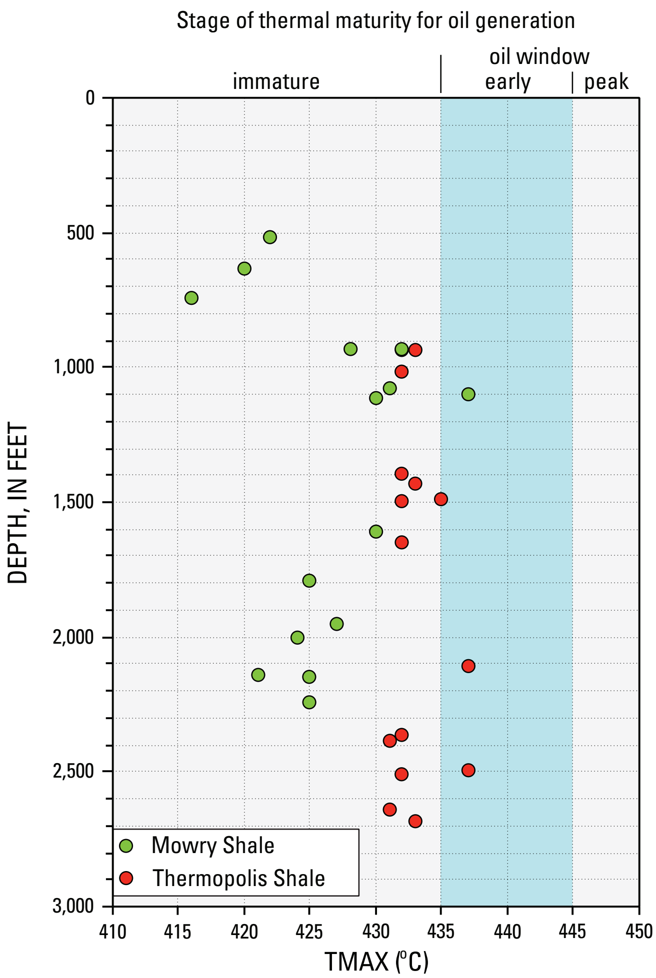

Figure 7. Tmax values plotted versus depth. Plot shows that all samples are immature or are in the early stages of thermal maturity with respect to oil generation. Parameters describing stages of thermal maturity for oil generation are from Peters and Casa (1994). Tmax, temperature (°C) corresponding to S2 peak from Rock-Eval pyrolysis.

1996). According to Hunt (1996), the type of hydrocarbons (oil or gas) generated from a source rock depends on the hydrogen content of the organic matter.

The HI and OI results from pyrolysis of the samples collected for the Thermopolis and Mowry Shales are shown on table 1 and plotted in figure 9. The plots for the 15 samples from the Thermopolis Shale show that most of the kerogen is Type-III indicating that the Thermopolis is a potential source rock mainly for gas (fig. 9). The plots for the 15 samples from the Mowry Shale show that most of the kerogen types are intermediate between Type-II and Type-III, indicating that the Mowry is a potential source for both oil and gas (fig. 9).

Another method of determining the type of hydrocarbons generated from a source rock is by using the ratio of the values S_2 and S_3 derived from pyrolysis analysis. According to Peters (1986), Peters and Cassa (1994), and Hunt (1996), the ratio S_2/S_3 is proportional to the amount of hydrogen in a source rock and is an indicator of the potential to generate oil and gas. According to Peters and Cassa (1994), rocks with an S_2/S_3 ratio less than 1 are not likely to produce any oil or gas, those with ratios between 1 and 5 produce gas, those with ratios between 5 and 10 produce both oil and gas, and those with ratios greater than 10 produce mainly oil.

The S_2/S_3 values for samples collected from the Thermopolis and Mowry Shales, are shown on table 1 and plotted in figure 10. The S_2/S_3 values for the Thermopolis Shale range from 1.35 to 7.76 indicating the Thermopolis is capable of generating both oil and gas (fig. 10). The S_2/S_3 values for the Mowry Shale range from 1.5 to 11.84 indicating the Mowry is capable of generating both oil and gas (fig. 10).

Distribution of Organic Matter in the Mowry Shale

Maps were constructed for the Mowry Shale to show variations in TOC and kerogen type (HI) across the Bighorn Basin (fig. 11). Maps were not constructed for the Thermopolis Shale due to the narrow range of values in TOC and HI (figs. 8, 9 and table 1).

Basin-wide variations of the type and amount of organic matter present in the Mowry Shale are shown in figure 11. Figure 11*A* shows that all of the samples with TOC contents greater than 2 weight percent occur in the southeastern and northeastern parts of the Bighorn Basin. This trend is in general agreement with mapping presented by Burtner and Warner (1984; their fig. 15). A similar trend was noted by Finn (2007) for the Mowry in the Wind River Basin to the south. Regional studies by Schrayer and Zarrella (1963, 1966, 1968), Nixon (1973), Byers and Larson (1979), Davis (1986), and Davis and others (1989) discussed a similar trend of decreasing TOC content from east to west and suggested several possibilities for this trend, including 1) clastic dilution of organic matter due to higher sedimentation rates along the western shoreline of the WIS as sediments were eroded from the Western Cordillera, 2) greater input of marine organic matter in the central part of the seaway, and 3) post-depositional biodegradation of organic matter near the margins of the basin where less anoxic conditions existed. Differences in sampling methodology in this study from previous studies, and the small number of samples may also bias trends. Figure 11*B* shows little variation in kerogen types based on HI for the Mowry Shale in the Bighorn Basin indicating that the Mowry is capable of generating both oil and gas throughout the basin.

Table 1. Rock-Eval and total organic carbon data for the Wyoming part of the Bighorn Basin. Map number in column 1 refers to the map location shown on figure 6. Depths are in feet. S1, milligrams of hydrocarbons per gram of rock; S2, milligrams of hydrocarbons per gram of rock; S3, milligrams of CO2 per gram of rock; PI, production index; TOC, total organic carbon in weight percent; HI, hydrogen index; OI, oxygen index; API, well number assigned by American Petroleum Institute; Tmax, temperature (°C) corresponding to S2 peak from Rock-Eval pyrolysis.

Map no.	API	Operator	Well name	Township	Range	Section	Top depth	Bottom depth	Formation	TOC	S1	S2	S1+S2	S3	S2/S3	Tmax	HI	OI	PI
1	49017205470000	Teton Energy	19-1 Hayes Ranch	42N	91W	19	740	770	Mowry	1.27	0.19	4.61	4.8	0.84	5.5	416	363	66	0.04
1	49017205470000	Teton Energy	19-1 Hayes Ranch	42N	91W	19	1,020	1,050	Thermopolis	1.55	0.17	2.36	2.53	0.57	4.14	432	152	37	0.07
2	49017202360000	Brinkerhoff Drlg.	Husky 3X-A	44N	96W	7	1,115	1,195	Mowry	1.8	0.31	2.31	2.62	0.82	2.81	430	128	46	0.12
2	49017202360000	Brinkerhoff Drlg.	Husky 3X-A	44N	96W	7	1,435	1,495	Thermopolis	1.5	0.34	2.32	2.66	0.52	4.46	433	155	35	0.13
3	49043202510000	Ashland Expl. Inc.	1-20 Chabot	43N	88W	20	630	690	Mowry	1.92	0.14	1.16	1.3	0.77	1.5	420	60	40	0.11
3	49043202510000	Ashland Expl. Inc.	1-20 Chabot	43N	88W	20	940	1,000	Thermopolis	1.71	0.22	3.49	3.71	0.45	7.76	433	204	26	0.06
4	49043201400000	Samedan Oil	1 Kellogg-Federal	46N	89W	13	520	560	Mowry	2.24	0.3	3.33	3.63	0.82	4.06	422	149	37	0.08
4	49043201400000	Samedan Oil	1 Kellogg-Federal	46N	89W	13	940	980	Thermopolis	1.45	0.21	2.19	2.4	0.48	4.56	432	151	33	0.09
5	49043050420000	Pacific Western	2 State Prescott	44N	92W	36	2,150	2,180	Mowry	2.13	0.44	4.47	4.91	0.75	5.96	425	210	35	0.09
5	49043050420000	Pacific Western	2 State Prescott	44N	92W	36	2,500	2,550	Thermopolis	1.5	0.24	2.67	2.91	0.5	5.34	437	178	33	0.08
6	49029213230000	Apache Corp.	36-11 State	47N	102W	36	930	990	Mowry	1.57	0.46	3.44	3.9	0.41	8.93	432	219	26	0.12
6	49029213230000	Apache Corp.	36-11 State	47N	102W	36	1,490	1,550	Thermopolis	1.19	0.16	1.53	1.69	0.24	6.38	435	129	20	0.09
7	4900320695000	DATA Bighorn	DATA 43-6	51N	91W	6	1,100	1,160	Mowry	1.73	0.02	0.08	0.1	0.02	4	437	5	1	0.2
7	4900320695000	DATA Bighorn	DATA 43-6	51N	91W	6	1,650	1,710	Thermopolis	1.42	0.15	2.06	2.21	0.37	5.57	432	145	26	0.07
8	49003305100000	Amerada	1 USA-Neal	49N	91W	28	2,140	2,220	Mowry	2.34	0.42	5.26	5.68	0.84	6.26	421	225	36	0.07
8	49003305100000	Amerada	1 USA-Neal	49N	91W	28	2,640	2,670	Thermopolis	1.91	0.35	3.19	3.54	0.58	5.5	431	167	30	0.1
9	49029210900000	National Oil Co.	33-30 Rawhide	49N	101W	30	2,000	2,010	Mowry	1.83	0.23	3.77	4	0.56	6.73	424	206	31	0.06
9	49029210900000	National Oil Co.	33-30 Rawhide	49N	101W	30	2,390	2,410	Thermopolis	1.84	0.2	3.09	3.29	0.42	7.36	431	168	23	0.06
10	49003205130000	Northern Natural Gas	Fed. 362 1-32	54N	94W	32	2,240	2,260	Mowry	1.75	0.23	4.38	4.61	0.37	11.84	425	250	21	0.05
10	49003205130000	Northern Natural Gas	Fed. 362 1-32	54N	94W	32	2,690	2,720	Thermopolis	1.42	0.11	2.15	2.26	0.34	6.33	433	151	24	0.05
11	49029212000000	National Oil Co.	42-10 Federal	57N	98W	10	1,950	1,960	Mowry	1.11	0.28	1.98	2.26	0.38	5.21	427	178	34	0.12
11	49029212000000	National Oil Co.	42-10 Federal	57N	98W	10	2,510	2,530	Thermopolis	1.34	0.12	1.41	1.53	0.41	2.78	432	105	31	0.08
12	49003050480000	True Oil	1 Dever	57N	96W	7	1,080	1,130	Mowry	1.71	0.48	3.71	4.19	0.54	6.87	431	217	32	0.11
12	49003050480000	True Oil	1 Dever	57N	96W	7	1,500	1,530	Thermopolis	1.07	0.21	1.04	1.25	0.77	1.35	432	97	72	0.17
13	49003063720000	Graves-Davis Oil	3 Asay	56N	96W	23	1,790	1,820	Mowry	2.65	0.65	8.41	9.06	0.92	9.14	425	317	35	0.07
13	49003063720000	Graves-Davis Oil	3 Asay	56N	96W	23	2,370	2,410	Thermopolis	1.04	0.21	0.82	1.03	0.5	1.64	432	79	48	0.21
14	49029055880000	Aztec Oil and Gas	Federal-H M 1	51N	102W	27	930	970	Mowry	1.56	0.17	1.68	1.85	0.51	3.29	428	108	33	0.09
14	49029055880000	Aztec Oil and Gas	Federal-H M 1	51N	102W	27	1,400	1,430	Thermopolis	1.53	0.14	2.29	2.43	0.54	4.24	432	150	35	0.06
15	49029214170000	Texaco Inc.	1 H C Sheets	54N	102W	21	1,610	1,650	Mowry	1.38	0.22	1.79	2.01	0.78	2.29	430	130	57	0.11
15	49029214170000	Texaco Inc.	1 H C Sheets	54N	102W	21	2,110	2,160	Thermopolis	1.62	0.21	2.52	2.73	0.54	4.67	437	156	33	0.08

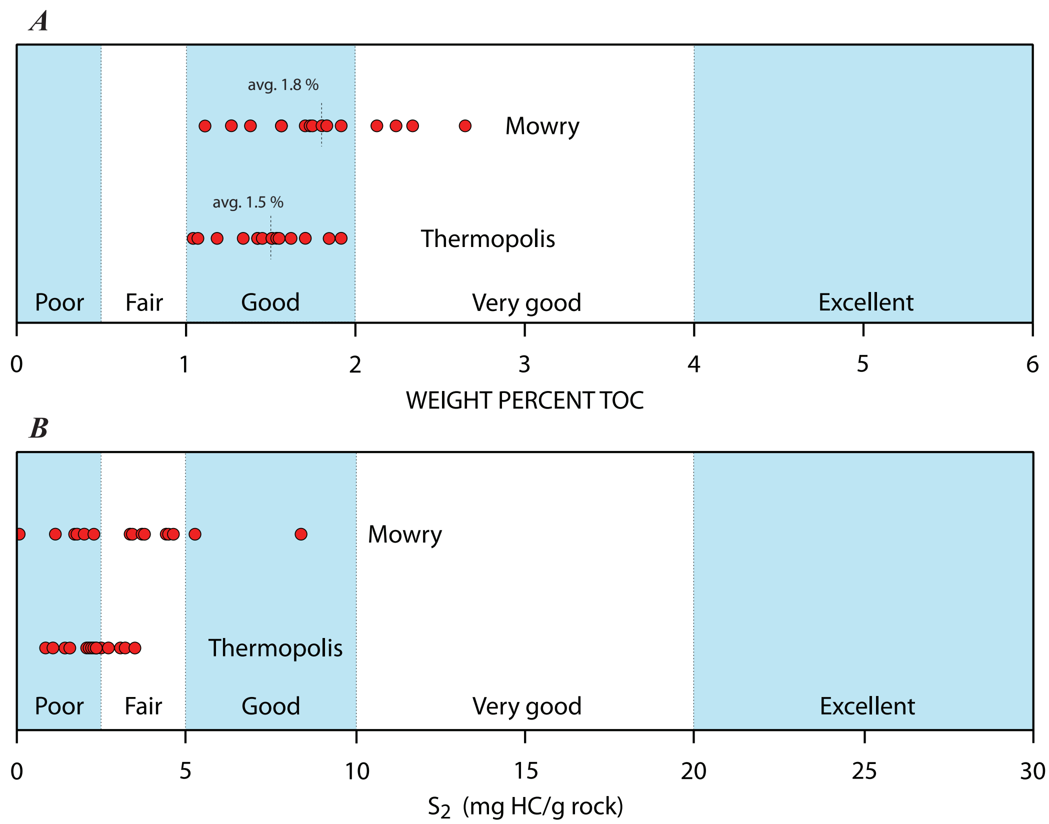

Figure 8. Plots showing source rock potential of the Thermopolis and Mowry Shales based on (*A*) total organic carbon content and (*B*) S2 values derived from Rock-Eval pyrolysis. Parameters describing source rock generative potential are from Peters and Casa (1994). TOC, total organic carbon; mg HC/g rock, milligrams of hydrocarbons per gram of rock.

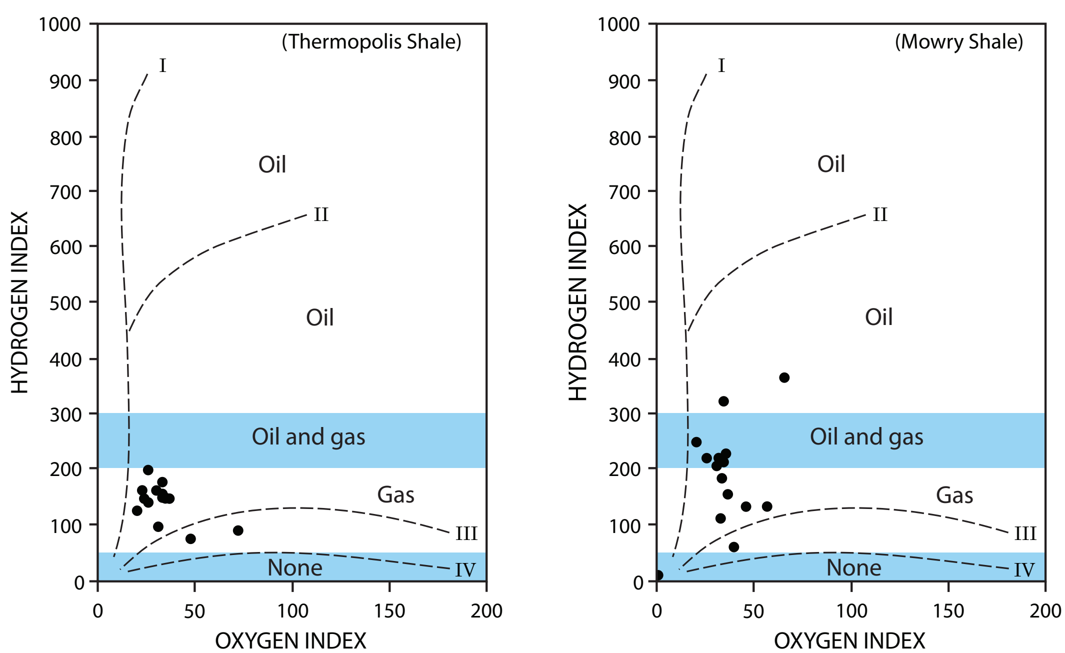

Figure 9. Plots of hydrogen index versus oxygen index showing kerogen types for samples (black dots) from the Thermopolis and Mowry Shales in the Bighorn Basin. Hydrocarbon type (oil or gas) from Peters and Casa (1994).

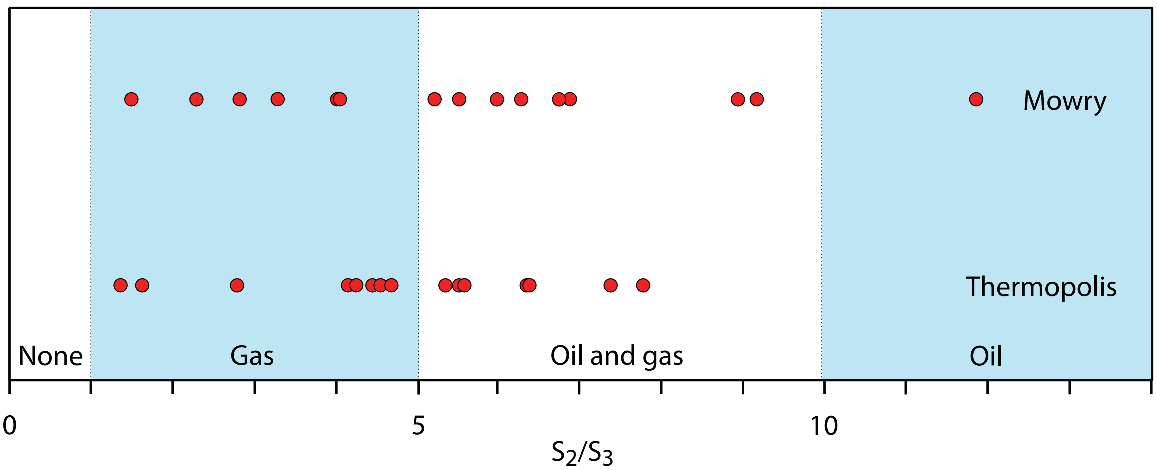

Figure 10. S_2/S_3 ratios for Thermopolis and Mowry Shales in the Bighorn Basin. Parameters describing type of hydrocarbons generated are from Peters and Cassa (1994). S_2, milligrams of hydrocarbons per gram of rock; S_3, milligrams of CO_2 per gram rock (Peters, 1986).

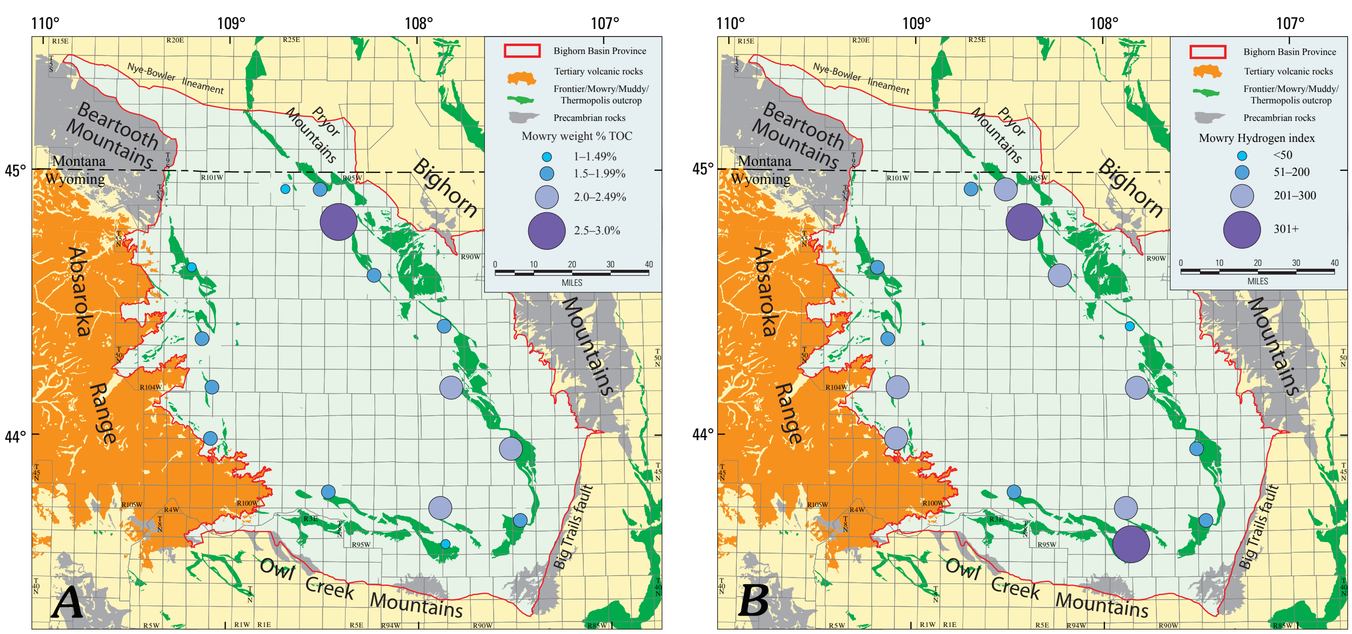

Figure 11. Maps of Bighorn Basin showing variations of (*A*) total organic carbon (TOC) content and (*B*) kerogen type based on hydrogen index for the Mowry Shale.

Summary

Results of TOC and Rock-Eval analyses of potential hydrocarbon-source rocks for the Thermopolis and Mowry Shales in the Bighorn Basin are summarized as follows:

1. The Mowry Shale has poor to good generative potential, with organic matter intermediate between kerogen Types-II and -III and the capability of generating both oil and gas.

2. The Thermopolis Shale has poor to fair generative potential, and contains mainly Type-III gas-prone kerogen based on hydrogen indices. However; S_2/S_3 ratios indicate that the Thermopolis is capable of generating both oil and gas.

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