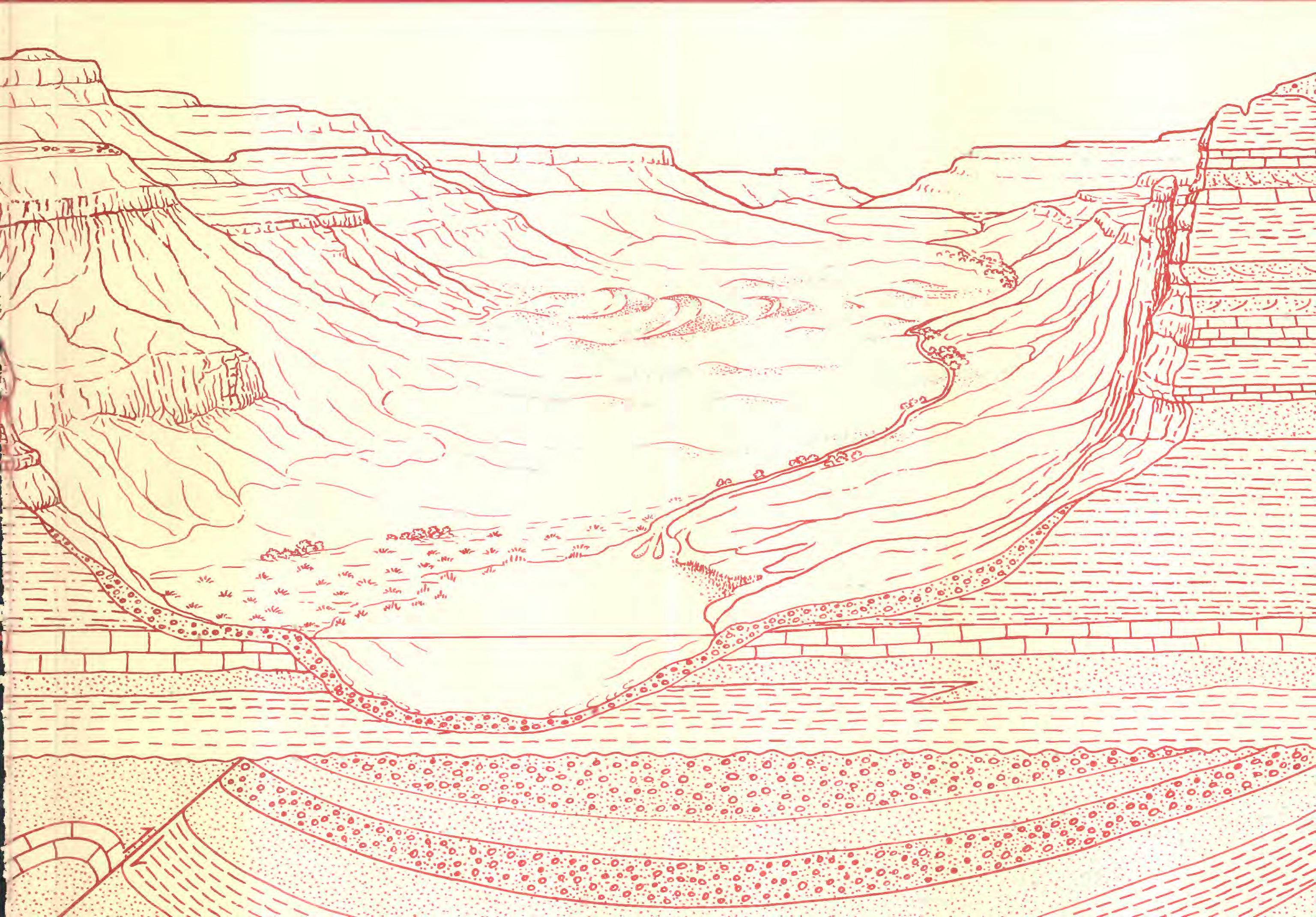
Burial, Thermal, and Petroleum Generation History of the Upper Cretaceous Steele Member of the Cody Shale (Shannon Sandstone Bed Horizon), Powder River Basin, Wyoming

U.S. GEOLOGICAL SURVEY BULLETIN 1917–A



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Chapter A

Burial, Thermal, and Petroleum Generation History of the Upper Cretaceous Steele Member of the Cody Shale (Shannon Sandstone Bed Horizon), Powder River Basin, Wyoming

By VITO F. NUCCIO

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1917

EVOLUTION OF SEDIMENTARY BASINS—POWDER RIVER BASIN

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
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To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	0.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C=(temp °F-32)/1.8

Burial, Thermal, and Petroleum Generation History of the Upper Cretaceous Steele Member of the Cody Shale (Shannon Sandstone Bed Horizon), Powder River Basin, Wyoming

By Vito F. Nuccio

Abstract

The burial, thermal, and petroleum generation history of the Upper Cretaceous Steele Member of the Cody Shale at approximately the Shannon Sandstone Bed horizon has been reconstructed for the northwestern and southwestern parts of the Powder River Basin of Wyoming by using vitrinite reflectance and Rock-Eval pyrolysis data and time-temperature and kinetic modeling. Organic geochemical and petrographic data indicate that the Steele Member contains enough kerogen of the proper types (II and III) to be considered a potential source rock for both oil and gas in the western part of the Powder River Basin.

In the northwestern part of the basin, the Shannon Sandstone Bed was buried to approximately 12,000 ft (3,660 m) and attained a paleotemperature of 230 °F (110 °C) at maximum burial 10 Ma. From 10 Ma to present, erosion of 2,700 ft (824 m) of section has caused a lowering of temperatures. Vitrinite reflectance and Rock-Eval pyrolysis data indicate that the Steele Member is immature to mature, and thus initiation of oil generation is constrained to at or near maximum burial 10 Ma. Time-temperature and kinetic modeling (assuming type II kerogen) puts the beginning of oil generation between 35 and 25 Ma, after the Laramide orogeny and before maximum burial. Kinetic modeling (type III kerogen) indicates that some hydrocarbon generation began as early as 36 Ma.

In the southwestern part of the basin, the Shannon Sandstone Bed was buried to approximately 13,000 ft (3,965 m) and reached a temperature of 248 °F (120 °C) at maximum burial. Erosion of 2,070 ft (631 m) of section has resulted in a lowering of temperatures. Vitrinite reflectance and Rock-Eval pyrolysis data again show that the Steele Member is immature to mature and that oil generation began at or near maximum burial 10 Ma. Time-temperature and kinetic modeling of type II kerogen, on the other hand, constrain oil generation to between 47 and 38 Ma—both during and after the Laramide orogeny and before maximum burial. Kinetic modeling using type II kerogen shows that the Steele Member attained a transformation ratio or production index of 0.40 at 10 Ma and that thermal cracking of oil to gas possibly occurred. Results of this modeling, along with the fact that the Steele Member has generated some thermogenic gas (based on kinetic modeling of type III kerogen), suggest that Shannon Sandstone reservoirs could contain some volumes of gas.

Each of the four independent maturity indicators (vitrinite reflectance, Rock-Eval pyrolysis, time-temperature modeling, and kinetic modeling) yields a different time for the beginning of oil generation. Vitrinite reflectance and Rock-Eval pyrolysis data indicate the most recent time for oil generation. Time-temperature and kinetic modeling indicate a higher level of maturity and an earlier time for petroleum generation. These different results indicate the importance of using as many techniques as possible when assessing the thermal maturity and timing of petroleum generation for a potential source rock.

INTRODUCTION

The lower Campanian Shannon Sandstone Bed of the lower and middle Campanian Steele Member of the Cody Shale is a prolific oil and gas reservoir in parts of the Powder River Basin, Wyoming (fig. 1), and probably contains oil and gas from several different source rocks. Nixon (1973), in a study of the Upper Cretaceous Mowry Shale, and Merewether and Claypool (1980), in a study of Lower and Upper Cretaceous source rocks, concluded

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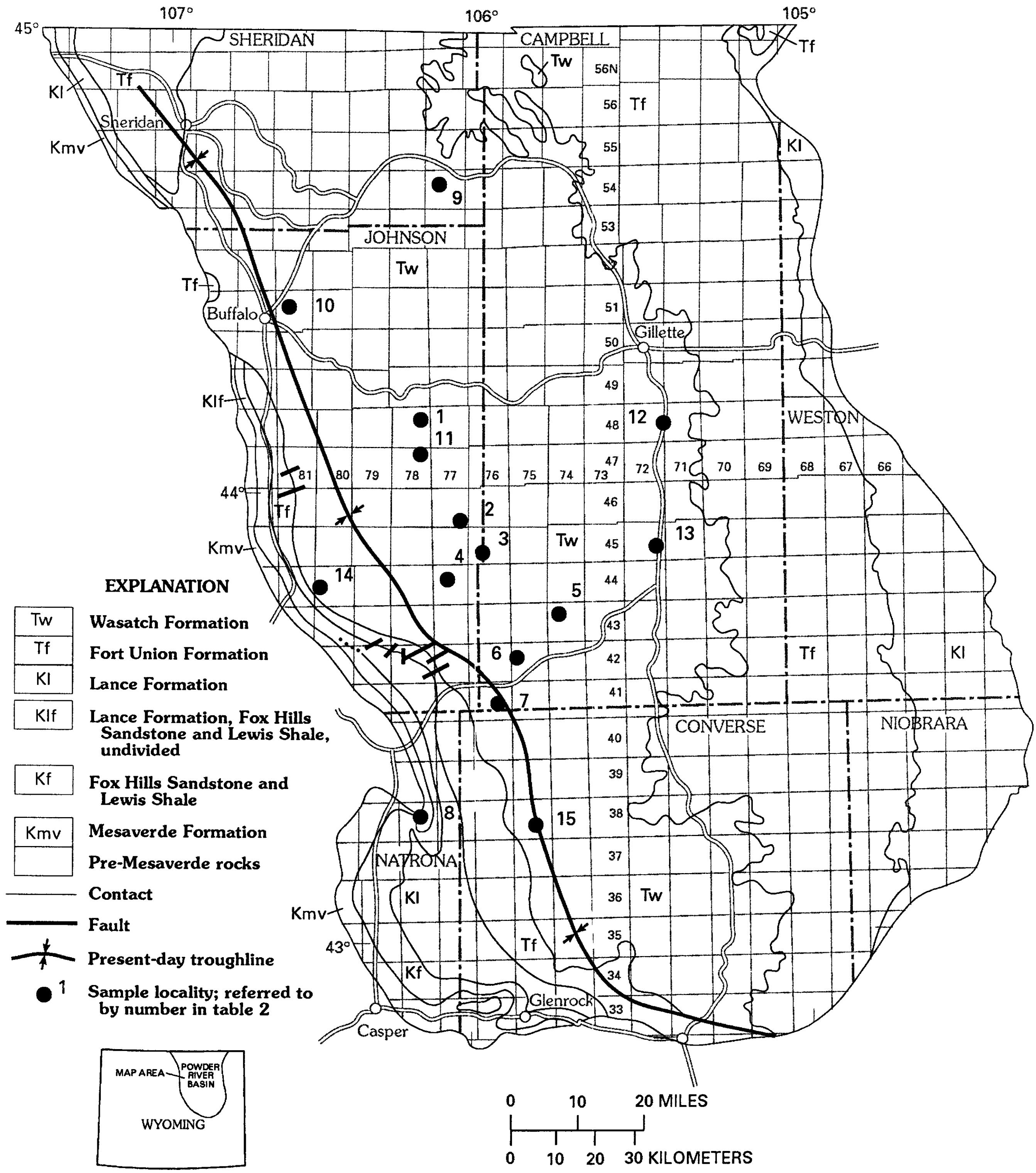

Figure 1. Geology of the Powder River Basin of Wyoming. Location of present-day trough line also shown. Sample localities (solid circles) are described by number in table 2.

that these strata are important source rocks for oil in the Powder River Basin. Momper and Williams (1984) presented geochemical data for the Upper Cretaceous Mowry Shale and the Upper Cretaceous Sage Breaks and Niobrara Members of the Cody Shale and stated that these source rocks expelled most of the discovered oil in the Powder River Basin. Burial, thermal, and geochemical data presented in this study suggest that the

Steele Member of the Cody Shale is also a potential petroleum source rock over large areas of the western part of the Powder River Basin. It is likely that oil and gas generated from the Steele is contained in Shannon reservoirs.

The purposes of this study are to (1) present burial histories representative of the northwestern and southwestern parts of the Powder River Basin (south of lat 45° N.), (2) show the maximum level of thermal maturity for the Steele Member and its Shannon Sandstone Bed, and (3) show the source-rock potential and timing of petroleum generation for the Steele. It is hoped that data presented in this study will also lead to a better understanding of the burial and temperature history of the Shannon Sandstone Bed, an understanding crucial for diagenetic studies, fluid-flow modeling, and reservoir-rock characterization.

REGIONAL GEOLOGY

Only the geologic history of the Steele Member of the Cody and overlying stratigraphic units (fig. 2) is discussed because this study concerns the burial history of the Steele (Shannon Sandstone Bed horizon).

Upper Cretaceous Strata

During the Cretaceous, the Powder River Basin was part of a larger subsiding trough (fig. 1) that occupied much of the central United States and central Canada. This trough formed on the east side of the rising Sevier orogenic belt and was filled by an epicontinental sea during much of the Cretaceous. Upper Cretaceous strata in the Powder River Basin are characterized by deposition during a series of westward transgressions and eastward regressions of the epeiric sea. Upper Cretaceous rocks thicken from about 4,000 ft (1,220 m) at the northern margin of the basin to about 10,000 ft (3,050 m) at the southern margin (D.K. Higley and B.L. Crysdale, U.S. Geological Survey, written commun., 1988) and contain coarser grained detritus in the western part of the basin.

The Steele Member of the Cody Shale of eastern Wyoming is a thick marine sequence deposited in the seaway during middle Late Cretaceous time (early and middle Campanian). These dark-gray marine shales are considered to be fair to good petroleum source rocks (Merewether and Claypool, 1980; Momper and Williams, 1984). A succession of marine sandstones, possibly nearshore deposits (in ascending order, the "Fishtooth" sandstone and the Shannon and Sussex Sandstone Beds of the Steele), were also deposited in the seaway. These shallow-water marine sandstones have been the object of oil and gas exploration in many parts of the Powder River Basin.

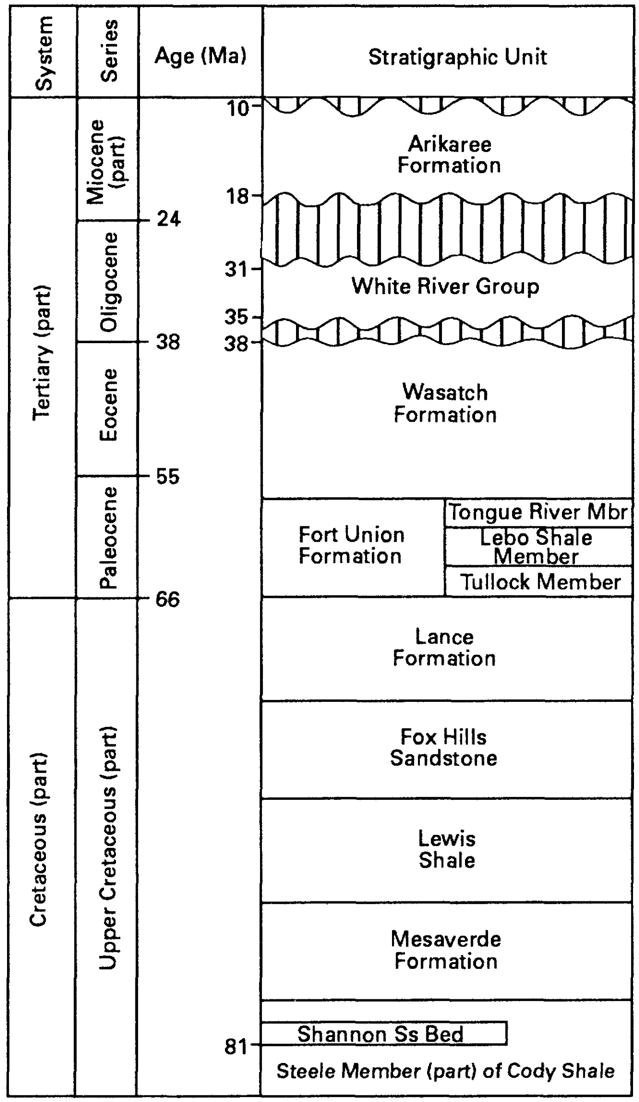

Figure 2. Stratigraphy of Cretaceous and Tertiary rocks in the western part of the Powder River Basin, Wyoming. Nomenclature and ages of units correspond to those in table 1.

In middle Campanian to early Maastrichtian time, coincident with the eastward withdrawal of the Cretaceous sea, deposition in the study area changed from marine to marginal marine and nonmarine. The Mesaverde Formation, deposited in fluvial, coastal-plain, and shallow-water marine environments, is representative of this time period (fig. 2). The overlying marine Lewis Shale represents another westward transgression of the seaway during early to middle Maastrichtian time. In middle Maastrichtian time, in response to the beginning of the Laramide orogeny, there was a final eastward withdrawal of the sea from the Powder River Basin. During this regressive stage, marginal-marine sediments of the Fox Hills Sandstone and fluvial sediments of the Lance Formation were deposited. The

Table 1. Data used to reconstruct burial history of the Shannon Sandstone Bed of the Steele Member of the Cody Shale, Powder River Basin, Wyoming

[Mean annual surface temperature of 50 °F (10 °C) is assumed for the entire burial history]

Age (Ma)	Formation or event	Thickness (feet)	(meters)
	Northwestern Powder River Basin		
0-10	Uplift and erosion	-2,735	-834
10-18	Arikaree Formation	1,000	305
18-31	Hiatus	0	0
31-35	White River Formation	800	244
35-38	Hiatus	0	0
38-55	Wasatch Formation	2,000	610
55-66	Fort Union Formation	5,100	1,556
66-81	Steele Member (part) and overlying Cretaceous formations	3,125	953
	Southwestern Powder River Basin		
0-10	Uplift and erosion	-2,068	-631
10-18	Arikaree Formation	1,000	305
18-31	Hiatus	0	0
31-35	White River Formation	1,000	305
35-38	Hiatus	0	0
38-55	Wasatch Formation	1,000	305
55-66	Fort Union Formation	4,400	1,342
66-81	Steele Member (part) and overlying Cretaceous formations	5,500	1,678

Fox Hills Sandstone is dominantly sandstone and sandy shale, whereas the Lance Formation comprises shale, lenticular sandstone, and, in the lower half, several thin coal beds (Seeland, 1985).

Upper Cretaceous strata (Shannon Sandstone Bed of the Steele Member through the Lance Formation) in the northwestern part of the study area are about 3,125 ft (953 m) thick and in the southwestern part about 5,500 ft (1,678 m) thick, based on the selection of formation tops from geophysical borehole logs (table 1, fig. 2).

Paleocene Strata

The contact between the Lance Formation and the nonmarine Paleocene Fort Union Formation is gradational and in most areas difficult to determine. The boundary between the Cretaceous and Tertiary may be at the contact between these two formations or within the Lance Formation (Bohor and others, 1987; Fox and others, in press). Laramide uplifts were not prominent features in eastern Wyoming until late Paleocene time (Seeland, 1985), when the first coarse clastic orogenic sediments of Tertiary age were deposited in the Powder River Basin. The Fort Union Formation is divided into three members, in ascending order, the Tullock, the Lebo Shale, and the Tongue River Members.

Isopach maps of the Tullock Member (Curry, 1971) indicate that there was subsidence, represented by moderate thickening, in the southern and southwestern parts of the basin; however, no major subsidence along the present structural axis of the basin is indicated. The Tullock Member is interpreted as a fluvial and paludal unit consisting of thin sandstone and mudstone and discontinuous, mostly thin coal beds (Seeland, 1985; Ayers, 1986).

The Lebo Shale Member may represent subsidence along the basin axis. A lake could have formed where the mudstone, shale, discontinuous sandstone, and sparce carbonate rocks of the Lebo are found (Ayers, 1986).

The upper Paleocene Tongue River Member shows the first evidence of significant Laramide activity. Uplift along the western margin of the basin is represented by coarse sandstone and conglomerate (Weaver and Flores, 1985).

For this study, thicknesses are reported for the entire Fort Union Formation and not for individual members. In the northwestern part of the study area, the Fort Union Formation is about 5,100 ft (1,556 m) thick, as determined from geophysical borehole logs. In the southwestern part, it is about 4,400 ft (1,342 m) thick (table 1, fig. 2).

Eocene Strata

By early Eocene time, the basins of Wyoming were well defined, and boulder conglomerates of the Kingsbury and Moncrief Members of the Paleocene and Eocene Wasatch Formation had been deposited in alluvial fans along the east side of the Bighorn Mountains in the Powder River Basin (Seeland, 1985). The composition of the Wasatch Formation has been described as arkosic sandstone, lenticular conglomerate, siltstone, carbonaceous shale, many coal beds, and some variegated mudstone (Seeland, 1985). The Wasatch Formation ranges from 2,000 ft (610 m) thick in the northwestern part of the study area to 1,000 ft (305 m) thick in the southwestern part (Curry, 1971; Seeland, 1985; N.M Denson, U.S. Geological Survey, oral commun., 1989) (table 1, fig. 2). It should be noted that Tschudy (1976) documented the lower 300 ft (100 m) of the Wasatch Formation in the Powder River Basin as being Paleocene in age.

Oligocene Strata

Laramide deformation abruptly ceased before Oligocene time, during which volcaniclastic deposits of the White River Group buried the Precambrian cores of mountains and filled the basin (Curry, 1971). Seeland (1985) stated that the Oligocene White River Group overlies a late Eocene land surface that formed on many different stratigraphic units throughout the northern Great Plains. The White River Group is dominantly a fine-grained fluvial unit derived in large part from air-fall volcanic ash, but it also contains pre-Oligocene sands and gravels derived from Laramide uplifts (Seeland, 1985).

Determining the thickness of the Oligocene White River Group in the Powder River basin is difficult because only a few remaining occurrences of these strata remain. McKenna and Love (1972) diagrammatically reconstructed the thickness of Eocene, Oligocene, and Miocene rocks across the Powder River Basin by correlating units from the Bighorn Mountains on the west margin of the basin with those from North Pumpkin Buttes in the middle of the basin and from the Black Hills on the east side of the basin. In the northern part of the study area, the White River Group is about 800 ft (244 m) thick (N.M Denson, oral commun., 1989). In the southern part, the group is about 1,000 ft (305 m) thick (McKenna and Love, 1972; N.M Denson, oral commun., 1989) (table 1, fig. 2).

Miocene Strata

Reconstructing the thickness and paleogeography of the Miocene Arikaree Formation in the study area is difficult due to the lack of preservation of these strata. The closest remaining occurrences of the Arikaree that can be studied in detail are in the northwestern part of Nebraska.

In northwestern Nebraska, fluvial erosion in the late Oligocene produced an unconformity that separates the Arikaree Group from older Cenozoic units (Swinehart and others, 1985). The estimated stratigraphic position of this unconformity in the study area is shown in figure 2. The Arikaree Group was deposited on this unconformable erosion surface and is made up of gray and brownish-gray, volcaniclastic silty sandstone and local occurrences of coarser grained sandstone at the base (Swinehart and others, 1985).

Using published data for the Bighorn Mountains (McKenna and Love, 1972) and northwestern Nebraska (Swinehart and others, 1985) and unpublished work by N.M. Denson (oral commun., 1989), the original thickness of the Arikaree Formation in the Powder River Basin is estimated as 1,000 ft (305 m) for both the northern and southern parts of the study area.

Beginning approximately 10 Ma, regional uplift and erosion removed most Oligocene and Miocene strata, leaving only Eocene and older rocks exposed in the Powder River Basin.

METHODS

Mean random vitrinite reflectance (Rm) analyses (Stach and others, 1982) for samples of the Steele Member from 15 wells throughout the central and western parts of the study area were used to determine levels of thermal maturity (fig. 1, table 2). Samples 1–8 are from core of Steele collected immediately below the Shannon Sandstone Bed. Samples 9–15 were collected by Amoco Oil Company, and the vitrinite reflectance data (unpublished) represent the thermal maturity of the Steele at approximately the Shannon horizon. Figure 3, a vitrinite reflectance map of the Steele Member at the Shannon Sandstone Bed horizon in the central and western parts of the basin in Wyoming, illustrates where the Steele is sufficiently thermally mature to have generated petroleum.

Rock-Eval pyrolysis analysis, a rapid hydrocarbon source rock evaluation technique and maturation indicator, was used for samples 2–8 (table 3). Details of the analytical technique are given in Espitalié and others (1977).

The burial histories of the Shannon and younger rocks in the two parts of the study area (northwestern and southwestern parts of the basin) were constructed by using stratigraphic thicknesses (table 1) obtained mainly from Curry (1971), Seeland (1985), Swinehart and others (1985), Ayers (1986), N.M. Denson (oral commun., 1989), F.W. Pierce (U.S. Geological Survey, oral commun., 1989), and D.A. Seeland (U.S. Geological Survey, oral commun., 1989).

Time-temperature index (TTI) modeling was performed to define levels of thermal maturity and the timing of petroleum generation for the Steele Member in the two parts of the study area. Kinetic modeling—

Table 2. Mean random vitrinite reflectance data for Cretaceous rocks, Powder River Basin, Wyoming
[Sample numbers and locations keyed to index map (fig. 1) and vitrinite reflectance (Rm) map (fig. 3). Location is in section, township (north), and range (west)]

Sample number	USGS Core Library number	Location	Formation	Depth (feet)	Depth (meters)	Rm (percent)
1	A729	1, 48 N., 78 W.	Steele Member	8,606	2,625	0.61
				8,610	2,626	.59
2	B626	36, 46 N., 77 W.	Steele Member	9,377	2,860	.58
			Steele Member	9,385	2,862	.56
			Steele Member	9,389	2,864	.56
3	A771	16, 45 N., 76 W.	Steele Member	9,447	2,881	.55
4	A817	22, 44 N., 77 W.	Steele Member	9,886	3,015	.58
			Steele Member	9,892	3,017	.57
			Steele Member	9,947	3,034	.57
5	A915	4, 43 N., 74 W.	Steele Member	9,327	2,845	.55
			Steele Member	9,344	2,850	.54
			Steele Member	9,352	2,852	.54
			Steele Member	9,374	2,859	.59
6	C651	7, 42 N., 75 W.	Steele Member	10,197	3,110	.64
			Steele Member	10,228	3,120	.62
			Steele Member	10,242	3,124	.62
7	C652	13, 41 N., 76 W.	Steele Member	10,807	3,296	.66
			Steele Member	10,828	3,303	.65
			Steele Member	10,832	3304	.66
8	C221	10, 38 N., 78 W.	Steele Member	258	79	.39
			Steele Member	352	107	.40
			Steele Member	359	110	.39
9		9, 54 N., 77 W.	Steele Member	7,065	2,155	.49
			Niobrara Member	7,200	2,194	.50
			Niobrara Member	7,275	2,217	.47
			Carlile Shale	7,545	2,300	.50
			Mowry Shale	8,505	2,592	.56
			Mowry Shale	8,550	2,606	.58
			Mowry Shale	8,630	2,630	.55
			Mowry Shale	8,675	2,644	.50
			Muddy Sandstone	8,770	2,673	.51
			Skull Creek Shale	8,845	2,696	.65
			Skull Creek Shale	8,890	2,710	.66
			Muddy Sandstone	13,842	4,219	1.30
			Muddy Sandstone	13,900	4,237	1.45
10		16, 51 N., 81 W.	Steele Member	9,290	2,833	.50
11		2, 47 N., 78 W.	Steele Member	9,095	2,774	.54
12		13, 48 N. 72 W.	Steele Member	8,820	2,690	.51
13		25, 45 N., 72 W.	Steele Member	8,040	2,452	.49
			Steele Member	8,130	2,480	.47

estimating the temperatures and chemical reactions of organic matter during burial and thermal metamorphism—was also used to determine the level of thermal maturity and the timing of petroleum generation maturation for the Steele Member. The computer program BasinMod (Platte River Associates, 1989) was used for the TTI modeling, and the program MATOIL (Institut français du Pétrole, 1987) was used for the kinetic modeling.

Variable paleogeothermal gradients were assumed for the TTI and kinetic models. A paleogeothermal gradient of 1.60 °F/100 ft (29.2 °C/km), consistent with that of stable continental platforms and foreland basins (Tissot and Welte, 1984), was assumed for part of the Late Cretaceous (80–66 Ma) in the Powder River Basin. From the beginning of the Tertiary (66 Ma) through the Eocene (38 Ma), a paleogeothermal gradient of 1.40 °F/100 ft (25.4 °C/km) was used. This lower gradient represents a cooling of geothermal gradients in the western part of the basin resulting from circulation of relatively cool meteoric water into the basin along faults associated with the Bighorn mountain front during the Laramide orogeny (Momper and Williams, 1984; J.L. Clayton and J.D. King, U.S. Geological Survey, written commun., 1988). From 38 Ma to present, a paleogeothermal gradient of 1.60 °F/100 ft (29.2 °C/km) was

Table 2. Continued

Sample number	USGS Core Library number	Location	Formation	Depth (feet)	Depth (meters)	Rm (percent)
14		30, 44 N., 80 W.	Steele Member	9,870	3,010	.54
			Steele Member	10,235	3,122	.55
			Steele Member	10,655	3,250	.58
			Steele Member	10,880	3,318	.53
			Steele Member	11,045	3,369	.58
			Steele Member	11,180	3,410	.55
			Steele Member	11,315	3,451	.53
			Steele Member	11,585	3,533	.56
			Steele Member	11,750	3,584	.56
			Niobrara Member	11,900	3,627	.52
			Niobrara Member	12,005	3,659	.57
			Niobrara Member	12,075	3,680	.57
			Niobrara Member	12,155	3,705	.65
			Sage Breaks Member	12,290	3,746	.72
			Sage Breaks Member	12,410	3,783	.68
			Sage Breaks Member	12,510	3,813	.66
			Frontier Formation	12,600	3,840	.69
			Frontier Formation	12,720	3,877	.65
			Frontier Formation	12,865	3,921	.66
			Frontier Formation	12,955	3,949	.68
			Frontier Formation	13,040	3,975	.69
			Frontier Formation	13,135	4,004	.71
			Frontier Formation	13,230	4,033	.68
			Mowry Shale	13,305	4,055	.70
			Mowry Shale	13,380	4,078	.82
			Mowry Shale	13,450	4,100	.85
			Mowry Shale	13,520	4121	1.02
			Muddy Sandstone	13,585	4,141	1.00
			Skull Creek Shale	13,630	4,154	1.07
			Skull Creek Shale	13,690	4,173	1.10
			Fuson Shale	13,760	4,194	1.18
15		26, 38 N., 75 W.	Steele Member.	7,875	2,402	.61
			Niobrara Member	8,050	2,454	.61
			Niobrara Member	8,150	2,484	.62
			Niobrara Member	8,200	2,499	.63
			Sage Breaks Member	8,360	2,548	.66
			Sage Breaks Member.	8,455	2,577	.72
			Frontier Formation	8,850	2,697	.66
			Frontier Formation	9,050	2,758	.69
			Frontier Formation	9,265	2,824	.71
			Frontier Formation	9,370	2,856	.69
			Mowry Shale	9,455	2,882	.73
			Mowry Shale	9,550	2,911	.71
			Skull Creek Shale	9,680	2,950	.74

assumed; this is the present-day, measured geothermal gradient in the western part of the Powder River Basin (Geothermal Survey of North America Subcommittee, 1976).

Unlike vitrinite reflectance and Rock-Eval pyrolysis, which are direct measurements, TTI modeling is a method of calculating thermal maturity. In TTI modeling, both time and temperature are considered important to the maturation process. The TTI models, as outlined by Waples (1980, 1985), were used to estimate the time during which the Steele Member was in the oil window (the time when a source rock has reached the proper thermal requirements to generate petroleum). Rock-Eval and organic petrographic data from this study and from studies by Merewether and Claypool (1980) and Momper and Williams (1984) suggest that organic matter of the Steele Member contains a mixture of types II and III kerogen, capable of generating both oil and gas. For type II source rocks, a TTI of 10 corresponding to a Rm of 0.60 percent is assumed to be the point at which oil will begin to be generated, and a TTI of 180 corresponding to a Rm of 1.35 percent is assumed to be

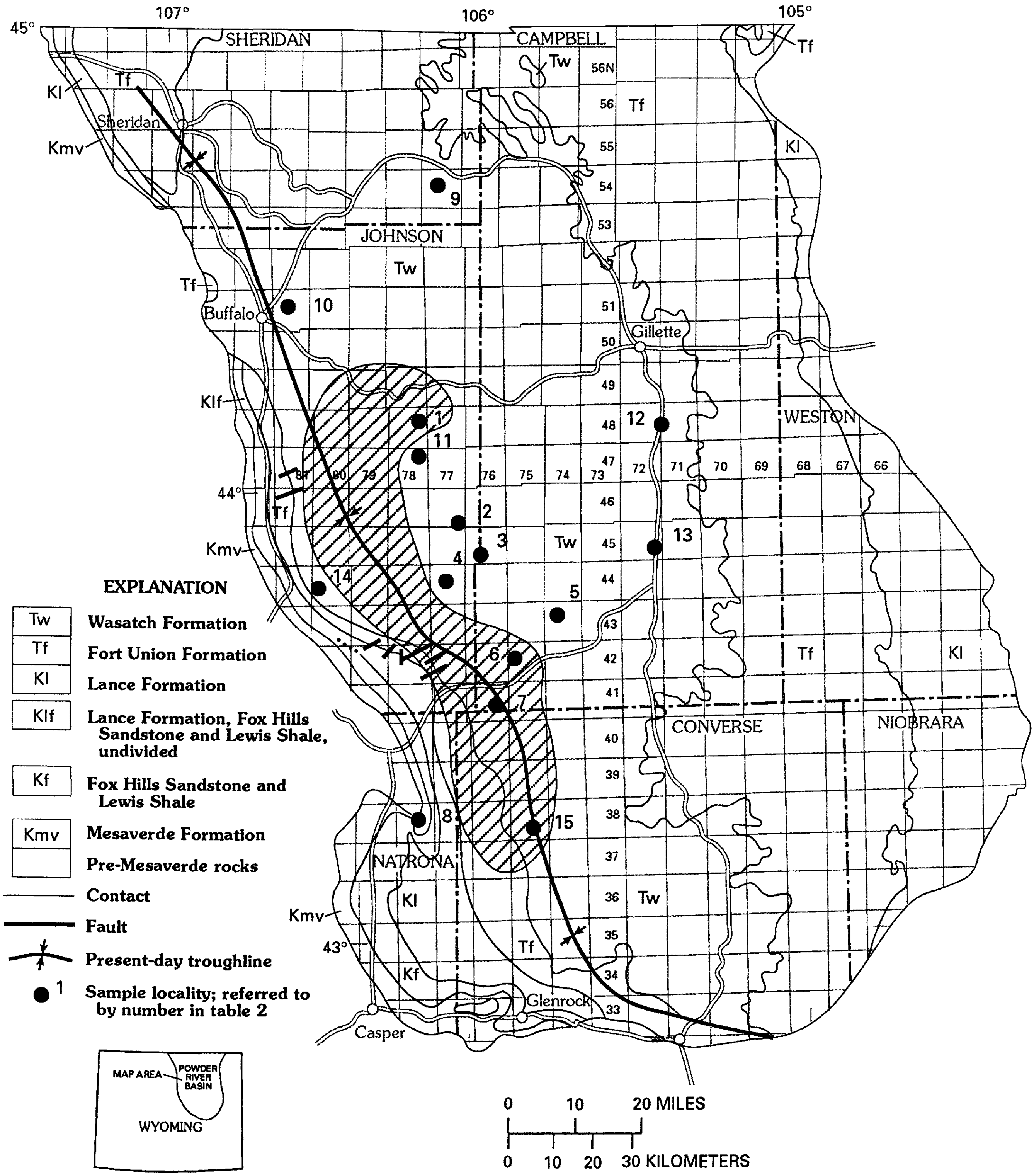

Figure 3. Area of vitrinite reflectance (Rm) values greater than 0.60 percent (the beginning of oil generation), Powder River Basin, Wyoming. Sample localities (solid circles) described by number in table 2; Rm values given in table 2.

approximately the point at which liquid hydrocarbons begin to be thermally destroyed and break down to wet gas and condensate (Waples, 1980, 1985). For type III source rocks, a TTI of 15 corresponding to a Rm of 0.65 percent is assummed to be the onset of oil generation, and a TTI of 180 corresponding to a Rm of 1.35 percent is assumed to be the oil deadline and onset of thermally generated gas (Waples, 1980, 1985). The onset of

Table 3. Rock-Eval pyrolysis data for selected samples of the Steele Member of the Cody Shale, Powder River Basin, Wyoming.

[Sample numbers keyed to index map (fig. 1); USGS Core Library numbers follow in parentheses]

Sample number	Thickness (feet)	(meters)	TOC	Tmax	HI	OI	PI	S1	S2	S3
2 (B626)	9,377	2,860	0.84	438	138	23	0.12	0.16	1.16	0.20
	9,385	2,862	.80	437	91	18	.13	.11	.73	.15
	9,389	1,864	.71	438	125	21	.19	.20	.89	.15
3 (A771)	9 446	2,881	.77	436	122	36	.21	.25	.94	.28
4 (A817)	9,886	3,015	.83	439	115	22	.12	.24	.96	.19
	9,947	3,034	.67	441	98	37	.21	.09	.66	.25
5 (A915)	9,352	2,852	.89	431	125	85	.22	.31	1.12	.76
	9,374	2,859	.82	438	100	30	.15	.14	.82	.25
6 (C651)	10,197	3,110	.89	441	114	21	.21	.27	1.02	.19
	10,228	3,120	1.15	441	135	34	.43	1.16	1.56	.40
7 (C652)	10,828	3,303	.79	444	120	25	.10	.11	.95	.20
8 (C221)	258	79	1.67	403	240	51	.59	5.70	4.01	.86

Abbreviations and units of measurements:

TOC Total organic carbon (in weight percent)
Tmax Temperature at which maximum yield of hydrocarbons occurs during pyrolysis of organic matter (in °C)
HI Hydrogen index (S2/TOC)
OI Oxygen index (S3/TOC)
PI Production index (S1/S1+S2)
S1 Integral of first peak (existing hydrocarbons volatized at 250 °C for 5 minutes (in milligrams per gram)
S2 Integral of second peak (hydrocarbons produced by pyrolysis of solid organic matter (kerogen between 250 and 550 °C)(in milligrams per gram)
S3 Integral of third peak (CO_2 produced by pyrolysis of kerogen between 250 and 390 °C)(in milligrams per gram)

significant gas generation from type III source rocks is assumed to begin at a TTI of 25 corresponding to a Rm of 0.75 percent (Juntgen and Karweil, 1966).

Kinetic modeling was also used to estimate the time when the Steele Member entered the oil window. Kinetic modeling is the best method for predicting the timing of hydrocarbon generation and the amount of hydrocarbon generated because it is based on the kinetic reactions of organic matter (in this case, types II and III) during the thermal maturation process. For types I, II, and III kerogen, the kinetic models of petroleum generation are described as two-step processes: kerogen to oil and oil to gas. All reaction steps are treated as kinetically first order; that is, the rate is proportional to the amount of reactant. The Arrhenius equation is used to describe the temperature dependence of the rate constant. The model that results for a particular kerogen relates amounts of oil and gas generation to time and temperature. For a complete explanation of kinetic modeling, see discussions in Tissot and Espitalié (1975), Ungerer (1983), Yukler and Kokesh (1984), Sweeney and others (1987), and Tissot and others (1987).

For this study, I used kinetics for types II and III organic matter as defined by workers at the Institut français du Pétrole (1987) and a total transformation ratio (amount of petroleum actually formed by kerogen compared to amount the kerogen is capable of producing) of 0.1 percent for the beginning of significant oil generation. Figures 5–10 show burial and thermal

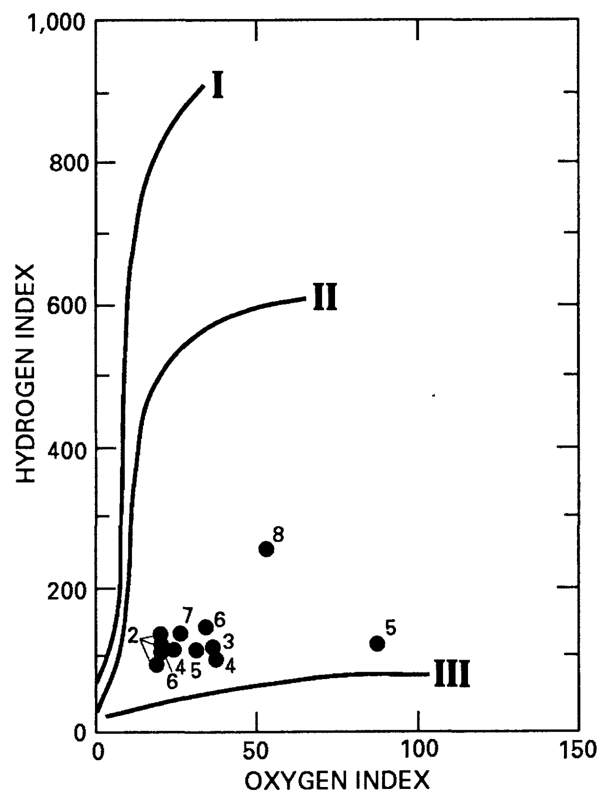

Figure 4. Modified van Krevelen diagram for samples of Steele Member showing type of kerogen and location along thermal evolutionary path. Data are given in table 3.

histories for the northwestern and southwestern parts of the study area and the temperatures and predicted oil windows as determined by TTI and kinetic modeling.

RESULTS

Source Rock Evaluation

Organic Matter Quantity

Total organic carbon content is a useful parameter for evaluating the quantity of organic material in a source rock. Depending on the type of organic matter, fine-grained rocks having a total organic carbon content of 1–2 percent are considered good source rocks (Tissot and Welte, 1984), and the minimum amount of organic carbon required for generation of commercial hydrocarbon deposits is believed to be 0.50 weight percent (Hunt, 1979).

The total organic carbon content of samples of carbonaceous Steele shale collected immediately below the Shannon Sandstone Bed is from 0.67 to 1.67 percent (samples 2–8, table 3); the average content is 0.90 percent. Except for samples 6 and 8, total organic carbon contents are very consistent across the study area. If a total organic carbon content of 0.50 weight percent is assumed to be the minimum for petroleum generation, then the carbonaceous shales analyzed for this study are potential petroleum source rocks in terms of quantity of organic matter.

Organic Matter Quality

The type of organic matter in a source rock is determined by the organisms present during deposition, the state of preservation (dictated by physical conditions such as burial and thermal diagenesis), and biological degradation. Organic matter type determines the quality and kind of hydrocarbons that will be generated, and it can be determined by using several methods. For this study, Rock-Eval pyrolysis of whole-rock samples (Espitalie and others, 1977) and visual kerogen analysis (organic petrography) were used to determine organic matter type.

In general, there are four types of organic matter or kerogen (Tissot and Welte, 1984; Waples, 1985). Type I kerogen is of lacustrine origin; it is derived from algal material, has a high hydrogen index and low oxygen index, and produces mainly oil during catagenesis. Type II kerogen is generally of marine origin; it is derived from a mixture of phytoplankton, zooplankton, and other micro-organisms, has intermediate hydrogen and oxygen indices, and can generate oil and gas. Type III kerogen is of terrestrial origin; it is derived mainly from woody plant remains, has a low hydrogen index and high oxygen index, and generates mainly gas during its burial and thermal history. Type IV kerogen is comprised of inert organic material (oxidized and biologically altered organic material, charcoal, and recycled organic matter); it has low hydrogen and oxygen indices and virtually no hydrocarbon-generating potential.

The Steele Member of the Cody Shale is a marine shale and thus should contain type II organic matter; however, visual kerogen analysis indicates a significant quantity of types III and IV kerogen, suggesting proximity to a terrestrial source. Figure 4 shows a modified van Krevelen plot of the hydrogen and oxygen indices, as determined by Rock-Eval pyrolysis, for samples 2–8. (van Krevelen diagrams are used to illustrate the type of kerogen and its relative position on the maturation evolutionary path (van Krevelen, 1961; Tissot and Welte, 1984).) The samples plot near the type III category and show a fairly high level of thermal maturity; that is, they have low hydrogen and oxygen indices. They plot near the convergence of types I, II, and III, a location that usually indicates a high level of maturation; in this case, however, the samples plot there because of their relatively low total organic carbon content. It is likely that the kerogen in the Steele had higher hydrogen indices in the past. These data, in conjunction with the total organic carbon content data (table 3), indicate that the samples could be considered potential source rocks for oil and gas. Because the Steele is a marine shale, it probably contains a mixture of both types II and III kerogen, and kinetic models for both types of kerogen will be presented and compared.

Vitrinite Reflectance

The level of thermal maturity required for oil generation generally is believed to be 0.60 percent Rm for type II source rocks and 0.65 percent Rm for type III source rocks (Waples, 1985). For type II source rocks, the conversion of oil to gas occurs at a vitrinite reflectance of 1.35 percent. Type III source rocks, however, begin to generate significant amounts of gas at a vitrinite reflectance of 0.73 percent. Mean random vitrinite reflectance data from this study indicate that the Steele Member at the horizon of the Shannon Sandstone Bed is either immature or marginally mature with respect to oil generation and immature for gas generation (table 2). Figure 3 shows the area in which vitrinite reflectance values are greater or equal to 0.60 percent—favorable maturation levels for oil generation from types II and III source rocks.

The vitrinite reflectance data for the Steele are remarkably consistent and do not seem to increase with increasing depth. For instance, sample 1 has a vitrinite reflectance value of 0.61 percent at a depth of 8,606 ft (2,625 m), whereas sample 14, to the southwest, has a vitrinite reflectance value of 0.56 percent at 11,750 ft (3584 m). Even vitrinite reflectance values from stratigraphically lower formations are relatively low considering their depth of burial. Samples from well 15 of the Mowry Shale, 2,000 ft deeper than the Steele Member, have vitrinite reflectance values of only about 0.73 percent, or marginally mature with respect to oil and gas generation. A sample of the Fuson Shale (Lower Cretaceous) at a depth of almost 14,000 ft from well number 14 has a vitrinite reflectance value of only 1.18 percent. There are two possible explanations for these low values. (1) Circulation of relatively colder meteoric water along the mountain-front faults of the Big Horn Mountains resulted in a westward cooling of geothermal gradients. (2) Although the Steele Member was more deeply buried in the southwestern part of the basin during the Late Cretaceous than in the northwestern part, burial was rapid enough that the vitrinite did not equilibrate to reflect the difference in burial depths.

Rock-Eval Pyrolysis

Rock-Eval pyrolysis data indicate that the samples are marginally mature to mature (Tmax 431–444 °C and production index 0.10–0.43). Sample 8 yielded a very low Tmax value of 403 °C and a relatively high production index of 0.59. These extreme values are the result of oil staining of the sample and should not be considered representative of the entire Steele Member. If Rock-Eval data record maximum thermal maturity of the kerogen, which occurred at maximum burial and temperature, then the timing of petroleum generation is constrained to about 10 Ma.

Time-Temperature and Kinetic Models

Northwestern Part of the Study Area

Figure 5 shows the TTI model for the northwestern part of the study area and illustrates the burial and thermal history for the various stratigraphic units. The

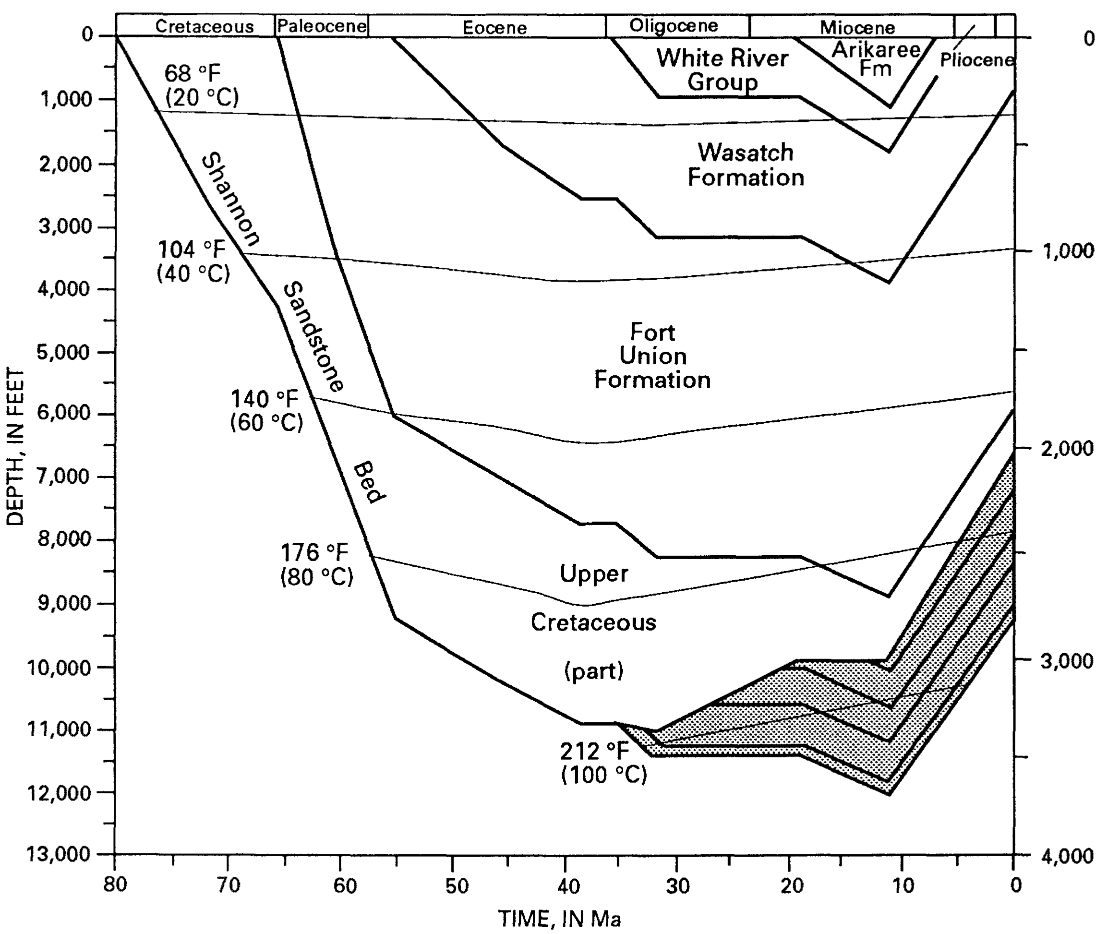

Figure 5. Time-temperature model for northwestern part of study area. Shaded area represents oil window (10–180 TTI); isotherms show temperatures with depth and through time.

model was constructed using the burial data in table 1. The TTI model indicates that oil generation from the Steele Member began approximately 35 Ma and that the Steele is still in the oil window today. Thermal cracking of oil to gas and condensate has not occurred. The Shannon Sandstone Bed was buried to approximately 12,000 ft (3,660 m) in the northwestern part of the study area at maximum burial 10 Ma. Isotherms show that temperatures for that horizon were as high as about 230 °F (110 °C) before cooling occurred in response to uplift and erosion of about 2,700 ft (824 m) of overburden.

Figures 6 and 7 show kinetic models for the Steele Member (Shannon Sandstone Bed horizon) in the northwestern part of the study area. Because the Steele has relatively low total organic carbon contents, it was not possible to define kinetic parameters for the shale. Therefore, hydrocarbon kinetic reaction parameters for types II and III kerogen from the Institut français du Pétrole (IFP) (1987) were used to calculate the level of thermal maturity, timing of oil generation, and milligrams of hydrocarbons produced per gram of organic carbon (mg HC/g TOC) for the Steele Member.

Results of kinetic modeling for type II kerogen (fig. 6) indicate that the Steele Member in the northwestern part of the study area began to generate minor amounts of hydrocarbons as early as 70 Ma (Cretaceous). A transformation ratio of 0.10 was assumed for the beginning of significant oil generation (Tissot and Welte, 1984). Using this value, significant hydrocarbon generation, in amounts sufficient for migration and accumulation in the Shannon Sandstone Bed, probably did not occur until about 25 Ma (Oligocene) at about 212 °F (100 °C) and at a depth of about 11,550 ft (3,523 m). At the present time, after uplift and erosion and at a depth of 9,250 ft (2,821 m), the Steele has a total

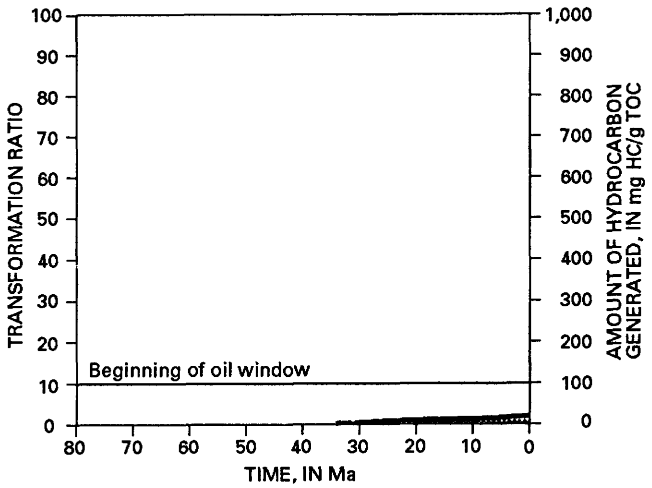

Figure 7. Kinetic model, assuming type III kerogen, for northwestern part of study area. Shaded area represents oil generation; heavy line indicates total transformation ratio through time.

transformation ratio of about 0.20; hence, it is still in the oil window. The type II kerogen kinetic model indicates that the Steele has reached the thermal requirements to have generated about 100 mg HC/g TOC (as oil, shaded area in fig. 6) and a relatively small quantity of gas.

Results of kinetic modeling for type III kerogen (fig. 7) suggest that minor amounts of hydrocarbons (probably both oil and gas) were being generated at 40 Ma (Eocene) at a temperature of about 203 °F (95 °C) and a depth of 10,700 ft (3,264 m). Using type III kerogen, the total transformation ratio for the Steele Member is less than 0.10 and the Steele has not reached the thermal requirements for significant oil or gas generation.

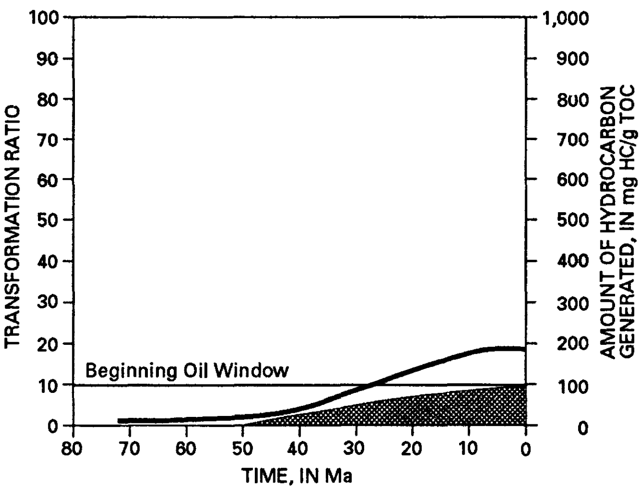

Figure 6. Kinetic model, assuming type II kerogen, for northwestern part of study area. Shaded area represents oil generation; heavy line indicates total transformation ratio through time.

Southwestern Part of the Study Area

Figure 8 shows the TTI model for the southwestern part of the study area and illustrates the burial and thermal history of the various stratigraphic units. The data used to construct this model are presented in table 1. The TTI model shows that oil generation began at about 47 Ma (Eocene), about 10 million years earlier than in the northwestern part of the study area. The Steele Member is still in the oil window today and has not reached the thermal requirements for cracking of oil to wet gas and condensate. The Shannon Sandstone Bed was buried to almost 13,000 ft (3,965 m) at 10 Ma, 875 ft (267 m) more than in the northwestern part of the study area, and reached a temperature of more than 248 °F (120 °C) (10 °C higher than in the northwestern part of the study area). About 2,070 ft (631 m) of overburden has been eroded in the southwestern part of the study area.

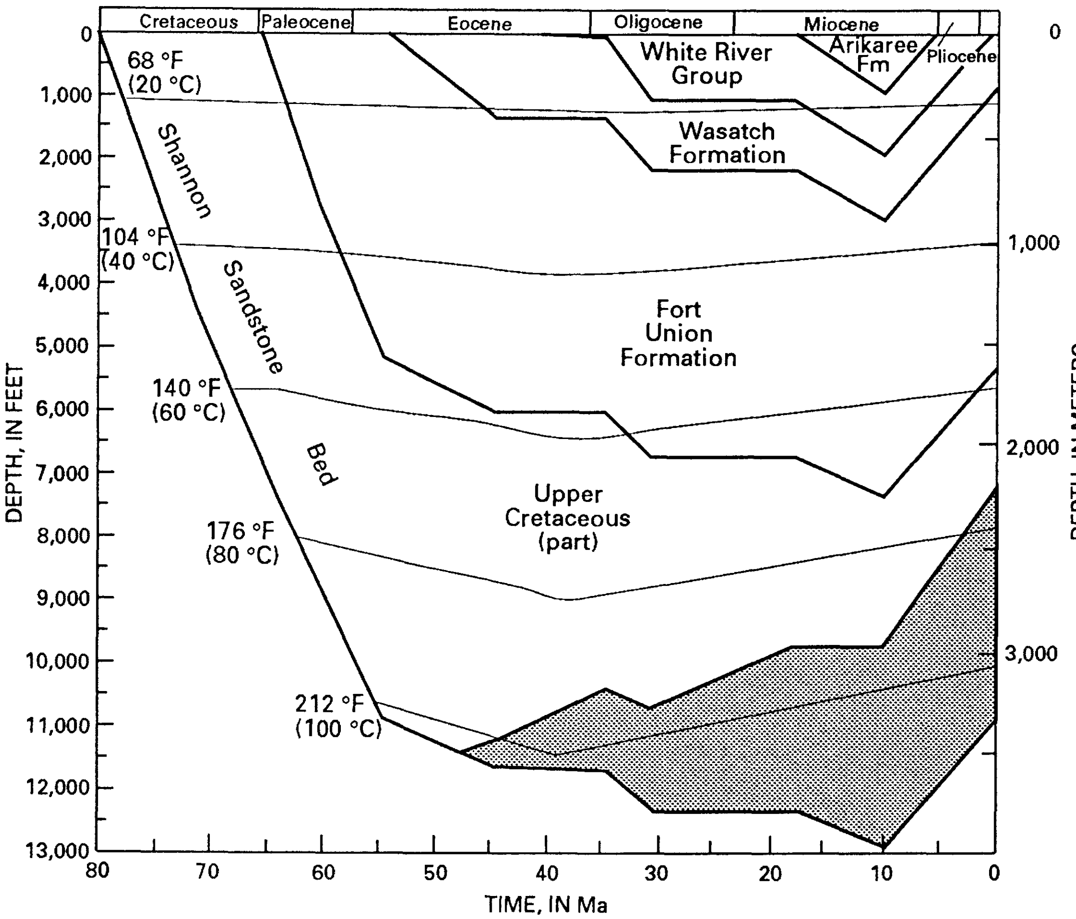

Figure 8. Time-temperature model for southwestern part of study area. Shaded area represents oil window (10–180 TTI); isotherms show temperatures with depth and through time.

Figure 9 illustrates the results of kinetic modeling of type II kerogen for the Steele Member in the southwestern part of the study area. The Steele began to generate some hydrocarbons about 70 Ma (Cretaceous). Significant amounts of hydrocarbons were being generated by 38 Ma (Eocene-Oligocene) at a temperature of 212 °F (100 °C) and a depth of 11,600 ft (3,538 m). The Steele has reached the thermal requirements to have generated as much as 210 mg HC/g TOC (as oil) in the southwestern part of the study area, twice the amount generated in the northwestern part of the study area. Today the Steele has a total transformation ratio of about 0.40; hence it is still in the oil window.

Figure 10 shows the kinetic model for type III kerogen in the southwestern part of the study area. This model indicates that the Steele Member began to generate some minor amounts of oil and gas about 44 Ma (Eocene) at a temperature of about 212 °F (100 °C) and a depth of 11,600 ft (3,538 m). Significant amounts of oil, sufficient for migration and accumulation, were probably never generated. Assuming type III kerogen parameters, only 10 mg HC/g TOC (oil and gas) has been generated.

It should be noted that the kinetic models for type III kerogen are two-stage conversions: kerogen to oil and oil to gas. Gas generation from type III kerogen, however, is more likely a kerogen to gas conversion without the oil-cracking stage. Thus, the type III kinetic models probably underestimate the amount of gas that has been generated by type III kerogen in the Steele Member.

DISCUSSION

In the southwestern part of the study area, the depth of burial for the Steele Member of the Cody Shale at the Shannon Sandstone Bed horizon is only 875 ft (267 m) greater than in the northwestern part and the maximum temperature only about 10 °C higher, yet the hydrocarbon generation history is vastly different. The

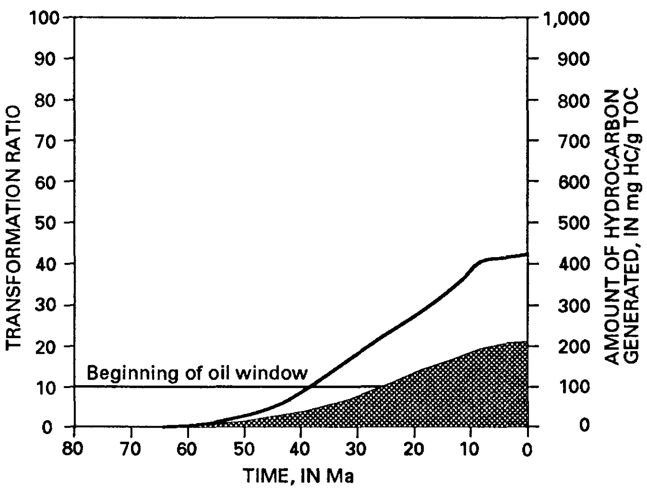

Figure 9. Kinetic model, assuming type II kerogen, for southwestern part of study area. Shaded area represents oil generation; heavy line indicates total transformation ratio through time.

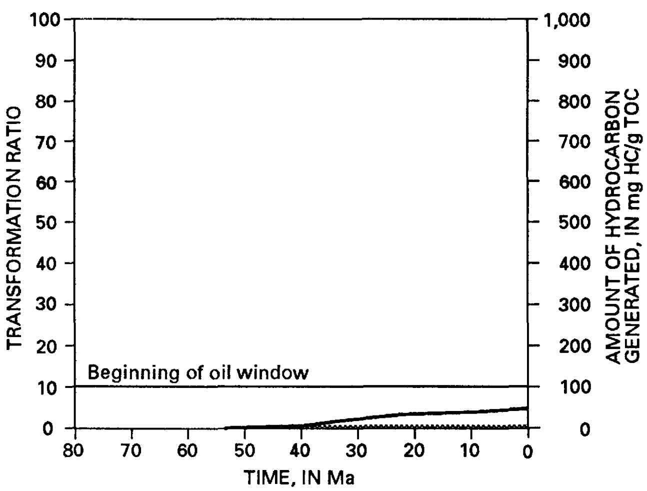

Figure 10. Kinetic model, assuming type III kerogen, for southwestern part of study area. Shaded area represents oil generation; heavy line indicates total transformation ratio through time.

four independent maturity indicators (vitrinite reflectance, Rock-Eval pyrolysis, time-temperature modeling, and kinetic modeling) yield different timing of hydrocarbon generation for the two areas. The vitrinite reflectance data suggest that the two areas are not very different and that the Steele Member is immature to marginally mature with respect to the oil window over much of the western part of the basin (fig. 3). If the burial and thermal models are representative, maximum temperatures for the northwestern and southwestern parts of the study area were 230 °F (110 °C) and more than 248 °F (120 °C), respectively. These temperatures are well in excess of those needed for significant oil generation. Most petroleum generation occurs during catagenesis, commencing at about 122 °F (50 °C) and ending at the threshold of dry gas generation at about 392 °F (200 °C) (Hunt, 1979; Ammosov, 1981). Recently, Quigley and Mackenzie (1988) suggested that most oil is formed between 212 and 302 °F (100–150 °C). Even this higher estimate for the temperature of significant oil generation is within the limits suggested by the burial and thermal models in this study. Vitrinite reflectance records the maximum temperature achieved by a rock. Maximum temperatures were achieved approximately 10 Ma at maximum burial; thus, based on the vitrinite reflectance data, oil generation for the Steele Member probably did not begin much earlier.

Rock-Eval pyrolysis data indicate that the Steele Member is marginally mature to mature and constrain the timing of oil generation to about 10 Ma.

Time-temperature index (TTI) and kinetic modeling for the Steele yield an earlier timing for oil generation than do vitrinite reflectance and Rock-Eval pyrolysis data. For the northwestern part of the study area, estimates from TTI modeling place the beginning of the oil window at approximately 35 Ma (Oligocene), and the conservative estimate from the type II kerogen kinetic modeling (transformation ratio of 0.10) puts the beginning of significant oil generation at around 25 Ma (Oligocene). Therefore, the beginning of oil generation could be constrained to between 35 and 25 Ma—after the end of the Laramide orogeny and before maximum burial. Oil could have migrated updip, along structure, from the deeper parts of the basin or could have accumulated in stratigraphic traps. If type III kerogen is assumed, gas generation may have begun approximately 40 Ma (Eocene) and could be found in Shannon Sandstone Bed reservoirs.

For the southwestern part of the study area, estimates from TTI and kinetic modeling again yield a much earlier timing for oil generation from the Steele than do the vitrinite reflectance data. The modeling also suggests an earlier timing for oil generation than does modeling for the northwestern part of the study area. Estimates from TTI modeling place the beginning of oil generation for the Steele at 47 Ma (Eocene), whereas the conservative estimate from kinetic modeling puts the beginning of the oil window at 38 Ma (Eocene-Oligocene). Thus, as indicated by the two models, oil generation began during and after the Laramide orogeny. This timing has important implications because oil generated in the structurally deeper parts of the basin could have migrated updip and been deposited in less mature and less deeply buried reservoirs. Alternatively, structural movement associated with the Laramide orogeny may have adversely affected potential structural and stratigraphic traps, and oil generated before the end of the structural deformation associated with the Laramide orogeny could have been lost. Results of the TTI modeling suggest that the Steele Member is still in the oil window; however, even if the Steele is still in the oil window, oil generation will not occur if present-day temperatures are too low. Results of the type III kerogen modeling indicate that generation of hydrocarbons began about 44 Ma, timing that suggests Shannon Sandstone Bed reservoirs in the southwestern part of the study area are likely to contain some volumes of methane gas.

To a large extent, rate and depth of burial during the Late Cretaceous controlled the thermal maturity and hence the timing of the oil window for the Steele Member in the study area. In the southwestern part of the study area, the Upper Cretaceous section is 2,375 ft (724 m) thicker than in the northwestern part. The Tertiary section, however, is 1,500 ft (458 m) thicker in the northwestern part. Because the difference in the overall burial history is only 875 ft (267 m) (that is, thicker in the southwestern part of the basin), the Steele Member in the southwestern part of the study area was more deeply buried earlier and thus for a longer period of time than in the northwestern part. Petroleum generation for the Steele in the southwestern part of the study area, therefore, began earlier and produced a greater volume.

In a study of petroleum geochemistry in the Powder River Basin, Momper and Williams (1984) concluded that oil expulsion from the Mowry Shale began in the late Paleocene or early Eocene in the deep, southwestern part of the basin. This timing of oil generation for the Mowry Shale agrees well with the timing scenario for oil generation of the Steele Member determined in the present study because the Mowry Shale is as much as several thousand feet deeper than the Steele; therefore, oil generation should have begun earlier.

Kinetic modeling is probably the best method for estimating the petroleum generation history of a source rock because it takes into account the kinetic properties of the kerogen during catagenesis. Unfortunately, I was not able to use the kinetic properties of the kerogen in the Steele Member for this study, but the kerogen kinetic parameters of IPF are a good approximation of the source rock generation history in the basin. The Steele Member is probably a mixture of types II, III, and IV kerogen, and the kinetic models should be used with this in mind.

Production records from Shannon Sandstone Bed reservoirs show that large volumes of oil and gas have been produced throughout the basin (Wyoming Geological Association, 1981). Further work must be done in order to correlate hydrocarbons in the Shannon reservoirs with the various source rocks in the basin. Geochemical studies will help show to what extent the Steele Member has generated and contributed to the oil and gas in the Shannon reservoirs.

SUMMARY

In the northwestern part of the study area, the Steele Member of the Cody Shale at the Shannon Sandstone Bed horizon was buried to about 12,000 ft (3,660 m) and reached a maximum temperature of about 230 °F (110 °C) at 10 Ma at maximum burial. From 10 Ma to present, cooling has occurred in response to erosion of about 2,700 ft (824 m) of section. In the southwestern part of the study area, the Shannon Sandstone Bed was buried to almost 13,000 ft (3,965 m) and reached maximum temperatures of about 248 °F (120 °C) during maximum burial 10 Ma. About 2,070 ft (631 m) of overburden has been eroded since 10 Ma in the southwestern part of the study area.

Rock-Eval pyrolysis data for selected samples of Steele indicate that these rocks contain enough organic matter of the proper type to be potential source rocks for both oil and gas in the western part of the Powder River Basin. On a modified van Krevelen diagram the samples plot closer to the type III kerogen category, and organic petrography results show an abundance of types III and IV kerogen. Because the Steele is a marine shale, yet contains significant amounts of type III kerogen, results of kinetic modeling should be compared and extrapolated in order to determine the petroleum generation history of the Steele Member.

Vitrinite reflectance data for samples of the Steele are very consistent over the entire western part of the Wyoming part of the Powder River Basin and do not vary substantially with depth. Vitrinite reflectance data indicate that the Steele Member is either immature or just entering the oil window. Assuming that vitrinite reflectance records maximum maturity, vitrinite reflectance values were set at maximum burial and temperature 10 Ma; hence, oil generation began about at that time.

Rock-Eval pyrolysis data indicate that the Steele Member is marginally mature to mature and constrain the timing of oil generation to about 10 Ma.

Results of time-temperature and kinetic modeling constrain the timing of oil generation to between 35 and 25 Ma in the northwestern part of the study area and between 47 and 38 Ma in the southwestern part. Kinetic modeling of type III kerogen shows that some gas generation from the Steele may have begun about 40 Ma in the northwestern part of the study area and about 44 Ma in the southwestern part. The Shannon reservoirs therefore could contain some quantities of gas.

The four methods used to determine thermal maturity and timing of oil generation in this study yield quite different sets of results. There are innate problems with all of the techniques; hence, the "true" maturity and timing of petroleum generation is probably somewhere between the two extremes. These differences stress the importance of using as many techniques or methods as possible when assessing the thermal maturity and constraining timing of petroleum generation of a potential source rock.

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