Chapter 8

Source Rock Potential of Upper Cretaceous Marine Shales in the Wind River Basin, Wyoming

By Thomas M. Finn

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By Thomas M. Finn

Abstract

Seventy-eight samples collected from marine shales from the Cretaceous Mowry Shale, the lower part of the Frontier Formation, and the lower shaly and upper sandy members of the Cody Shale in the Wind River Basin, Wyoming, were analyzed using Rock-Eval and total organic carbon analysis to determine the source rock potential. Results indicate that the Mowry Shale has a generative potential based on organic richness that is considered to be fair to very good, and hydrogen indices and S_2/S_3 ratios indicate a capability to generate both oil and gas. Maps of the Mowry indicate that it is most organic rich and oil-prone in the eastern part of the basin. Results of total organic carbon and Rock-Eval analyses for the Frontier Formation indicate that it is composed of mainly type III gas-prone kerogen, with organic richness levels that are generally poor to fair. Results of similar analyses of samples from the lower shaly member of the Cody Shale show a generative potential ranging from fair to excellent, and hydrogen indices and S_2/S_3 ratios indicate that it is capable of generating both oil and gas. Maps showing the distribution of kerogen types and organic richness for the lower shaly member of the Cody Shale are similar to the Mowry and show that lower shaly member of the Cody is more organic rich and more oil-prone in the eastern part of the basin. Analyses of samples of the upper sandy member of the Cody Shale indicate that it has little or no potential as a source rock. Thermal maturity mapping based on vitrinite reflectance measurements in the coal-bearing post-Cody Upper Cretaceous and Paleocene rocks shows that Upper Cretaceous marine shales in the deeper parts of the Wind River Basin are thermally mature to overmature with respect to hydrocarbon generation.

Introduction

The Wind River Basin (WRB) 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 200 miles (mi) long, 70 mi wide, and encompasses about 7,400 square miles (mi^2) in central Wyoming (fig. 1). The basin is structurally bounded by the Washakie Range and Owl Creek and southern Bighorn Mountains on the north, the Casper arch on the east and northeast, the Granite Mountains on the south, and the Wind River Range on the west (fig. 2).

The first commercial oil well completed in Wyoming was drilled near an oil seep in 1884 at Dallas dome along the southwest edge of the WRB (Mullen, 1989). Since then many important conventional oil and gas fields producing from reservoir rocks ranging in age from Mississippian through Tertiary have been discovered in the basin (fig. 2) (Keefer, 1969; Fox and Dolton, 1989, 1996; De Bruin, 1993; Kirschbaum and others, Chapter 3, this CD-ROM; Johnson and others, Chapter 4, this CD-ROM; and Roberts and others, Chapter 5, this CD-ROM). In addition, an extensive unconventional overpressured basin-centered gas accumulation has been identified in Cretaceous and Tertiary reservoirs in the deeper parts of the basin by numerous authors including Spencer (1987), Johnson and others (1996), Jiao and Surdam (1997), Surdam and others (1997), Surdam (2003), Surdam and others (2004), Forster and Horne (2005), Johnson and others (2005), Meckel and Thomasson (2005), and Johnson and others (Chapter 4, this CD-ROM).

It has long been believed that various Upper Cretaceous marine shales are the principal hydrocarbon source rocks within the WRB (Keefer, 1969; Meissner and others, 1984; Fox and Dolton, 1989, 1996; Johnson and Rice, 1993; Nuccio and others, 1996; and Schelling and Wavrek, 1999, 2001), which agrees with the work by numerous researchers who have discussed the source rock potential of equivalent Cretaceous marine strata in other Rocky Mountain basins. Basin-scale or regional studies of various Upper Cretaceous marine shales in the Rocky Mountain region by several authors, including Schrayer and Zarrella (1963, 1966, 1968), Nixon (1973), Clayton and Swetland (1977), Merewether and Claypool (1980), Burtner and Warner (1984), Hagen and Surdam (1984), Momper and Williams (1984), Davis (1986), Davis and others (1989), Nuccio (1990a,b), Longman and others (1998), and Landon and others (2001), have led to the general conclusion that these rocks have generated or are capable of generating oil and (or) gas. However, with the

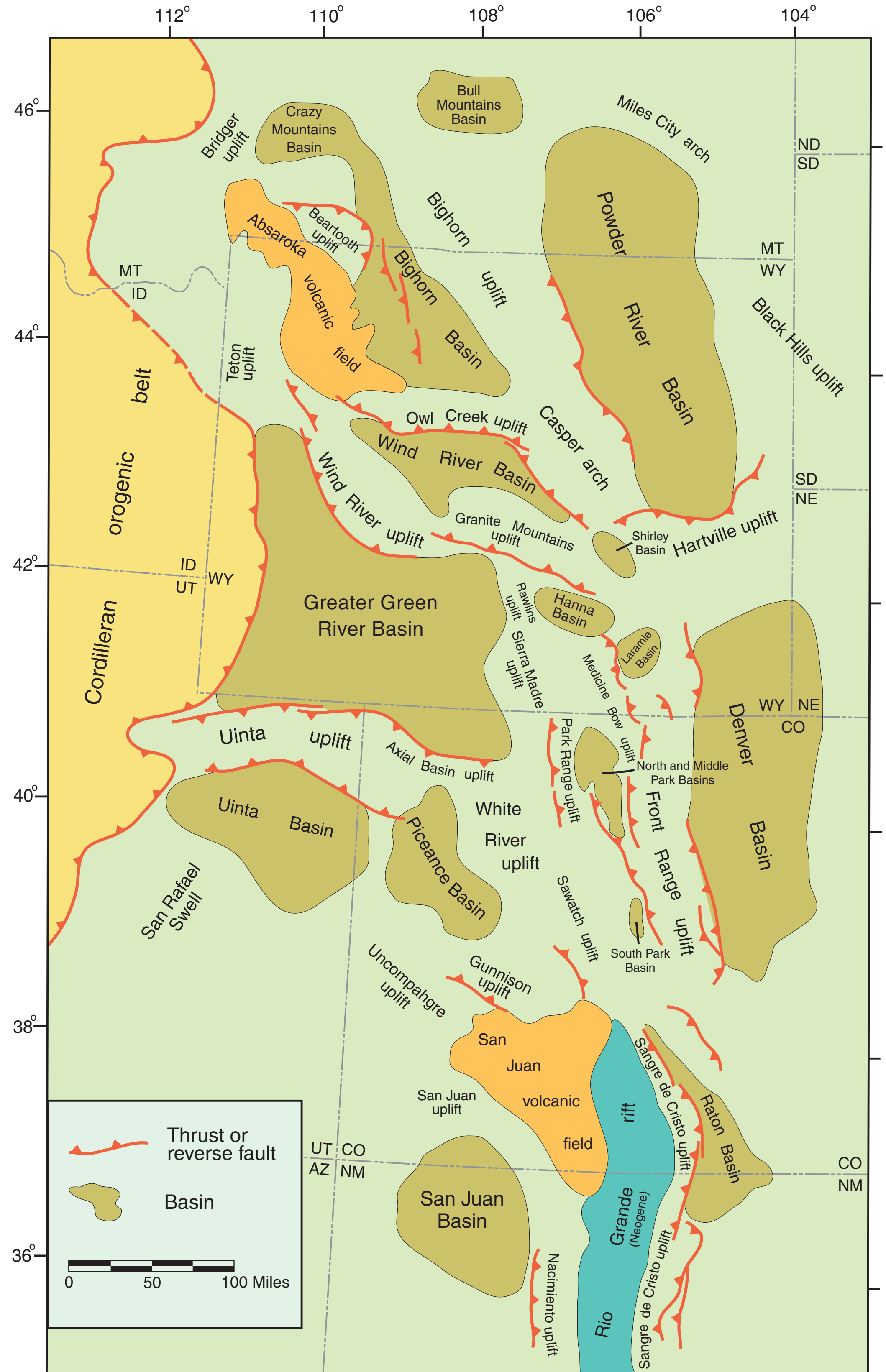

Figure 1. Map of the Rocky Mountain region extending from southern Montana to northern New Mexico showing locations of Laramide sedimentary and structural basins and intervening uplifts. Modified from Dickinson and others (1988).

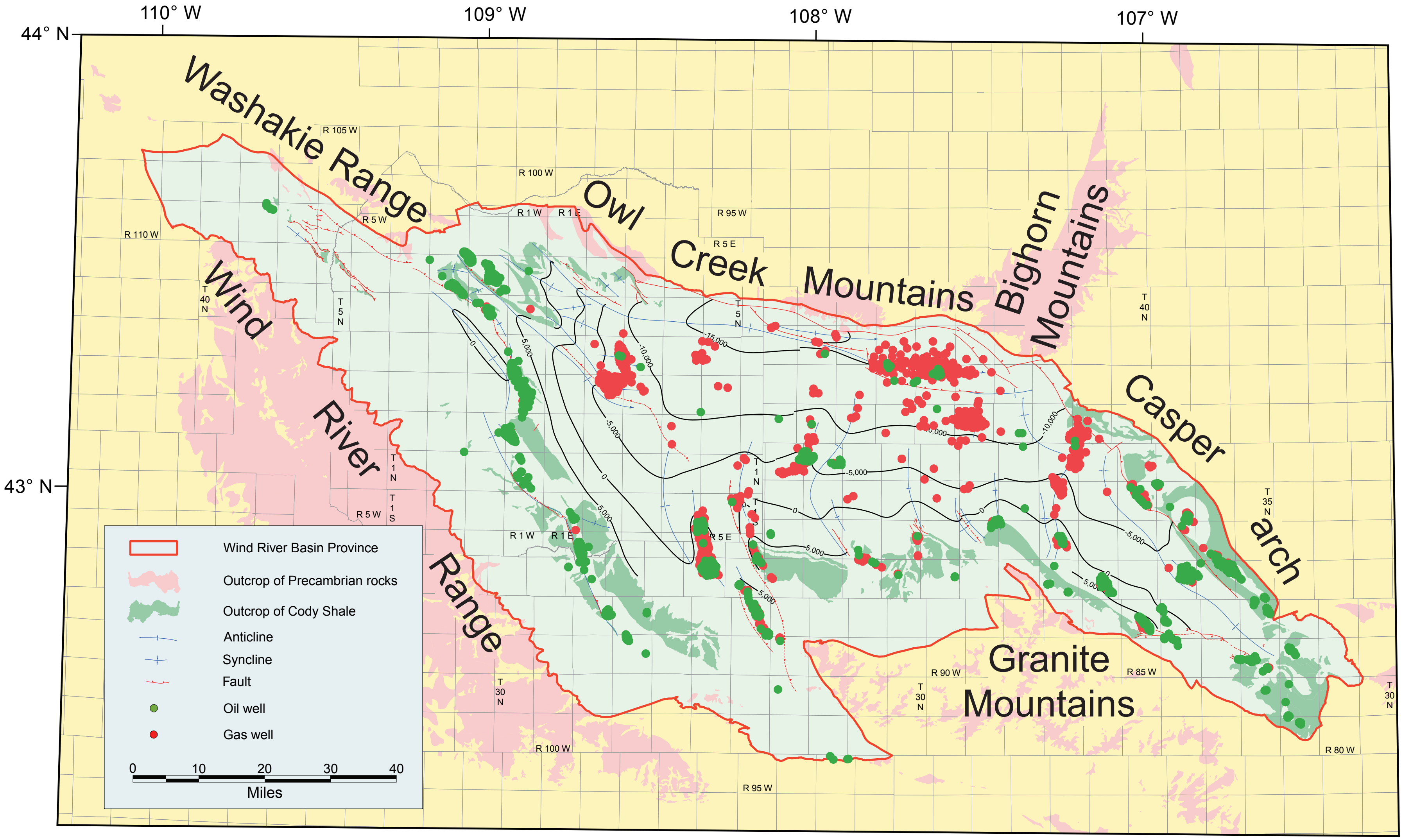

Figure 2. Map of the Wind River Basin in central Wyoming showing locations of oil and gas fields, generalized structure, and Cody Shale outcrop. Structure contours drawn on top of the Cody Shale; contour interval, 5,000 ft.

exception of Mowry Shale studies by Schrayer and Zarella (1963, 1966, 1968), Nixon (1973), and Burtner and Warner (1984), little or no geochemical data have been published about the source rock characteristics of Upper Cretaceous marine shales in the WRB. The purpose of this report is to present the results of Rock-Eval and total organic carbon (TOC) analysis for samples collected from Upper Cretaceous marine shales in the WRB and characterize their source rock potential. This study was conducted as part of the U.S. Geological Survey's assessment of undiscovered oil and gas resources of the Wind River Basin in 2005.

Depositional Setting

During much of Late Cretaceous time, the part of central Wyoming that is now the WRB 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 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 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 (Gries and others, 1992). Figure 5 is a correlation diagram showing the stratigraphic relations of Upper Cretaceous rocks in the WRB.

Stratigraphy

Mowry Shale

The Mowry Shale in the WRB consists of two distinct units (Keefer and Johnson, 1997) (fig. 6). The lower 50 to 125 ft is soft fissile clay-rich shale that has been referred to as the Shell Creek Shale in the adjacent Bighorn and Powder River Basins (Burtner and Warner, 1984). The upper part is composed of 200 to 350 ft of hard brittle siliceous shale (Keefer and Johnson, 1997), with numerous gray to tan bentonite beds ranging in thickness from 1 centimeter (cm) to 2 meters (m) (Byers and Larson, 1979). The shales, of marine origin, are dark brown to black, organic rich, and contain an abundance of fish scales (Burtner and Warner, 1984). Paleontologic evidence and radiometric dating indicates that the Mowry is mainly early Late Cretaceous (Cenomanian) in age (Cobban and Kennedy, 1989; Merewether and others, 1997; Obradovich and others, 1996), but the lower part (Shell Creek Shale equivalent) has been dated radiometrically as Early Cretaceous (Albian) by Obradovich and others (1996). However, for convenience all of the formation is treated as being part of the Upper Cretaceous in this report.

Frontier Formation

Throughout most of the WRB the Frontier Formation consists of alternating sandstone, shale, and bentonite that accumulated in marine and marginal marine environments (Keefer, 1972). In the western part of the basin the Frontier also contains some continental rocks including minor coal deposits. Sandstones generally dominate in the upper part of the formation; whereas, the lower part is mostly marine shale (fig. 6). Many individual sandstones are blanket-like and can be traced over several miles, but locally some are discontinuous and pinch out into marine shale. The shales are generally sandy or silty and gray or black in color. The formation is Cenomanian to Coniacian in age (Merewether and others, 1997) and ranges in thickness from 400 to 800 ft.

Cody Shale

The Cody Shale consists of marine shale, siltstone, and sandstone that were deposited during a major transgressive-regressive cycle referred to as the Niobrara Cyclothem by Kauffman (1977). The formation is the thickest marine unit in the WRB, ranging in thickness from about 3,250 to about 5,500 ft (Johnson and others, Chapter 4, this CD-ROM). The lower and upper contacts are conformable and interfinger extensively with the underlying Frontier and overlying Mesaverde Formations (fig. 4). Four members are recognized, in ascending order the unnamed lower shaly

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).

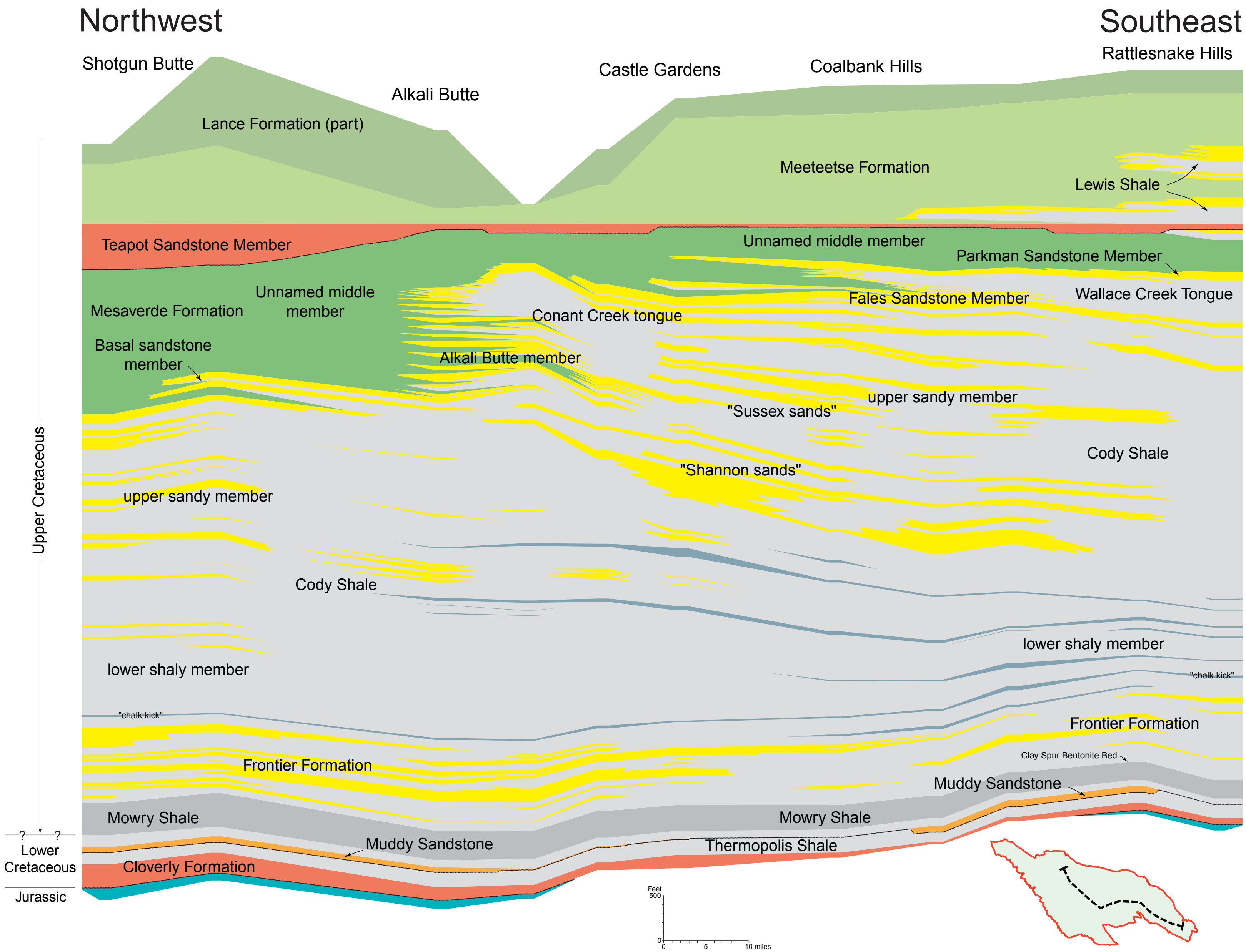

Figure 4. Generalized east-west stratigraphic cross section of Cretaceous rocks in the Wind River Basin showing the complex intertonguing relation of marine and nonmarine deposits. Sandstones and conglomerates of predominantly fluvial origin are shown in red; marine and marginal marine sandstones, yellow; coastal plain and alluvial plain sandstone, shale, and coal, various shades of green; marine shales, various shades of gray; estuarine and fluvial sandstones shown in orange. Inset map shows cross section location.

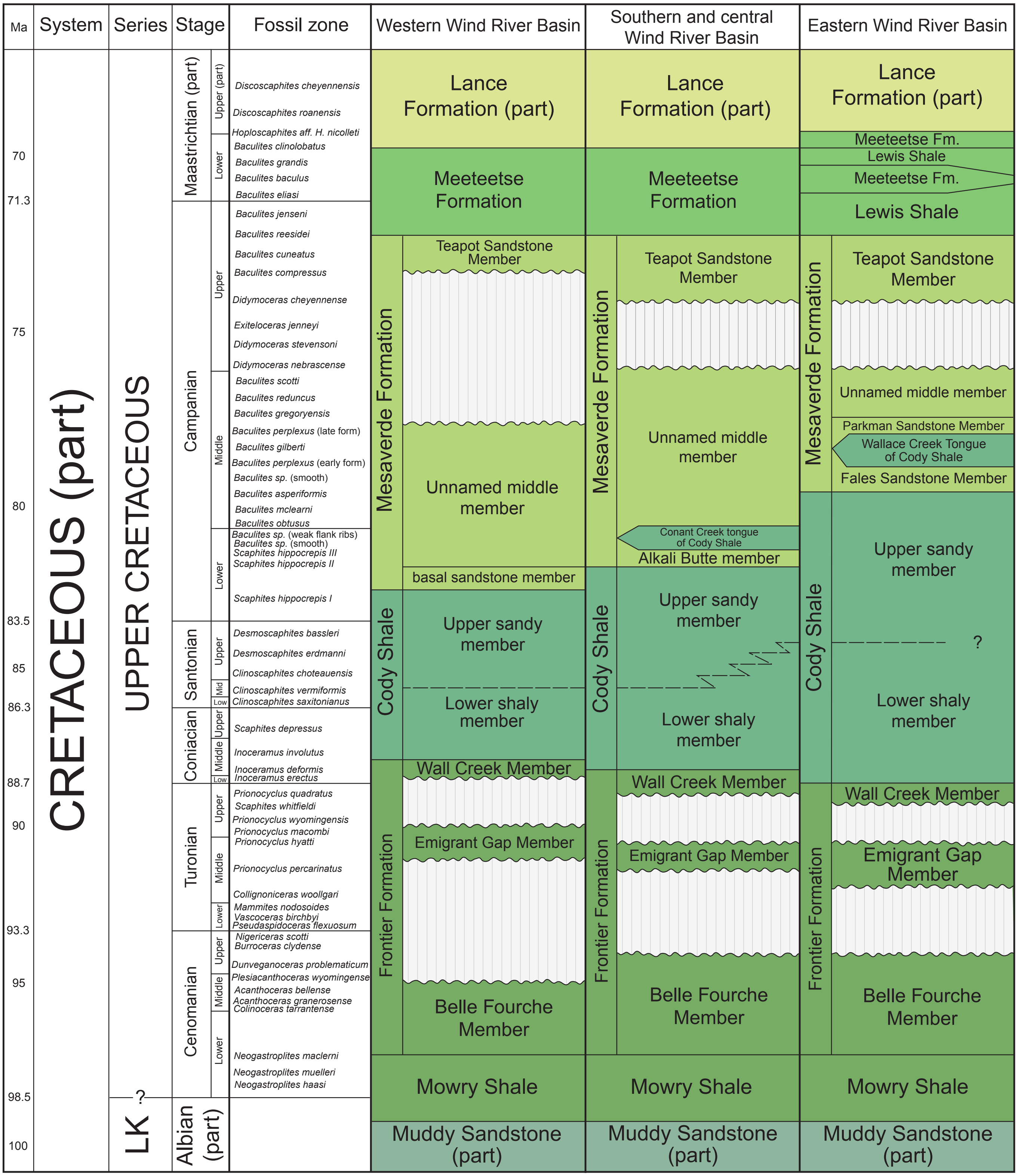

Figure 5. Correlation chart showing the stratigraphic relation of Upper Cretaceous rocks in the Wind River Basin. Radiometric ages and fossil zones are from Obradovich (1993), and Merewether and others (1997). Modified from Finn, Chapter 9, this CD-ROM.

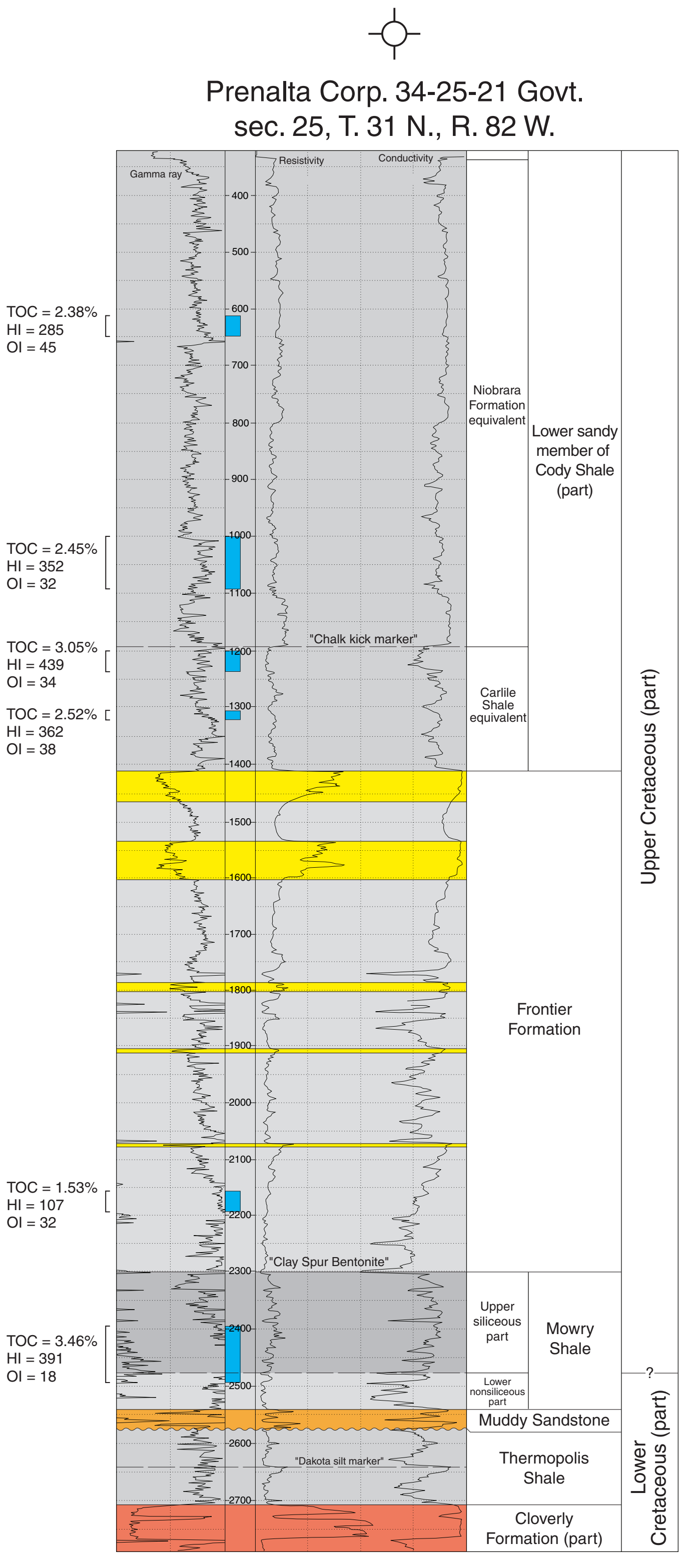

Figure 6. Well log of Lower and lowermost Upper Cretaceous rocks in the southeastern part of the Wind River Basin. Sandstones and conglomerates of predominantly fluvial origin are shown in red; marine and marginal marine sandstones, yellow; marine shales, various shades of gray; estuarine and fluvial sandstones shown in orange. Blue bar indicates sample interval. Location shown in figure 7.

member (Thompson and White, 1954; Yenne and Pipiringos, 1954; and Keefer and Troyer, 1964), the unnamed upper sandy member (Thompson and White, 1954; Yenne and Pipiringos, 1954; Keefer and Troyer, 1964), the informally named Conant Creek tongue (Szmajter, 1993), and the Wallace Creek Tongue (Barwin, 1961) (fig. 4). The age of the Cody ranges from Coniacian to middle Campanian (Keefer, 1972).

The unnamed lower shaly member is about 1,750 ft thick in the western part of the basin and thickens to the east to more than 2,250 ft (see Johnson and others, Chapter 4, this CD-ROM). It is composed of gray to black shale and bentonite that were deposited in an offshore marine environment. A persistent zone referred to as the “chalk kick” by Keefer (1972) is recognized on geophysical logs in the lower 100-300 ft of the lower member (fig. 6). This zone, which can be traced in the subsurface throughout most of the basin, separates noncalcareous shales in the lower part of the shaly member from overlying calcareous shales (see Finn, Chapter 9, this CD-ROM). Based on sample descriptions from well cuttings, this calcareous interval is about 1,000 ft thick in the eastern part of the basin; Merewether and others (1977a, b) correlated this interval with the Niobrara Formation in the Powder River Basin. Above the calcareous shale, but below the base of the overlying sandy member of the Cody, the shaly member is less calcareous and commonly contains numerous bentonite beds. Merewether and others (1977a, b) correlated that part of the noncalcareous interval between the “chalk kick” and the top of the uppermost sandstone in the Frontier Formation with the Carlile Shale in the Powder River Basin (fig. 6).

The upper sandy member, ranging in thickness from about 1,800 ft to about 3,500 ft, consists of light to medium gray sandstones and tan and gray shales. The sandstones in the upper part of the member are commonly referred to as the “Sussex” and “Shannon” sandstone beds, which, according to Dunleavy and Gilbertson (1986) were deposited “as a near-shore bar complex along the edge of a delta”. Like sandstones in the underlying Frontier Formation, many individual sandstones in the upper part of the Cody are blanket-like and can be traced over several miles, before pinching out into marine shale in all directions. The upper sandy member becomes less distinct in the southeastern part of the basin where it grades laterally into a more shaly facies (Finn, 1993).

The Conant Creek tongue of the Cody Shale, informally named by Szmajter (1993), trends north-south across the central part of the basin and is separated from the upper sandy member by an eastward thinning clastic wedge of marginal marine and nonmarine rocks informally referred to as the Alkali Butte member of the Mesaverde Formation by Hogle and Jones (1991) (fig. 4). The Conant Creek tongue is typically 400 to 900 ft thick, but thins to zero where it grades westward into the Mesaverde Formation.

The Wallace Creek Tongue of the Cody Shale occupies the eastern and southeastern parts of the WRB and is stratigraphically higher and younger than the Conant Creek tongue to the west. It is a westward-thinning tongue of marine shale that splits the Fales Sandstone Member at the base of the Mesaverde Formation from the upper part of the formation (Barwin, 1961) (fig. 4). The Wallace Creek Tongue is nearly 500 ft thick in the southeastern corner of the basin and thins to zero in the northern part of the Coalbank Hills, where it grades into the main part of the Mesaverde Formation, (fig. 4).

Methods

Seventy-eight samples from 31 wells were collected from well cuttings of Upper Cretaceous marine shales stored at the U.S. Geological Survey Core Research Center in Lakewood, Colorado. Most of the wells selected are located near the outcrop belt along the gently dipping south and southwest margins of the WRB in order to obtain samples that were not subjected to the effects of deep burial and subsequent thermal maturation (fig. 7). Seventeen samples are from the Mowry Shale, 7 from the lower part of the Frontier Formation, 49 from the lower shaly member of the Cody Shale, and 5 from the upper sandy member of the Cody Shale. Two samples were collected from core chips, and the remainder from well cuttings. Sample intervals were determined by examining a gamma-ray log, if available, and the interval(s) with the highest gamma-ray intensity was selected (fig. 6), 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) who suggested that TOC content generally increases as color goes from gray to black and therefore is a rough indicator of organic richness. If a gamma-ray log was not available, then sample intervals were determined strictly by color. The cuttings were composited into one sample from thickness intervals that were generally 50 to 80 ft thick, but ranged from 10 to 200 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 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. (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 show the results of TOC analyses of Cretaceous marine shales in the WRB.

The results of TOC analyses of the 17 samples collected from the Mowry Shale show values ranging from 1.59 to 3.46 percent, with an average of 2.42 percent (fig. 8). All samples have greater than one percent TOC and 12 have TOC contents greater than 2 percent, indicating good to very good generative potential. The 7 samples collected from the lower part of the Frontier Formation have TOC contents that range from 1.22 to 1.9 percent (average 1.42 percent), indicating good generative potential (fig. 8). The 48 samples collected from lower shaly member of the Cody Shale have TOC contents that range from 0.81 to 5.85 percent (average 2.07 percent) (fig.8). All but 2 have values greater than 1 percent, and 21 have values greater than 2 percent, indicating good to very good generative potential. TOC contents for the 5 samples collected from the upper sandy member range from 0.43 to 1.13 percent (average 0.81 percent) (fig. 8), which indicates fair to good generative potential for some strata within the member.

Peters and Cassa (1994) 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. They (Peters and Cassa, 1994) believe 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 hyrdrocarbons 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 and (or) gas (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 Mowry Shale, Frontier Formation, and lower and upper parts of the Cody Shale are presented in table 1 and on figure 9. The 17 samples from the Mowry Shale show a range of S_2 values from 1.89 to 13.54

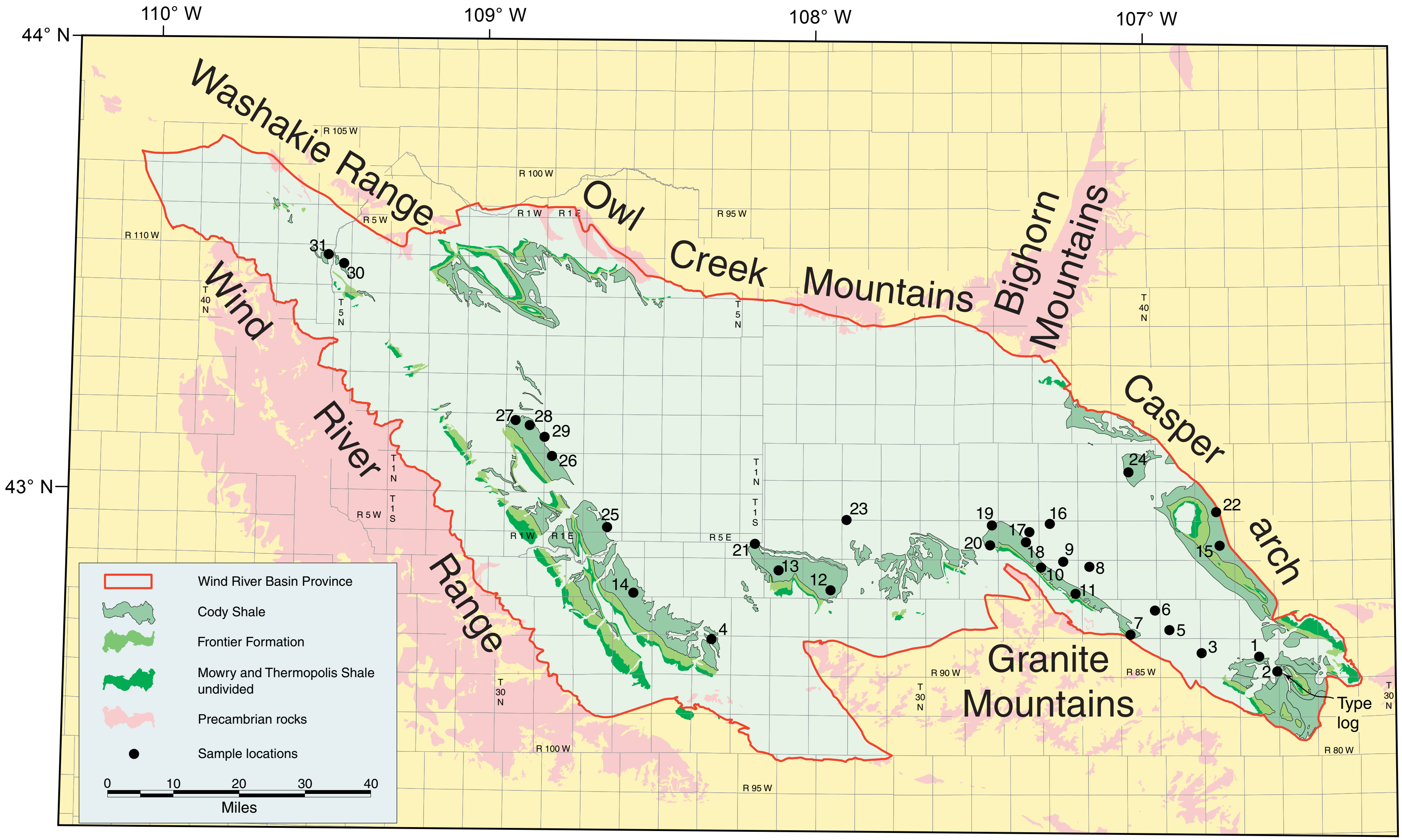

Figure 7. Index map of the Wind River Basin showing sample localities.

Table 1. Rock-Eval and total organic carbon data for the Wind River Basin, central Wyoming.

Map number in column 1 refers to location shown on figure 7. Depths are in feet. S_1, milligrams of hydrocarbons per gram of rock; S_2, milligrams of hydrocarbons per gram of rock; S_3, milligrams of CO_2 per gram of rock; PI, production index; TOC, total organic carbon in weight percent; HI, hydrogen index; OI, oxygen index.

Map no.	Operator	Well	Township	Range	Section	Top depth	Bottom depth	FM/MBR	Tmax	S_1	S_2	S_1+S_2	S_3	PI	S_2/S_3	TOC	HI	OI
1	Shell Oil	43-16 State	31N	82W	16	5,590	5,680	lower Cody	419	0.27	4.23	4.50	0.80	0.06	5.29	1.78	238	45
1	Shell Oil	43-16 State	31N	82W	16	6,340	6,400	lower Cody	417	0.37	9.46	9.83	1.07	0.04	8.84	2.69	352	40
1	Shell Oil	43-16 State	31N	82W	16	7,590	7,640	Mowry	422	0.34	6.05	6.39	0.80	0.05	7.56	2.47	245	32
2	Prenalta	34-25-31-82 Govt	31N	82W	25	620	650	lower Cody	415	0.31	6.78	7.09	1.07	0.04	6.34	2.38	285	45
2	Prenalta	34-25-31-82 Govt	31N	82W	25	1,000	1,090	lower Cody	420	0.30	8.63	8.93	0.79	0.03	10.92	2.45	352	32
2	Prenalta	34-25-31-82 Govt	31N	82W	25	1,200	1,240	lower Cody	415	0.46	13.40	13.86	1.03	0.03	13.01	3.05	439	34
2	Prenalta	34-25-31-82 Govt	31N	82W	25	1,310	1,320	lower Cody	416	0.23	9.11	9.34	0.97	0.02	9.39	2.52	362	38
2	Prenalta	34-25-31-82 Govt	31N	82W	25	2,170	2,190	Frontier	427	0.14	1.64	1.78	0.49	0.08	3.35	1.53	107	32
2	Prenalta	34-25-31-82 Govt	31N	82W	25	2,390	2,490	Mowry	417	0.78	13.54	14.32	0.63	0.05	21.49	3.46	391	18
3	Mobil-General Crude	4-18 Eagle Creek	31N	83W	18	1,500	1,560	lower Cody	421	0.16	2.53	2.69	1.11	0.06	2.28	1.79	141	62
3	Mobil-General Crude	4-18 Eagle Creek	31N	83W	18	2,170	2,300	lower Cody	412	0.41	7.18	7.59	1.11	0.05	6.47	2.26	318	49
4	Apache Corp.	1 USA Morton	31N	96W	4	2,770	2,830	lower Cody	425	0.13	1.62	1.75	0.90	0.07	1.80	1.64	99	55
4	Apache Corp.	1 USA Morton	31N	96W	4	4,200	4,250	Mowry	424	0.22	2.71	2.93	0.67	0.07	4.04	1.80	151	37
5	Wolf Expl	1 Govt	32N	84W	29	5,650	5,710	lower Cody	423	0.18	3.17	3.35	7.30	0.05	0.43	0.98	323	745
5	Wolf Expl	1 Govt	32N	84W	29	6,010	6,110	lower Cody	422	0.19	4.03	4.22	1.03	0.04	3.91	1.94	208	53
5	Wolf Expl	1 Govt	32N	84W	29	6,600	6,670	lower Cody	414	0.38	8.33	8.71	1.35	0.04	6.17	2.77	301	49
6	Cities Service	Govt C-1	32N	85W	12	9,690	9,750	lower Cody	425	0.35	4.85	5.20	1.02	0.07	4.75	2.21	219	46
6	Cities Service	Govt C-1	32N	85W	12	10,850	10,900	Mowry	424	0.33	4.33	4.66	0.73	0.07	5.93	2.16	200	34
7	Forest Oil	Grieve Unit 36-32-1	32N	85W	32	380	420	lower Cody	424	0.29	3.37	3.66	0.91	0.08	3.70	1.82	185	50
7	Forest Oil	Grieve Unit 36-32-1	32N	85W	32	980	1,100	lower Cody	421	0.49	4.10	4.59	1.42	0.11	2.89	2.30	178	62
7	Forest Oil	Grieve Unit 36-32-1	32N	85W	32	2,140	2,200	Mowry	424	0.30	5.10	5.40	1.13	0.06	4.51	2.47	206	46
8	Continental	1 McClanahan Draw	33N	86W	5	9,510	9,560	lower Cody	427	0.18	1.29	1.47	0.650	0.12	1.98	1.11	116	59
8	Continental	1 McClanahan Draw	33N	86W	5	10,010	10,080	lower Cody	418	0.58	6.12	6.70	0.910	0.09	6.73	2.22	276	41
8	Continental	1 McClanahan Draw	33N	86W	5	10,630	10,670	lower Cody	423	0.63	5.78	6.41	1.02	0.10	5.67	2.16	268	47
8	Continental	1 McClanahan Draw	33N	86W	5	11,900	11,940	Mowry	424	0.36	3.55	3.91	0.90	0.09	3.94	2.30	154	39
9	Davis Oil	1 Govt-Clare	33N	87W	3	6,940	7,000	lower Cody	423	0.14	0.81	0.95	0.700	0.15	1.16	1.04	78	67
9	Davis Oil	1 Govt-Clare	33N	87W	3	7,400	7,460	lower Cody	420	0.22	2.02	2.24	1.040	0.10	1.94	1.47	137	71
9	Davis Oil	1 Govt-Clare	33N	87W	3	8,080	8,130	lower Cody	418	0.28	4.47	4.75	0.900	0.06	4.97	1.86	240	48
9	Davis Oil	1 Govt-Clare	33N	87W	3	9,250	9,300	Mowry	424	0.32	3.82	4.14	0.770	0.08	4.96	1.81	211	43
10	Cities Service	Govt. 1-D	33N	87W	7	1,070	1,150	lower Cody	419	0.18	1.80	1.98	0.93	0.09	1.94	1.47	122	63
10	Cities Service	Govt. 1-D	33N	87W	7	2,000	2,050	lower Cody	418	0.35	4.12	4.47	1.34	0.08	3.07	2.09	197	64
10	Cities Service	Govt. 1-D	33N	87W	7	3,020	3,080	Frontier	423	0.20	0.51	0.71	0.83	0.28	0.61	1.23	41	67
10	Cities Service	Govt. 1-D	33N	87W	7	3,367	3,369	Mowry	417	0.45	9.30	9.75	0.84	0.05	11.07	2.85	326	29
10	Cities Service	Govt. 1-D	33N	87W	7	3,425	3,427	Mowry	422	0.50	4.64	5.14	0.83	0.10	5.59	2.37	196	35
11	Kentta-Drwenski	2-36 State	33N	87W	36	650	740	lower Cody	418	0.32	3.34	3.66	1.43	0.09	2.34	2.44	137	59
11	Kentta-Drwenski	2-36 State	33N	87W	36	1,430	1,450	lower Cody	411	0.90	22.23	23.13	2.30	0.04	9.67	5.85	380	39
11	Kentta-Drwenski	2-36 State	33N	87W	36	2,350	2,390	Frontier	427	0.15	1.14	1.29	0.71	0.12	1.61	1.27	90	56
11	Kentta-Drwenski	2-36 State	33N	87W	36	2,620	2,670	Mowry	417	0.20	1.89	2.09	1.04	0.10	1.82	2.68	71	39
12	Oil Resources Inc.	26-12 Govt-Curry	33N	93W	26	1,060	1,180	lower Cody	422	0.27	3.72	3.99	1.05	0.07	3.54	1.74	214	60

Table 1. Rock-Eval and total organic carbon data for the Wind River Basin, central Wyoming.—Continued

Map number in column 1 refers to location shown on figure 7. Depths are in feet. S_1, milligrams of hydrocarbons per gram of rock; S_2, milligrams of hydrocarbons per gram of rock; S_3, milligrams of CO_2 per gram of rock; PI, production index; TOC, total organic carbon in weight percent; HI, hydrogen index; OI, oxygen index.

Map no.	Operator	Well	Township	Range	Section	Top depth	Bottom depth	FM/MBR	Tmax	S_1	S_2	S_1+S_2	S_3	PI	S_2/S_3	TOC	HI	OI
12	Oil Resources Inc.	26-12 Govt-Curry	33N	93W	26	2,200	2,290	Frontier	423	0.33	2.79	3.12	0.81	0.10	3.44	1.90	147	43
12	Oil Resources Inc.	26-12 Govt-Curry	33N	93W	26	2,470	2,520	Mowry	421	0.36	4.34	4.70	0.89	0.80	4.88	2.26	192	39
13	Alliance Expl.	3-9 Federal	33N	94W	9	2,200	2,320	lower Cody	418	0.17	2.80	2.97	0.88	0.06	3.18	1.55	181	57
14	Apache Corp.	1 Amber	33N	98W	35	2,740	2,800	lower Cody	418	0.35	4.43	4.78	1.43	0.07	3.10	2.65	167	54
15	Cardinal Pet.	1 Smith-Elsman	34N	83W	22	400	500	lower Cody	417	0.56	12.82	13.38	1.25	0.04	10.26	3.04	422	41
15	Cardinal Pet.	1 Smith-Elsman	34N	83W	22	1,460	1,610	Frontier	430	0.19	1.02	1.21	0.70	0.16	1.46	1.36	75	51
15	Cardinal Pet.	1 Smith-Elsman	34N	83W	22	1,750	1,860	Mowry	421	0.85	9.08	9.93	1.11	0.09	8.18	3.04	299	37
16	Gulf Oil	1 Hornbeck - Fed	34N	87W	5	10,850	10,920	lower Cody	427	0.25	1.84	2.09	0.65	0.12	2.83	1.49	123	44
16	Gulf Oil	1 Hornbeck - Fed	34N	87W	5	12,130	12,180	Mowry	428	0.52	2.33	2.85	0.51	0.18	4.57	1.59	147	32
17	Pubco	11-11 Empire	34N	88W	11	7,940	8,020	lower Cody	419	0.60	10.68	11.28	1.23	0.05	8.68	2.90	368	42
18	Davis Oil	1 Mohawk	34N	88W	22	2,200	2,270	upper Cody	418	0.09	0.20	0.29	0.85	0.31	0.24	0.68	29	125
18	Davis Oil	1 Mohawk	34N	88W	22	3,000	3,200	upper Cody	410	0.18	0.44	0.62	0.81	0.30	0.54	0.94	47	86
18	Davis Oil	1 Mohawk	34N	88W	22	4,000	4,070	lower Cody	417	0.20	0.91	1.11	1.11	0.18	0.82	1.37	66	81
18	Davis Oil	1 Mohawk	34N	88W	22	4,770	4,850	lower Cody	423	0.68	5.14	5.82	1.40	0.12	3.67	2.59	199	54
19	Continental	Unit 4	34N	89W	2	1,880	1,980	upper Cody	513	0.07	0.10	0.17	1.32	0.41	0.08	0.43	23	307
19	Continental	Unit 4	34N	89W	2	2,800	2,900	upper Cody	417	0.19	0.42	0.61	1.34	0.31	0.31	1.13	37	119
20	Penzoil	1 Cyclone Ridge	34N	89W	23	700	800	lower Cody	470	0.08	0.25	0.33	1.09	0.24	0.23	0.81	31	135
20	Penzoil	1 Cyclone Ridge	34N	89W	23	1,340	1,440	lower Cody	415	0.26	2.40	2.66	1.19	0.10	2.02	1.82	132	66
20	Penzoil	1 Cyclone Ridge	34N	89W	23	2,250	2,350	lower Cody	421	0.34	6.10	6.44	1.69	0.05	3.61	3.12	196	54
20	Penzoil	1 Cyclone Ridge	34N	89W	23	3,200	3,300	Frontier	425	0.28	1.93	2.21	1.19	0.13	1.62	1.44	134	83
20	Penzoil	1 Cyclone Ridge	34N	89W	23	3,500	3,600	Mowry	414	0.32	4.87	5.19	0.92	0.06	5.29	2.74	178	34
21	Wind River Oil	1 Govt.	34N	95W	23	1,110	1,160	upper Cody	412	0.18	0.39	0.57	0.93	0.32	0.42	0.88	44	106
21	Wind River Oil	1 Govt.	34N	95W	23	4,000	4,050	lower Cody	425	0.30	1.73	2.03	0.84	0.15	2.06	1.15	150	54
22	Eastern Petroleum	1 Govt-Forest	35N	83W	27	1,000	1,050	lower Cody	418	0.54	13.15	13.69	1.41	0.04	9.33	3.36	391	42
22	Eastern Petroleum	2 Govt-Forest	35N	83W	27	2,090	2,140	Frontier	431	0.34	1.38	1.72	0.53	0.20	2.60	1.22	113	43
22	Eastern Petroleum	3 Govt-Forest	35N	83W	27	2,290	2,390	Mowry	419	0.81	11.52	12.33	1.15	0.07	10.02	3.43	336	34
23	Sun Oil	1 Wolf - Federal	35N	92W	31	8,800	8,850	lower Cody	425	0.43	3.73	4.16	0.95	0.10	3.93	1.82	205	52
23	Sun Oil	1 Wolf - Federal	35N	92W	31	8,940	8,970	lower Cody	426	0.41	2.58	2.99	0.54	0.14	4.78	1.47	176	37
23	Sun Oil	1 Wolf - Federal	35N	92W	31	9,990	10,000	Mowry	432	0.65	3.14	3.79	0.47	0.17	6.68	1.80	174	26
24	Terra Resources	8-29 Terra-Manning	36N	85W	29	2,910	2,970	lower Cody	419	0.21	3.72	3.93	0.78	0.05	4.77	1.94	192	40
24	Terra Resources	8-29 Terra-Manning	36N	85W	29	4,110	4,210	lower Cody	418	0.83	15.34	16.17	1.25	0.05	12.27	3.32	462	38
25	General Crude	2-34 Hudson LL&E	1S	2E	34	3,510	3,570	lower Cody	425	0.18	0.69	0.87	0.990	0.21	0.70	1.77	39	56
26	Phillips Pet	1 Johnson Draw - C	1N	1E	5	2,650	2,700	lower Cody	418	0.17	0.69	0.86	1.050	0.20	0.66	1.48	47	71
27	Amoco Production	1 SA Tribal - T	2N	1W	5	1,550	1,600	lower Cody	422	0.14	2.03	2.17	0.720	0.06	2.82	1.63	125	44
28	Phillips Pet	1 Johnson Draw - A	2N	1W	10	2,150	2,250	lower Cody	420	0.24	1.91	2.15	0.910	0.11	2.10	1.49	128	61
29	Phillips Pet	1 Johnson Draw - B	2N	1W	24	3,300	3,400	lower Cody	423	0.16	0.69	0.85	0.84	0.19	0.82	1.32	52	64
29	Phillips Pet	1 Johnson Draw - B	2N	1W	24	4,600	4,700	Mowry	422	0.32	2.91	3.23	0.77	0.10	3.78	1.98	147	39
30	Juniper Oil	42-11 Tribal	6N	6W	11	2,670	2,760	lower Cody	424	0.20	0.84	1.04	0.670	0.19	1.25	1.05	80	64
31	True Oil	Pan Am 22-8	41N	105W	8	1,790	1,880	lower Cody	420	0.39	1.87	2.26	0.860	0.17	2.17	1.23	152	70

(fig. 9); all but 2 have an S_2 greater than 2.5, indicating that it is a fair to very good source rock. Six of the 7 samples from the lower part of the Frontier Formation, with S_2 values less than 2.5, show poor generative potential (fig. 9). Sixteen of the 49 samples from the lower shaly member of the Cody Shale have S_2 values less than 2.5, hence are considered poor source rocks. The remaining 33 samples were generally in the fair to good range with 6 samples having very good to excellent generative potential (fig. 9). The 5 samples for the upper sandy member of the Cody Shale have S_2 values less than 2.5 and are considered to have low potential for generating hydrocarbons (fig. 9).

Another method of describing the generative potential of a source rock using the results of pyrolysis analysis is the genetic potential (G.P.), which is the sum of the values S_1 and S_2 (Tissot and Welte, 1978; Hunt, 1996). The value S_1, like S_2, is expressed as milligrams of hydrocarbons per gram of rock and represents the fraction of original kerogen in the source rock that has been converted to hydrocarbons (Tissot and Welte, 1978). According to Hunt (1996), source rocks with a G.P. less than 2 are considered to have poor generative potential, source rocks with a G.P. ranging from 2 to 5 are considered to have fair generative potential, source rocks with a G.P. ranging from 5 to 10 have good generative potential, and source rocks with a G.P. greater than 10 have very good generative potential. The G.P. of the Mowry Shale, Frontier Formation, and lower and upper members of the Cody Shale as defined by Hunt (1996) are presented in table 1 and figure 10. Using the parameters described by Hunt (1996), the G.P. is fair to very good for the Mowry Shale, poor to fair for the Frontier Formation, poor to very good for the lower shaly member of the Cody Shale, and poor for the upper sandy member of the Cody Shale.

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 (Jacobson, 1991; and Peters and Cassa, 1994). 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), which are defined as (S_2/TOC) ×100, and (S_3/TOC) ×100, respectively (Espitalie and others, 1977; Tissot and Welte, 1978; and Hunt, 1996). According to Hunt (1996), the type of hydrocarbons (oil and (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 Mowry Shale, lower part of the Frontier Formation, and lower and upper members of the Cody Shale

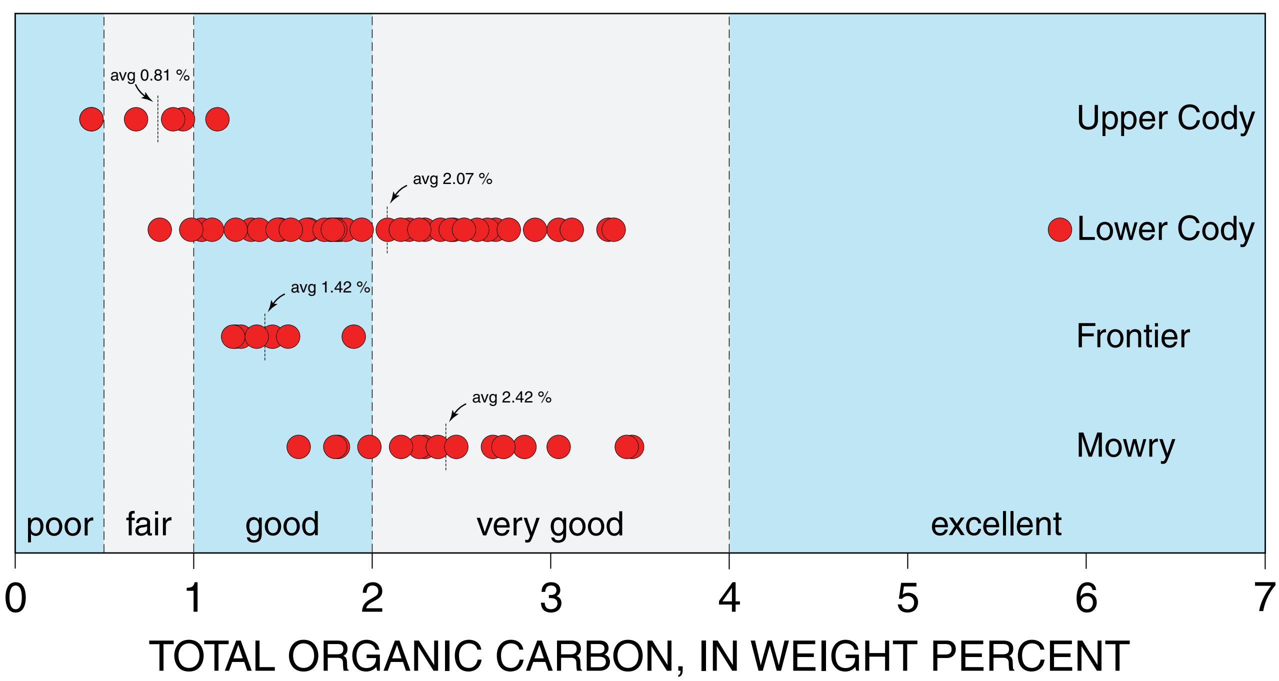

Figure 8. Total organic carbon content of marine shale samples for Mowry Shale, Frontier Formation, and lower shaly and upper sandy members of the Cody Shale in the Wind River Basin. Parameters describing source rock generative potential are from Peters and Casa (1994).

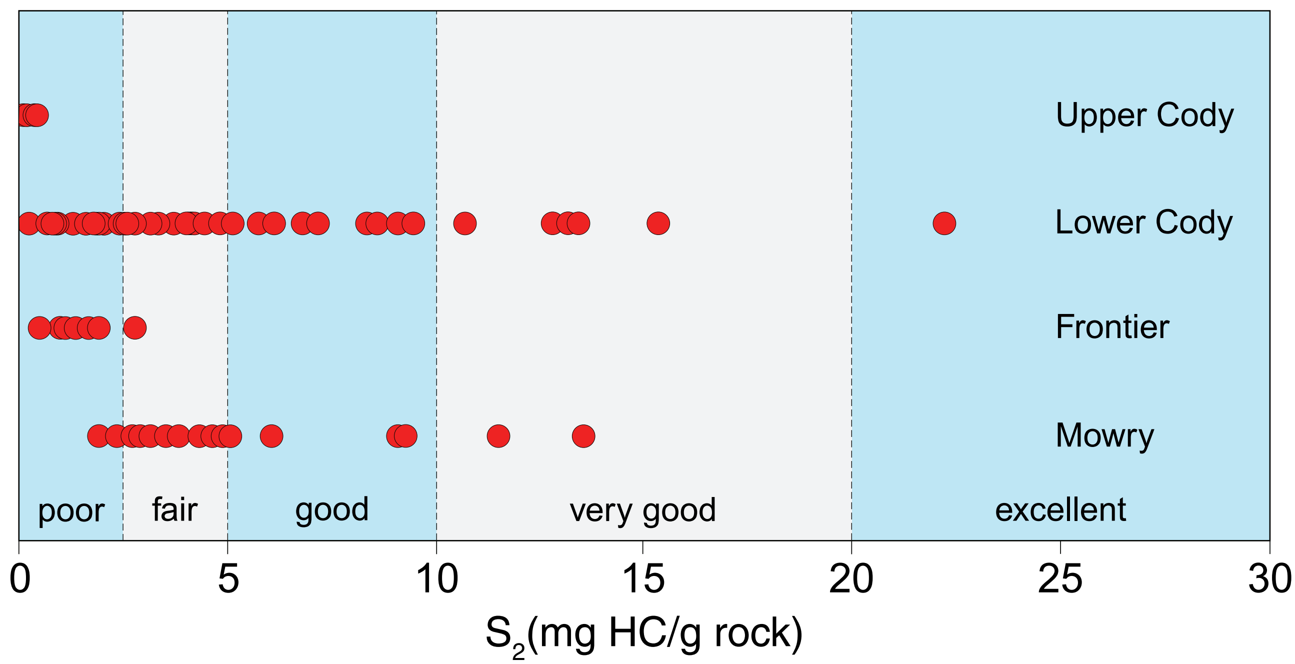

Figure 9. Generative potential of the Mowry Shale, Frontier Formation, and lower shaly and upper sandy members of the Cody Shale based on S_2 values in milligrams of hydrocarbon per gram of rock (mg HC/g rock). Parameters describing source rock generative potential are from Peters and Cassa (1994).

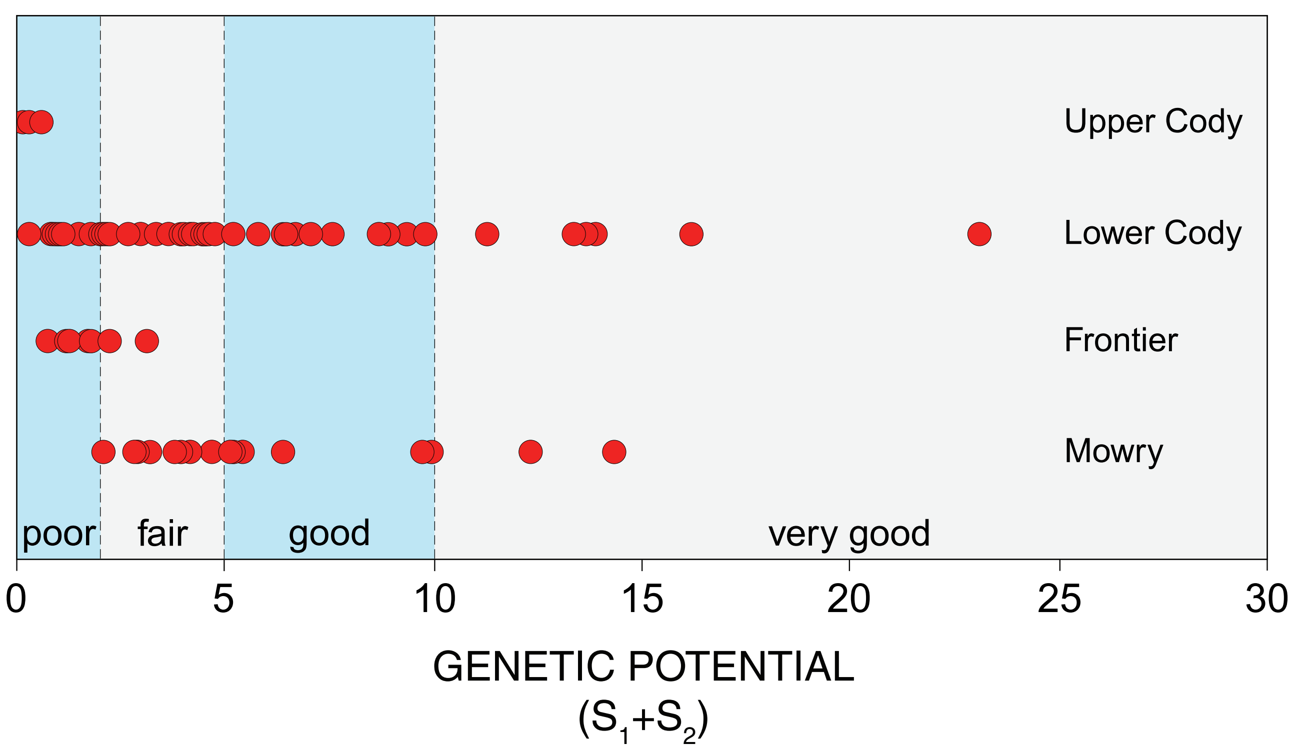

Figure 10. Genetic potential ($S_1 + S_2$) of marine shale samples for Upper Cretaceous Mowry Shale, Frontier Formation, and lower shaly and upper sandy members of the Cody Shale in the Wind River Basin. Parameters describing source rock generative potential are from Hunt (1996).

are shown on table 1 and plotted in figure 11. The plots for the 17 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. 11). The plots for the 7 samples from the lower part of the Frontier Formation indicate that most of the kerogen is type III indicating that the Frontier is a potential source rock mainly for gas (fig. 11). The plots of samples from the lower shaly member of the Cody Shale indicate that it is composed of both type II and type III kerogen indicating a potential source for both oil and gas (fig. 11). The plots for the 5 samples from the upper sandy member of the Cody indicate that most of the kerogen is type IV and has little or no potential to generate hydrocarbons (fig. 11).

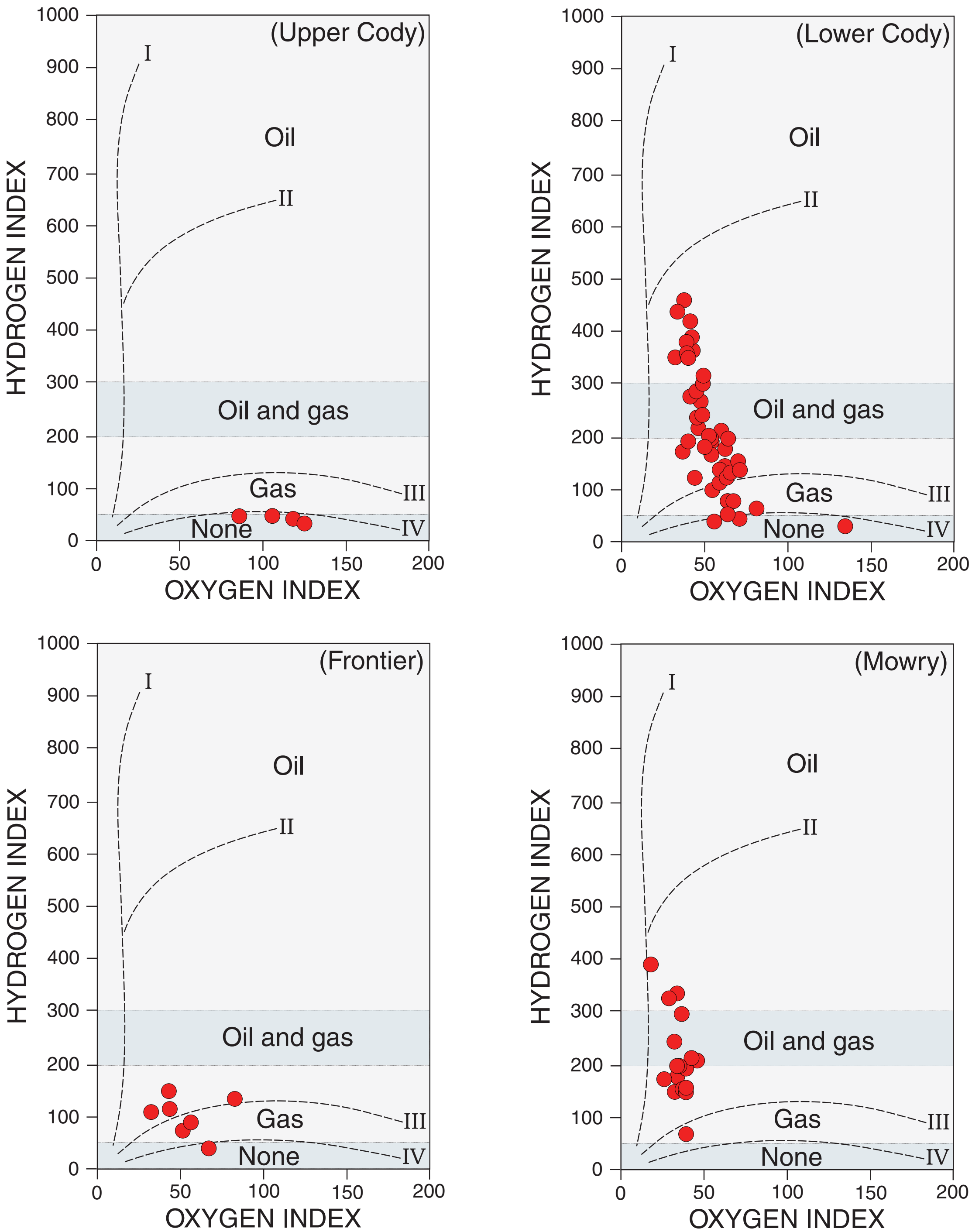

Figure 11. Plots of hydrogen index vs. oxygen index showing kerogen type maturation lines (Hunt, 1996) (dashed lines) and results for samples (red dots) from the Mowry Shale, Frontier Formation, and lower shaly and upper sandy members of the Cody Shale in the Wind River Basin. Hydrocarbon type (oil or gas) from Peters and Casa (1994).

Another method of determining the type of hydrocarbons (such as oil and (or) gas) 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 a 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 Mowry Shale, the lower part of the Frontier Formation, and the lower and upper members of the Cody Shale are shown on table 1 and plotted in figure 12. The lowest S_2/S_3 value for the Mowry Shale is about 1.82 indicating that it is gas prone. The remaining 16 samples from the Mowry have S_2/S_3 values greater than 3, indicating the Mowry is capable of generating both oil and gas (fig. 12). One sample from the lower part of the Frontier Formation has an S_2/S_3 value less than 1 and is not likely to generate any hydrocarbons. Six of the remaining Frontier samples have S_2/S_3 values less than four but greater than one indicating that these samples are mainly gas prone but may possibly generate some oil (fig. 12). The S_2/S_3 values from the lower shaly member of the Cody Shale range from 0.23 to about 13 with most samples being greater than 3, indicating that the lower Cody is capable of generating both oil and gas (fig. 12). The S_2/S_3 values for all samples from the upper sandy member of the Cody are less than 1, indicating little or no capacity to generate hydrocarbons (table 1).

Distribution of Organic Matter

Maps were constructed for the Mowry Shale and lower shaly member of the Cody Shale to show variations in kerogen type and TOC content across the WRB (figs. 13, 14). Maps were not constructed for the lower part of the Frontier Formation or the upper sandy member of the Cody Shale because of a lack of widely distributed control points, as well as the generally poor source rock potential demonstrated by the Rock-Eval and TOC analyses of the these units.

Basin-wide variations of the type and amount of organic matter present in the Mowry Shale are shown in figure 13. The map in figure 13*A* shows that the richest source rocks based on TOC content are in the eastern part of the WRB, near the Casper arch where TOC values range up to about 3.5 weight percent. The area near the present-day Casper arch was located near the central part of the WIS where anoxic bottom conditions existed and clastic input was minimal, creating conditions favorable for the accumulation and preservation of organic matter during the time that the Mowry Shale accumulated (Davis, 1986; Davis and others, 1989). The TOC content decreases in the western part of the WRB to less than 2 weight percent (fig. 13*A*). Regional studies by Schrayer and Zarrella (1963, 1966, 1968), Nixon (1973), Byers and Larson (1979), Burtner and Warner (1984), Davis (1986), and Davis and others (1989) documented 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

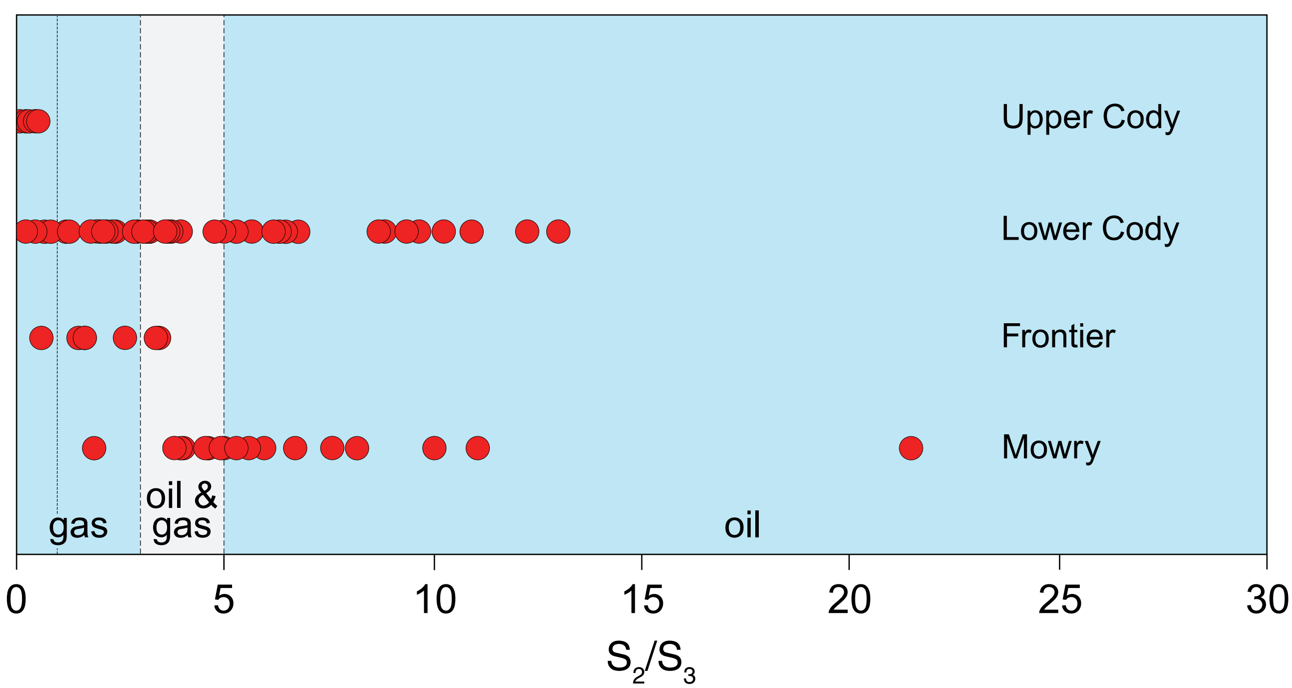

Figure 12. S_2/S_3 ratios for Mowry Shale, lower part of Frontier Formation, and lower shaly and upper sandy members of the Cody Shale. Parameters describing type of hydrocarbons generated are from Peters (1986).

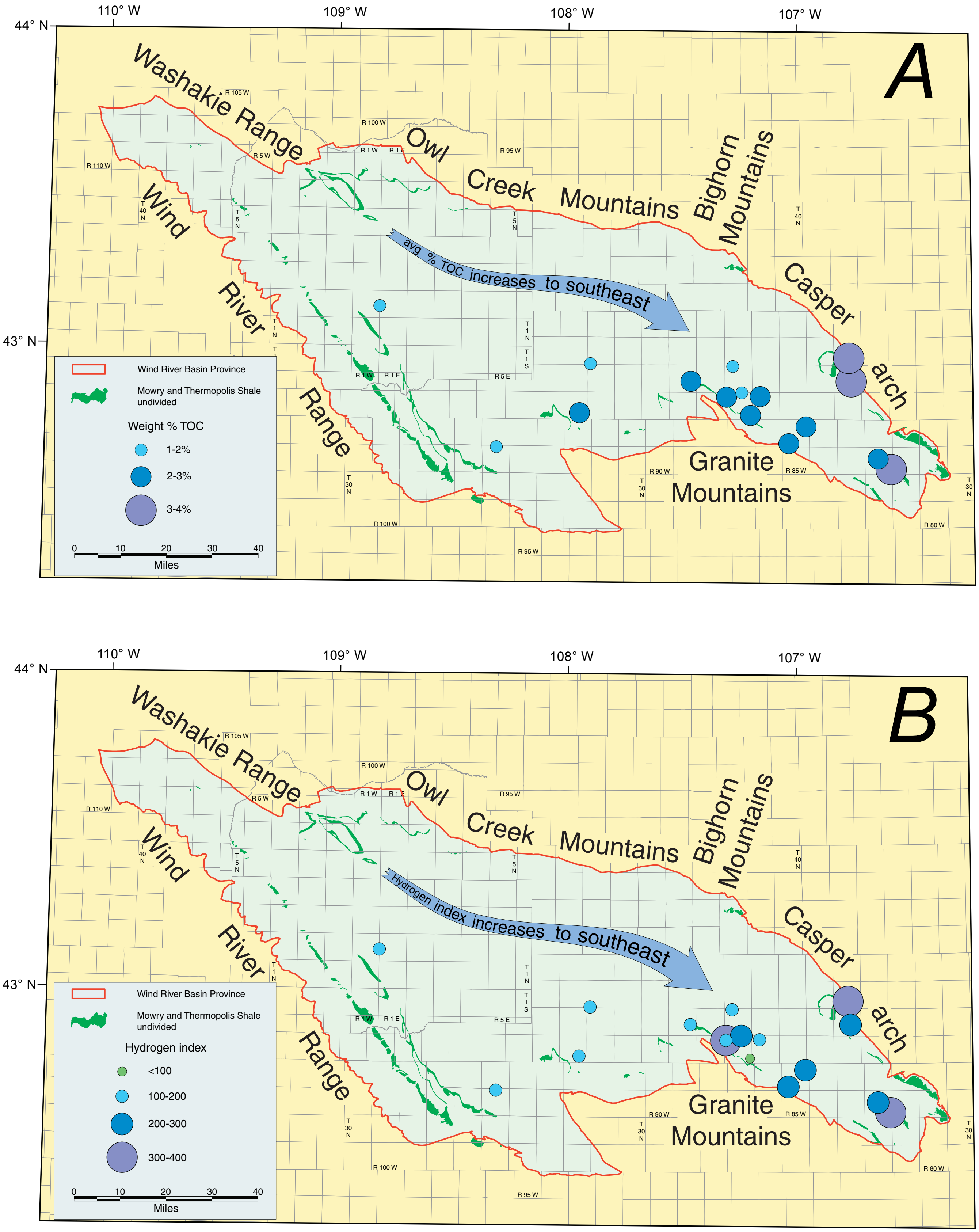

Figure 13. Maps of Wind River Basin showing (*A*) distribution of total organic carbon content and (*B*) kerogen types for Mowry Shale.

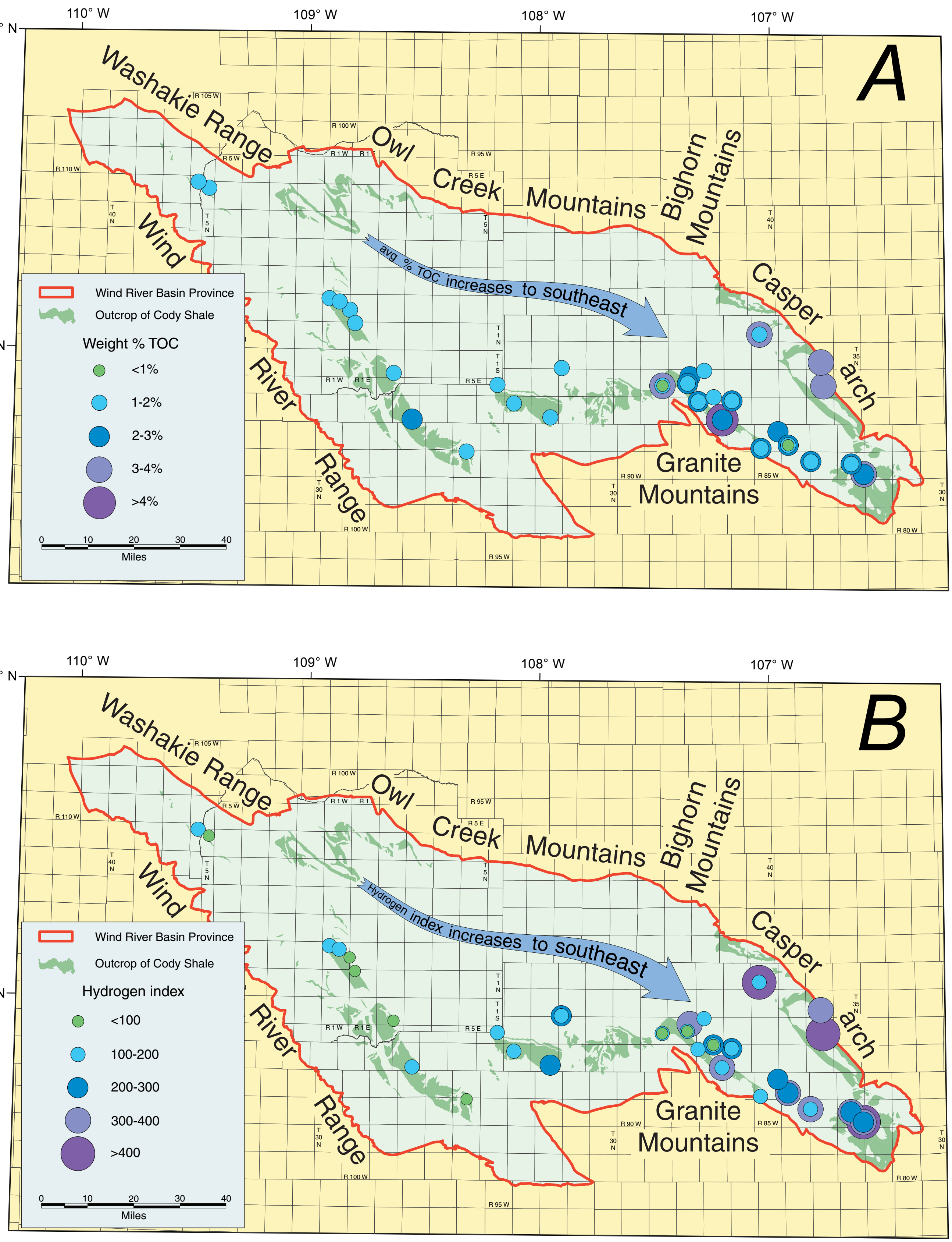

Figure 14. Maps of Wind River Basin showing (*A*) distribution of total organic carbon content and (*B*) kerogen types for lower shaly member of the Cody Shale.

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.

Figure 13*B* shows the variation in kerogen types for the Mowry Shale in the WRB. The map shows that the more oil-prone source rocks lie in the eastern part of the basin where HI values range to nearly 400; whereas, values decrease to less than 150 in the western part. This indicates that the OM in the formation to the east is predominantly type II oil-prone kerogen derived from marine sources and the OM to the west is predominantly type III gas-prone kerogen derived mainly from terrestrial sources west of the basin (Meissner and others, 1984; Burtner and Warner, 1984; Davis, 1986; Davis and others, 1989).

Distribution of TOC contents for the lower shaly member of the Cody Shale is similar to the Mowry Shale and range from nearly 6 weight percent in the eastern part of the WRB to less than 2 weight percent in the western part (fig. 14*A*). Regional studies of the Niobrara Formation and equivalent rocks in the WIS by Longman and others (1998) and Landon and others (2001) documented this same trend of overall decreasing organic richness from east to west. They 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 14*B* shows the variation in kerogen types for the lower shaly member of the Cody Shale in the WRB. The more oil-prone source rocks are in the eastern part of the basin, where maximum HI values exceed 400 and the predominant kerogen is type II derived from marine sources. In the western part, HI values decrease to less than 100, and the OM 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 WRB is presented in figure 15. The map was constructed using R_o data published by Johnson and others (1991), Barker and Crysdale (1993), Barker and others (1993), Nuccio and others (1993), Pawlewicz (1993), Nuccio and others (1996), and Finn and others (2006) for the post-Cody Upper Cretaceous and Paleocene coal-bearing strata (fig. 4). The isoreflectance contours are drawn on top of the Cody Shale, which is generally 3,000 to 5,000 ft above the potential source rock units that have been discussed, so the R_o values presented on this map (fig. 15) are considered to represent the very minimum levels of thermal maturation. The R_o values are shown to increase from the basin margins toward the deeper central part, a pattern that generally reflects the basin structure (fig. 2) and indicates that thermal maturation trends are mainly related to structural development. Based on the R_o data, all potential source rocks in the Cretaceous marine shales in the deeper parts of the WRB are thermally mature with respect to hydrocarbon generation; further more, in the deepest parts thermal maturity has reached levels sufficient to initiate thermal cracking of oil to gas. For a detailed discussion of the thermal maturation, burial history, and hydrocarbon generation history of the various source rocks in the WRB see Roberts and others (Chapter 6, this CD-ROM).

Conclusions

Results of TOC and Rock-Eval analyses of potential hydrocarbon source rocks in Cretaceous marine strata in the WRB are summarized as follows:

1. The Mowry shale has fair to very good generative potential, with organic matter intermediate between kerogen types II and III and the capability of generating both oil and gas. Data show the formation to be most organic-rich and oil-prone in the eastern part of the basin.

2. The Frontier Formation contains mainly type III kerogen and is gas-prone, but the organic content is generally only poor to fair so generative potential is low.

3. The lower shaly member of the Cody Shale contains types II and III kerogen at levels that make it a fair to excellent source rock for both oil and gas. It is most organic-rich and oil-prone in the eastern part of the basin.

4. The upper sandy member of the Cody Shale, containing mostly type IV kerogen with organic richness levels only poor to fair, has little or no potential to generate hydrocarbons.

Thermal maturity mapping based on vitrinite reflectance data collected from coal beds in the overlying Upper Cretaceous and Paleocene strata, and thermal modeling and burial reconstructions by Roberts and others (Chapter 6, this CD-ROM) indicate that the Upper Cretaceous marine shale source rock interval is well within the oil window and in many places is well within the gas generating or oil cracking thermal areas.

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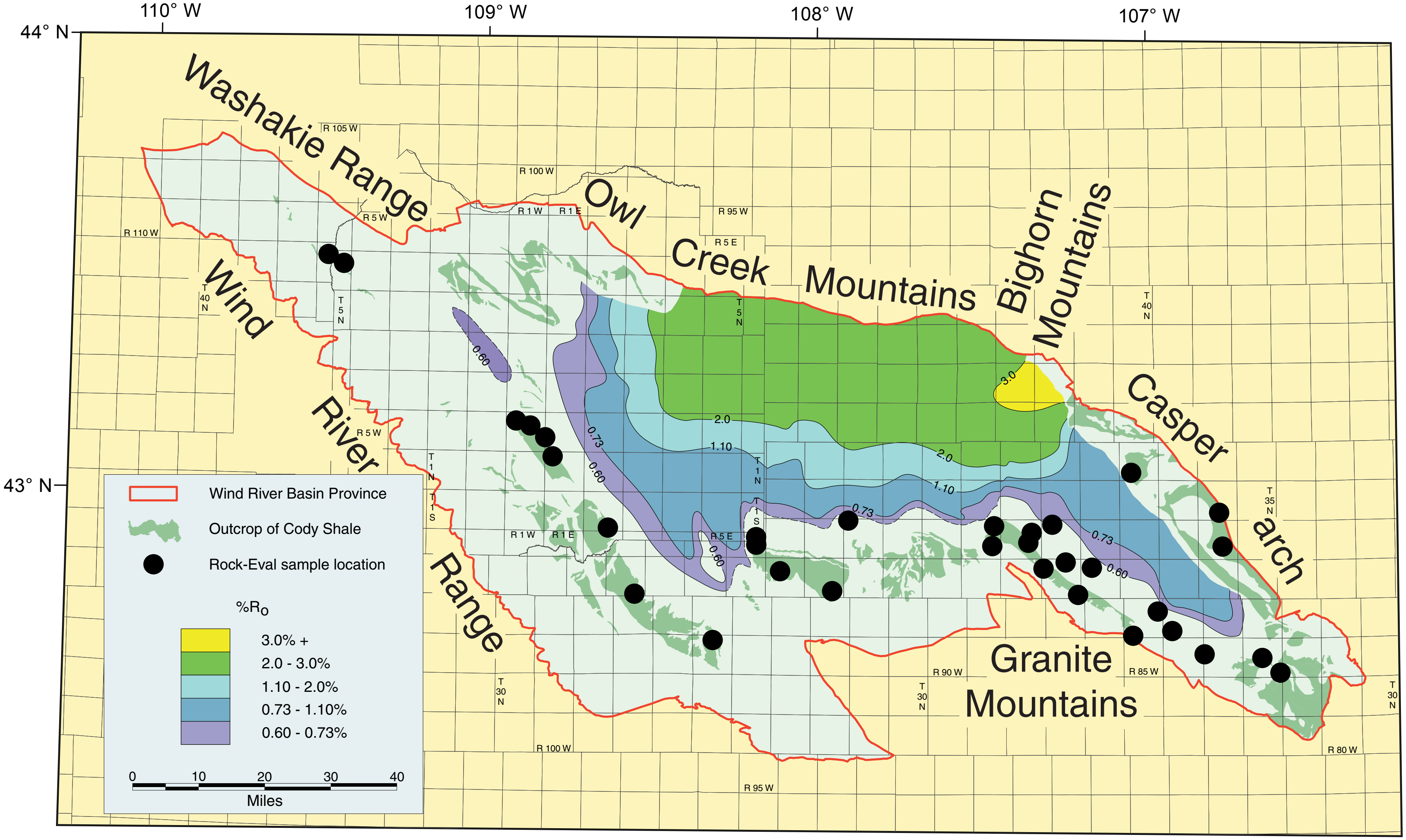

Figure 15. Map of Wind River Basin showing thermal maturity at top of Cody Shale based on vitrinite reflectance (R_0). From Johnson and others (Chapter 4, this CD-ROM).

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