Lower Cody Shale (Niobrara Equivalent) in the Bighorn Basin, Wyoming and Montana—Thickness, Distribution, and Source Rock Potential

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By Thomas M. Finn

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Lower Cody Shale (Niobrara Equivalent) in the Bighorn Basin, Wyoming and Montana—Thickness, Distribution, and Source Rock Potential

By Thomas M. Finn

Abstract

The lower shaly member of the Cody Shale in the Bighorn Basin, Wyoming and Montana is Coniacian to Santonian in age and is equivalent to the upper part of the Carlile Shale and basal part of the Niobrara Formation in the Powder River Basin to the east. The lower Cody ranges in thickness from 700 to 1,200 feet and underlies much of the central part of the basin. It is composed of gray to black shale, calcareous shale, bentonite, and minor amounts of siltstone and sandstone. Sixty-six samples, collected from well cuttings, from the lower Cody Shale were analyzed using Rock-Eval and total organic carbon analysis to determine the source rock potential. Total organic carbon content averages 2.28 weight percent for the Carlile equivalent interval and reaches a maximum of nearly 5 weight percent. The Niobrara equivalent interval averages about 1.5 weight percent and reaches a maximum of over 3 weight percent, indicating that both intervals are good to excellent source rocks. S_2 values from pyrolysis analysis also indicate that both intervals have a good to excellent source rock potential. Plots of hydrogen index versus oxygen index, hydrogen index versus T_{max} , and S_2/S_3 ratios indicate that organic matter contains both Type II and Type III kerogen capable of generating oil and gas. Maps showing the distribution of kerogen types and organic richness for the lower shaly member of the Cody Shale show that it is more organic-rich and more oil-prone in the eastern and southeastern parts of the basin. Thermal maturity based on vitrinite reflectance (R_o) ranges from 0.60–0.80 percent R_o around the margins of the basin, increasing to greater than 2.0 percent R_o in the deepest part of the basin, indicates that the lower Cody is mature to overmature with respect to hydrocarbon generation.

Introduction

The Bighorn Basin is a large intermontane basin that formed in the Rocky Mountain foreland during the Laramide orogeny (Late Cretaceous through early Eocene). The basin is nearly 180 miles (mi) long, 100 mi wide, and encompasses about 10,400 square miles (mi²) in north-central Wyoming

and south-central Montana (fig. 1). The basin is bounded by major basement uplifts that include the Pryor Mountains on the northeast, the Beartooth Mountains on the northwest, the Bighorn Mountains on the east, and the Owl Creek Mountains on the south. The northern margin includes a zone of faulting and folding referred to as the Nye-Bowler lineament (Wilson, 1936). The western margin is formed by volcanic rocks of the Absaroka Range (fig. 2).

Hydrocarbon production from Cretaceous reservoirs was established in 1906 and 1907 with the discoveries of Garland and Greybull fields, respectively (Fox and Dolton, 1996). 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 in the deeper parts of the basin (Ryder, 1987; Surdam and others, 1997; Johnson and Finn, 1998; Johnson and others, 1999; Finn and others, 2010). It has been suggested that various Cretaceous marine shales are the principal hydrocarbon source rocks for these accumulations (Burtner and Warner, 1984; Hagen and Surdam, 1984; Meissner and others, 1984; Fox and Dolton, 1989, 1996).

Recent advances and success in horizontal drilling and multistage fracture stimulation have led to an increase in exploration and completion of wells in Cretaceous marine shales in other Rocky Mountain basins that were traditionally thought of only as source rocks (Sterling and others, 2009; Sonnenberg, 2011). Studies of the Mowry Shale by numerous authors, including Schroyer and Zarella (1963, 1966, 1968), Nixon (1973), Burtner and Warner (1984), Davis (1986), Miskell-Gerhardt (1989), and Finn (2010), have demonstrated its source rock potential in the Bighorn Basin. However, with the exception of a study of Cretaceous source rocks by Hagen and Surdam (1984), little or no geochemical data have been published about the source rock potential of the Upper Cretaceous Cody Shale in the Bighorn Basin. The purpose of this report is to present the results of Rock-Eval and total organic carbon (TOC) analysis for samples collected from lower Cody Shale in the Bighorn Basin and characterize its source rock potential.

Figure 1. Map of the 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).

Depositional Setting

During much of Late Cretaceous time, the part of Wyoming and Montana 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 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 of the WIS was part of the stable craton that was topographically low and supplied little sediment (Molenaar and Rice, 1988). During much of Late 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 nonmarine deposits are represented by eastward-thinning wedges of marginal marine and nonmarine sandstone, siltstone, shale, carbonaceous shale, and coal. The marine deposits are represented by westward-thinning tongues of marine shale, siltstone, and marine sandstone. 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 (Gries and others, 1992). These transgressions also resulted in two episodes of carbonate deposition in the WIS, the first being the Greenhorn Formation and the second being the Niobrara Formation (Longman and others, 1998; Sonnenberg, 2011). The Niobrara interval is characterized by deposition of cherts and marls composed of foraminifers and coccolith debris that accumulated in the eastern part of the seaway (Longman and others, 1998; Sonnenberg, 2011). The cherts grade westward into more siliciclastic beds that were derived from the eroding highlands to the west, that diluted the carbonate sediments (Longman and others, 1998; Sonnenberg, 2011) (fig. 5). In the Bighorn Basin of north-central Wyoming and southern Montana, the Niobrara equivalent rocks are represented by shales, calcareous shales, siltstones, and sandstones of the Cody Shale (fig. 6).

Figure 3. Map showing approximate extent of the Western Interior Seaway in North America during late Coniacian (*Scaphites depressus* Zone) time. Modified from Cobban and others (2005).

Figure 4. Regional northwest-southeast stratigraphic cross section of Cretaceous (part) rocks in the Bighorn Basin, Wyoming and Montana. Modified from Finn and others (2010).

Figure 5. Paleogeographic reconstruction of the Rocky Mountain region during late Coniacian (*Scaphites depressus* Zone) time showing major depositional trends. Bighorn Basin Province is outlined in red. Modified from McGookey (1972).

Ma	System	Series	Stage	Fossil zone	Montana	Northern Bighorn Basin	Western and southwestern Bighorn Basin	Eastern and southeastern Bighorn Basin	Western Powder River Basin	Eastern Powder River Basin
80	CRETACEOUS (part)	UPPER CRETACEOUS (part)	Campanian (part)	U	Judith River Formation (part)	Mesaverde Formation (part)	Mesaverde Formation (part)	Mesaverde Formation (part)	Mesaverde Formation (part)	Pierre Shale (part)
				Middle						
83.5				L						
85			Santonian	U	Cody Shale	Cody Shale	Cody Shale	Cody Shale	Cody Shale	Niobrara Member
86.3				L						
88.7			Coniacian	U	Cody Shale	Cody Shale	Cody Shale	Cody Shale	Cody Shale	Cody Shale
90				L						
93.3			Turonian	U	Frontier Formation	Frontier Formation	Frontier Formation	Frontier Formation	Frontier Formation	Frontier Formation
95				L						
98.5			Cenomanian	U	Frontier Formation	Frontier Formation	Frontier Formation	Frontier Formation	Frontier Formation	Frontier Formation
100				L						
		LK (part)	Albian (part)							

Figure 6. Correlation chart showing the stratigraphic nomenclature for Upper Cretaceous rocks in the Bighorn Basin and the relationship to various localities in the Powder River Basin to the east. Radiometric ages and fossil zones are from Obradovich (1993) and Merewether (1996). Powder River Basin columns modified from Merewether (1996). Bighorn Basin columns compiled from Merewether (1996), Obradovich and others (1996), Keefer and others (1998), and Kirschbaum and others (2009). LK, Lower Cretaceous.

Stratigraphy

Cody Shale

The Cody Shale in the Bighorn Basin is in part the equivalent to the Niobrara Formation in the Powder River basin to the east (fig. 6). It consists of marine shale, interbedded with siltstone and sandstone, with the amount of sandstone increasing in the upper part (Keefer and others, 1998). The Cody was deposited during a major transgressive-regressive cycle referred to as the “Niobrara Cyclothem” by Kauffman (1977), and ranges in age from Coniacian to middle Campanian (Keefer, 1972; Keefer and others, 1998). The lower and upper contacts interfinger extensively with the underlying Frontier and overlying Mesaverde Formations (fig. 4). The formation is about 1,750 ft thick in the northern part of the basin increasing to nearly 3,800 ft in the southeastern part (fig. 7). This southeastward thickening is due to the eastward stratigraphic rise and intertonguing of the contact between the Cody Shale and the overlying Mesaverde Formation, and the west to northwestward backstepping nature of the Frontier/Cody contact (fig. 4). Three members are recognized, in ascending order: (1) the unnamed lower shaly member (Keefer, 1972); (2) the unnamed upper sandy member (Keefer, 1972); and (3) the Claggett Member (Keefer and others, 1998) (figs. 4 and 6).

The unnamed lower shaly member reaches a maximum thickness of about 1,200 ft in the southern part of the basin and thins to the north to about 700 ft (fig. 8). It is composed of gray to black shale, calcareous shale, and bentonite, with minor amounts of siltstone and sandstone that were deposited in an offshore marine environment. A persistent zone referred to as the “chalk kick” marker by Keefer (1972) is recognized on resistivity logs in the lower part of the lower member (figs. 9 and 10). This zone, which can be traced in the subsurface throughout most of the basin, separates calcareous beds above from noncalcareous beds below. Based on correlations across the Powder River and Wind River Basins, the calcareous interval extending from the “chalk kick” to the base of the overlying upper sandy member is equivalent to the basal part of the Niobrara Formation in the Powder River Basin (Keefer, 1972; Merewether and others, 1977a, b; Finn, 2007a). This interval thickens from about 500–700 ft in the southeastern and northern parts of the basin to about 1,000 ft in the southwestern part of the basin reflecting an increase in sediment supply eroded from the western Cordilleran highlands (fig. 11). In the subsurface, numerous marker beds or resistivity patterns can be identified in this interval on electric logs (fig. 10). According to Asquith (1970) and Molenaar and Baird (1991), these distinct patterns are a response to variations in bentonite, sand, silt, and carbonate content, and can be considered time markers. In the basal Niobrara equivalent, the strata produce clinoform patterns that dip to the east, downlapping onto the “chalk kick” marker (fig. 10). The interval extending downward from the “chalk kick” marker to the top of the uppermost sandstone bed in

the Frontier Formation is equivalent to the upper part of the Carlile Shale in the Powder River Basin to the east (figs. 6, 9, and 10). This interval, ranging in thickness from greater than 400 ft in the southeastern part of the basin to less than 100 ft in the northern part, reflects the back-stepping stacking pattern of the sandstones in the underlying Frontier Formation (figs. 10 and 12).

The upper sandy member ranges in thickness from about 2,700 ft in the southern part of the basin to around 1,000 ft in the northern part of the basin. It consists of buff, or light- to medium-gray sandstones, and gray shales (Johnson and others, 1998). According to Johnson and others (1998), the sandstones are very fine to medium-grained, laterally persistent, and exhibit a variety of bedding features including horizontal laminae, ripple laminae, and hummocky crossbedding.

The Claggett Member of the Cody Shale (known as the Claggett Shale in Montana) is a westward thinning tongue of marine shale that is split from the upper part of the Cody Shale by the lower member of the Mesaverde Formation (Eagle Sandstone in Montana) (figs. 4 and 6). It is composed predominantly of light- to medium-gray shale interbedded with thin siltstone and fine- to medium-grained sandstone (Johnson and others, 1998). The Claggett Member extends across the eastern and central parts of the basin, and thickens eastward from zero to nearly 500 ft thick at its eastern limit where it merges with the upper part of the main body of the Cody Shale (fig. 4) (Finn and others, 2010).

Methods

Sixty-six samples from 26 wells were collected from well cuttings from the lower member of the Upper Cretaceous Cody Shale stored at the U.S. Geological Survey Core Research Center in Lakewood, Colorado. The wells selected are located near the outcrop belt along the margins of the basin in order to obtain samples that were not subjected to the effects of deep burial and subsequent organic carbon loss due to thermal maturation as described by Daly and Edman (1987) (figs. 13 and 14). Twenty samples are from the Carlile equivalent, and 46 from the lower Cody interval extending from the “chalk kick” marker to the base of the upper sandy member of the Cody (basal Niobrara equivalent of the Powder River Basin). Sample intervals were determined by examining the cuttings 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), who suggested that TOC content generally increases as color goes from gray to black and therefore is a rough indicator of organic richness. Obvious material from cavings and contamination, such as wood chips, metal, and plastic, were removed. The cuttings were composited into samples from thickness intervals that were generally 60 to 140 ft thick but ranged from 30 to 330 ft depending on how much material was available for a proper analysis.

Figure 9. Type log of Lower Cretaceous and lowermost Upper Cretaceous rocks in the southeastern part of the Bighorn Basin. Location shown in figure 2. GR, gamma ray; Res., resistivity.

Figure 10. West-east electric log cross section of the lower Cody Shale and associated strata.

The whole-rock samples were ground to a fine powder and splits were sent with an internal U.S. Geological Survey laboratory standard to an outside geochemical laboratory for analysis. Total organic carbon content was determined using the Leco combustion method described by Jarvie (1991), and the pyrolysis analysis was done using a Rock-Eval 2 pyroanalyzer. (See Espitalie and others, 1977; Tissot and Welte, 1978; Peters, 1986; Hunt, 1996, for detailed discussions of the pyrolysis method.) The results are presented in table 1.

Results

Quantity of Organic Matter

According to Jarvie (1991), the quantity of organic matter in a formation measured as weight percent total organic carbon (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 have fair generative potential; rocks with 1–2 weight percent TOC have good generative potential; rocks with 2–4 weight percent TOC are considered to have very good generative potential; and rocks with greater than 4 weight percent TOC are considered to have excellent generative potential (Peters and Cassa, 1994). Table 1 and figure 15 show the results of TOC analyses of the lower Cody Shale in the Bighorn Basin.

The results of TOC analyses of the 20 samples collected from the Carlile equivalent of the lower Cody Shale show values ranging from about 1.0 to nearly 5 percent, with an average of 2.28 percent indicating a good to excellent generative potential (fig. 15). The 46 samples collected from the basal Niobrara equivalent part of the lower Cody Shale have TOC values that range from about 0.5 to 3.36 percent, with an average of 1.46 percent. However, most samples from this interval have TOC contents greater than 1 percent, indicating a good to very good generative potential.

Peters and Cassa (1994) and Dembicki (2009) point 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, and 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 lower Cody Shale are presented in table 1 and on figure 16. The 20 samples from the Carlile equivalent show a range of S_2 values from 0.9 to 22; all but 6 have an S_2 greater than 2.5, indicating that it is a fair to excellent source rock. Around 30 of the samples from the Niobrara equivalent part of the lower Cody Shale have S_2 values of less than 2.5 and therefore are considered poor source rocks. The remaining samples from the Niobrara equivalent have S_2 values in the fair to very good range.

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 found in lacustrine and some marine sediments; Type II, also composed of oil-prone, hydrogen-rich organic matter mainly found 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 from plots showing hydrogen index (HI) versus oxygen index (OI) which are defined as $(S_2/TOC) \times 100$ and $(S_3/TOC) \times 100$, respectively (Espitalie and others, 1977; Tissot and Welte, 1978; Hunt, 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 analysis of the samples collected for the lower Cody Shale are shown on table 1 and plotted in figure 17A. The plots for the samples from the Carlile equivalent and basal Niobrara equivalent strata from the lower Cody Shale show that most of the kerogen is Type II and mixed Type II and Type III, indicating that both intervals in the lower Cody have the potential to generate both oil and gas. Similar results are shown on a plot of HI versus T_{max} (fig. 17B).

S_2/S_3 ratios are also an indicator of the type of hydrocarbons generated from a source rock. 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 (1986), rocks with an S_2/S_3 ratio less than 3 produce gas, those with ratios between 3 and 5 produce both oil and gas, and those with ratios greater than 5 produce mainly oil. Peters and Cassa (1994) went on to state that rocks with S_2/S_3 values less than 1 are not likely to produce any oil or gas.

The S_2/S_3 values for samples collected from the lower Cody Shale are shown on table 1 and plotted in figure 18. Three samples from the Carlile equivalent have S_2/S_3 values between 1 and 3, indicating that it is gas prone. The remaining

Figure 14. $T_{\max}$ values versus depth. Plot shows that samples are immature with respect to oil generation. Parameters describing stages of thermal maturity are from Peters and Cassa (1994).

17 samples from the Carlile equivalent strata have S_2/S_3 values ranging from 3 to nearly 15, indicating this interval is capable of generating both oil and gas (fig. 18). Ten samples from the basal Niobrara equivalent part of the Cody Shale have an S_2/S_3 value of less than 1 and are not likely to generate any hydrocarbons. Twenty-one samples fall between 1 and 3 and are gas prone. The remaining samples have S_2/S_3 values ranging from 3 to about 9, indicating kerogen types capable of generating both oil and gas.

Distribution of Organic Matter

Basin-wide variations of the type and amount of organic matter present in the lower Cody Shale are shown in figures 19 and 20. Figure 19 shows that the richest source rocks based on TOC content occur in the eastern and southeastern part of the basin. Here the TOC content is generally greater than 2

weight percent and reaches a maximum of nearly 5 weight percent. The TOC content decreases to the west where it is generally less than 2 weight percent (fig. 19). Regional studies of the Niobrara and equivalent rocks in the WIS by Longman and others (1998) and Landon and others (2001) documented a similar trend of decreasing TOC content from east to west. Finn (2007b) also noted a similar trend for equivalent rocks in the Wind River Basin to the south. Longman and others (1998) and Landon and others (2001) believed that sediments with the higher TOC contents accumulated in the sediment-starved central and eastern parts of the seaway and that the westward decrease in TOC content was due to clastic dilution.

Figure 20 shows the variation in kerogen types for the lower member of the Cody Shale in the Bighorn Basin. The more oil-prone source rocks occur in the eastern and southeastern part of the basin. Here, HI values are generally greater than 200 and maximum values are up to over 500, the predominant kerogen being Type II derived from marine sources. In the western part of the basin, HI values decrease to less than 200, and the organic matter is predominantly Type III gas-prone kerogen. Meissner and others (1984) and Landon and others (2001) observed these same geographic variations for equivalent rocks from regional studies and concluded that the Type III organic material was derived mainly from terrestrial sources to the west.

Thermal Maturity

A map showing the levels of thermal maturation based on vitrinite reflectance (R_o) measurements for the Bighorn Basin is presented in figure 21. The map is from Finn and Pawlewicz (2014) and was constructed using R_o data published by Nuccio and Finn (1998), Finn and Pawlewicz (2007), Roberts and others (2008), and Pawlewicz and Finn (2012). The isorefectance contours are drawn on top of the lower Cody Shale, which ranges from 700 to 1,200 ft thick across the basin (fig. 8); so the R_o values presented here (fig. 21) are considered to represent minimum levels of thermal maturation for the interval. The R_o values generally range from less than 0.60–0.80 percent around the basin margins, increasing to greater than 2.0 percent in the deeper part of the basin, a pattern that generally reflects the basin structure (fig. 2). Figure 22 is a generalized west-east structural cross section extending across the central part of the basin showing the relationship between present-day structure and thermal maturity. In general, the isorefectance lines are subhorizontal and cut across structures indicating that the thermal maturation trends developed after structural development of the basin (Bustin and others, 1985).

Two burial history curves (using PetroMod 1D Express) were used to determine the depth of burial, and the timing of petroleum generation of the lower Cody Shale (figs. 23A–B). The Forest Oil 1 Emblem Bench, located near the basin axis, in sec. 2, T. 51 N., R. 98 W., represents an area of the basin that underwent maximum burial (fig. 2). The Exxcel Energy

Table 1. Rock-Eval and total organic carbon data for the Bighorn Basin, Wyoming and Montana.

[Map number in column 1 refers to well locations shown on figure 13. API, American Petroleum Institute; top and bottom 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 [S₁/(S₁+S₂)]; TOC, total organic carbon in weight percent; HI, hydrogen index; OI, oxygen index]

Map no.	API	Operator	Well	Township	Range	Section	Top	Bottom	Formation	T _{max}	S ₁	S ₂	S ₁ +S ₂	S ₃	PI	S ₂ /S ₃	TOC	HI	OI
1	49043050320000	Sohio Pet.	1 Bruce Unit	43N	89W	7	510	770	Niobrara equiv.	429	0.43	1.60	2.03	0.98	0.21	1.63	1.40	114	70
1	49043050320000	Sohio Pet.	1 Bruce Unit	43N	89W	7	770	1,100	Niobrara equiv.	431	0.41	0.80	1.21	0.86	0.34	0.93	1.18	68	73
1	49043050320000	Sohio Pet.	1 Bruce Unit	43N	89W	7	1,140	1,360	Niobrara equiv.	433	0.4	2.66	3.06	0.76	0.13	3.50	1.61	165	47
1	49043050320000	Sohio Pet.	1 Bruce Unit	43N	89W	7	1,390	1,480	Carlile equiv.	419	0.65	10.95	11.6	1.27	0.06	8.60	2.69	407	47
2	49043050290000	Arrowhead Expl.	State 11–16	43N	90W	16	1,240	1,410	Niobrara equiv.	422	0.21	1.38	1.59	0.63	0.13	2.19	1.18	117	53
2	49043050290000	Arrowhead Expl.	State 11–16	43N	90W	16	1,510	1,670	Niobrara equiv.	420	0.13	0.28	0.41	0.69	0.31	0.41	0.48	60	144
2	49043050290000	Arrowhead Expl.	State 11–16	43N	90W	16	1,910	2,090	Niobrara equiv.	428	0.4	2.44	2.84	0.87	0.14	2.80	1.52	161	57
3	49017053320000	Cosden Pet.	1 Govt.	43N	91W	14	800	990	Niobrara equiv.	432	0.09	0.81	0.9	0.92	0.10	0.88	1.12	72	82
3	49017053320000	Cosden Pet.	1 Govt.	43N	91W	14	1,000	1,240	Niobrara equiv.	426	0.34	3.48	3.82	1.20	0.09	2.90	1.54	226	76
3	49017053320000	Cosden Pet.	1 Govt.	43N	91W	14	1,290	1,360	Carlile equiv.	421	0.41	9.67	10.08	1.70	0.04	5.69	2.78	348	61
4	49043050480000	Texas Pacific	USA 1–B	44N	88W	35	500	640	Niobrara equiv.	424	0.30	2.82	3.12	1.40	0.10	2.00	1.81	156	77
4	49043050480000	Texas Pacific	USA 1–B	44N	88W	35	940	1,030	Niobrara equiv.	421	0.41	7.51	7.92	1.67	0.05	4.50	2.86	263	58
4	49043050480000	Texas Pacific	USA 1–B	44N	88W	35	1,050	1,100	Carlile equiv.	425	0.16	4.27	4.43	1.39	0.04	3.10	2.16	198	64
5	49043050690000	Sohio Pet.	1 Govt–Wilson	44N	91W	28	3,350	3,510	Niobrara equiv.	431	0.27	2.18	2.45	0.77	0.11	2.83	1.64	133	47
6	49043050390000	Shannon O& G	1 Govt. Gardner	44N	91W	31	900	1,000	Niobrara equiv.	425	0.21	0.80	1.01	0.63	0.21	1.27	0.98	82	64
6	49043050390000	Shannon O& G	1 Govt. Gardner	44N	91W	31	1,020	1,220	Niobrara equiv.	429	0.31	2.82	3.13	0.64	0.10	4.41	1.41	200	45
6	49043050390000	Shannon O& G	1 Govt. Gardner	44N	91W	31	1,250	1,310	Niobrara equiv.	414	0.5	11.69	12.19	1.24	0.04	9.43	2.61	448	48
6	49043050390000	Shannon O& G	1 Govt. Gardner	44N	91W	31	1,320	1,390	Carlile equiv.	424	0.24	4.33	4.57	1.06	0.05	4.08	2.17	200	49
7	49043050680000	Arrowhead Expl.	Federal 14–27	44N	92W	27	1,000	1,140	Niobrara equiv.	430	0.09	0.82	0.91	0.57	0.10	1.44	1.08	76	53
7	49043050680000	Arrowhead Expl.	Federal 14–27	44N	92W	27	1,140	1,380	Niobrara equiv.	426	0.16	1.03	1.19	0.43	0.14	2.40	1.03	100	42
7	49043050680000	Arrowhead Expl.	Federal 14–27	44N	92W	27	1,410	1,560	Niobrara equiv.	429	0.19	1.69	1.88	0.53	0.10	3.19	1.30	130	41
7	49043050680000	Arrowhead Expl.	Federal 14–27	44N	92W	27	1,620	1,850	Niobrara equiv.	429	0.18	1.35	1.53	0.45	0.12	3.00	1.28	105	35
8	49017201820000	NCRA	Federal–Mercer 1	44N	93W	21	1,420	1,510	Niobrara equiv.	430	0.08	0.45	0.53	0.81	0.16	0.56	1.03	44	79
8	49017201820000	NCRA	Federal–Mercer 1	44N	93W	21	1,600	1,690	Niobrara equiv.	428	0.11	0.46	0.57	0.75	0.20	0.61	1.05	44	71
8	49017201820000	NCRA	Federal–Mercer 1	44N	93W	21	1,720	1,810	Niobrara equiv.	426	0.1	0.60	0.7	0.51	0.14	1.18	1.00	60	51
8	49017201820000	NCRA	Federal–Mercer 1	44N	93W	21	1,810	1,900	Niobrara equiv.	423	0.12	2.20	2.32	0.81	0.05	2.72	1.66	133	49
9	49017054630000	Continental Oil	Kiralay 1	44N	94W	28	1,370	1,460	Niobrara equiv.	452	0.18	0.32	0.5	0.47	0.35	0.68	0.81	40	58
9	49017054630000	Continental Oil	Kiralay 1	44N	94W	28	1,880	2,090	Niobrara equiv.	427	0.09	0.26	0.35	0.38	0.26	0.68	0.91	29	42
9	49017054630000	Continental Oil	Kiralay 1	44N	94W	28	2,090	2,290	Niobrara equiv.	429	0.16	0.84	1	0.40	0.16	2.10	0.96	88	42
9	49017054630000	Continental Oil	Kiralay 1	44N	94W	28	2,290	2,390	Carlile equiv.	429	0.3	3.80	4.1	0.69	0.07	5.51	1.52	250	45

Table 1. Rock-Eval and total organic carbon data for the Bighorn Basin, Wyoming and Montana.—Continued

[Map number in column 1 refers to well locations shown on figure 13. API, American Petroleum Institute; top and bottom 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 [S₁/(S₁+S₂)]; TOC, total organic carbon in weight percent; HI, hydrogen index; OI, oxygen index]

Map no.	API	Operator	Well	Town-ship	Range	Sec-tion	Top	Bottom	Formation	T _{max}	S ₁	S ₂	S ₁ +S ₂	S ₃	PI	S ₂ /S ₃	TOC	HI	OI
10	49017058750000	Western Empire	1 Govt.	44N	96W	11	1,400	1,510	Niobrara equiv.	417	0.25	0.49	0.74	1.04	0.33	0.50	1.07	46	97
11	49043204100000	Chorney Oil	W. Bud Kimball 31–1	45N	89W	1	2,190	2,490	Niobrara equiv.	424	0.17	3.88	4.05	0.93	0.04	4.17	1.60	243	58
11	49043204100000	Chorney Oil	W. Bud Kimball 31–1	45N	89W	1	2,690	2,870	Niobrara equiv.	428	0.16	1.80	1.96	0.80	0.08	2.25	1.37	131	58
11	49043204100000	Chorney Oil	W. Bud Kimball 31–1	45N	89W	1	2,900	2,990	Niobrara equiv.	425	0.24	4.91	5.15	1.01	0.05	4.86	2.03	242	50
	49043204100000	Chorney Oil	W. Bud Kimball 31–1	45N	89W	1	2,990	3,050	Carlile equiv.	422	0.53	21.84	22.37	1.49	0.02	14.66	4.02	543	37
12	49017059910000	Signal O & G	LA Sheep 35–1	46N	98W	35	1,900	2,000	Niobrara equiv.	426	0.14	2.04	2.18	0.37	0.06	5.50	1.23	166	30
12	49017059910000	Signal O & G	LA Sheep 35–1	46N	98W	35	2,040	2,120	Carlile equiv.	427	0.30	2.55	2.85	0.52	0.11	4.90	1.49	171	35
13	49043052730000	Pan American Pet.	Unit 6	47N	90W	18	2,320	2,390	Niobrara equiv.	410	0.44	14.17	14.61	1.97	0.03	7.20	3.36	422	59
13	49043052730000	Pan American Pet.	Unit 6	47N	90W	18	2,420	2,480	Carlile equiv.	409	0.54	20.21	20.75	2.22	0.03	9.10	4.87	415	46
14	49017600010000	Pan American Pet.	USA C–1	47N	99W	17	2,080	2,150	Niobrara equiv.	429	0.15	2.43	2.58	0.54	0.06	4.50	1.45	167	37
14	49017600010000	Pan American Pet.	USA C–1	47N	99W	17	2,170	2,220	Carlile equiv.	428	0.10	0.99	1.09	0.54	0.09	1.80	1.01	98	54
15	49043054950000	Ajax Oil & Dev.	Govt.-Lockhart 1	48N	91W	9	2,210	2,310	Niobrara equiv.	423	0.28	6.59	6.87	1.55	0.04	4.30	2.67	247	58
15	49043054950000	Ajax Oil & Dev.	Govt.-Lockhart 1	48N	91W	9	2,320	2,370	Carlile equiv.	416	0.29	12.89	13.18	1.66	0.02	7.70	3.62	354	46
16	49029052680000	Ashmun & Hilliard	3 Ltd.	48N	101W	9	1,600	1,700	Niobrara equiv.	427	0.20	1.75	1.95	0.83	0.10	2.10	1.42	123	58
16	49029052680000	Ashmun & Hilliard	3 Ltd.	48N	101W	9	1,700	1,790	Carlile equiv.	426	0.12	0.94	1.06	0.68	0.11	1.40	1.17	81	58
17	49003052790000	MKM Expl.	Unit 2	50N	92W	6	630	750	Niobrara equiv.	421	0.28	1.29	1.57	0.97	0.18	1.30	1.18	110	83
17	49003052790000	MKM Expl.	Unit 2	50N	92W	6	1,300	1,400	Niobrara equiv.	420	0.36	6.39	6.75	0.69	0.05	9.30	2.17	294	32
17	49003052790000	MKM Expl.	Unit 2	50N	92W	6	1,400	1,490	Carlile equiv.	424	0.36	4.59	4.95	0.9	0.07	5.10	1.81	253	50
18	49003204060000	Grayrock Corp.	1–14 Chambers–Fed.	50N	92W	14	920	1,000	Niobrara equiv.	421	0.33	7.10	7.43	1.02	0.04	7.00	2.20	323	46
19	49003052550000	Empire State	1 Govt.	50N	92W	24	1,500	1,600	Carlile equiv.	411	0.57	13.83	14.40	1.83	0.04	7.60	4.33	319	42
20	49029053390000	Occidental Pet.	1 Govt.–Social	50N	100W	15	1,610	1,750	Niobrara equiv.	429	0.15	0.81	0.96	0.83	0.16	1.00	0.82	98	101
20	49029053390000	Occidental Pet.	1 Govt.–Social	50N	100W	15	1,910	1,990	Niobrara equiv.	427	0.21	2.99	3.20	0.97	0.07	3.10	1.59	189	61
20	49029053390000	Occidental Pet.	1 Govt.–Social	50N	100W	15	2,000	2,050	Carlile equiv.	427	0.15	1.86	2.01	0.89	0.08	2.10	1.33	140	67
21	49003204970000	Viking Expl.	1 Henderson	51N	93W	16	1,700	1,760	Niobrara equiv.	423	0.21	2.01	2.22	1.09	0.09	1.80	1.70	118	64
21	49003204970000	Viking Expl.	1 Henderson	51N	93W	16	1,760	1,840	Carlile equiv.	424	0.24	4.98	5.22	1.04	0.05	4.80	2.06	242	51
22	49029068330000	Aztec O & G	Federal LK 1	52N	100W	20	1,020	1,110	Niobrara equiv.	427	0.23	2.90	3.13	1.14	0.07	2.50	1.49	194	76

Table 1. Rock-Eval and total organic carbon data for the Bighorn Basin, Wyoming and Montana.—Continued

[Map number in column 1 refers to well locations shown on figure 13. API, American Petroleum Institute; top and bottom 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 [S₁/(S₁+S₂)]; TOC, total organic carbon in weight percent; HI, hydrogen index; OI, oxygen index]

Map no.	API	Operator	Well	Township	Range	Section	Top	Bottom	Formation	T _{max}	S ₁	S ₂	S ₁ +S ₂	S ₃	PI	S ₂ /S ₃	TOC	HI	OI
22	49029068330000	Aztec O & G	Federal LK 1	52N	100W	20	1,120	1,180	Carlile equiv.	428	0.32	4.33	4.65	1.21	0.07	3.60	1.90	228	64
23	49029207130000	Husky Oil	1–1 Pat O'Hara	54N	103W	1	1,650	1,800	Niobrara equiv.	424	0.27	0.89	1.16	1.27	0.23	0.70	1.34	66	95
23	49029207130000	Husky Oil	1–1 Pat O'Hara	54N	103W	1	1,800	1,920	Carlile equiv.	431	0.23	1.63	1.86	1.18	0.12	1.40	1.44	113	82
24	49003206060000	Huckabay Ltd	Jolly Unit 42–19	55N	95W	19	2,600	2,700	Niobrara equiv.	426	0.14	2.46	2.60	0.99	0.05	2.50	1.39	177	71
24	49003206060000	Huckabay Ltd	Jolly Unit 42–19	55N	95W	19	2,720	2,780	Carlile equiv.	430	0.05	0.87	0.92	0.64	0.06	1.40	1.12	78	57
25	49029059030000	Krueger Oil	Unit 73–27	56N	98W	27	2,750	2,840	Niobrara equiv.	432	0.22	1.52	1.74	0.98	0.13	1.60	1.14	134	86
25	49029059030000	Krueger Oil	Unit 73–27	56N	98W	27	2,850	2,940	Carlile equiv.	430	0.27	3.21	3.48	0.92	0.08	4.50	1.54	208	60
26	49029060310000	Mule Creek Oil	Unit 7	57N	98W	27	1,560	1,630	Niobrara equiv.	422	0.16	0.69	0.85	1.07	0.19	0.60	1.19	58	90
26	49029060310000	Mule Creek Oil	Unit 7	57N	98W	27	1,930	1,990	Niobrara equiv.	427	0.23	1.95	2.18	0.82	0.10	2.40	1.24	157	66
26	49029060310000	Mule Creek Oil	Unit 7	57N	98W	27	2,050	2,080	Carlile equiv.	422	0.41	7.45	7.86	1.2	0.05	6.20	2.53	295	47

Figure 15. Plot showing distribution of total organic carbon content for samples from the lower shaly member of the Cody Shale in the Bighorn Basin, Wyoming. Parameters describing source rock generative potential are from Peters and Cassa (1994).

Figure 16. Plot of S₂ versus total organic carbon for samples from the lower part of the Cody Shale in the Bighorn Basin. Parameters describing source rock generative potential are from Peters and Cassa (1994); mg HC/g rock, milligrams of hydrocarbons per gram of rock.

Figure 17. Plots showing: (A) hydrogen index versus oxygen index, and (B) hydrogen index versus T_{max} (°C) for samples from the lower part of the Cody Shale, Bighorn Basin. The plots indicate that the kerogen in the lower Cody Shale in the Bighorn Basin is a mix of Type II and Type III capable of generating both oil and gas. Maturation lines and kerogen types (dashed lines) for HI/OI diagram from Hunt (1996), maturation lines and kerogen types (dashed lines) for HI/ T_{max} diagram from P.G. Lillis, written commun. (2007).

Figure 18. S_2/S_3 ratios for the lower part of the Cody Shale, Bighorn Basin. Parameters describing types of hydrocarbons generated are from Peters (1986), and Peters and Cassa (1994). S_2 , milligrams of hydrocarbons per gram of rock; S_3 , milligrams of CO_2 per gram of rock.

Figure 22. West-east structure cross section showing the relationship between thermal maturity, based on vitrinite reflectance, and present-day structure. Arrows indicate relative movement along faults. Modified in part from Blackstone (1986), Stone (2004), and Finn and others (2010). Vertical exaggeration = 4x.

Figure 23. Burial history curves for the: (A) Exxcel Energy 1–11 Dobie Creek Unit and (B) the Forest Oil 1 Emblem Bench. Location of wells is shown on figures 2 and 21. Modified from Roberts and others (2008). Ma, millions of years; %, percent; R_o , vitrinite reflectance.

1-11 Dobie Creek Unit, located along the Five Mile trend in the eastern part of the basin, in sec. 11, T. 49 N., R. 94 W., represents a part of the basin that underwent shallower burial (fig. 2). In the eastern shallow part of the basin, modeling results for the Dobie Creek well show that hydrocarbon generation from the lower Cody Shale began (R_o of 0.6 percent) about 53 Ma at a burial depth of about 10,400 ft (fig. 23A). In the deeper part of the basin, modeling results for the Emblem Bench well indicate that generation began about 59 Ma at a burial depth of about 12,400 ft (fig. 23B). Based on the R_o levels and burial history modeling, the source rocks in the lower part of the Cody Shale in most of the Bighorn Basin are in the early to late stages of thermal maturity with respect to oil generation (0.6–1.35 percent R_o), except in the deepest parts, where it is post-mature (>1.35 percent R_o) with respect to oil generation (Peters and Cassa, 1994).

Conclusions

Results of TOC and Rock-Eval analyses of the lower Cody Shale in the Bighorn Basin indicate that it contains potential petroleum source rocks. Total organic carbon content for the Carlile equivalent strata is up to nearly 5.0 weight percent, and averages around 2.28 weight percent, while the basal Niobrara equivalent strata is up to over 3.0 weight percent and averages around 1.5 weight percent, indicating that both intervals are potential source rocks. Both intervals contain organic matter primarily composed of Type II and Type III kerogen capable of generating both oil and gas, with the most organic-rich and oil-prone rocks found in the eastern and southeastern parts of the basin. Maturity levels based on vitrinite reflectance and burial history reconstructions indicate that the lower Cody Shale is in the early to late stages of oil generation throughout most of the basin, except in the deeper parts where it is post-mature.

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