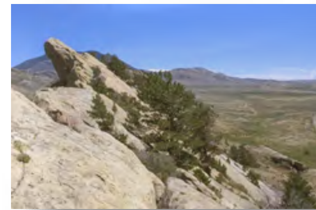
Chapter 3

Burial History, Thermal Maturity, and Oil and Gas Generation History of Petroleum Systems in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah



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By Laura N.R. Roberts, Michael D. Lewan, and Thomas M. Finn

Chapter 3 of

Petroleum Systems and Geologic Assessment of Oil and Gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah

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Abstract

Burial history, thermal maturity, and timing of petroleum generation were modeled for eight key source-rock horizons at seven locations throughout the Southwestern Wyoming Province. The horizons are the bases of the Lower Permian Phosphoria Formation, the Upper Cretaceous Mowry Shale, Niobrara Formation, Baxter Shale (and equivalents), upper part of the Mesaverde Group, Lewis Shale, Lance Formation, and the Tertiary (Paleocene) Fort Union Formation. Burial-history locations include three in the deepest parts of the province (Adobe Town in the Washakie Basin, Eagles Nest in the Great Divide Basin, and Wagon Wheel in the northern Green River Basin); two at intermediate basin depths (Federal 31-1 and Currant Creek in the central and southern parts of the Green River Basin, respectively); and two relatively shallow locations (Bear 1 on the southeastern margin of the Sand Wash Basin and Bruff 2 on the Moxa arch). An overall ranking of the burial-history locations in order of decreasing thermal maturity is Adobe Town > Eagles Nest > Wagon Wheel > Currant Creek > Federal 31-1 > Bear 1 > Bruff 2. The results of the models indicate that peak petroleum generation from Cretaceous oil- and gas-prone source rocks in the deepest parts of the province occurred from Late Cretaceous through middle Eocene.

At the modeled locations, peak oil generation from source rocks of the Phosphoria Formation, which contain Type-IIS kerogen, occurred in the Late Cretaceous (80 to 73 Ma [million years]). Gas generation from the cracking of Phosphoria oil reached a peak in the late Paleocene (57 Ma) only in the deepest parts of the province. The Mowry Shale, Niobrara Formation, and Baxter Shale (and equivalents) contain Type-II or a mix of Type-II and Type-III kerogens. Oil generation from these units, in the deepest parts of the province, reached peak rates during the latest Cretaceous to early Paleocene (66 to 61 Ma). Only at these deepest locations did these units reach peak gas generation from the cracking of oil, which occurred in the early to late Eocene (52 to 41 Ma). For the Mesaverde Group, which also contains a mix of Type-II and Type-III kerogen, peak oil generation occurred only in the deepest parts of the province during middle Eocene (50 to 41 Ma). Only at Adobe Town did cracking of oil occur and gas generation reach peak in the earliest Oligocene (33 Ma).

Gas-prone source rocks (Type-III kerogen) of the Mowry and Baxter (and equivalents) Shales reached peak gas generation in the latest Cretaceous (66 Ma) in the deepest parts of the province. At the shallower Bear 1 location, the Mancos Shale (Baxter equivalent) source rocks reached peak gas generation at about this same time. Gas generation from the gas-prone Mesaverde source rocks started at all of the modeled locations but reached peak generation at only the deepest locations in the early Eocene (54 to 49 Ma). The Lewis Shale, Lance Formation, and Fort Union Formation all contain gas-prone source rocks with Type-III kerogen. Peak generation of gas from the Lewis Shale occurred only at Eagles Nest and Adobe Town in the early Eocene (52 Ma). Source rocks of the Lance reached peak gas generation only at the deepest locations during the middle Eocene (48 to 45 Ma), and the Fort Union reached peak gas generation only at Adobe Town also in the middle Eocene (44 Ma).

Introduction

This report summarizes the burial history, thermal maturity, and timing of petroleum generation at seven locations for eight key petroleum system source-rock horizons throughout the Southwestern Wyoming Province that were presented in a report by Roberts and others (2004). The province occupies most of southwestern Wyoming, an adjacent northwestern portion of Colorado, and a portion of northeastern Utah (fig. 1). The horizons studied are (1) the base of the Lower Permian Phosphoria Formation, (2) the base of the Upper Cretaceous Mowry Shale, (3) the base of the Upper Cretaceous Niobrara Formation, (4) the base of the Upper Cretaceous Baxter Shale (and equivalents), (5) the base of the upper part of the Upper Cretaceous Mesaverde Group, (6) the base of the Upper Cretaceous Lewis Shale, (7) the base of the Upper Cretaceous Lance Formation, and (8) the base of the Tertiary (Paleocene) Fort Union Formation (fig. 2). Data and interpretations from this report supported the assessment of undiscovered oil and gas resources of the Southwestern Wyoming Province (Kirschbaum and others, 2002).

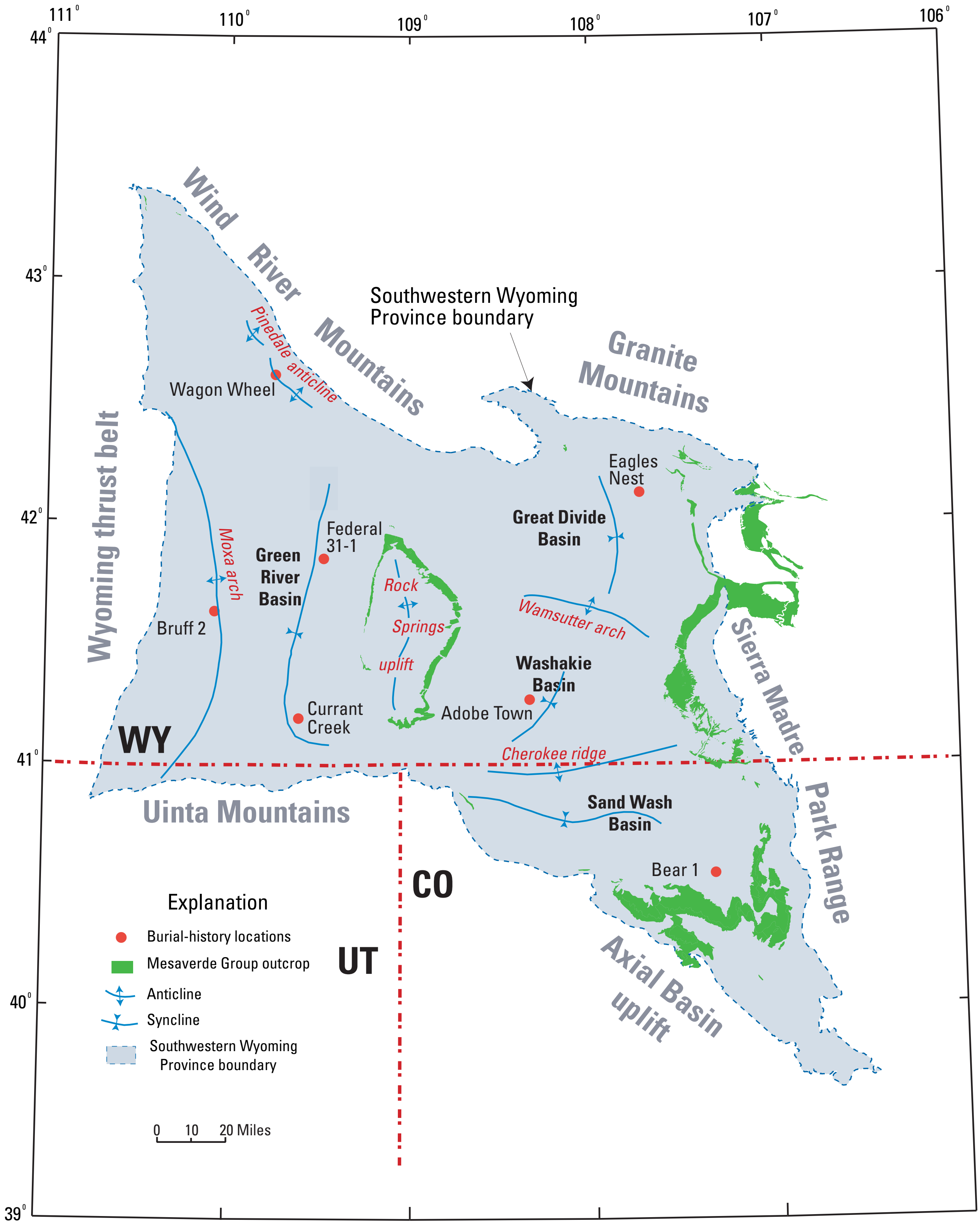

Figure 1. Index map of the Southwestern Wyoming Province showing major geologic and geographic features and seven burial-history locations (red dots).

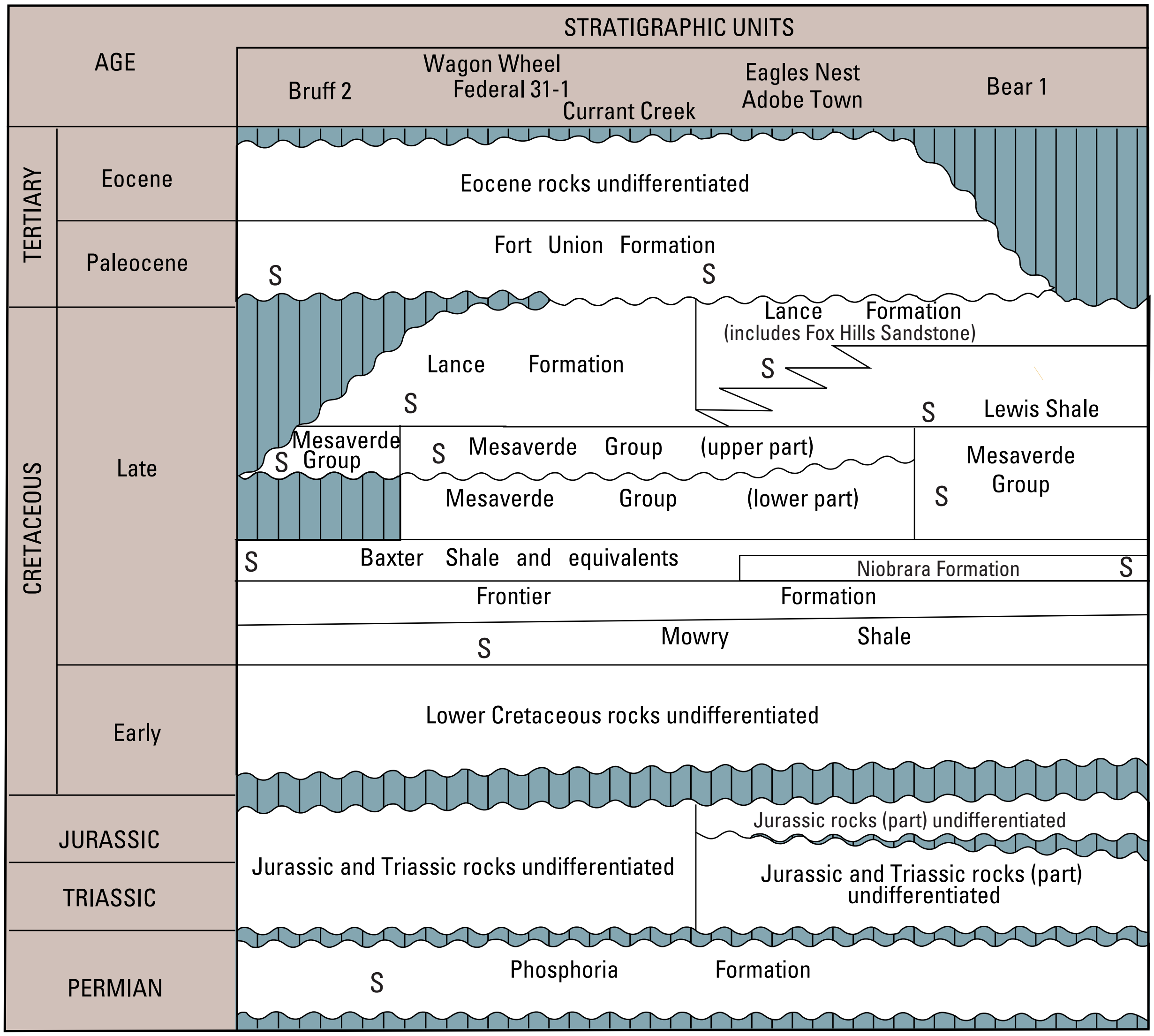

Figure 2. Generalized stratigraphy of the Southwestern Wyoming Province used for burial-history reconstructions. Time spans and thickness not shown in correct proportions. Hatching indicates erosion or nondeposition; wavy line represents unconformity. S, major source rocks. Location of wells shown in figure 1.

Acknowledgments

We thank Mark Kirschbaum, Ron Johnson, Steve Roberts, Robert Hettinger, and Edward Johnson for their valuable contributions regarding the stratigraphy at each location, for the lively discussions about modeling results, and for encouragement during the entire process. Ira Pasternack, Vito Nuccio, Tom Judkins, and Doug Waples provided constructive and valuable reviews of the manuscript, which greatly improved the product. We appreciate the rapid turnaround time of the many vitrinite reflectance measurements provided by Mark Pawlewicz, the timely assistance in the use of the IES software provided by Doug Steinshouer, and drafting assistance by Wayne Husband.

Methods—Burial History

One-dimensional modeling of burial history and thermal maturity was performed on seven well locations (table 1) using PetroMod1D Express (version 1.1) of Integrated Exploration Systems GmbH (IES), Germany. The well locations were chosen because (1) they were drilled to a depth that penetrated a significant part of the geologic section of interest, (2) they represent different geologic settings within the province, and (3) they have measured vitrinite reflectance and downhole temperature data to aid in calibrating maturation models. Table 2 shows the age, thickness, and generalized lithologic data used to construct the burial-history curves.

Table 1. Information on wells used for burial-history curves.

[Map name is shortened well name for use on figures, in tables, and for discussion in text. Asterisk indicates composite of two wells. TN, Township North; RW, Range West; GR, Ground level in feet; KB, Kelly bushing in feet; TD, Total depth in feet; WY, Wyoming; CO, Colorado]

Map name	Operator	Lease	Well	Section	TN	RW	Elevation	TD	County	State
*Adobe Town	Koch Exploration Co.	Adobe Town Unit	1	20	15	97	6,806 (KB)	17,662	Sweetwater	WY
*Adobe Town	Amoco	Bitter Creek Unit II	5	22	16	99	7,275 (KB)	21,322	Sweetwater	WY
*Eagles Nest	Southland Royalty	Eagles Nest	1	29	25	91	7,008 (GR)	17,014	Sweetwater	WY
*Eagles Nest	Hunt Oil	Federal	1-6	6	26	90	7,410 (KB)	13,615	Sweetwater	WY
*Wagon Wheel	El Paso Natural Gas	Wagon Wheel	1	5	30	108	7,062 (GR)	19,000	Sublette	WY
*Wagon Wheel	Williams Exploration Co.	Fed-Pacific Creek	1-34	34	27	103	7,048 (GR)	25,764	Sublette	WY
*Federal 31-1	Energy Reserves Group Inc.	Federal	31-1	31	22	106	6,687 (KB)	16,865	Sweetwater	WY
*Federal 31-1	Mountain Fuel Supply	UPRR-11-19-104	4	11	19	104	6,413 (KB)	9,290	Sweetwater	WY
Currant Creek	Brown Tom, Inc.	Currant Creek	1	20	14	108	6,254 (KB)	19,248	Sweetwater	WY
Bear 1	Texas Pacific	Bear	1	26	7	89	6,928 (GR)	13,536	Routt	CO
Bruff 2	Mountain Fuel	Bruff Unit	2	16	19	112	6,349 (KB)	17,425	Lincoln	WY

Age

Ages of stratigraphic units (table 2) were estimated using Love and others (1993) as a guide for the generalized ages of stratigraphic units and ages of regional unconformities throughout the province. The ages at system and series boundaries were adjusted to the 1999 Geologic Time Scale (Geological Society of America, 1999). Age of the Jurassic/Cretaceous boundary is from Sohn (1979) and Litwin and others (1998).

Thickness and Lithology

Thickness of the stratigraphic units in the subsurface was interpreted from geophysical logs or was determined from tops of units recorded in the Petroleum Information/Dwights PetroROM well-history database (IHS Energy Group, 2001). It was necessary at four of the locations (table 1) to choose a well nearby (within a few townships) that was drilled to a depth that would provide thickness data for the lower units that were not penetrated in the well that had yielded vitrinite reflectance data. Thicknesses of eroded sections represented by unconformities in the subsurface were modified from published reports (Law, 1981; Shuster, 1986; Dickinson, 1989; Dutton and Hamlin, 1992) or were interpreted from cross sections generated from geophysical logs. Lithologies of the stratigraphic units were also interpreted from geophysical logs and were generalized for modeling purposes (table 2).

Stratigraphy

Because of the large size of the Southwestern Wyoming Province and the complex stratigraphy, it was necessary to combine some of the stratigraphic units. Following is a brief description of the units that were combined and the names of these units used in this report.

The Triassic/Jurassic stratigraphy and nomenclature are complex within the province, and these units do not contain major source rocks. Triassic and Jurassic rocks were combined as one unit in modeled wells on the west side of the Rock Springs uplift. They were combined into two units in wells on the east side of the uplift where the time represented by the hiatus at the base of the Jurassic Sundance Formation is more significant (fig. 2).

Lower Cretaceous units were also combined because of the complex interfingering relationship among the Cloverly Formation, Dakota Sandstone, Thermopolis Shale, and Muddy Sandstone across the province. The nomenclature varies for the Upper Cretaceous interval that includes the Baxter Shale within the province. This thick marine shale is referred to as the Baxter Shale at the Wagon Wheel, Federal 31-1, and Adobe Town locations, the Steele Shale at the Eagles Nest location, the Mancos Shale at the Bear 1, and the Hilliard Shale at Bruff 2 and Currant Creek locations. To simplify tables and figures in this report, we refer to this interval as "Baxter Shale (and equivalents)." The Upper Cretaceous Mesaverde Group in the province consists of several formations whose names vary by location. The stratigraphic interval of the Mesaverde Group that is above the unconformity at the base of the Ericson Sandstone or Pine Ridge Sandstone is referred to as the upper part of the Mesaverde Group. The interval below the unconformity is referred to as the lower part of the Mesaverde Group (fig. 2). There is no evidence for this unconformity at the Bear 1 location (Roehler, 1990); therefore, the entire interval is referred to as the Mesaverde Group. The Upper Cretaceous Lewis Shale is present only at the burial-history locations that are on the eastern side of the Rock Springs uplift (figs. 1 and 2). The Fox Hills Sandstone, which overlies the Lewis Shale, is included in the overlying Lance Formation for modeling purposes. Eocene rocks, including the Wasatch, Green River, Battle Spring, Bridger, and Washakie Formations, were combined as one unit due to complex interfingering relationships of the units and are referred to as "undifferentiated" in figure 2.

Table 2. Data used to generate burial-history curves for seven locations in the Southwestern Wyoming Province.

[Heat flow and thermal gradient used to calibrate model are given for each location. Fm., Formation; ft, feet; %, percent; ss, sandstone; sh, shale; ls, limestone; slst, siltstone; mW/m^2, milliWatts per square meter]

Adobe Town

System/series, unit, or event	Present thickness (ft)	Age range (Ma)	Deposited, later eroded (ft)	Amount of erosion (ft)	Generalized lithology			
					%ss	%sh	%ls	%slst
Erosion		5 - 0		3,200				
post-Eocene rocks	0	34 - 5	2,400		50	50		
Hiatus	0	41 - 34						
Eocene rocks	9,650	57 - 41	800		50	50		
Fort Union Fm.	3,615	66 - 57			50	50		
Lance Fm.	1,653	68 - 66			50	50		
Lewis Shale	1,921	71 - 68			70	30		
Mesaverde Group (upper part)	1,540	74 - 71			50	50		
Hiatus	0	76 - 74						
Mesaverde Group (lower part)	1,140	82 - 76			50	50		
Baxter Shale	5,340	85 - 82				100		
Niobrara Fm.	808	89 - 85			30		70	
Frontier Fm.	378	94 - 89			50			50
Mowry Shale	217	99 - 94				100		
Lower Cretaceous rocks	150	124 - 99			100			
Hiatus	0	148 - 124						
Jurassic rocks (part)	512	192 - 148			50	50		
Hiatus	0	205 - 192						
Jurassic and Triassic rocks (part)	1,612	248 - 205			50	50		
Hiatus	0	253 - 248						
Phosphoria Fm.	220	278 - 253				100		

Heat flow 63 mW/m^2 Thermal gradient 1.86°F/100 feet

Eagles Nest

System/series, unit, or event	Present thickness (ft)	Age range (Ma)	Deposited, later eroded (ft)	Amount of erosion (ft)	Generalized lithology			
					%ss	%sh	%ls	%slst
Erosion		5 - 0		3,000				
post-Eocene rocks	0	34 - 5	2,500		50	50		
Hiatus	0	42 - 34						
Eocene rocks (part)	0	47 - 42	500		70			30
Eocene rocks (part)	5,100	57 - 47			70			30
Fort Union Fm.	4,500	65 - 57			50	50		
Lance Fm.	5,610	68 - 65			50	50		
Lewis Shale	1,750	71 - 68			30	70		
Mesaverde Group (upper part)	800	74 - 71			70	30		
Hiatus	0	76 - 74						
Mesaverde Group (lower part)	2,700	82 - 76			50	50		
Steele Shale	2,510	85 - 82				100		
Niobrara Fm.	1,790	89 - 85			30		70	
Frontier Fm.	955	94 - 89			50	50		
Mowry Shale	345	99 - 94				100		
Lower Cretaceous rocks	180	124 - 99			30	70		
Hiatus	0	148 - 124						
Jurassic rocks (part)	390	192 - 148			50	50		
Hiatus	0	205 - 192						
Jurassic and Triassic rocks (part)	1,572	248 - 205			70	30		
Hiatus	0	253 - 248						
Phosphoria Fm.	355	278 - 253				100		

Heat flow 54 mW/m^2 Thermal gradient 1.53°F/100 feet

Table 2. Data used to generate burial-history curves for seven locations in the Southwestern Wyoming Province.—Continued

Wagon Wheel

System/series, unit, or event	Present thickness (ft)	Age range (Ma)	Deposited, later eroded (ft)	Amount of erosion (ft)	Generalized lithology			
					%ss	%sh	%ls	%slst
Erosion		5 - 0		2,938				
post-Eocene rocks	0	24 - 5	2,000		50	50		
Hiatus	0	41 - 24		100				
Eocene rocks (part)	0	52 - 41	1,038		50	50		
Eocene rocks (part)	2,998	57 - 52			70	30		
Fort Union Fm.	4,522	65 - 57			50	50		
Hiatus	0	66 - 65						
Lance Fm.	4,950	68 - 66			50	50		
Mesaverde Group (upper part)	700	74 - 68			50	50		
Hiatus	0	76 - 74						
Mesaverde Group (lower part)	4,530	84 - 76			50	50		
Baxter Shale	4,025	89 - 84			50	50		
Frontier Fm.	616	94 - 89			50	50		
Mowry Shale	657	100 - 94				100		
Lower Cretaceous rocks	69	124 - 100			100			
Hiatus	0	148 - 124						
Jurassic and Triassic rocks	2,420	248 - 148			50	50		
Hiatus	0	253 - 248						
Phosphoria Fm.	313	278 - 253			30		70	

Heat flow 56 mW/m^2 Thermal gradient 1.54°F/100 feet

Note: Thickness data from Law, 1981; Dickinson, 1989; Shuster, 1986.

Federal 31-1

System/series, unit, or event	Present thickness (ft)	Age range (Ma)	Deposited, later eroded (ft)	Amount of erosion (ft)	Generalized lithology			
					%ss	%sh	%ls	%slst
Erosion		5 - 0		3,300				
post-Eocene rocks	0	24 - 5	2,000		50	50		
Hiatus	0	41 - 24						
Eocene rocks (part)	0	44 - 41	1,300		50	50		
Eocene rocks (part)	3,370	57 - 44				70	30	
Fort Union Fm.	4,140	65 - 57			50	50		
Hiatus	0	66 - 65						
Lance Fm.	380	68 - 66			30	70		
Mesaverde Group (upper part)	1,110	74 - 68			50	50		
Hiatus	0	76 - 74						
Mesaverde Group (lower part)	2,110	83 - 76			50	50		
Baxter Shale	4,800	89 - 83				100		
Frontier Fm.	290	94 - 89			50	50		
Mowry Shale	410	99 - 94				100		
Lower Cretaceous rocks	225	124 - 99			50	50		
Hiatus	0	148 - 124						
Jurassic and Triassic rocks (part)	2,850	248 - 148			50	50		
Hiatus	0	253 - 248						
Phosphoria Fm.	260	278 - 253				30	70	

Heat flow 55 mW/m^2 Thermal gradient 1.58°F/100 feet

Table 2. Data used to generate burial-history curves for seven locations in the Southwestern Wyoming Province.—Continued

Currant Creek

System/series, unit, or event	Present thickness (ft)	Age range (Ma)	Deposited, later eroded (ft)	Amount of erosion (ft)	Generalized lithology			
					%ss	%sh	%ls	%slst
Erosion		5 - 0		3,750				
post-Eocene rocks	0	34 - 5	2,000		50	50		
Erosion		41 - 34		535				
Eocene rocks (part)	0	45 - 41	2,285		50	50		
Eocene rocks (part)	6,200	57 - 45			50	50		
Fort Union Fm.	2,000	65 - 57			50	50		
Lance Fm.	740	71 - 65			30	70		
Mesaverde Group (upper part)	860	74 - 71			100			
Hiatus	0	76 - 74						
Mesaverde Group (lower part)	2,420	85 - 76			50	50		
Hilliard Shale	4,640	89 - 85			30	70		
Frontier Fm.	100	94 - 89			50	50		
Mowry Shale	260	99 - 94				100		
Lower Cretaceous rocks	220	124 - 99			100			
Hiatus	0	148 - 124						
Jurassic and Triassic (part) rocks	1,808	206 - 148			70	30		

Heat flow 51 mW/m^2 Thermal gradient 1.40°F/100 feet

Bear 1

System/series, unit, or event	Present thickness (ft)	Age range (Ma)	Deposited, later eroded (ft)	Amount of erosion (ft)	Generalized lithology			
					%ss	%sh	%ls	%slst
Erosion		5 - 0		3,050				
post-Eocene rocks	0	34 - 5	2,500		50	50		
Erosion		41 - 34		850				
Paleocene and Eocene rocks	0	65 - 41	1,100		50	50		
Hiatus	0	66 - 65						
Lance Fm. (part)	0	67 - 66	300		50	50		
Lance Fm. (part)	1,020	68 - 67			50	50		
Lewis Shale	2,550	71 - 68			50	50		
Mesaverde Group	3,290	82 - 71			50	50		
Mancos Shale	2,600	85 - 82				100		
Niobrara Fm.	1,720	89 - 85			30		70	
Frontier Fm.	290	94 - 89			50			50
Mowry Shale	120	99 - 94				100		
Lower Cretaceous rocks	90	124 - 99			100			
Hiatus	0	148 - 124						
Jurassic rocks (part)	502	192 - 148			50	50		
Hiatus	0	205 - 192						
Jurassic and Triassic rocks (part)	964	248 - 205			50	50		
Hiatus	0	253 - 248						
Phosphoria Fm.	252	278 - 253				100		
Hiatus	0	323 - 278						
Pennsylvanian (part)	143	324 - 323			100			

Heat flow 73 mW/m^2 Thermal gradient 2.06°F/100 feet

Table 2. Data used to generate burial-history curves for seven locations in the Southwestern Wyoming Province.—Continued

Bruff 2

System/series, unit, or event	Present thickness (ft)	Age range (Ma)	Deposited, later eroded (ft)	Amount of erosion (ft)	Generalized lithology			
					%ss	%sh	%ls	%slst
Erosion		5 - 0		3,650				
post-Eocene rocks	0	34 - 5	2,500		50	50		
Hiatus		41 - 34						
Eocene rocks (part)	4,500	57 - 41	1,150		30	70		
Fort Union Fm.	2,500	65 - 57			50	50		
Erosion		68 - 65		800				
Mesaverde Group (upper part)	530	74 - 68	800		50	50		
Erosion		76 - 74		3,000				
Mesaverde Group (lower part) and Hilliard Shale	3,632	89 - 76	3,000			70		30
Frontier Fm. (part)	140	91 - 89			30	70		
Erosion		92 - 91		100				
Frontier Fm. (part)	40	94 - 92	100		30	70		
Mowry Shale	471	99 - 94				100		
Lower Cretaceous rocks	436	124 - 99			70	30		
Hiatus	0	148 - 124						
Jurassic and Triassic rocks	3,808	248 - 148			50	50		
Hiatus	0	253 - 248						
Phosphoria Fm.	392	278 - 253				30	70	
Weber Sandstone	541	303 - 278			100			

Heat flow 55 mW/m^2 Thermal gradient 1.58°F/100 feet

Unconformities

Figure 2 shows the major unconformities that were used for the burial-history reconstructions. The unconformity within the Triassic and Jurassic (Pipiringos and O'Sullivan, 1978; Love and others, 1993) probably does not represent a significant amount of erosion that would affect the thermal maturity of the underlying Phosphoria Formation source rock (Fred Peterson, oral commun., 2003). We included an erosional event in the Upper Cretaceous Frontier Formation only at the Bruff 2 burial-history location. Elsewhere in the province, more than one hiatus exists within this formation (Love and others, 1993), but, for the purpose of this study, they were not considered critical. We applied a hiatus for the unconformity at the base of the upper part of the Mesaverde Group from 76 to 74 Ma throughout the province. Because there is no evidence of this unconformity at the Bear 1 well, the base of the Mesaverde Group was modeled. However, at the Bruff 2 burial-history location, a significant erosional event took place during this time (76 to 74 Ma) when an estimated 3,000 ft of the lower part of the Mesaverde Group and upper part of the underlying Hilliard Shale was removed (table 2). This estimate for the amount of deposition and erosion is consistent with that of Roehler (1990) and Kristinik and DeJarnett (1995).

We assumed a hiatus at the base of the Paleocene at the Wagon Wheel, Federal 31-1, and Bear 1 locations. However, at the Bruff 2 location, information from subsurface cross sections indicate an estimated 800 ft of the upper part of the Mesaverde, and possibly some Lance Formation, was eroded prior to deposition of the Paleocene Fort Union Formation. Although there is an unconformity at the base of the Paleocene units preserved at Adobe Town, Currant Creek, and Eagles Nest, we assumed no erosion based on lack of data and the geologic premise that unconformities that are significant on basin margins may become less significant in the nearby deep basin centers.

Much of the Eocene stratigraphic section is eroded in the province. Restored isopach maps of the units and surface measurements of nearby outcrops (Pipiringos, 1961; Masursky, 1962; Bradley, 1964; Roehler, 1973; Rowley and others, 1979; Roehler, 1992) were used to estimate the missing section, which could be as much as 1,300 ft.

Because no post-Eocene rocks are preserved in areas where the burial histories were reconstructed, assumptions had to be made in regard to estimates of post-Eocene sedimentation and erosion. Based on the geology of areas surrounding the province, during the period from 34 to about 5 Ma, the amount of post-Eocene deposition is estimated at 2,000 to 2,500 ft for all locations. We arrived at these estimates by first determining an approximate elevation for an Eocene surface of erosion near each burial-history location (Bradley, 1936; Zeller and Stephens, 1964; Zeller and Stephens, 1969; Luft, 1985; Hansen, 1986) and then assuming that post-Eocene sediments filled the study area from the elevation of the Eocene erosion surface to a present-day elevation of 10,000 ft above sea level (McGrew, 1971; Flanagan and Montagne, 1993).

Methods—Thermal History

For each burial-history location, bottom-hole temperatures, vitrinite reflectance data, and assumed paleosurface temperatures were used to calibrate thermal models. The bottom-hole temperatures were taken from records on log headers of the individual wells used in modeling or from headers of wells nearby. The temperatures were corrected according to the American Association of Petroleum Geologists (AAPG) correction chart (Kehle, 1972; Meissner, 1978). Vitrinite reflectance data for the Adobe Town, Wagon Wheel, and Federal 31-1 locations are from Law (1984) and Merewether and others (1987), and data for the Eagles Nest, Currant Creek, Bear 1, and Bruff 2 locations are from Pawlewicz and Finn (2002).

In order to make a direct comparison of burial history and timing of petroleum generation described in a previous study conducted in southwestern Wyoming (Dutton and Hamlin, 1992), the average annual surface temperature for all the burial-history locations was assumed as follows: 50°F from the time the first units were deposited to 37 Ma, a uniform decrease in temperature from 50°F to 40°F during the period 37 to 4 Ma, and a constant 40°F from 4 Ma to present. The reader is referred to Barker and Crysdale (1993) and Barker (2000) for possible alternative paleosurface temperatures, generally warmer, that were used for a burial and temperature history study in the adjacent Wind River Basin of Wyoming.

The heat-flow value, which is an input parameter for the PetroMod1D program, is used for the burial-history reconstructions (table 2). A present-day heat-flow value at the base of the stratigraphic column at each modeled location was determined within the PetroMod1D program by calibrating with the measured downhole temperatures (corrected) and the present-day and assumed paleosurface temperatures. The estimated amounts of erosion, which could affect the calibration, were left unchanged. Although it is probable that heat flow varied through time, it was not necessary to make assumptions about when changes of heat flow occurred or the extent to which it changed through time because using a constant heat flow through time resulted in an acceptable match of calculated R_o values, as determined by EASY% R_o (Sweeney and Burnham, 1990) with the measured R_o values.

Methods—Petroleum-Generation History

Timing of oil and gas generation was determined for the eight petroleum source rocks at the seven burial-history locations. These source rocks are designated in table 3 as either gas- or oil-prone on the basis of available geochemical rock data and oil-to-rock correlations. In some wells, the possibility of a designated gas-prone source rock being an oil-prone source rock as a result of changes in organic facies is noted by the “G/O” abbreviation. Similarly, the possibility of a designated oil-prone source rock being a gas-prone source rock as a result of changes in organic facies is noted by the “O/G” abbreviation. For example, the Mowry Shale is considered a source rock with a mix of Type-II and Type-III kerogen at the burial-history locations west of the Rock Springs uplift. In these areas the western Mowry shoreline was relatively close, resulting in more terrestrial sediment input (Type-III) than on the other side of the uplift, which had predominantly marine sediment influence (Type-II) (Burtner and Warner, 1984).

Oil-Prone Source Rocks

Two types of oil-prone source rocks were distinguished on the basis of the organic sulfur content of their kerogen.

Table 3. Source rocks and type of petroleum potential for burial-history locations.

[Os, Oil from Type-IIS kerogen; O, Oil from Type-II kerogen; G, Gas from Type-III kerogen; G/O, Predominantly gas from Type-III kerogen, possibly oil-prone; O/G, Predominantly oil from Type-II kerogen, possibly gas-prone; Baxter Sh., Baxter Shale and equivalents; Fm., Formation; Sh., Shale; Gp., Group. Double hyphens indicate source rock horizon is not present. Asterisk indicates that the Lance Fm. is not considered a source rock, as such, at Currant Creek and Federal 31-1]

Burial-history location	Source rock							
	Phosphoria Fm.	Mowry Sh.	Niobrara Fm.	Baxter Sh.	Mesaverde Gp.	Lewis Sh.	Lance Fm.	Fort Union Fm.
Adobe Town	Os	O	O	G/O	G/O	G	G	G
Eagles Nest	Os	O	O	G/O	G/O	G	G	G
Wagon Wheel	Os	O/G	- -	G/O	G/O	- -	G	G
Federal 31-1	Os	O/G	- -	G/O	G/O	- -	*	G
Currant Creek	no data	O/G	- -	G/O	G/O	- -	*	G
Bear 1	Os	O	O	G/O	G/O	G	G	- -
Bruff 2	Os	O/G	- -	G/O	G/O	- -	- -	G

Oil-prone source rocks like the Phosphoria Formation typically consist of marine carbonate- or chert-dominated rocks and contain Type-IIS kerogen (Os in table 3), which generates high-sulfur oils. Conversely, oil-prone source rocks like the Niobrara Formation typically consist of marine clastic source rocks and contain Type-II kerogen (O in table 3), which generates low-sulfur oil. The distinction between Type-II and Type-IIS kerogen is important in determining the timing and extent of oil generation from the source rock. Source rocks containing Type-IIS kerogen have been found to generate oil at abnormally low thermal maturities in nature (Tannenbaum and Aizenshtat, 1985; Orr, 1986; Petersen and Hickey, 1987; Baskin and Peters, 1992; Mitchell-Tapping, 2002) and in laboratory experiments (for example, Lewan, 1985; Tomic and others, 1995). Oil generation from Type-IIS and Type-II kerogen in source rocks of this study was modeled at each burial-history location with hydrous-pyrolysis kinetic parameters (table 4). See Roberts and others (2004) for details on why these particular parameters were used. Source-rock oil-generation kinetic parameters from hydrous pyrolysis experiments, combined with burial history and thermal maturity, determine the timing of the generation of expelled oil, where expulsion is considered a consequence of generation (Momper, 1978; Lewan, 1997; Lewan and Ruble, 2002).

Although gas is generated during oil generation from oil-prone kerogen, the gas:oil ratios (GORs) are typically less than 1,000 ft^3/barrel during the main stage of oil generation (Lewan and Henry, 2001). Only when the thermal stress gets high enough to initiate the already generated oil cracking to gas does the GOR begin to increase significantly (Lewan and Henry, 2001). Comparisons of various published kinetic models for gas generation by Henry and Lewan (2001) indicate the mass of gas generated from the cracking of oil is 3 to 7 times greater than gas generated from source rocks with Type-II and Type-IIS kerogen. Therefore, gas generation during oil generation from oil-prone kerogen was not modeled, but cracking of generated oil to gas was modeled. Hydrous-pyrolysis kinetic parameters used to determine the timing of gas generation from oil cracking are from Tsuzuki and others (1999; C_{15+} saturates) and are listed in table 4.

Each set of kinetic parameters listed in table 4 has its own transformation ratios that express the extent of oil generation from Type-II and Type-IIS kerogen and oil cracking to gas. The transformation ratios are the decimal fraction of reaction completed (that is, 0.00 = no reaction, and 1.00 = completed reaction) for the various source rocks at the burial-history locations as determined by their kinetic parameters. Oil generation and oil cracking to gas are defined in this study by transformation ratios between 0.01 and 0.99. Immature source rocks and uncracked oils have transformation ratios less than 0.01, and source rocks and crude oils that have respectively completed oil generation and have completed cracking to gas have transformation ratios greater than 0.99. Peak oil generation and oil cracking to gas occur at a transformation ratio of 0.50 when the maximum rate of reaction is reached. The transformation ratios for oil generation and those for oil cracking are independent of each other, and the two cannot be equated. Therefore, a transformation ratio of 0.5 for oil cracking occurs at a higher thermal maturity than a transformation ratio of 0.5 for oil generation.

Gas-Prone Source Rocks

Unlike in oil-prone source rocks, the extent of gas generation in source rocks with Type-III kerogen can be equated to levels of vitrinite reflectance (%R_o) because this measurement is determined on the maceral that generates the gas. A vitrinite reflectance of 0.5 %R_o is typically prescribed for the start of gas generation from humic coals, based on field observations (Scott, 1993) and pyrolysis experiments (Tang and others, 1996). The putative threshold for the generation of sufficient gas to form economic accumulations or overpressuring ranges between 0.8 and 1.0 %R_o, also based on field studies (Law, 2002) and pyrolysis experiments (Tang and others, 1996). Closed-system pyrolysis experiments indicate that the end of gas generation from Type-III kerogen occurs at vitrinite reflectance values between 1.8 and 2.0 %R_o (Saxby and others, 1986; Rohrback and others, 1984; Kotarba and Lewan, 2004). As described by Roberts and others (2004), we determined the timing of gas generation from gas-prone source rocks based on these empirical relations between vitrinite reflectance and gas generation. Accordingly, EASY%R_o was used to model gas generation from gas-prone source rocks, with the start and end of gas generation occurring at 0.5 and 2.0 %R_o, respectively. Peak gas generation is defined as the threshold vitrinite reflectance of 0.8 %R_o. Unlike oil generation and oil cracking to gas, the lack of an acceptable kinetic model for gas-prone source rocks means that the prescribed vitrinite reflectance values for the start, peak, and end of gas generation cannot be related to specific transformation ratios. Gas generation discussed in this report refers only to thermogenic gas and not biogenic gas.

Table 4. Hydrous-pyrolysis kinetic parameters used to determine timing of oil and gas generation.

[kcal/mol, kilocalorie per mole; m.y., million years]

Organic matter type	Product generated	Activation energy (E_o = kcal/mol)	Frequency factor (A_o = m.y.$^{-1}$)
Type-II kerogen[1]	Expelled oil	52.16	5.707×10^{26}
Type-IIS kerogen[1]	Expelled oil	42.71	4.223×10^{23}
Crude oil (C_{15+})[2]	Generated gas	76	3.419×10^{33}

[1]Lewan and Ruble (2002); [2]Tsuzuki and others (1999).

Results—Burial History

Table 5 lists information on the current depth, calculated maximum depth of burial, and calculated temperatures at maximum depth for the source-rock horizons from the burial-history reconstructions. The time of maximum burial is 5 Ma for all stratigraphic units at all of the modeled locations based on Love and others (1993). Figures 3–9 are the burial-history curves. Following is a brief description of the burial history at each of the locations: three in the deepest parts of the province (Adobe Town, Eagles Nest, and Wagon Wheel), two at intermediate basin depths (Federal 31-1 and Currant Creek), Bear 1 at the shallowest location, and finally Bruff 2 on the structurally high Moxa arch (fig.1).

Table 5. Current depth, calculated maximum depth of burial, and calculated temperatures at maximum depth for source-rock horizons from burial-history reconstructions.

[ND = No data.(--, source rock is not present, except for Lance Formation at Federal 31-1 and Currant Creek where it is not considered a source rock, per se.) Depth values are in feet. Temperature values are degrees Fahrenheit. Fm., Formation; Sh., Shale; Gp., Group; Baxter Sh., Baxter Shale and equivalents]

Burial-history location	Source rock							
Adobe Town	**Phosphoria Fm.**	**Mowry Sh.**	**Niobrara Fm.**	**Baxter Sh.**	**Mesaverde Gp.**	**Lewis Sh.**	**Lance Fm.**	**Fort Union Fm.**
Current depth	28,756	26,262	25,667	24,859	18,379	16,839	14,918	13,265
Maximum depth	31,894	29,340	28,900	28,094	21,553	20,000	18,003	16,445
Temperature	640	585	575	560	430	400	360	330
Eagles Nest								
Current depth	28,557	26,060	24,760	22,970	17,760	16,960	15,210	9,600
Maximum depth	31,560	29,035	27,680	25,960	20,730	19,870	18,150	12,550
Temperature	525	480	460	430	350	335	305	225
Wagon Wheel								
Current depth	25,800	22,998	--	21,725	13,170	--	12,470	7,520
Maximum depth	28,740	25,825	--	24,650	16,080	--	15,405	10,475
Temperature	500	450	--	430	295	--	285	210
Federal 31-1								
Current depth	19,965	16,630	--	15,930	9,050	--	--	7,660
Maximum depth	23,265	19,910	--	19,275	12,290	--	--	10,930
Temperature	410	360	--	350	235	--	--	215
Currant Creek								
Current depth	ND	17,220	--	16,860	9,800	--	--	8,200
Maximum depth	ND	20,940	--	20,580	13,540	--	--	11,930
Temperature	ND	347	--	340	240	--	--	216
Bear 1								
Current depth	13,398	11,590	11,180	9,460	6,860	3,570	1,020	--
Maximum depth	16,430	14,590	14,200	12,485	9,865	6,600	4,045	--
Temperature	400	360	350	320	260	190	135	--
Bruff 2								
Current depth	16,449	11,813	--	11,162	7,530	--	--	7,000
Maximum depth	20,117	15,415	--	14,745	11,140	--	--	10,640
Temperature	370	295	--	285	220	--	--	215

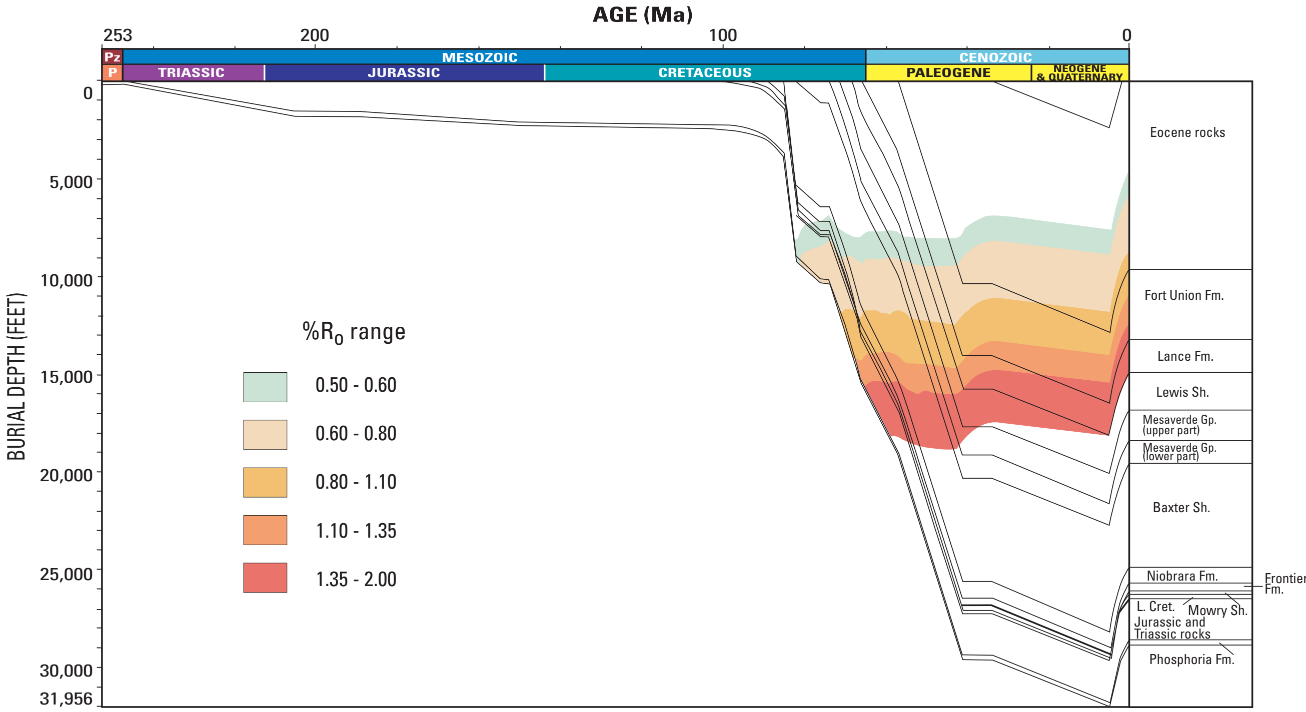

Figure 3. Burial-history curve at the Adobe Town location. Data used to construct the curve are presented in table 2. Location shown in figure 1. Fm., Formation; Sh., Shale; Gp., Group; L. Cret., Lower Cretaceous rocks.

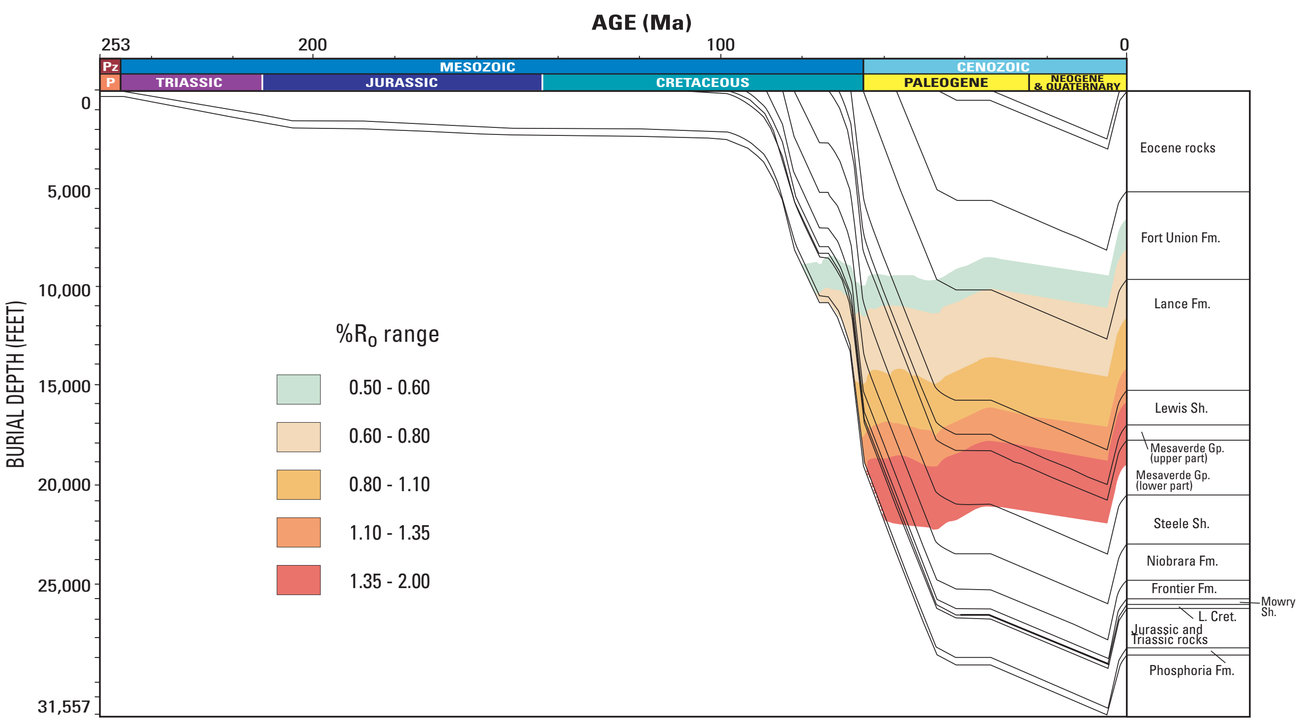

Figure 4. Burial-history curve at the Eagles Nest location. Data used to construct the curve are presented in table 2. Location shown in figure 1. Fm., Formation; Sh., Shale; Gp., Group; L. Cret., Lower Cretaceous rocks.

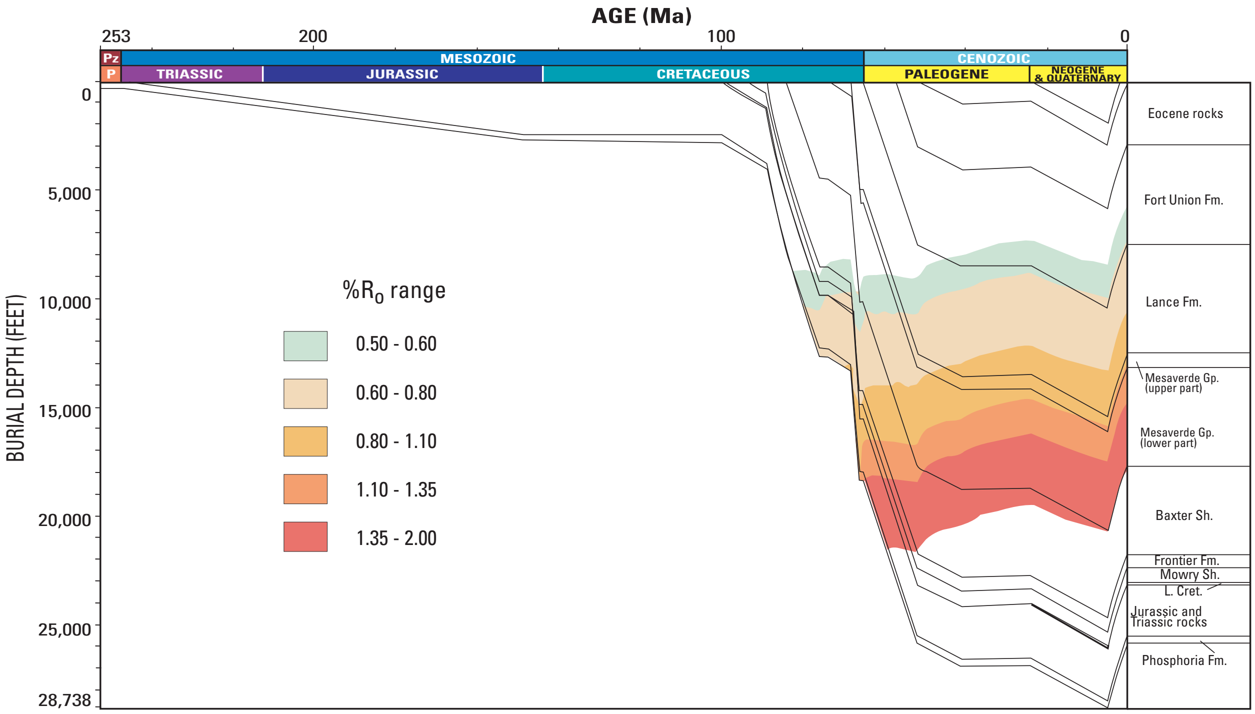

Figure 5. Burial-history curve at the Wagon Wheel location. Data used to construct the curve are presented in table 2. Location shown in figure 1. Fm., Formation; Sh., Shale; Gp., Group; L. Cret., Lower Cretaceous rocks.

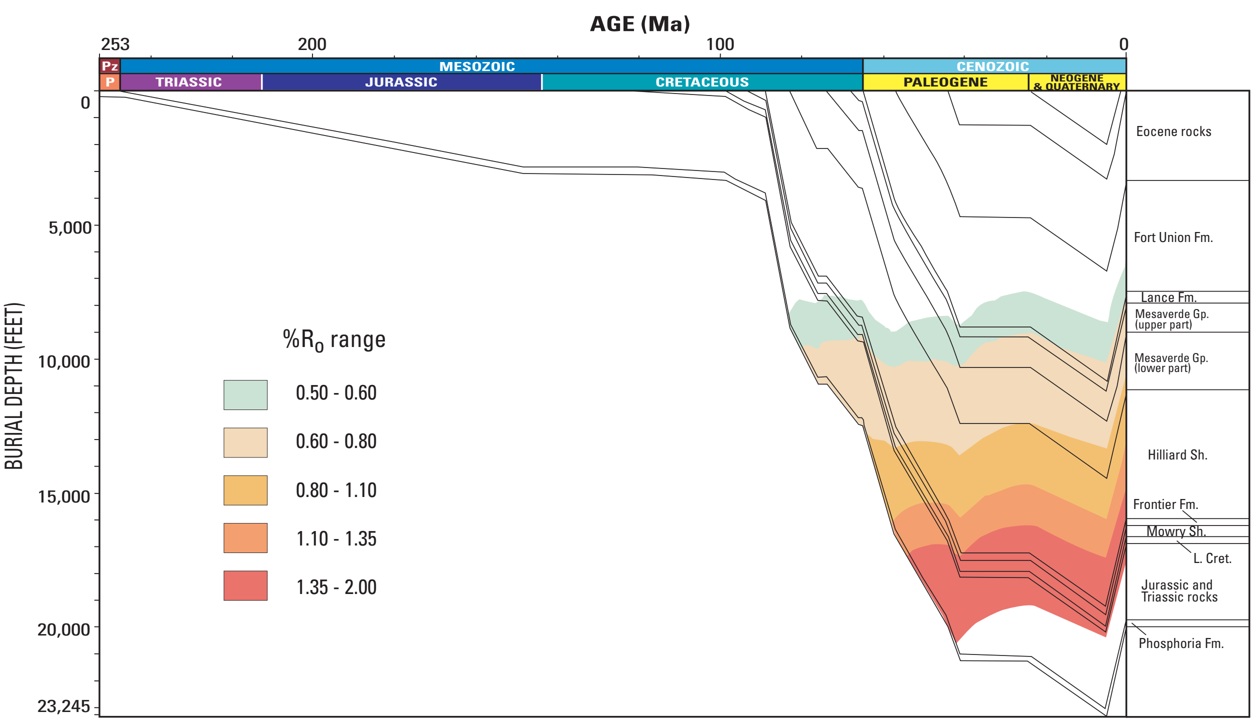

Figure 6. Burial-history curve at the Federal 31-1 location. Data used to construct the curve are presented in table 2. Location shown in figure 1. Fm., Formation; Sh., Shale; Gp., Group; L. Cret., Lower Cretaceous rocks.

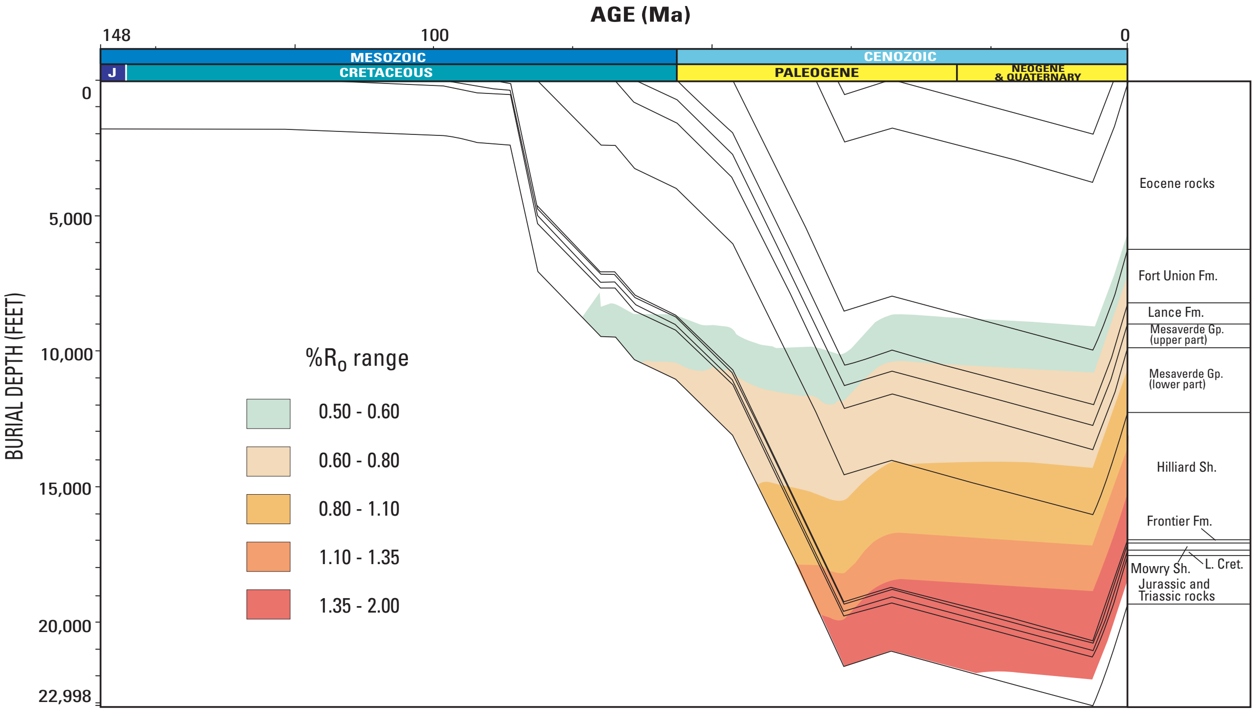

Figure 7. Burial-history curve at the Currant Creek location. Data used to construct the curve are presented in table 2. Location shown in figure 1. Fm., Formation; Sh., Shale; Gp., Group; L. Cret., Lower Cretaceous rocks.

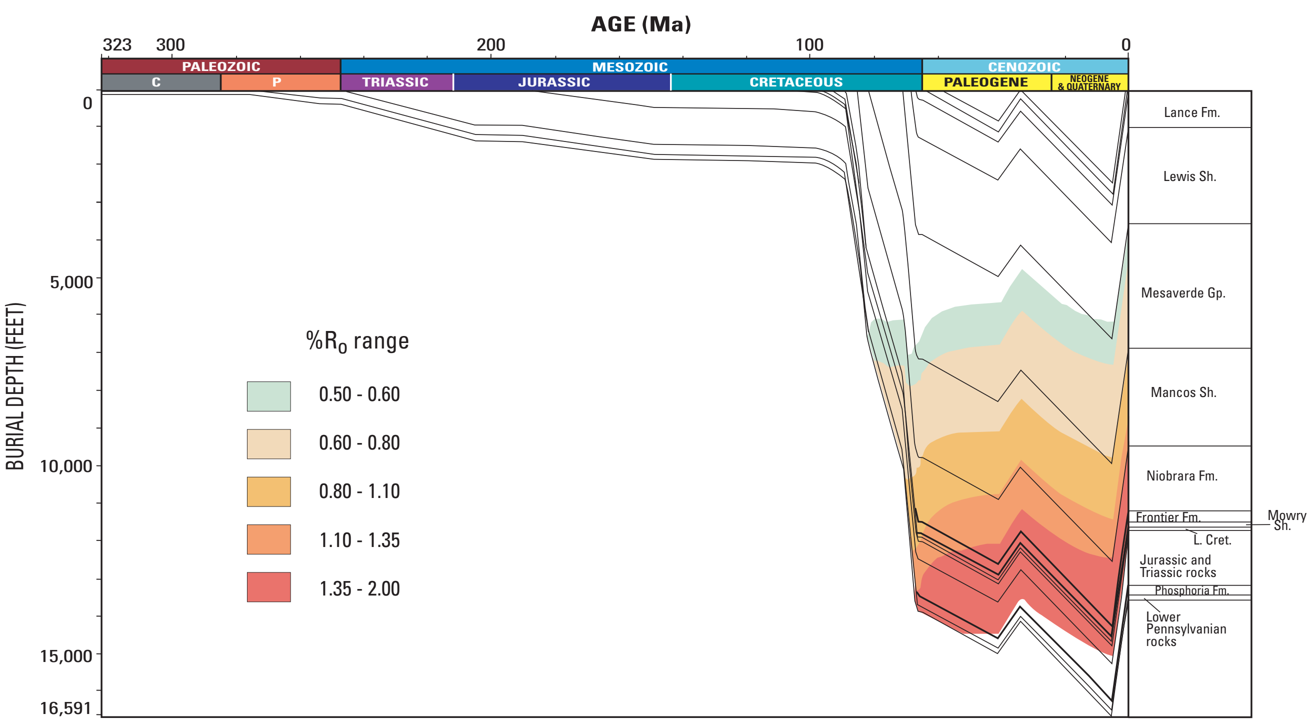

Figure 8. Burial-history curve at the Bear 1 location. Data used to construct the curve are presented in table 2. Location shown in figure 1. Fm., Formation; Sh., Shale; Gp., Group; L. Cret., Lower Cretaceous rocks.

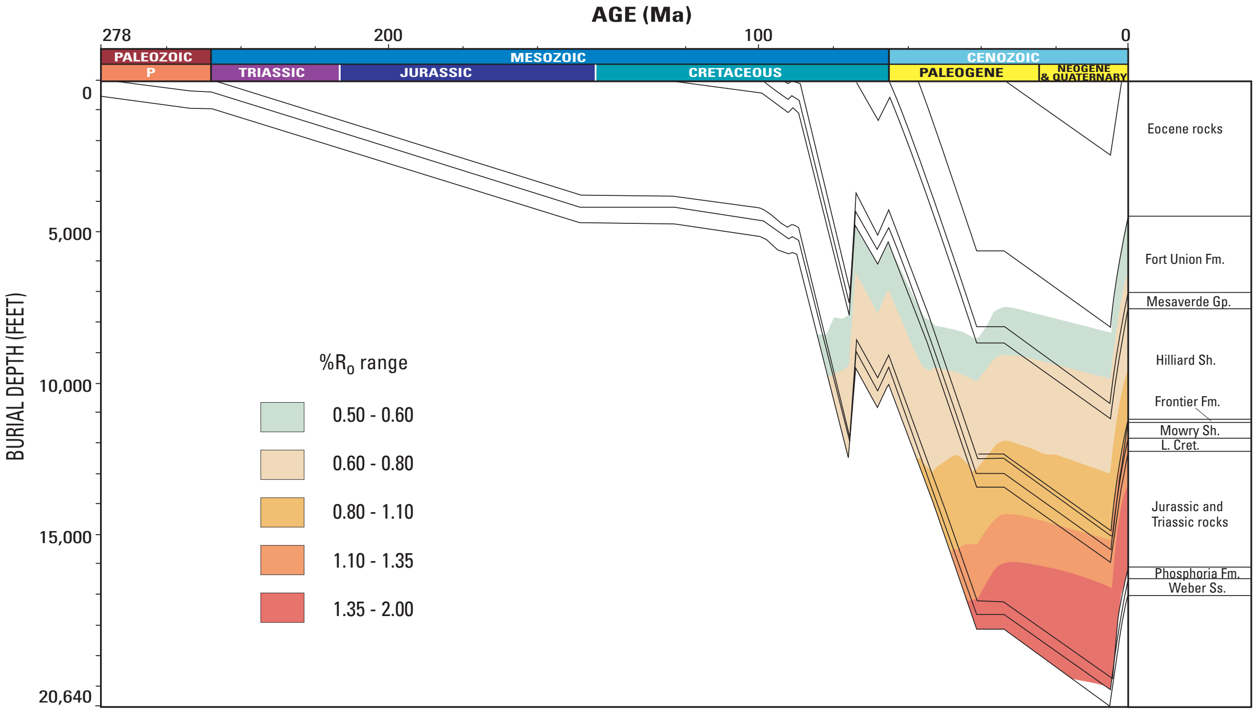

Figure 9. Burial-history curve at the Bruff 2 location. Data used to construct the curve are presented in table 2. Location shown in figure 1. Fm., Formation; Sh., Shale; Gp., Group; Ss., Sandstone; L. Cret., Lower Cretaceous rocks.

Adobe Town

The burial-history reconstruction at Adobe Town (fig. 3), located near the deep center of the Washakie Basin (fig. 1) illustrates the deepest burial in the Southwestern Wyoming Province. From 253 Ma to about 89 Ma, subsidence/sedimentation rates appear to be fairly constant and relatively slow. The rate of deposition increased substantially between 89 and about 41 Ma when more than 26,000 ft of sediment was deposited. A relatively brief period of nondeposition occurred in this time between 76 and 74 Ma. Another hiatus occurred for about 7 million years (m.y.) at 41 Ma and ended with the resumed deposition of post-Eocene sediments. Maximum burial occurred around 5 Ma (table 2) after which time uplift and erosion caused the removal of approximately 3,200 ft of section in this area.

Eagles Nest

The Eagles Nest location is in the deep part of the Great Divide Basin (fig. 1). The burial history here (fig. 4) is very similar to that at Adobe Town, except that the rate of sediment accumulation was not as rapid during deposition of the Steele Shale (Baxter Shale equivalent), resulting in about half the thickness of that unit here. A substantial increase in subsidence/sedimentation rate then occurred during Lance Formation deposition, yielding a unit that is more than three times thicker at Eagles Nest than at Adobe Town. These differences can be seen by the shift in the steepest part of the curves at each location (figs. 3 and 4) from 85 to 82 Ma (Steele deposition) and 68 to 65 Ma (Lance deposition).

Wagon Wheel

The third deep-basin burial-history setting is Wagon Wheel (fig. 5), in the Pinedale anticline area of the northern Green River Basin (fig. 1). Its history is most like that at Eagles Nest in terms of the rapid rates of subsidence/sedimentation during Lance deposition; however, the Tertiary history sets Wagon Wheel apart. Adobe Town and Eagles Nest have about 10,000 ft and 5,000 ft of Eocene rocks preserved, respectively, whereas Wagon Wheel has only about 3,000 ft. Only an additional 1,000 ft of deposition of Eocene rocks can be geologically justified at Wagon Wheel (Dickinson, 1989). Maximum burial occurred around 5 Ma (table 2), after which time uplift and erosion caused the removal of approximately 3,000 ft of section in this area.

Federal 31-1 and Currant Creek

These two burial-history locations are within the Green River Basin (fig. 1)—Federal 31-1 (fig. 6) on a subtle arch, known as the Sandy Bend arch, extending northwest from the Rock Springs uplift, and Currant Creek (fig. 7) in the deep southern part of the basin. Their burial-history curves are similar, especially the steep decline of the curve between 89 and 71 Ma representing the rapid increase in subsidence/sedimentation rate during Baxter/Hilliard Shale and Mesaverde Group time. The difference between the two occurs during and after the time of Fort Union deposition. The thickness of Fort Union sediment deposited at the Federal 31-1 location (about 4,100 ft) was twice that at the Currant Creek location (2,000 ft). However, the depocenter moved to the south near the Currant Creek area during the Eocene, where twice the thickness of sediment was deposited and preserved (6,200 ft) compared to 3,400 ft at Federal 31-1. We estimate that in the last 5 m.y., more than 3,000 ft of rock has been removed from these areas.

Bear 1

The Bear 1 location is near the southeastern margin of the Sand Wash Basin (fig. 1) and represents the shallowest depth to which the source rocks were buried (fig. 8 and table 5). The burial history is similar to that of Adobe Town except for the lack of evidence for the unconformity within the Mesaverde Group at about 76 Ma that was included at the other locations. Therefore, deposition was assumed to have continued uninterrupted until about 41 Ma when a 7-million-year period of erosion in this area removed an estimated 850 ft of section prior to renewed deposition of post-Eocene units. In the last 5 m.y., more than 3,000 ft of rock may have been removed from this area. It should be noted that because the rocks on the surface at this well location are latest Cretaceous in age, the depositional and erosional history of this area since then (65 Ma to present) is based on geologic reconstruction.

Bruff 2

The area around the Bruff 2 location is on the structurally high Moxa arch (fig. 1), which has a more complicated burial history than the other areas we examined (fig. 9). Although during the Triassic and Jurassic the sediment accumulation rates appear to be fairly constant and relatively slow, a greater thickness of sediments of this age was deposited in this area than at other modeled locations.

After deposition of the Mowry Shale, at least four episodes of uplift and erosion occurred in this area. The first erosional event was relatively minor, occurring at about 92 Ma during deposition of the Frontier Formation. The result was the removal of only about 100 ft of section. Later, from 89 to 76 Ma, the burial-history curve looks very similar to the others in the study area. The curve drops steeply, representing the rapid increase in sediment accumulation rate during Hilliard Shale (Baxter equivalent) and Mesaverde Group time. A major uplift and erosional event between 76 and 74 Ma removed an estimated 3,000 ft of section. Deposition of the upper part of the Mesaverde was at a rate consistent with deposition of the coeval unit at other locations. Another erosional event prior to the deposition of the Paleocene Fort Union Formation removed approximately 800 ft of the uppermost Mesaverde Group. A hiatus lasting about 7 m.y. began at 41 Ma and ended with the resumed deposition of post-Eocene sediments. An estimated 3,650 ft of rock was eroded after maximum burial from 5 Ma to the present (table 2).

Results—Maturation History

Maturation history is based on measured and calculated vitrinite reflectance (%R_o) for each burial-history location. Figures 3–9 show selected ranges of %R_o superimposed on the burial-history curves. As previously discussed, the range of 0.5 to 0.8 %R_o represents the prescribed start to peak of gas generation from humic coals. The %R_o values of 1.10 and 1.35 were added for information purposes only and represent intermediate maturities between peak (0.8 %R_o) and end (2.0 %R_o) of gas generation. The Mowry Shale, west of the Rock Springs uplift, the Baxter Shale (and equivalents), the Mesaverde Group, the Lewis Shale, and the Lance and Fort Union Formations are considered gas-prone source rocks (mostly composed of Type-III kerogen) (table 3), and so vitrinite reflectance (%R_o) can be used to estimate extent of gas generation. Table 6 summarizes the time (Ma) that the source rocks attained the %R_o values of 0.5, 0.8, and 2.0, the depths of the source rock at the specific %R_o maturity level, and the temperatures at that depth.

Results—Petroleum Generation History

The timing and extent of petroleum generation from the prescribed source rocks (table 3) at the seven burial-history locations are listed in tables 6 and 7 and summarized in figures 10 and 11. With the exception of the Bruff 2 location on the Moxa arch, the burial-history curves represent relatively deep parts of the Southwestern Wyoming Province. As a result, they represent the earliest timing and greatest extent of petroleum generation in the identified source-rock intervals of the province. Updip from these locations, the time at which petroleum generation occurs will be later and the extent of petroleum generation will be less. The position of the Bruff 2 burial-history location in the central part of the south-plunging Moxa arch (fig. 1) suggests that timing and extent of petroleum generation will become later and less northward, and earlier and greater southward, respectively, along the arch. This same conclusion was drawn based on the modeling efforts of Dutton and Hamlin (1992, their table 3).

Figures 10 and 11 show a vertical dashed line at 5 Ma, which is the time major uplift, erosion, and subsequent cooling started at all of the burial-history locations. Rates of oil generation, oil cracking to gas, and gas generation were significantly reduced after that time, with negligible generation during the last 5 m.y.

Table 6. Timing of gas generation for Type-III source-rock horizons at the seven burial-history locations.

[Age values are Ma. Depth values are calculated at depth at which $\%R_o$ value is reached (in feet). Temperature (Temp.) values are degrees Fahrenheit and are calculated for the recorded depth. Double hyphen indicates horizon did not attain $\%R_o$ value. Asterisk for the Mowry Shale indicates that it is considered a Type-II source rock, so no values are given. 'x' for Lewis Shale indicates it was not deposited. Single hyphen for the Lance Formation indicates it is not considered a source rock. 'e' indicates source rock was eroded]

Burial-history location	Mowry Shale			Baxter Shale			Mesaverde Group			Lewis Shale			Lance Formation			Fort Union Formation		
Adobe Town	Age	Depth	Temp.	Age	Depth	Temp.	Age	Depth	Temp.	Age	Depth	Temp.	Age	Depth	Temp.	Age	Depth	Temp.
$0.5\%R_o$ - Start	*	*	*	73	6,960	192	60	7,520	198	56	7,750	202	53	7,920	202	51	7,980	203
$0.8\%R_o$ - Peak	*	*	*	65	11,840	281	52	12,280	282	50	12,250	281	47	12,400	281	44	12,370	280
$2.0\%R_o$ - End	*	*	*	52	18,600	400	42	18,710	396	36	17,630	377	- -	- -	- -	- -	- -	- -
Eagles Nest																		
$0.5\%R_o$ - Start	*	*	*	67	9,310	208	63	9,180	201	62	9,140	200	58	9,260	200	47	9,520	196
$0.8\%R_o$ - Peak	*	*	*	64	14,200	280	54	14,370	274	52	14,500	274	48	14,800	273	- -	- -	- -
$2.0\%R_o$ - End	*	*	*	49	22,200	392	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
Wagon Wheel																		
$0.5\%R_o$ - Start	78	8,700	197	75	8,540	194	59	8,890	200	x	x	x	58	8,890	199	45	8,100	187
$0.8\%R_o$ - Peak	66	14,940	294	65	14,190	282	49	13,440	267	x	x	x	45	13,100	264	- -	- -	- -
$2.0\%R_o$ - End	54	21,580	397	52	21,690	398	- -	- -	- -	x	x	x	- -	- -	- -	- -	- -	- -
Federal 31-1																		
$0.5\%R_o$ - Start	75	7,570	189	70	7,570	188	47	8,300	193	x	x	x	-	-	-	41	8,610	194
$0.8\%R_o$ - Peak	57	13,290	276	55	13,070	272	- -	- -	- -	x	x	x	-	-	-	- -	- -	- -
$2.0\%R_o$ - End	- -	- -	- -	- -	- -	- -	- -	- -	- -	x	x	x	-	-	-	- -	- -	- -
Currant Creek																		
$0.5\%R_o$ - Start	69	8,540	185	65	8,590	187	45	9,820	199	x	x	x	-	-	-	42	9,900	200
$0.8\%R_o$ - Peak	49	14,970	276	49	15,030	277	- -	- -	- -	x	x	x	-	-	-	- -	- -	- -
$2.0\%R_o$ - End	- -	- -	- -	- -	- -	- -	- -	- -	- -	x	x	x	-	-	-	- -	- -	- -
Bear 1																		
$0.5\%R_o$ - Start	*	*	*	71	6,400	205	67	6,690	202	12	5,950	180	- -	- -	- -	e	e	e
$0.8\%R_o$ - Peak	*	*	*	65	9,730	274	7	9,730	258	- -	- -	- -	- -	- -	- -	e	e	e
$2.0\%R_o$ - End	*	*	*	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	e	e	e
Bruff 2																		
$0.5\%R_o$ - Start	56	7,510	187	53	7,920	193	42	8,450	197	x	x	x	e	e	e	39	8,150	193
$0.8\%R_o$ - Peak	41	12,870	275	38	12,310	266	- -	- -	- -	x	x	x	e	e	e	- -	- -	- -
$2.0\%R_o$ - End	- -	- -	- -	- -	- -	- -	- -	- -	- -	x	x	x	e	e	e	- -	- -	- -

Table 7. Timing of oil generation and of oil cracking to gas for Type-IIS (Phosphoria Formation) and Type-II source-rock horizons at seven burial-history locations.

[Start, peak, and end of oil generation and of oil cracking to gas are represented by transformation ratios of 0.01, 0.50, and 0.99, respectively. Values are Ma. Blank cell indicates horizon did not attain transformation ratio. Values in brackets are transformation ratio at the present time]

	Adobe Town											
	Oil generation						**Oil cracking to gas**					
Source-rock horizon	**Start**	**(%R_o)**	**Peak**	**(%R_o)**	**End**	**(%R_o)**	**Start**	**(%R_o)**	**Peak**	**(%R_o)**	**End**	**(%R_o)**
Phosphoria Formation	83	0.46	80	0.64	75	0.73	61	1.75	56	2.40	54	2.73
Mowry Shale	70	0.69	66	0.92	63	1.13	56	1.74	52	2.38	50	2.73
Niobrara Shale	68	0.69	64	0.92	60	1.17	54	1.72	51	2.39	49	2.80
Baxter Shale	67	0.69	62	0.92	58	1.18	53	1.69	49	2.37	47	2.84
Mesaverde Group (upper part)	54	0.69	50	0.92	48	1.15	43	1.73	33	2.44	8	2.88
	Eagles Nest											
Phosphoria Formation	82	0.47	73	0.66	68	0.75	62	1.74	57	2.38	54	2.77
Mowry Shale	67	0.68	65	0.92	63	1.13	57	1.74	51	2.40	48	2.76
Niobrara Shale	66	0.69	64	0.92	61	1.13	54	1.76	48	2.40	42	2.79
Steele Shale (Baxter equiv.)	65	0.69	61	0.92	58	1.15	50	1.74	40	2.43	11	2.89
Mesaverde Group (upper part)	57	0.69	50	0.91	46	1.16	No gas					
	Wagon Wheel											
Phosphoria Formation	83	0.48	78	0.65	74	0.74	61	1.75	56	2.39	54	2.74
Mowry Shale	67	0.68	65	0.92	62	1.15	56	1.74	51	2.40	41	2.85
Baxter Shale	66	0.68	63	0.92	60	1.14	54	1.74	44	2.43	12	2.87
Mesaverde Group (upper part)	53	0.69	41	0.93	7	1.12	No gas					
	Federal 31-1											
Phosphoria Formation	85	0.46	77	0.65	70	0.73	46	1.78	24	2.47	0 [0.89]	2.70
Mowry Shale	60	0.70	53	0.92	47	1.13	6	1.83			0 [0.01]	1.86
Baxter Shale	58	0.69	50	0.92	44	1.14	No gas					
Mesaverde Group (upper part)	12	0.70			0 [0.02]	0.72	No gas					
	Currant Creek											
Mowry Shale	53	0.69	46	0.91	43	1.13	No gas					
Hilliard Shale (Baxter equiv.)	52	0.69	45	0.92	42	1.14	No gas					
Mesaverde Group (upper part)	17	0.69			0 [0.03]	0.73	No gas					
	Bear 1											
Phosphoria Formation	83	0.46	77	0.65	73	0.74	55	1.80			0 [0.41]	2.43
Mowry Shale	70	0.68	68	0.92	65	1.12	No gas					
Niobrara Shale	70	0.68	67	0.92	61	1.14	No gas					
Mancos Shale (Baxter equiv.)	68	0.68	54	0.92	14	1.17	No gas					
Mesaverde Group (base)	44	0.69			0 [0.13]	0.81	No gas					
	Bruff 2											
Phosphoria Formation	84	0.47	79	0.65	76	0.73	17	1.82			0 [0.03]	1.99
Mowry Shale	46	0.69	29	0.92	0 [0.98]	1.11	No gas					
Hilliard Shale (Baxter equiv.)	43	0.68	12	0.92	0 [0.06]	0.85	No gas					
Mesaverde Group (upper part)	No oil											

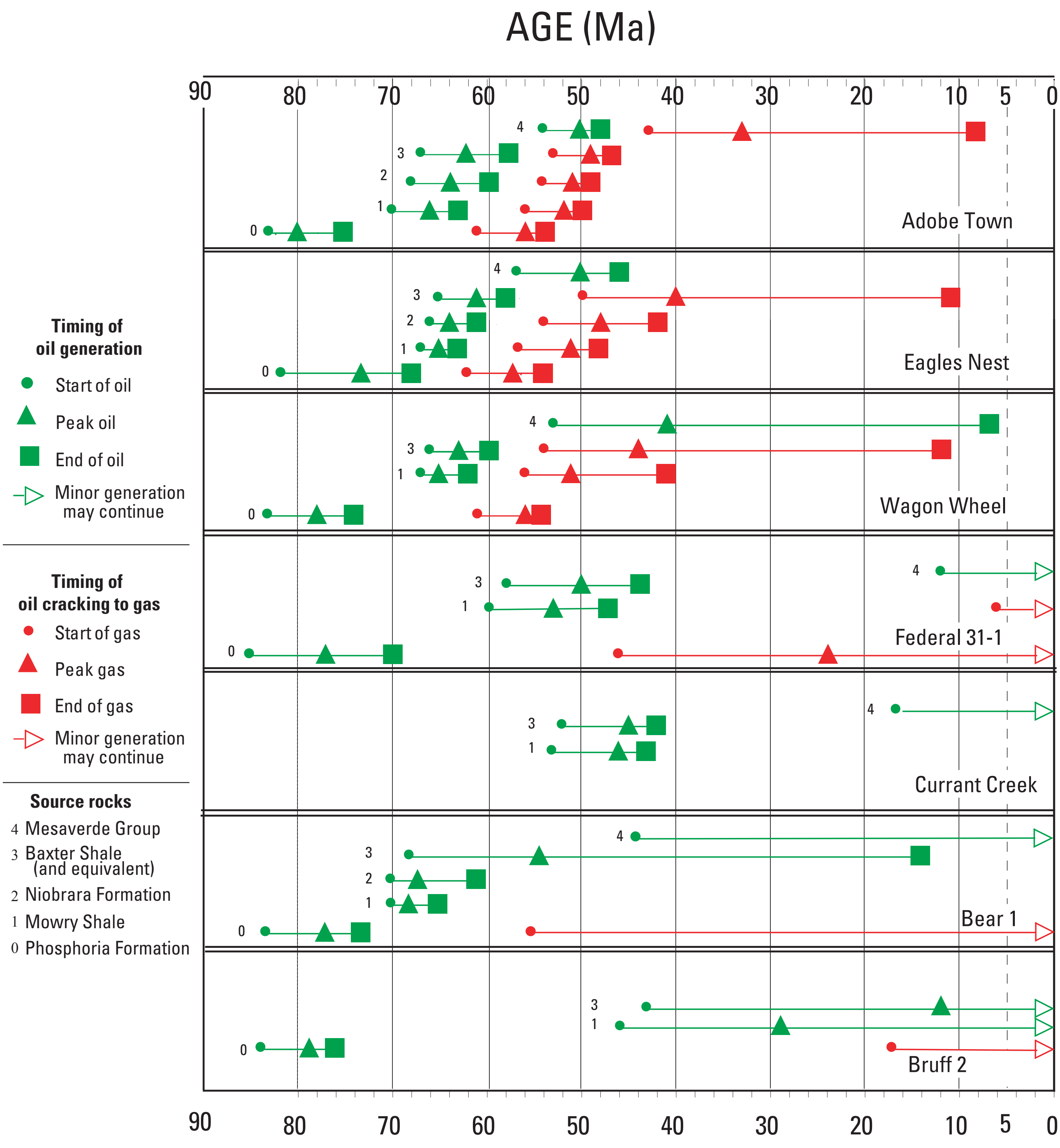

Figure 10. Timing of oil and gas generation from Type-II and Type-IIS source rocks by source rock and burial-history location. Vertical dashed line at 5 Ma represents beginning of major uplift, erosion, and subsequent cooling. If oil generation or oil cracking to gas has not ended by present day (0 Ma) based on the models, the rate of these reactions was significantly reduced with negligible generation during the last 5 million years.

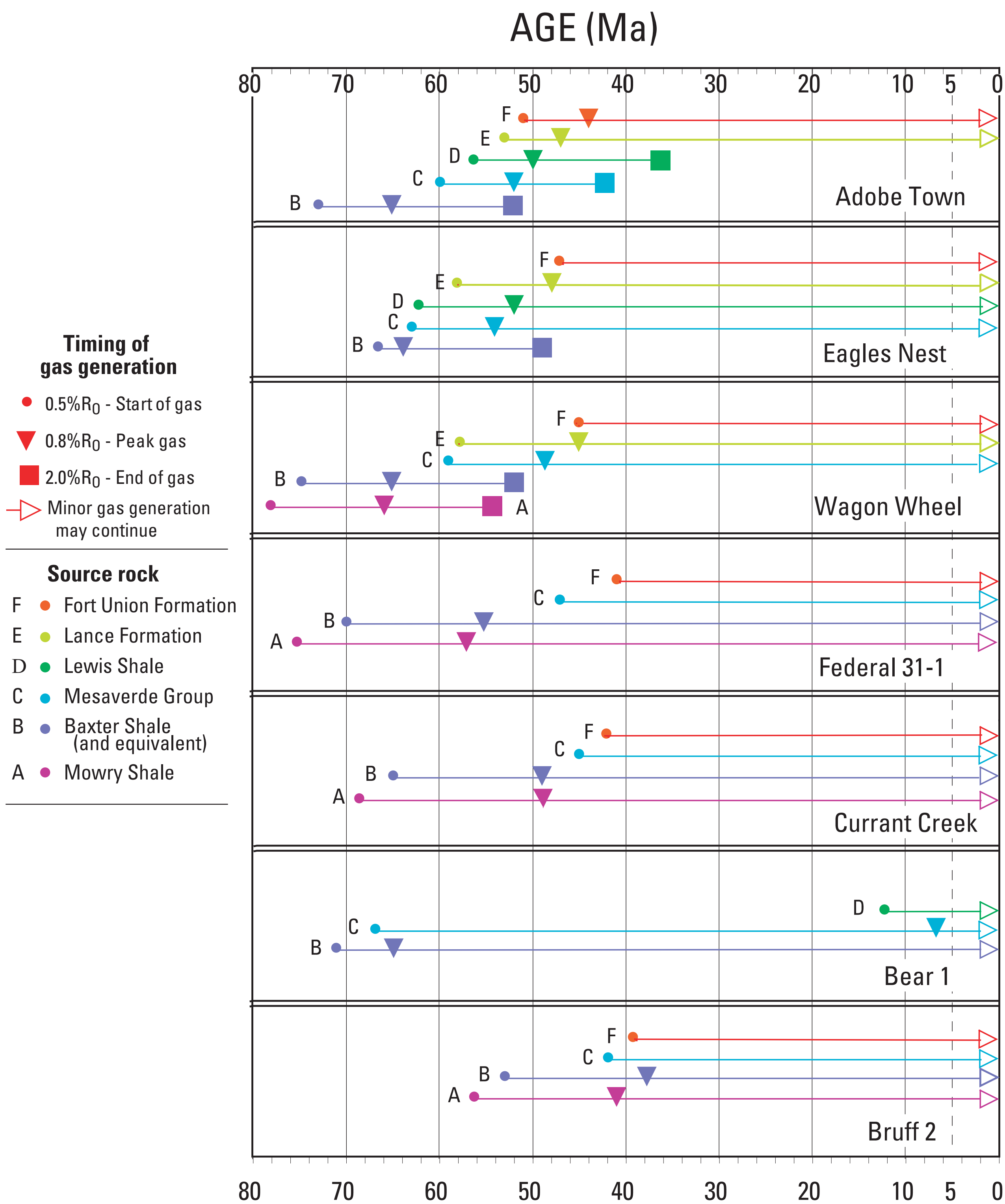

Figure 11. Timing of gas generation from Type-III source rocks by source rock and burial-history location. Vertical dashed line at 5 Ma represents beginning of major uplift, erosion, and subsequent cooling. If gas generation has not ended by present day (0 Ma) based on the models, the rate of gas generation was significantly reduced with negligible generation during the last 5 million years.

As expected, the most extensive petroleum generation occurs at the locations where source rocks were most deeply buried, which include the Adobe Town, Eagles Nest, and Wagon Wheel locations (figs. 10 and 11). The Federal 31-1 and Currant Creek locations, which represent intermediate burial depths, and have moderately extensive petroleum generation and the shallowest burial depths at the Bear-1 location, result in the least extensive petroleum generation. Burial depths at the Bruff 2 location on the Moxa arch are slightly deeper than at Bear 1, but because of a lower thermal gradient, the timing of petroleum generation at Bruff 2 is later and the extent of petroleum generation is less (figs. 10 and 11).

Oil Generation from Source Rocks

Timing of the start, peak, and end of oil generation (transformation ratios of 0.01, 0.50, and 0.99, respectively) is given in table 7 and shown in figure 10. Oil generation in the Phosphoria Formation began as early as 85 to 82 Ma and was completed at all of the studied locations between 76 to 68 Ma. This pre-Tertiary age for completion of oil generation suggests that generation of Phosphoria oil was not significantly affected by the later Laramide-induced structural elements defining the current Greater Green River Basin (Gries, 1983) or by thrusting in the western Wyoming thrust belt (66 to 55 Ma, Wiltschko and Dorr, 1983). Timing of oil generation from the Cretaceous oil-prone source rocks followed the expected order of older rocks generating before younger rocks at any given location (table 7, fig. 10).

Oil Cracking to Gas

Timing of the start, peak, and end of oil cracking to gas (transformation ratios of 0.01, 0.50, and 0.99, respectively) is given in table 7 and shown in figure 10. These transformation ratios pertain to generated oils that are retained in their source rock or in immediately adjacent reservoirs. Figure 10 shows that a distinct time gap exists between the end of oil generation and the start of oil cracking to gas. The duration of this gap is dependent on the conditions of the thermal-burial history and ranges from 59 m.y. for Phosphoria oil at Bruff 2 to 5 m.y. for Baxter and Mesaverde oils at Adobe Town. This gap is greater at any given location for source rocks with Type-IIS kerogen (that is, Phosphoria Formation) than for those with Type-II kerogen. This difference is a result of oil generation from Type-IIS kerogen occurring earlier and at lower temperatures than Type-II kerogen and oils from both kerogen types having the same kinetic parameters for cracking to gas (table 4). This gap is also demonstrated in the vitrinite reflectance values. End of oil generation for Phosphoria oil is at about 0.73 %R_o, and for the other oil-prone source rocks it is between 1.12 and 1.18 %R_o. The start of cracking of oil to gas for both source-rock types is between 1.74 and 1.82 %R_o (table 7), which equates to about a 1.0 to 0.7 %R_o gap in the vitrinite reflectance values.

The Adobe Town location has the greatest potential for gas from oil cracking because oils from all five source rocks would have been cracked to gas by 8 Ma. An overall ranking of the burial-history locations in order of decreasing potential for gas generation from the cracking of oil is Adobe Town > Eagles Nest > Wagon Wheel > Federal 31-1 > Bear 1 > Bruff 2 > Currant Creek. An important caveat to this ranking is that the likelihood of retaining generated oil in or adjacent to its source rock is assumed to be the same for all the oil-prone source rocks at all the locations.

Gas Generation from Source Rocks

Extent of gas generation from gas-prone source rocks in this study is directly related to vitrinite reflectance values based on empirical observations and not a specific kinetic model. As a result, timing of gas generation is directly related to vitrinite reflectance values (that is, start = 0.5 %R_o, peak = 0.8 %R_o, and end = 2.0 %R_o), and the burial-history curves for vitrinite reflectance (figs. 3–9) equate gas generation from gas-prone source rocks. The timing of the start, peak, and end of gas generation for each gas-prone source rock is given in table 6 and shown in figure 11. The most complete gas generation in the Southwestern Wyoming Province occurred in the gas-prone source rocks in the deepest basin settings at Adobe Town, Eagles Nest, and Wagon Wheel (fig. 11).

Summary

Burial history, thermal maturity, and timing of petroleum generation have been modeled for eight petroleum source-rock horizons at seven locations throughout the Southwestern Wyoming Province. The results indicate that burial history, thermal maturity, and timing of petroleum generation can vary widely depending on location within the province and on source-rock type. This type of information is important for delineating areas of petroleum generation and for assessing the undiscovered petroleum resources of the province.

Results for the base of the Phosphoria Formation, a source rock consisting of Type-IIS kerogen, indicate that the timing for the start of oil generation occurred within a relatively narrow range, from 85 to 82 Ma, and oil generation was completed at all of the locations by 68 Ma. In the deep parts of the province, the generation of gas from the cracking of Phosphoria oil began at about 61 Ma, within a maximum of 14 m.y. since oil generation ended. Gas generation ended at these deep locations by 54 Ma. Generation of gas from the cracking of oil may still be continuing at locations where the Phosphoria reached a maximum burial depth of less than 24,000 ft.

The start of oil generation for the base of the Mowry Shale, a mix of Type-II and Type-III kerogen, occurred from 70 to 46 Ma and ended at all locations by 43 Ma except on the Moxa arch, where generation of oil is a possibility today. In the deepest parts of the province, the generation of gas from the cracking of oil began at about 56 Ma, within about 6 m.y. of the end of oil generation. Gas generation from oil cracking ended at these deep locations by about 41 Ma. Gas-prone source rocks of the Mowry began generating gas at about 78 Ma. Gas generation from the Mowry has reached a peak at all locations but has ended only at Wagon Wheel.

Oil generation began as early as 70 Ma for the Niobrara Formation, a source rock containing Type-II kerogen, and ended by 60 Ma at the three locations where the Niobrara is present. At the deeper basin locations, gas generation from oil cracking began within 6 m.y. of the end of oil generation and was completed by 42 Ma; but at the shallower Bear 1 location, oil cracking has not occurred.

Results for the base of the Baxter Shale (and equivalents), a mix of Type-II and Type-III kerogen, indicate that the start of oil generation occurred from 68 to 43 Ma and ended at most locations by 42 Ma except on the Moxa arch, where minor oil generation may be continuing. In the deepest parts of the province, the cracking of oil to gas began at about 54 Ma and ended by 11 Ma. As yet, cracking of oil has not occurred at the shallower locations. Gas-prone source rocks of the Baxter began generating gas at 75 Ma, reached a peak at all locations, but ended in only the deep parts of the province by 49 Ma.

For the Mesaverde Group, also containing a mix of Type-II and Type-III kerogen, oil generation began as early as 57 to 53 Ma and ended between 48 and 7 Ma in the deepest parts of the province. At the other locations, except at Bruff 2, peak oil generation has not occurred. Only at Adobe Town did cracking of oil occur, and it ended as recently as 8 Ma. Gas generation from the gas-prone Mesaverde source rocks took place at all locations, starting at 63 Ma at Eagles Nest, reaching peak generation at all the deep-basin locations, but ending only at Adobe Town at 42 Ma.

The Lewis Shale, the Lance Formation, and the Fort Union Formation all contain Type-III kerogen. The earliest generation of gas from source rocks of the Lewis Shale was at Eagles Nest at 62 Ma, and the latest was at Bear 1 as recently as 12 Ma. The only location where these source rocks reached peak and complete gas generation was at Adobe Town, at 50 and 36 Ma, respectively. Results indicate that, at the three locations where the Lance Formation is considered a source rock, the start of gas generation occurred from 58 to 53 Ma, peaked between 48 and 45 Ma and may still be taking place. Source rocks of the Fort Union Formation began generating gas between 51 and 39 Ma and may currently be generating gas at all locations.

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