Chapter 4

Thermal Maturity and Oil and Gas Generation History of Petroleum Systems in the Uinta-Piceance Province, Utah and Colorado

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Volume Title Page

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Chapter 4 *of*
Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta-Piceance Province, Utah and Colorado
By USGS Uinta-Piceance Assessment Team

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Abstract

Burial history, thermal maturity, and timing of hydrocarbon generation have been modeled for four petroleum source-rock horizons throughout the Uinta-Piceance Province of Utah and Colorado. These horizons are the lower part of the Tertiary Green River Formation, the base of the Cretaceous Mesaverde Group/top of Mancos Shale, the base of the Mancos Shale, and the base of the Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. The results indicate that burial history, thermal maturity, and timing of hydrocarbon generation vary widely depending on location within the province. This type of information is important for delineating areas of hydrocarbon generation, and for assessing the petroleum resources of a basin or province.

Results for the lower part of the Green River Formation indicate that maximum depth of burial and associated temperatures range from 4,000 ft and 150°F in the shallowest parts of the province to 22,000 ft and 350°F in the deep basin centers. Vitrinite reflectance and timing of onset of hydrocarbon generation also show a wide range, from <0.60 percent and 0 Ma (immature) to 1.5 percent and 23 Ma, depending on location.

For the base of the Mesaverde Group/top of Mancos Shale, maximum depth of burial and associated temperatures range from 6,500 ft and 200°F to 25,000 ft and 400°F. Vitrinite reflectance and timing of onset of hydrocarbon generation range from <0.60 percent and 0 Ma (immature) to 2.0 percent and 40 Ma.

Results for the base of the Mancos Shale indicate a maximum depth of burial and associated temperatures ranging from 10,000 ft and 275°F to 30,000 ft and 450°F. Vitrinite reflectance and timing of onset of hydrocarbon generation range from 0.90 percent and 35 Ma to 3.6 percent and 60 Ma, depending on location.

For the base of the Phosphoria or other potential Pennsylvanian-Permian source rocks, maximum depth of burial and associated temperatures range from 12,000 ft and 300°F to 35,000 ft and 525°F, depending on location. Vitrinite reflectance and timing of onset of hydrocarbon generation also show a variability, ranging from 1.3 percent and 73 Ma to >4.0 percent and around 80 Ma.

Introduction

Characterizing the level of thermal maturity and hydrocarbon generation history of a potential source rock is critical in defining a total petroleum system and its associated assessment units, and in assessing the oil and gas resources of that system. This report discusses the burial history, thermal maturity, and timing of hydrocarbon generation for four key petroleum system source-rock horizons throughout the Uinta-Piceance Province of Utah and Colorado (fig. 1). The horizons addressed are: (1) the lower part of the Tertiary Green River Formation, (2) the base of the Cretaceous Mesaverde Group/top of Cretaceous Mancos Shale, (3) the base of the Mancos Shale, and (4) the base of the Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks (fig. 2). Data and interpretations from this report supported other studies of the Uinta-Piceance Province oil and gas assessment project.

Methods

The thermal maturity of the lower part of the Upper Cretaceous Mesaverde Group throughout the Uinta-Piceance Province is well established based on hundreds of vitrinite reflectance (R_o) analyses (Nuccio and Johnson, 1983, 1986; Johnson and Nuccio, 1986; Nuccio and others, 1992), and serves as a "calibration horizon" for defining the thermal maturity of the other petroleum system horizons (table 1). The thermal maturity of the other three horizons was determined for 12 locations throughout the basin by calculating vitrinite reflectance values using burial history reconstructions. Because thermal maturity generally follows structure in the Uinta-Piceance Province, trends of the vitrinite reflectance contour lines for the other three horizons were approximated using structure contour maps of the Rollins Sandstone Member, the Castlegate Sandstone, and the base of the Mancos Shale.

The geothermal gradients used for the burial history reconstructions were determined by calibrating with the measured R_o values at the lower Mesaverde horizon. This

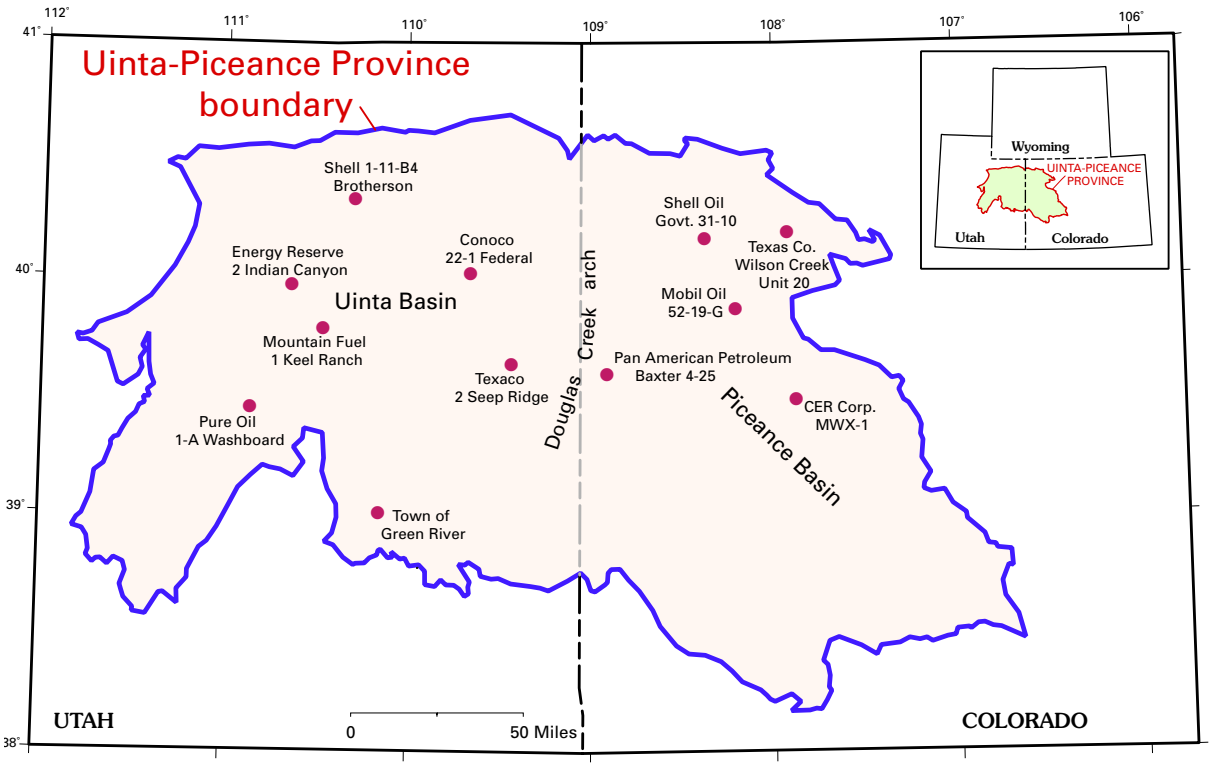


Figure 1. Index map of Uinta-Piceance Province showing major geologic and geographic features, and 12 locations (red dots) where burial reconstructions were modeled. See table 2 for details on the 12 locations.

calibration was made by keeping the burial reconstructions constant, and varying geothermal gradients until the calculated R_o values at the lower Mesaverde horizon matched the measured R_o values. Once the model for a particular area or well was calibrated at the Mesaverde horizon, R_o values at the other three horizons were calculated. Applying this procedure at 12 geographically dispersed areas enabled us to construct thermal maturity maps at the four petroleum system horizons throughout the study area.

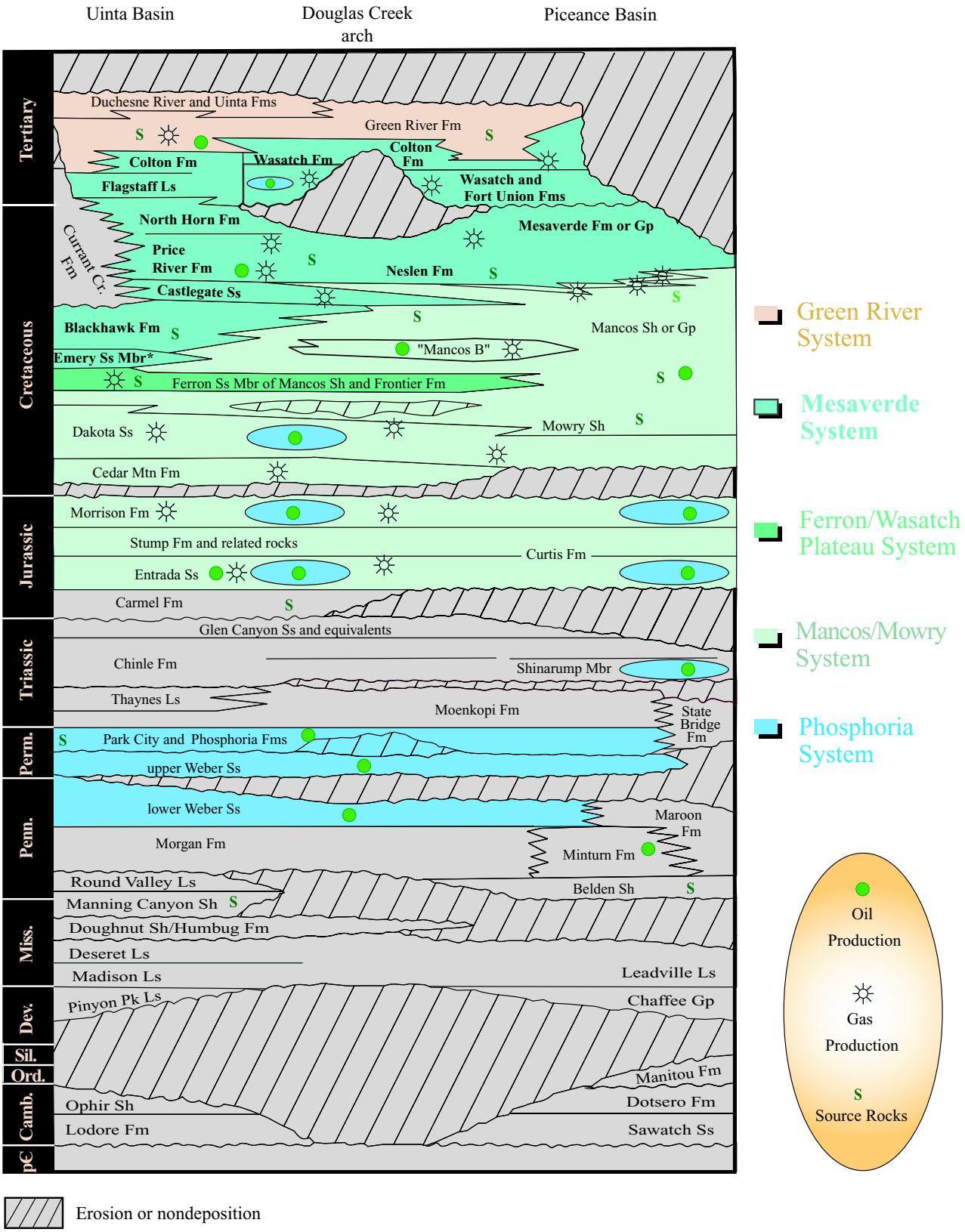
Hydrocarbon-generation kinetic models were then applied to the burial reconstructions to determine the petroleum generation history of the four petroleum system source rocks throughout the study area. The computer program BasinMod (Platte River Associates, version 7.01) was used for the burial, thermal, and kinetic modeling. Kinetic modeling is useful in estimating the time at which source rocks were in the oil and (or) gas window. It is the best method for predicting petroleum-generation histories because it is based on the kinetic reactions of organic matter during burial and thermal maturation. For a complete explanation of kinetic modeling, see discussions in Tissot and Espitalie (1975), Ungerer (1983), Sweeney and others (1987), Tissot and others (1987), and Ruble and others (2001).

Kerogen Types and Related Hydrocarbons

Three general types of kerogen have the potential, under optimum conditions, to generate hydrocarbons: Type I, alginite (sapropelic or lipid rich); Type II, exinite (phytoplankton, zooplankton, and other microorganisms); and Type III, vitrinite and huminite (terrestrial plant debris). There is no absolute point for the onset of hydrocarbon generation, and it probably begins over a range of R_o values depending on the specific type of organic matter involved. The following is a brief summary of several models that have been developed for hydrocarbon generation by the different types of kerogen.

Type I kerogen is hydrogen rich, occurs primarily in marine and lacustrine rocks, and generates mainly oil during catagenesis. The R_o value for the onset of oil generation from Type I organic matter varies for different models. Dow (1977) used 0.50 percent R_o as the onset of oil generation for Type I kerogen, whereas Anders and Gerrild (1984) and Tissot and Welte (1984) used 0.70 percent R_o.

Type II kerogen occurs mainly in marine rocks, but can occur in lacustrine rocks as well, and generates both oil and gas during catagenesis. Waples (1985) stated that the onset of



* Emery Sandstone Member of the Mancos Shale

Figure 2. Generalized stratigraphy of Uinta-Piceance Province (modified from Sanborn, 1977, and Spencer and Wilson, 1988).

Table 1. Data points used in generation of vitrinite reflectance map of the base of the Mesaverde Group in the Uinta-Piceance Province.
[R_o values in percent. Blank boxes indicate data not available. S, South; N, North; W, West; E, East; Meas., measurements]

API Number	Operator Name	Well Name	State	Kelly Elevation (feet)	Township	Range	Section	R_o Mean	No. of Meas.	Standard Deviation	Sample Depth (feet)
05045050560000	California Co.	Baldy Creek Unit 1	CO	8011	7S	90W	17	2.10			
05045050750000	El Paso Nat Gas Co.	Standard Shale 1	CO	8256	7S	99W	6	0.74	101	0.06	5585
05045052010000	Chevron Oil Co.	Pacific Oil Co 1-12-13	CO	7815	5S	98W	13	1.39	130	0.08	7245
05045060530000	Atlantic Richfield Co.	Arco-Exxon 1-36	CO	5864	6S	93W	36	1.60			
05045060920000	Tipperary Corp.	Bear Gulch Unit 1-30F	CO	8884	5S	100W	30	0.63	125	0.04	3975
05045063250000	Cer Corp.	Superior MWX-1	CO	5174	6S	94W	34	1.90			
05045063500000	Snyder Oil Corp.	Snyder-Barton 1-16	CO	6935	6S	90W	16	1.01	101	0.03	6605
05045063550000	Snyder Oil Corp.	Jolley 1-8	CO	6612	6S	91W	8	1.45	101	0.07	7085
05045063950000	Koch Exploration Co.	Frick /Mc/ 11-26	CO	6030	6S	92W	26	1.66	50	0.07	7045
05045064760000	Barrett Energy Co.	Crystal A-2	CO	8562	6S	97W	23	1.83			8855
05045065000000	TRW Exploration & Prod	Sunlight Federal 2	CO	8421	7S	89W	32	0.89	51	0.03	4788
05045065020000	Tenneco Oil Co.	Cameo 20-4	CO	6860	6S	91W	8	1.27	95	0.04	4422
05045065220000	Barrett Energy Co.	Federal MV-12-3	CO	5820	7S	96W	3	1.78	54	0.06	6605
05051060090000	Riviera Drilling & Exploration	Monoline 10-90-31SE	CO	7901	10S	90W	31	0.90			
05077082940000	Exxon Corp.	Old Man Mountain 2	CO	7956	10S	95W	36	0.70	100	0.05	5448
05077082950000	Exxon Corp.	Kinney Creek 1	CO	9578	11S	93W	9	0.79	101	0.03	6942
05077084250000	Exxon Corp.	Dan Kenney Estate 1	CO	7030	9S	95W	11	1.35	105	0.06	6595
05077085520000	Resource Enterprises	Deep Seam 32-2 1	CO	6751	9S	94W	32	1.25	201	0.03	5627
05077653500000	Marathon Oil Co.	Debeque Unit-Govt 2	CO	7276	8S	99W	34	0.68	101	0.04	3735
05081056460000	Sinclair Oil & Gas Co.	Krause 15-1	CO	6087	4N	97W	15	0.65			6175
05081060190000	Champlin Petroleum Company	Govt-Mobil 1	CO	6005	4N	97W	20	0.55			3445
05103053660000	Grynberg Jack J	Govt 1	CO	6284	1N	100W	5	0.60	150	0.03	1325
05103073490000	Fuel Resources Dev Co.	Govt 1	CO	5858	2N	96W	31	0.67	100	0.06	6450
05103074320000	Chorney Oil Co.	East Rangely-Govt 1-14	CO	6919	1N	100W	14	0.65	101	0.04	3765
05103074680000	Cities Services Oil Co.	Federal-A 4	CO	5973	2N	97W	26	0.67	126	0.03	5822
05103075410000	Fuel Resources Dev Co.	Federal 21-2	CO	8402	3S	102W	21	0.54	106	0.11	2025
05103076170000	Cities Services Oil Co.	Preece-Federal B-1	CO	6089	3N	96W	19	0.67	101	0.04	7485
05103077100000	Equity Oil Co.	Emerald 168	CO	7489	3S	102W	8	0.51	100	0.04	1550
05103080970000	Rio Blanco Natural Gas	Govt 298-29-2	CO	7055	2S	98W	29	1.26	103	0.06	8455
05103081830000	Munson David M	Chevron 36-1-100	CO	7853	1S	100W	36	0.73	150	0.05	5865
05103083110000	Twin Arrow	C & K-Federal 4-14X	CO	6938	3S	101W	14	0.49	75	0.05	1144
05103084420000	CSG Exploration Co.	Federal 398-17-4	CO	7362	3S	98W	17	1.37	105	0.06	8985

Table 1.—(Continued). Data points used in generation of vitrinite reflectance map of the base of the Mesaverde Group in the Uinta-Piceance Province.

API Number	Operator Name	Well Name	State	Kelly Elevation (feet)	Township	Range	Section	R_o Mean	No. of Meas.	Standard Deviation	Sample Depth (feet)
05103084530000	CSG Exploration Co.	Govt 398-33-4	CO	7106	3S	98W	33	1.35	101	0.06	7955
05103085280000	CSG Exploration Co.	Govt 397-8-4	CO	6815	3S	97W	8	1.40	101	0.08	9830
05103088170000	Calvert Western Exploration	Govt 397-3-1	CO	6696	3S	97W	3	1.78	115	0.06	11005
05103089140000	Rio Blanco Natural Gas	Govt 398-10-1	CO	6971	3S	98W	10	1.47	102	0.07	9515
05103664230000	Mobil Oil Corp.	Piceance Creek 52-19-G	CO	6885	2S	96W	19	1.56	101	0.09	10955
43007050620000	Reserve Oil & Gas Co.	Peters Point-Humble 8	UT	6872	12S	16E	34	1.03	41	0.07	8505
43007104800000	Carter Oil Co.	Govt-Dial 1	UT	7427	12S	10E	27	0.54	83	0.03	1595
43007107520000	Mountain Fuel Supply	Bartles 1	UT	9268	13S	14E	9	0.68	45	0.10	7730
43013102270000	Continental Oil Co.	Kralovec 1	UT	5495	9S	17E	29	1.76	71	0.11	10555
43013303270000	Exxon Co. U S A	Wilkin-Ridge Unit 1	UT	6193	10S	17E	29	1.60	101	0.07	12185
43019108050000	Pacific Natural Gas	Unit 1	UT	8352	17S	21E	9	0.74	101	0.06	5450
43019159330000	Sunray Dx Oil Co.	Utah-Federal 1	UT	6103	17S	23E	8	0.69	82	0.04	1590
43047051090000	General Petroleum Corp.	Unit 1	UT	5550	11S	23E	2	0.69	50	0.05	6772
43047104770000	Honolulu Oil Corp.	Bitter Creek 1	UT	5902	11S	23E	30	0.69	107	0.06	6855
43047106920000	Marathon Oil Co.	Two Waters Unit 1	UT	6672	14S	25E	8	0.62	61	0.05	2435
43047108120000	Mid-America Minerals	Unit 1	UT	5469	9S	24E	24	0.69	60	0.05	6073
43047109120000	Phillips Petroleum et al	Flat Rock Unit 1	UT	7033	14S	20E	7	0.83	50	0.05	7255
43047110770000	El Paso Natural Gas Co.	Southman Canyon 5	UT	5382	10S	24E	28	0.68	64	0.04	6705
43047111170000	Sinclair Oil & Gas Co.	Uintah-Fed-122 1	UT	6055	13S	22E	18	0.95	86	0.07	5195
43047111190000	Sinclair Oil & Gas Co.	Uintah Federal-219 1	UT	7076	14S	19E	15	0.77	65	0.07	6575
43047111200000	Sinclair Oil & Gas C	Uintah Oil Assoc 1	UT	5945	13S	21E	8	0.89	51	0.05	6635
43047150510000	Belco Petroleum North America	Chapita 5	UT	4957	9S	22E	22	1.20	79	0.05	9495
43047156720000	Pacific Natural Gas	Evacuation Creek 23-2-1	UT	5796	12S	25E	2	0.62	100	0.07	3575
43047200140000	Chevron U S A Inc.	Red Wash Unit 212 41-08F	UT	5528	8S	24E	8	0.70	51	0.04	8750
43047300970000	Webb Resources	Federal 31-13	UT	8272	15S	24E	31	0.65	50	0.06	3445
43047301110000	Continental Oil Co.	Conoco-Federal 22-1	UT	5799	9S	20E	22	1.46	103	0.07	10655
43047301890000	Mapco Incorporated	Hope Unit-Federal 2-8	UT	5486	11S	21E	8	0.94	68	0.06	9195
43047303550000	Exxon Co. U S A	Wolf Point Unit 1	UT	7138	15S	21E	2	0.76	100	0.05	5235
43047303690000	Enserch Exploration Inc.	Crooked Canyon-Fed 1-17	UT	5347	10S	23E	17	0.71	101	0.05	4565

oil generation begins over a range of about 0.45–0.50 percent R_o for high-sulfur kerogen and 0.60 percent R_o for "typical" Type II kerogen.

Huminite and vitrinite, or Type III kerogen, is oxygen rich and hydrogen poor; occurs mainly in coal, terrestrial shales, and marginal-lacustrine or marginal-marine rocks; and generates mostly dry gas (methane) during catagenesis. For Type III kerogen, R_o is the best and most widely used measure of thermal maturity. Two important R_o thresholds are used to define regions of gas generation from Type III kerogen: 0.75 percent and 1.10 percent. An R_o of about 0.75 percent is the thermal maturity required for the onset of significant gas generation (Juntgen and Karweil, 1966; Juntgen and Klein, 1975). In the Piceance, Uinta, and Wind River Basins, an R_o of 0.73 percent was used to help define the limits of basin-centered gas accumulations (Johnson, 1989; Johnson and others, 1987; Nuccio and others, 1992, 1996). An R_o of 1.10 percent represents the level of maximum gas generation and expulsion from Type III kerogen (Meissner, 1984). The upper limit of thermal maturity for gas preservation is still unknown, but could be as high as 3.5 percent (Dow, 1977) or 4.0 percent R_o (Waples, 1980).

Wet gas is generated from mixed lacustrine-marine-terrestrial organic matter and from the thermal breakdown of oil between R_o values of 0.80 percent and 2.0 percent. Dry gas, or thermogenic methane, is generated from humic organic matter and from the thermal breakdown of wet gas between R_o values of about 1.0 percent and 3.0 percent. Biogenic gas can be generated by organic matter at any level of thermal maturity provided that conditions are suitable for methane-generating microbes.

In order to model the kinetic reactions and hydrocarbon generation of the four petroleum source rocks in the Uinta-Piceance Province, the following kerogen types were assumed:

- Green River Formation—Type I
- Mesaverde Group—Type III
- Mancos Shale—50 percent Type II and 50 percent Type III
- Phosphoria Formation or other Pennsylvanian-Permian source rocks—Type II.

Also, the following thermal maturity thresholds were assumed:

Type I source rock:	
Beginning of oil generation	0.60 percent R_o
Overmature for oil; thermal cracking to gas	1.35 percent R_o
Type II source rock:	
Beginning of oil generation	0.60 percent R_o
Beginning of some gas generation	0.75 percent R_o
Overmature for oil; thermal cracking to gas	1.35 percent R_o
Type III source rock:	
Beginning of significant gas generation	0.75 percent R_o
Beginning of intense gas generation and overpressuring	1.10 percent R_o

Burial Reconstructions

Burial history reconstructions were made for 12 areas throughout the Uinta-Piceance Province (figs. 1, 3–14). Thicknesses and ages of units were determined using Franczyk (1991), R.C. Johnson and S.Y. Johnson (1991), S.Y. Johnson and R.C. Johnson (1991), Fouch and others (1994), and Nuccio and Condon (1996). Table 2 shows the data used to construct the burial curves. Estimates of uplift and erosion were calculated by subtracting the present depth of the units from their depth at maximum burial.

Four burial curves were selected out of the twelve to illustrate the extremes in burial histories of the four key petroleum system horizons throughout the Uinta-Piceance Province: (1) the Shell, 1-11-B4 Brotherson well (fig. 3), representing the deep Uinta Basin; (2) the Texaco, 2 Seep Ridge well (fig. 8), near the southern margin of the Uinta Basin; (3) the Pan American Petroleum, Baxter 4-25 well (fig. 10), on the structurally high Douglas Creek arch; and (4) the Mobil Oil, 52-19-G well (fig. 12), characterizing the deep Piceance Basin.

Shell, 1-11-B4 Brotherson (Deep Uinta Basin)

The burial history reconstruction of the Shell, 1-11-B4 Brotherson well in the northern part of the Uinta Basin (fig. 3) illustrates the deepest burial in the Uinta-Piceance Province. Maximum burial occurred between 20 and 10 Ma (table 2). Uplift and erosion, starting about 10 Ma, removed approximately 5,900 ft of section in this area. During maximum burial, the Phosphoria Formation was buried to 35,000 ft and reached temperatures as high as 525°F; the base of the Mancos Shale was buried to more than 30,000 ft and achieved a temperature of about 450°F; the base of the Mesaverde Group/top of Mancos Shale was buried to greater than 25,000 ft and achieved temperatures of nearly 400°F; and the lower part of the Green River Formation was buried to more than 22,000 ft and reached temperatures greater than 350°F.

Texaco, 2 Seep Ridge (Southern Margin of the Uinta Basin)

In contrast to the Brotherson well, the area around the Texaco, 2 Seep Ridge well (fig. 8) is characterized by a much shallower burial history. Maximum burial was again achieved between 20 and 10 Ma with about 4,000 ft of strata removed since about 10 Ma (table 2). During maximum burial, the Phosphoria Formation was buried to about 16,000 ft and reached temperatures around 375°F; the base of the Mancos Shale was buried to about 14,000 ft and achieved a temperature of 325°F; the base of the Mesaverde Group/top of Mancos Shale was buried to over 9,000 ft and reached temperatures of around 250°F; and the lower part of the Green River Formation was buried to 8,000 ft and reached temperatures of 200°F.

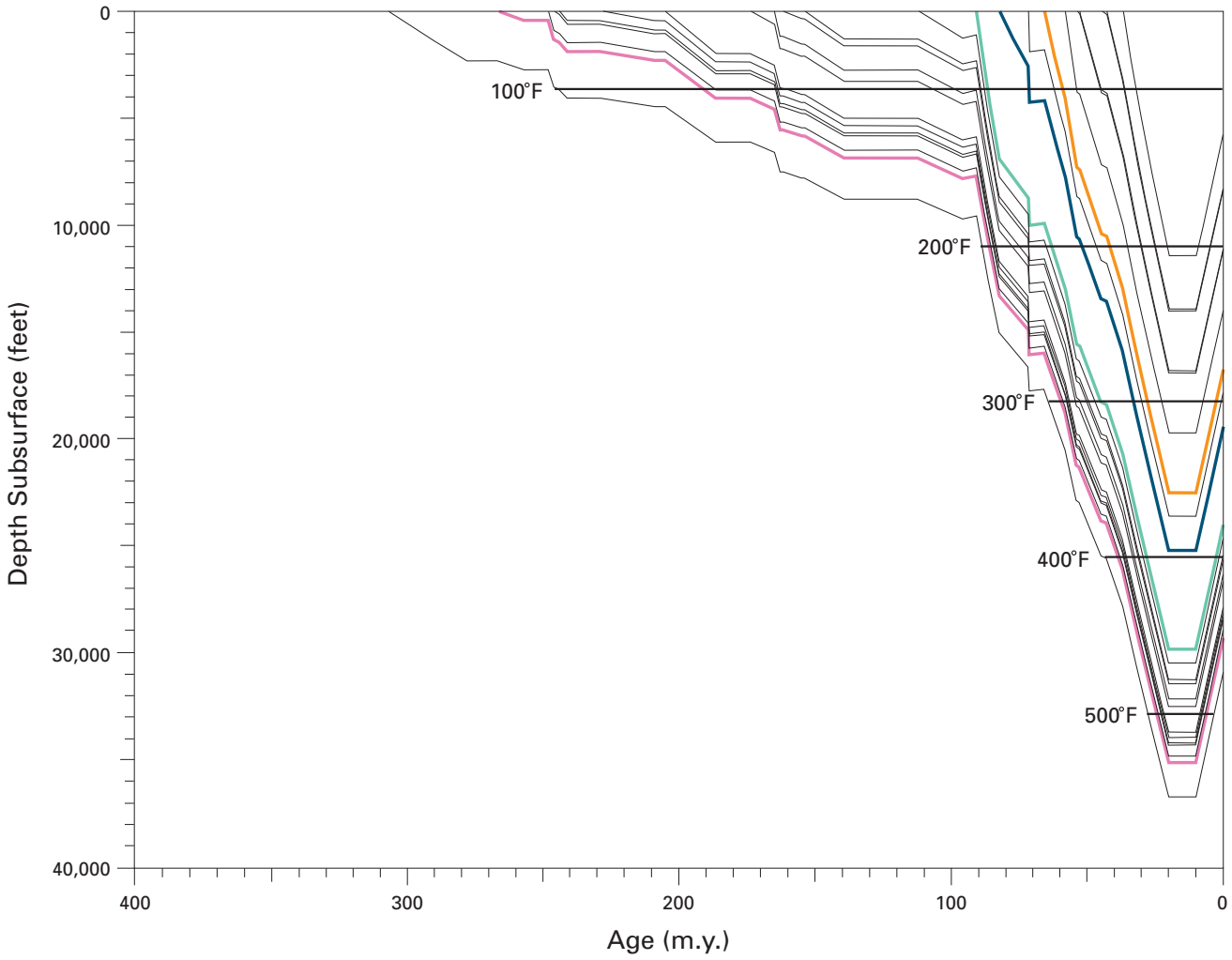


Figure 3. Burial curve representing area around the Shell, 1-11-B4 Brotherson well. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Green curve represents base of Mancos Shale. Blue curve represents base of Mesaverde Group/top of Mancos Shale. Orange curve represents lower part of Green River Formation.

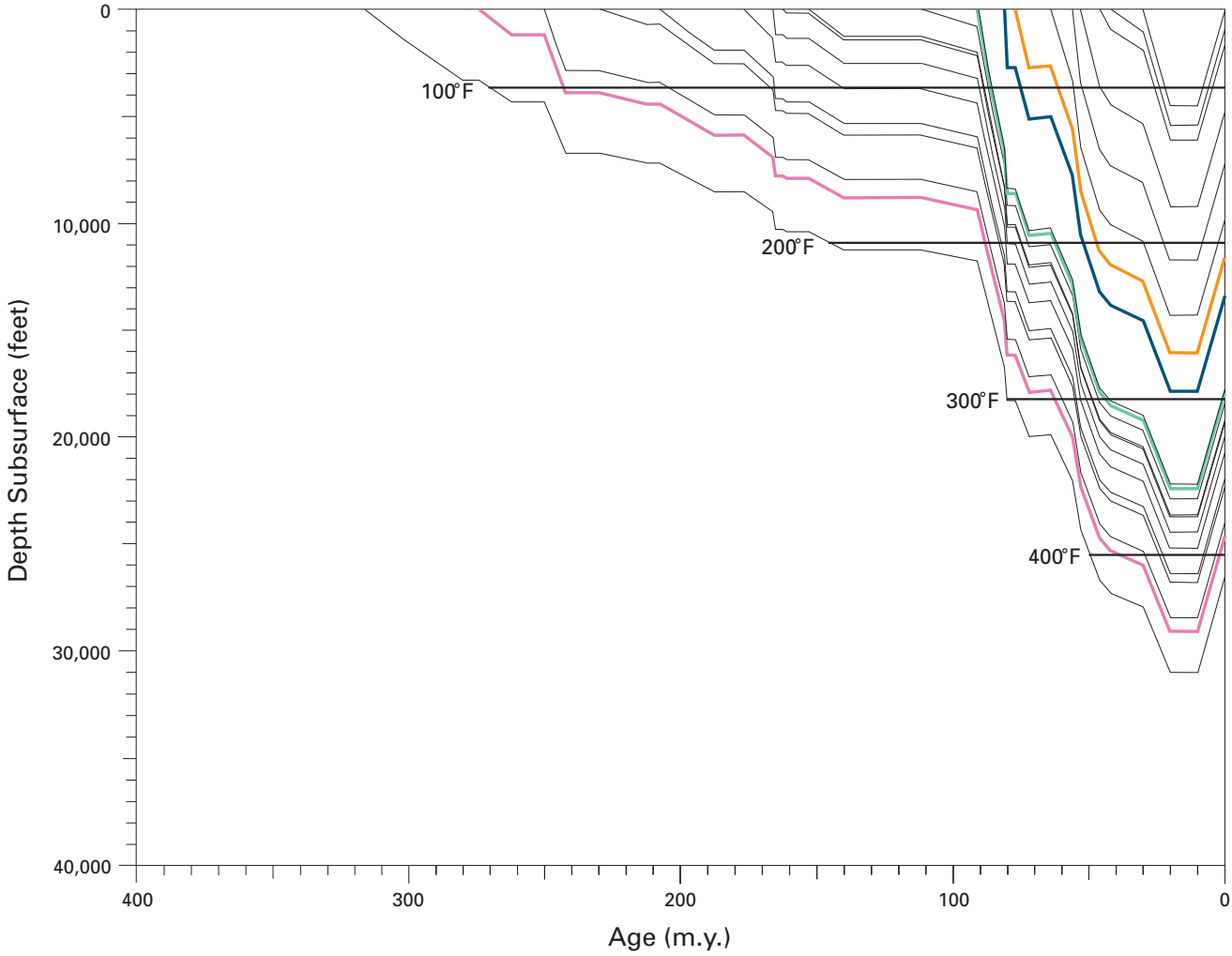


Figure 4. Burial curve representing area around the Energy Reserve, 2 Indian Canyon well. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Green curve represents base of Mancos Shale. Blue curve represents base of Mesaverde Group/top of Mancos Shale. Orange curve represents lower part of Green River Formation.

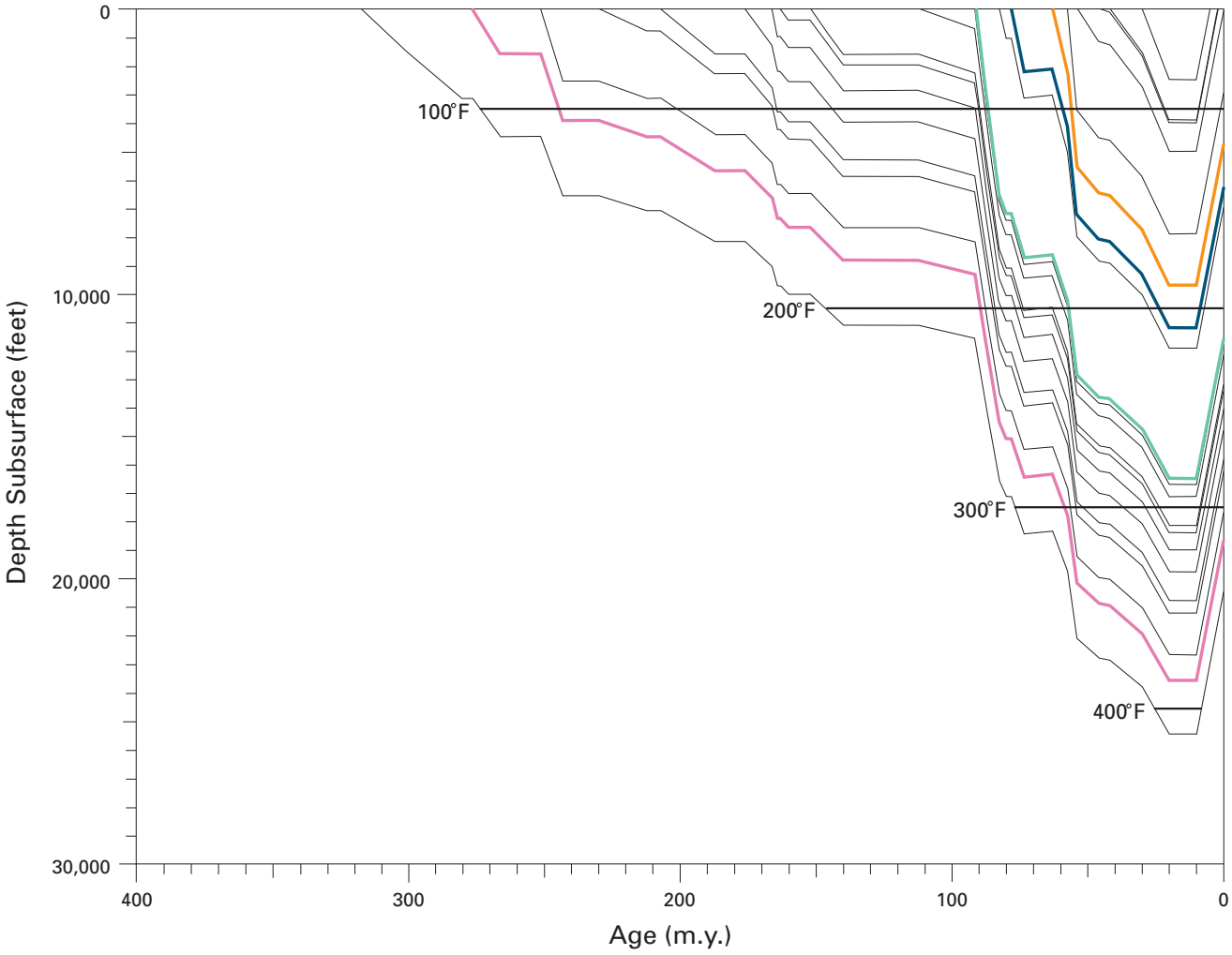


Figure 5. Burial curve representing area around the Mountain Fuel, 1 Keel Ranch well. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Green curve represents base of Mancos Shale. Blue curve represents base of Mesaverde Group/top of Mancos Shale. Orange curve represents lower part of Green River Formation.

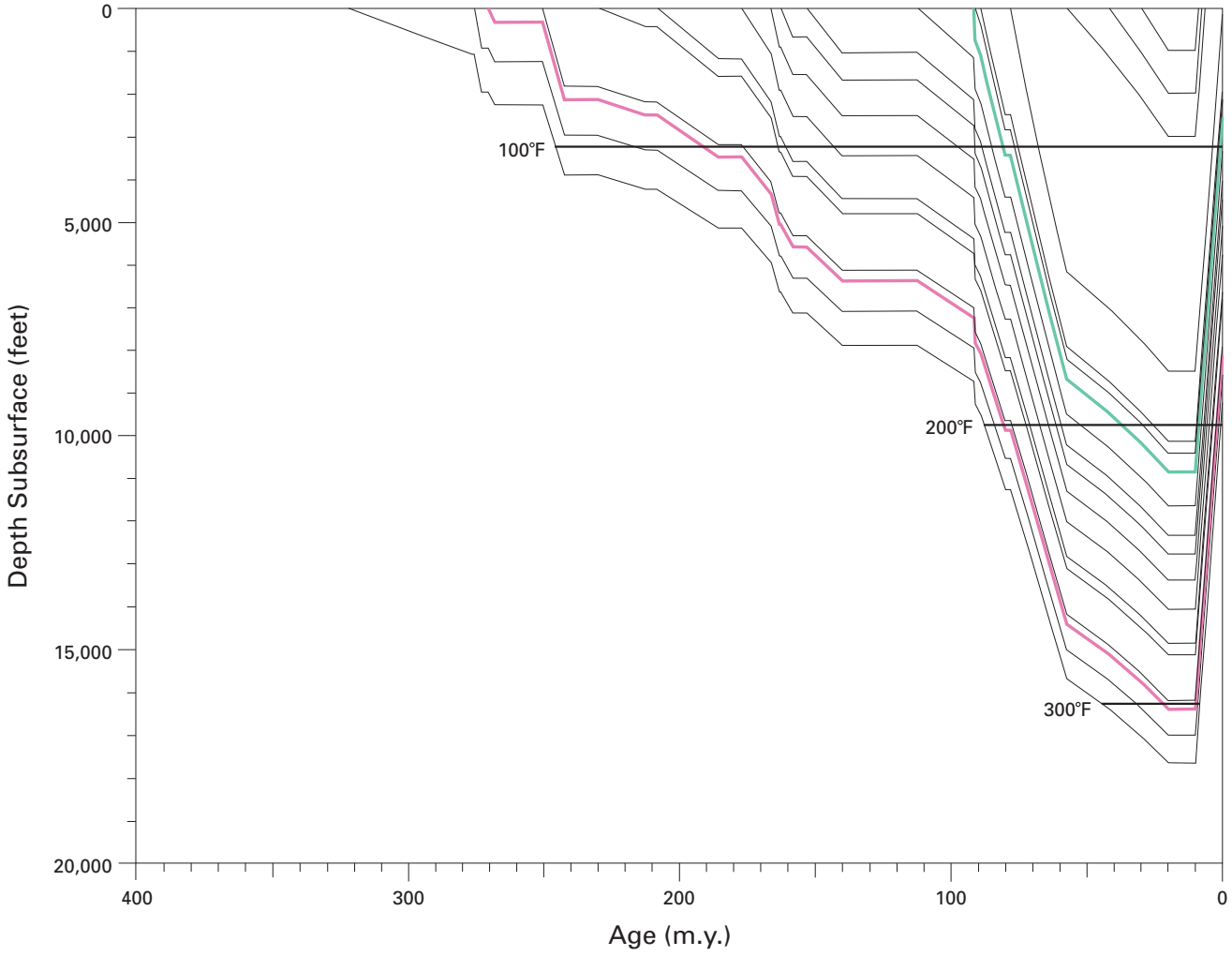


Figure 6. Burial curve representing area around the Pure Oil, 1-A Washboard well. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Green curve represents base of Mancos Shale. Rocks younger than upper part of Mancos Shale have been eroded.

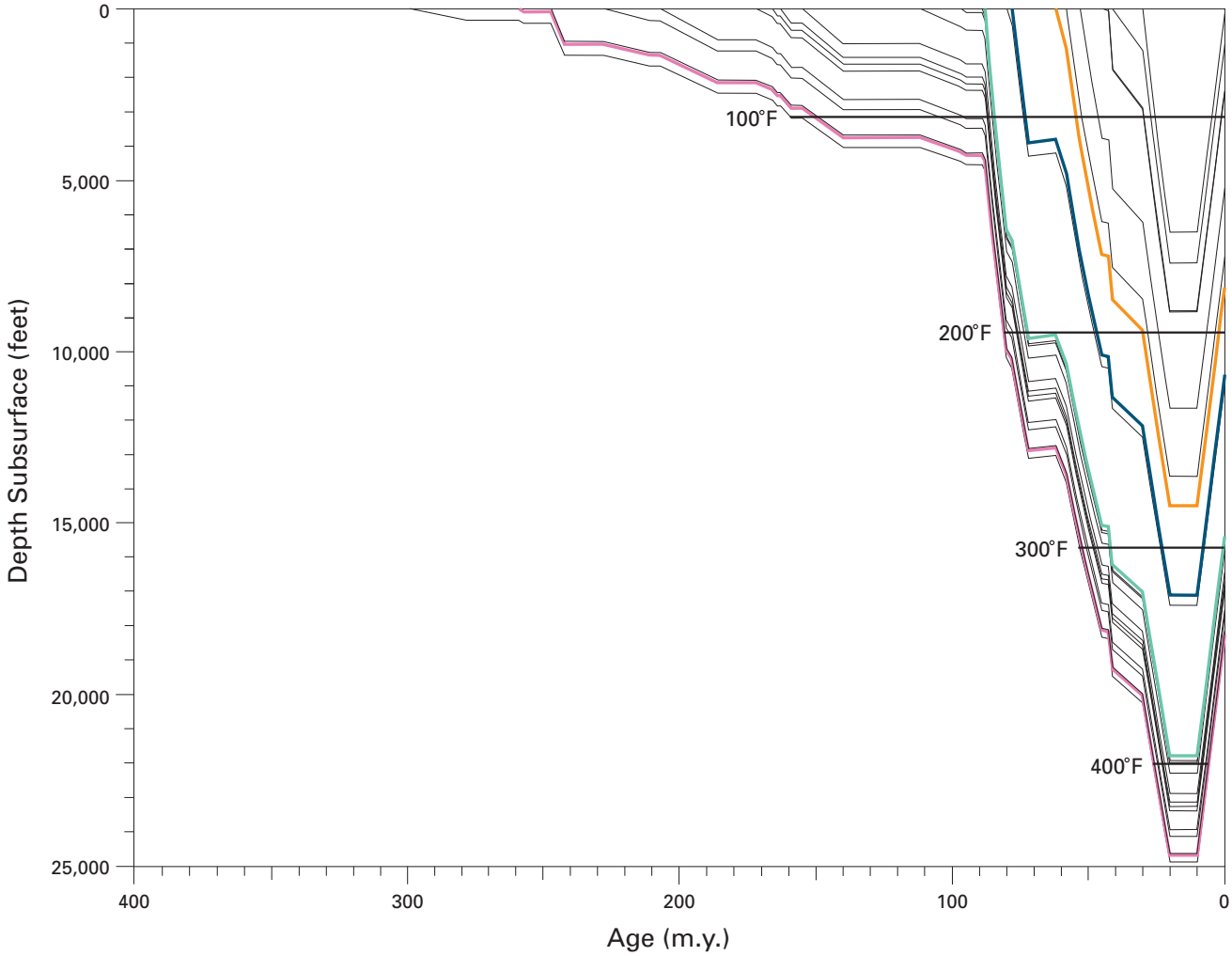


Figure 7. Burial curve representing area around the Conoco, 22-1 Federal well. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Green curve represents base of Mancos Shale. Blue curve represents base of Mesaverde Group/top of Mancos Shale. Orange curve represents lower part of Green River Formation.

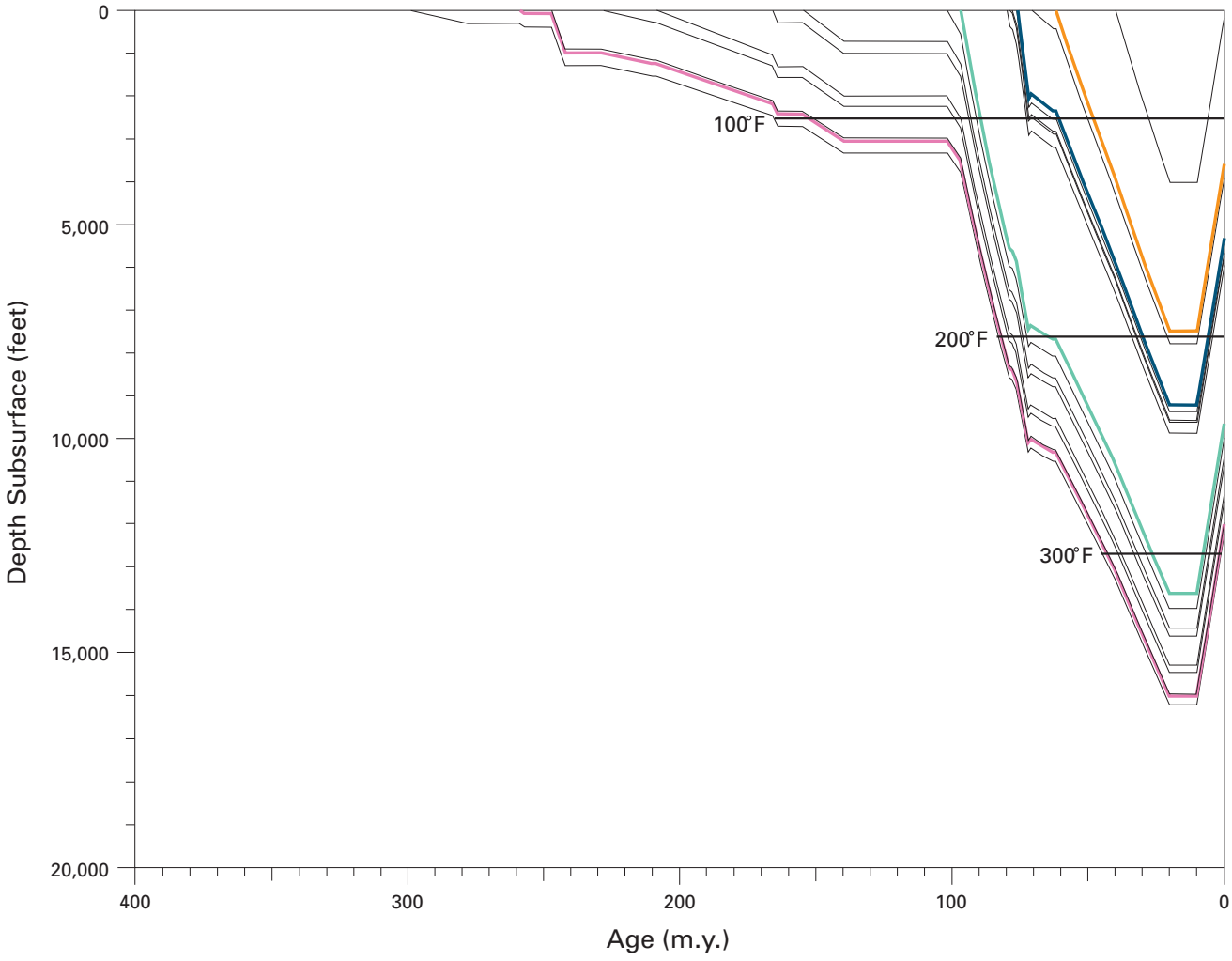


Figure 8. Burial curve representing area around the Texaco, 2 Seep Ridge well. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Green curve represents base of Mancos Shale. Blue curve represents base of Mesaverde Group/top of Mancos Shale. Orange curve represents lower part of Green River Formation.

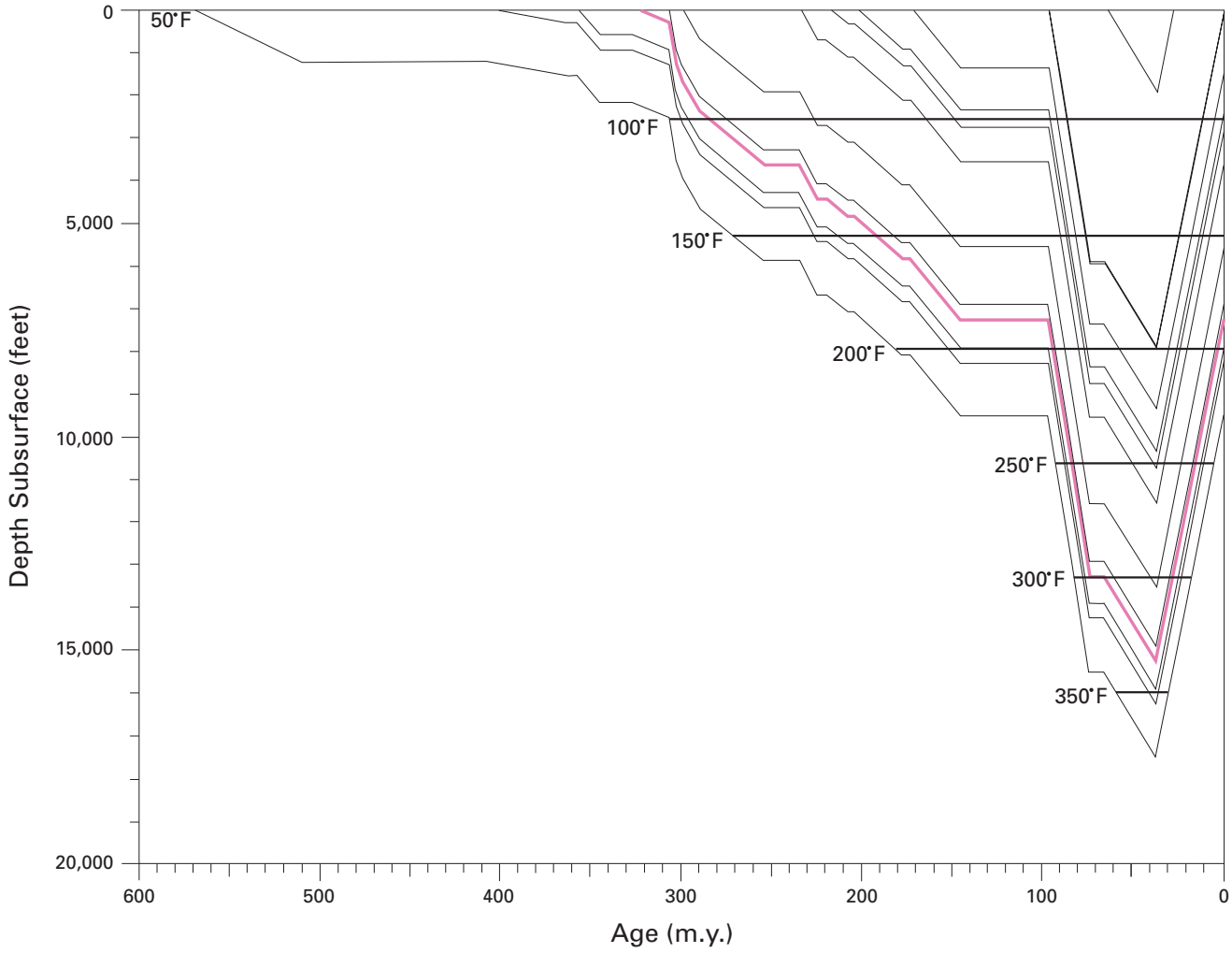


Figure 9. Burial curve representing area around the town of Green River, Utah. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Cretaceous and younger rocks have been eroded.

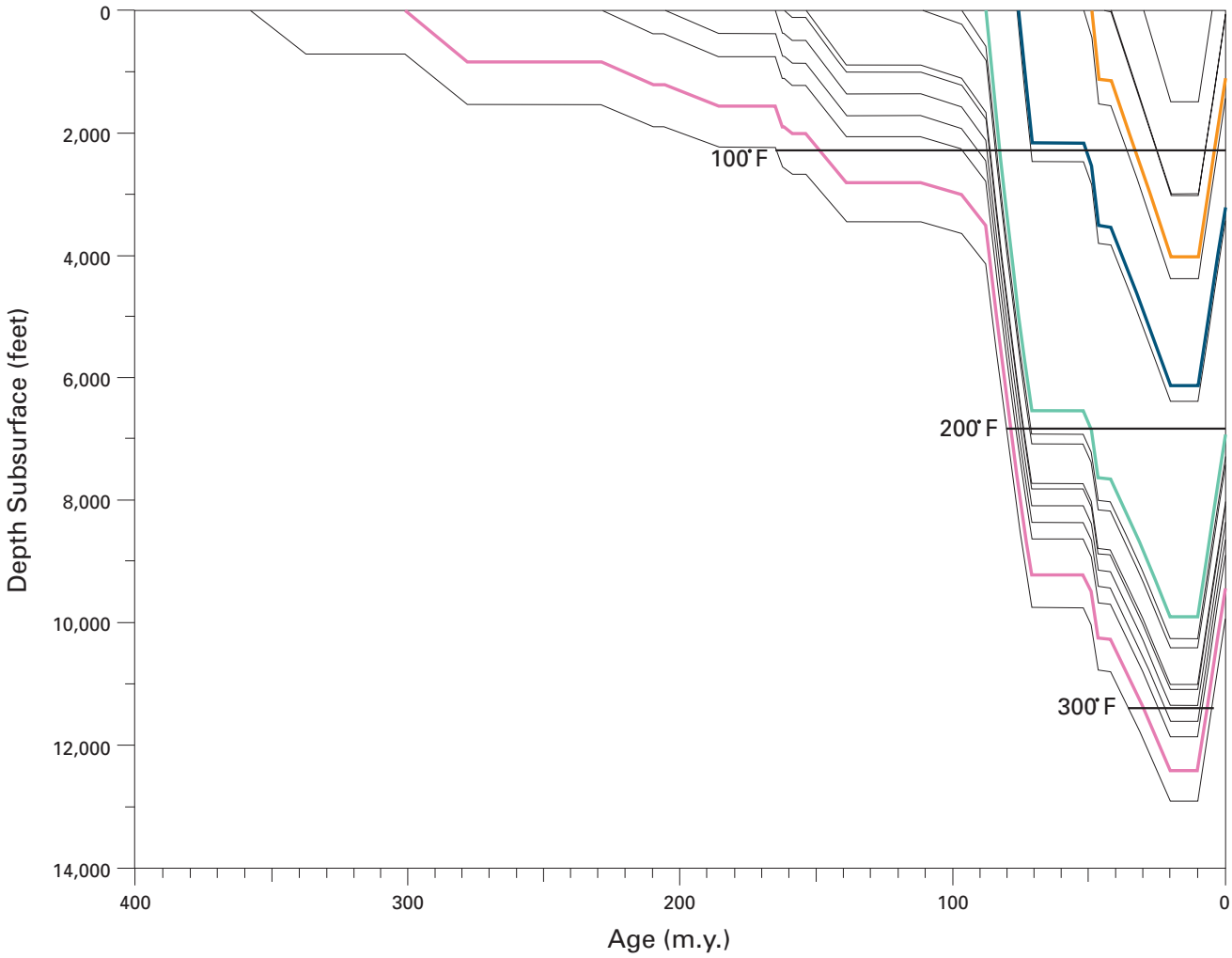


Figure 10. Burial curve representing area around the Pan American Petroleum, Baxter 4-25 well. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Green curve represents base of Mancos Shale. Blue curve represents base of Mesaverde Group/top of Mancos Shale. Orange curve represents lower part of Green River Formation.

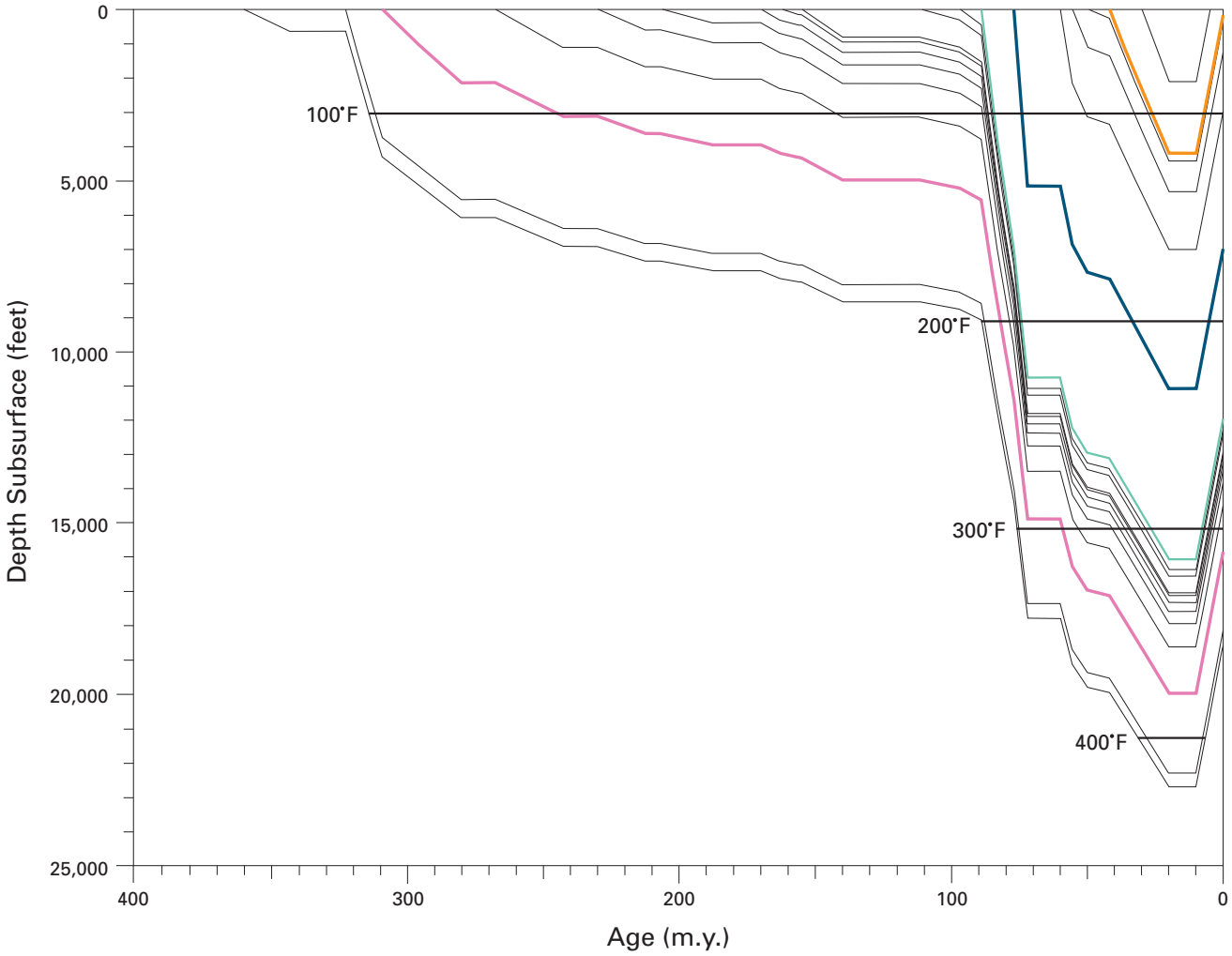


Figure 11. Burial curve representing area around the Shell Oil, Govt. 31-10 well. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Green curve represents base of Mancos Shale. Blue curve represents base of Mesaverde Group/top of Mancos Shale. Orange curve represents lower part of Green River Formation.

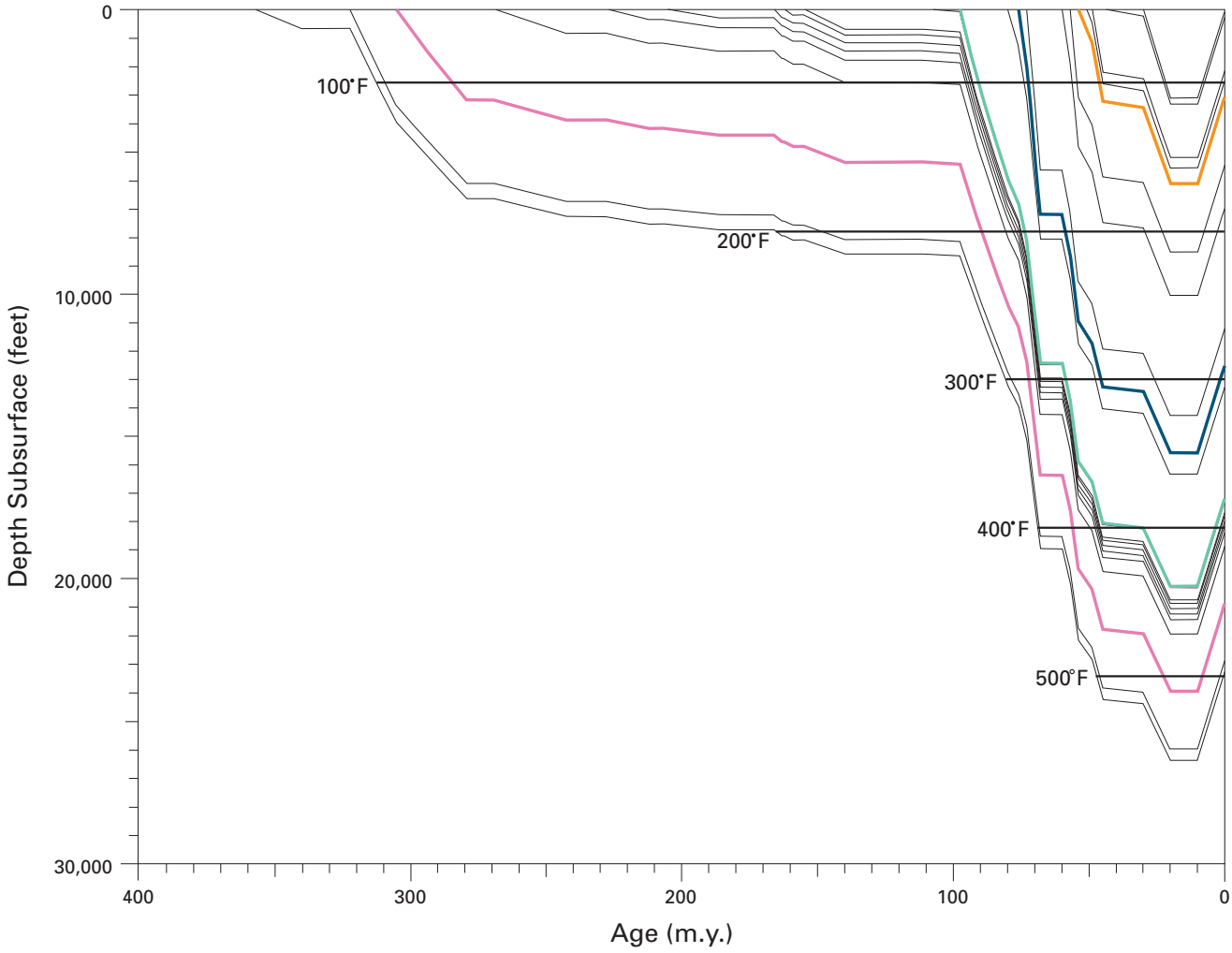


Figure 12. Burial curve representing area around the Mobil Oil, 52-19-G well. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Green curve represents base of Mancos Shale. Blue curve represents base of Mesaverde Group/top of Mancos Shale. Orange curve represents lower part of Green River Formation.

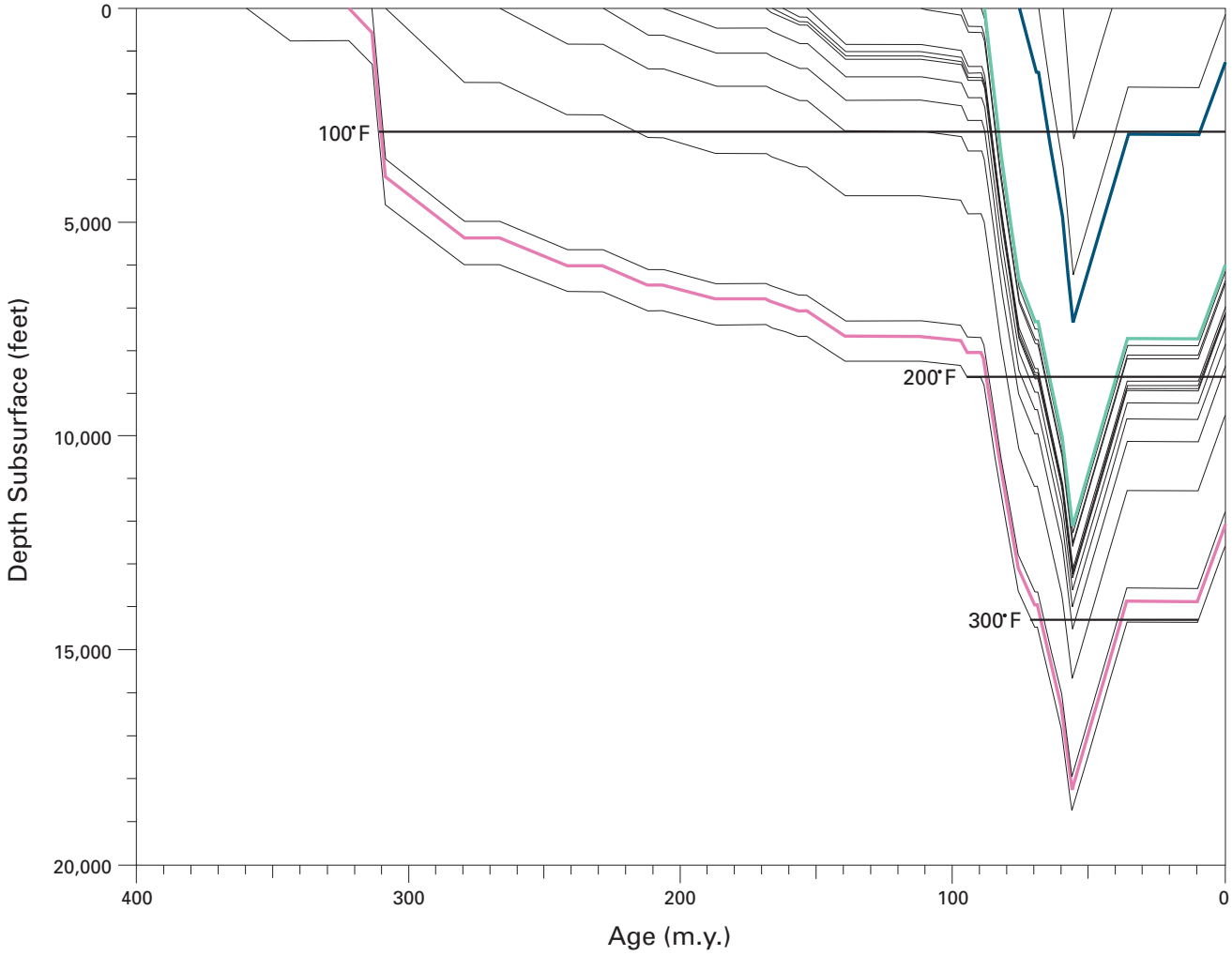


Figure 13. Burial curve representing area around the Texas Co., Wilson Creek Unit 20 well. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Green curve represents base of Mancos Shale. Blue curve represents base of Mesaverde Group/top of Mancos Shale. Erosion has removed most of the Mesaverde Group and younger rocks.

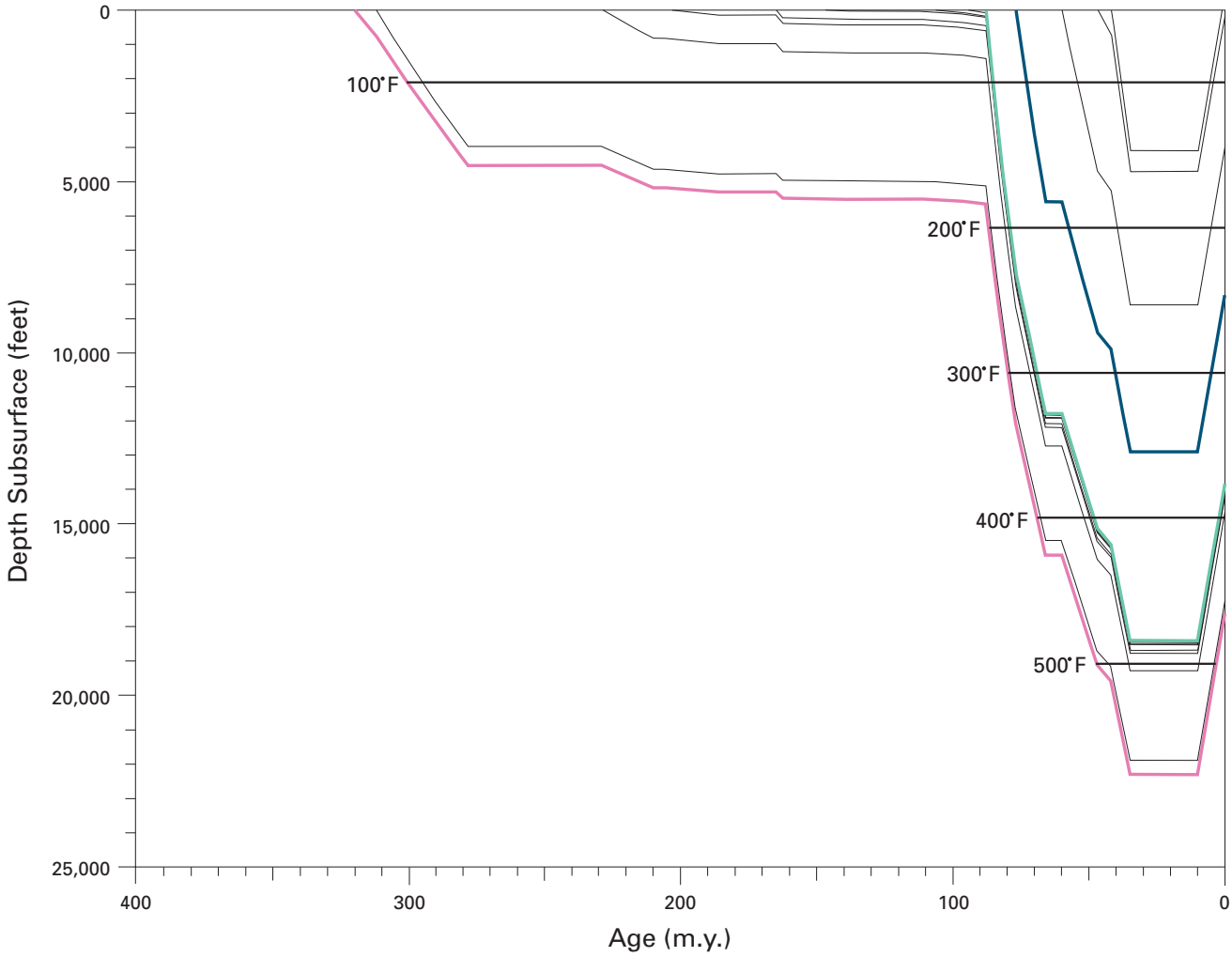


Figure 14. Burial curve representing area around the CER Corp., MWX-1 well. Data used to construct the curve are presented in table 1. Location shown in figure 1. Red curve represents base of Permian Phosphoria Formation or other potential Pennsylvanian-Permian source rocks. Green curve represents base of Mancos Shale. Blue curve represents base of Mesaverde Group/top of Mancos Shale. All but a few hundred feet of Tertiary rocks has been eroded.

Table 2. Data used to construct burial curves for 12 locations in the Uinta-Piceance Province.
[Ma, millions of years; Fm., Formation; Ls., Limestone; Ss., Sandstone; Sh., Shale; G.R., Green River Formation; N.H., North Horn Formation; Flag., Flagstaff Limestone; Dak, Dakota Sandstone; Cedar, Cedar Mountain Formation; Mow, Mowry Shale; Front, Frontier Formation; sec., Section; T., Township; R. Range; TD, Total depth. Geologic time scale from Haq and Van Eysinga (1987)]

Shell, 1-11-B4 Brotherson, sec. 11, T. 2 S., R. 4 W., Duchesne Co., UT, TD 17,766 ft
Geothermal gradient: 25°C/km

System/series, Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-10	-5893
Hiatus	10-20	0
Uinta Fm.	20-37	5504
upper part Green River Fm.	37-43	2500
Mahogany oil shale zone	43-45	100
G.R. upper black shale facies	45-53	2808
Carbonate marker	53-54	100
main part Green River Fm.	54-58.3	2808
G.R. black shale facies/N.H./Flag.	58.3-66	2808
Erosion	66-71.5	-100
Cretaceous rocks undifferentiated	71.5-72	1100
Mesaverde Group	72-82.5	1600
Mancos Shale	82.5-91	4600
Erosion	91-96	-150
Dak/Cedar/Mow/Front	96-112.5	650
Hiatus	112.5-139.5	0
Morrison Fm.	139.5-154	750
Hiatus	154-155	0
Stump Fm.	155-162	200
Hiatus	162-163	0
Preuss Sandstone	163-165	700
Twin Creek Limestone	165-174	350
Hiatus	174-186.5	0
Glen Canyon Sandstone	186.5-205	1200
Hiatus	205-209	0
Chinle Fm.	209-229	250
Hiatus	229-241	0
Ankareh Fm.	241-244	250
Thaynes Limestone	244-246	100
Woodside Fm.	246-248	500
Hiatus	248-257	0
Park City/Phosphoria Fms.	257-267	300
Hiatus	267-278	0
Weber Sandstone	278-307	1600

Energy Reserve, 2 Indian Canyon, sec. 14, T. 6 S., R. 7 W., Duchesne Co., UT, TD 18,003 ft
Geothermal gradient: 25°C/km

System/series Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-10	-4500
Hiatus	10-20	0
Uinta Fm.	20-30	4500
Green River Fm. (part)	30-42	900
Mahogany oil shale zone	42-46	700
Green River Fm. (part)	46-53	3100
Colton Fm.	53-56	2500
Green River Fm./N.H.	56-64	2600
Erosion	64-72	-100
Price River Fm./Castlegate Ss.	72-77	1760
Hiatus	77-80	0

Table 2—Continued. Data used to construct burial curves for 12 locations in the Uinta-Piceance Province.

Blackhawk Fm.	80-81	1800
Mancos Shale (part)	81-90.5	4350
Mancos Shale (part)	90.5-91	210
Dak/Cedar	91-112	475
Hiatus	112-140	0
Morrison Fm.	140-153	750
Hiatus	153-161	0
Stump Fm.	161-162.5	100
Hiatus	162.5-165	0
Entrada Sandstone	165-166	700
Carmel Fm.	166-176.5	770
Hiatus	176.5-187.5	0
Glen Canyon Sandstone	187.5-207.5	1180
Hiatus	207.5-212	0
Chinle Fm.	212-230	400
Hiatus	230-242	0
Ankareh Fm./Thaynes Ls./Woodside Fm.	242-250	1650
Hiatus	250-262	0
Park City Fm.	262-274	650
Hiatus	274-280	0
Weber Sandstone/Morgan Fm.	280-316	1900

Mountain Fuel, 1 Keel Ranch, sec. 16, T. 12 S., R. 13 E., Carbon Co., UT, TD 9,182 ft
Geothermal gradient: 26°C/km

System/series, Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-10	-5000
Hiatus	10-20	0
Uinta Fm.	20-30	2500
Green River Fm. (part)	30-42	1400
Mahogany oil shale zone	42-46	100
Green River Fm. (part)	46-54	1000
Colton Fm.	53-57.5	2900
Green River Fm./N.H.	57.5-63	1800
Erosion	63-73.5	-100
Price River Fm./Castlegate Ss.	73.5-78	1500
Hiatus	78-80	0
Blackhawk Fm.	80-82.5	700
Mancos Shale (part)	82.5-91	4606
Mancos Shale (part)	91-91.5	206
Dak/Cedar	91.5-112.5	438
Hiatus	112.5-140	0
Morrison Fm.	140-152	1000
Hiatus	152-160	0
Stump Fm.	160-163	250
Hiatus	163-164	0
Entrada Sandstone	164-166	620
Carmel Fm.	166-176	760
Hiatus	176-187	0
Glen Canyon Sandstone	187-207	1000
Hiatus	207-212	0
Chinle Fm.	212-230	450
Hiatus	230-243	0
Ankareh Fm./Thaynes Ls./Woodside Fm.	243-251	1450
Hiatus	251-266	0
Park City Fm.	266-276	900
Hiatus	276-280	0
Weber Sandstone	280-317	1850

Pure Oil, 1-A Washboard, sec. 12, T. 16 S., R. 9 E., Emery Co., UT, TD 11,670 ft
Geothermal gradient: 28°C/km

System/series, Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-10	-8500

Table 2 Continued. Data used to construct burial curves for 12 locations in the Uinta-Piceance Province.

Hiatus	10-20	0
Uinta Fm.	20-30	1000
Green River Fm. (part)	30-42	1000
Colton Fm.	42-57.5	1000
Price River Fm./Castlegate Ss.	57.5-78	5500
Hiatus	78-80	0
Mancos Shale (part)	80-89	1650
Mancos Shale (part)	89-91	270
Mancos Shale (part)	91-91.5	450
Dak/Cedar	91.5-112.5	790
Hiatus	112.5-140	0
Morrison Fm.	140-153	690
Hiatus	153-158	0
Stump Fm.	158-162.5	440
Hiatus	162.5-163	0
Entrada Sandstone	163-166	610
Carmel Fm.	166-177	680
Hiatus	177-185.5	0
Navajo/Kayenta/Wingate Fms.	185.5-208	790
Hiatus	208-212.5	0
Chinle Fm.	212.5-230	270
Hiatus	230-242	0
Moenkopi Fm.	242-250	1060
Hiatus	250-267.5	0
Park City Fm.	267.5-270	200
Hiatus	270-272.5	0
White Rim Sandstone	272.5-275	600
Hiatus	275-276	0
Weber Ss./Morgan Fm.	276-322	650

Conoco, 22-1 Federal, sec. 22, T. 9 S., R. 20 E., Uintah Co., UT, TD 20,053 ft
Geothermal gradient: 29°C/km

System/series, Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-10	-6500
Hiatus	10-20	0
Uinta Fm. (part)	20-30	6500
Uinta Fm. (part)	30-41	900
Green River Fm. (part)	41-42.5	1400
Mahogany oil shale zone	42.5-45	40
Green River Fm. (part)	45-53	2800
Wasatch Fm.	53-58	2000
Green River Fm./N.H.	58-62	860
Erosion	62-72	-100
Tuscher/Farrer/Neslen Fms.	72-78	2600
Castlegate Ss.	78-80	300
Mancos Shale	80-88	4350
Frontier Fm.	88-89	140
Hiatus	89-95	0
Mowry Shale	95-97	60
Dak/Cedar	97-112	300
Hiatus	112-140	0
Morrison Fm.	140-155	600
Hiatus	155-159	0
Stump Fm.	159-163	250
Hiatus	163-164	0
Entrada Sandstone	164-166	125
Carmel Fm.	166-172	125
Hiatus	172-186	0
Glen Canyon Sandstone	186-207	550
Hiatus	207-211	0
Chinle Fm.	211-228	200
Hiatus	228-242	0
Moenkopi Fm.	242-247	500
Hiatus	247-257	0
Phosphoria Fm.	257-259	50
Hiatus	259-278	0

Table 2—Continued. Data used to construct burial curves for 12 locations in the Uinta-Piceance Province.

Weber Sandstone	278-300	200

Texaco, 2 Seep Ridge, sec. 3, T. 14 S., R. 22 E., Uintah Co., UT, TD 12,154 ft
Geothermal gradient: 36°C/km

System/series, Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-10	-4000
Hiatus	10-20	0
Eocene rocks	20-40	4000
Green River/Wasatch Fms.	40-62	3470
Hiatus	62-63	0
Dark Canyon sequence	63-71	300
Erosion	71-72	-100
Tuscher/Farrer/Neslen Fms.	72-76	1430
Sego Ss.	76-76.5	160
tongue of Mancos Shale	76.5-78	200
Castlegate Ss.	78-79	50
Blackhawk Fm.	79-80	250
Mancos Shale	80-97	3740
Dak/Cedar	97-102	350
Hiatus	102-140	0
Morrison Fm.	140-155	460
Hiatus	155-164	0
Entrada Ss.	164-166	190
Nugget Ss.	166-209	670
Hiatus	209-210	0
Chinle Fm.	210-229	170
Hiatus	229-242	0
Moenkopi Fm.	242-247	500
Hiatus	247-257	0
Phosphoria Fm.	257-259	50
Hiatus	259-278	0
Weber Sandstone	278-300	200

Town of Green River, UT. From Nuccio and Condon (1996)
Geothermal gradient: 34°C/km

System/series, Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-37	-8050
Tertiary	37-66	2000
Hiatus	66-74	0
Cretaceous	74-97	6000
Hiatus	97-146	0
Jurassic (part)	146-147	50
Jurassic (part)	147-174	1400
Hiatus	174-178	0
Jurassic (part)	178-205	1000
Hiatus	205-208	0
Triassic (part)	208-220	400
Hiatus	220-225	0
Triassic (part)	225-235	800
Hiatus	235-255	0
Permian	255-290	1250
Honaker Trail Fm.	290-300	750
Ismay-Desert Creek intervals	300-303	360
Pennsylvanian (part)	303-307	1000
Pennsylvanian (part)	307-327	350
Hiatus	327-345	0
Mississippian	345-358	650
Hiatus	358-363	0
Devonian	363-409	350
Hiatus	409-510	0
Cambrian	510-570	1250

Table 2—Continued. Data used to construct burial curves for 12 locations in the Uinta-Piceance Province.

Pan American Petroleum, Baxter 4-25, sec. 25, T. 5 S. R. 103 W., Garfield Co., CO, TD 9,850 ft
Geothermal gradient: 40°C/km

System/series, Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-10	-3000
Uinta Formation	20-30	1500
Green River Fm. (part)	30-42	1500
Mahogany oil shale zone	42-46.5	25
Green River Fm. (part)	46.5-49	1000
Wasatch Fm.	49-52	350
Hiatus	52-71	0
Mount Garfield/Hunter Canyon Fms.	71-76	1750
Sego Ss.	76-76.5	260
Mancos Shale	76.5-88	3520
Frontier Fm./Mowry Shale	88-97	350
Dak/Cedar	97-112	150
Hiatus	112-139	0
Morrison Fm.	139-154	600
Hiatus	154-159	0
Sundance Fm.	159-162	80
Hiatus	162-162.5	0
Entrada Ss.	162.5-165	257
Hiatus	165-186	0
Glen Canyon Sandstone	186-206	258
Hiatus	206-210	0
Chinle Fm.	210-229	250
Hiatus	229-278	0
Maroon Fm.	278-301	550
Hiatus	301-337.5	0
Madison Limestone	337.5-358	500

Shell Oil, Govt. 31-10, sec. 10, T. 2 N., R. 98 W., Rio Blanco Co., CO, TD 15,430 ft
Geothermal gradient: 30°C/km

System/series, Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-10	-4200
Hiatus	10-20	0
Uinta Formation	20-30	2100
Green River Fm. (part)	30-42	2100
Green River Fm. (part)	42-50	230
Wasatch Fm.	50-55.5	880
Fort Union Formation	55.5-60	1700
Hiatus	60-72	0
Mesaverde Group	72-77	4070
Mancos Shale	77-89	5000
Frontier Fm./Mowry Shale	89-97	290
Dak/Cedar	97-112	190
Hiatus	112-140	0
Morrison Fm.	140-155	500
Hiatus	155-156	0
Sundance Fm.	156-163	80
Entrada Ss./Carmel Fm.	163-170	200
Hiatus	170-187.5	0
Glen Canyon Sandstone	187.5-207	250
Hiatus	207-212.5	0
Chinle Fm.	212.5-230	360
Hiatus	230-242.5	0
State Bridge Fm.	242.5-267.5	680
Hiatus	267.5-280	0
Weber Ss./Maroon Fm.	280-309	1340
Morgan Fm.	309-322.5	2320
Hiatus	322.5-343	0
Madison Limestone	343-360	400

Table 2—Continued. Data used to construct burial curves for 12 locations in the Uinta-Piceance Province.

Mobil Oil, 52-19-G, sec. 19, T. 2 S., R. 96 W., Rio Blanco Co., CO, TD 19,710 ft
Geothermal gradient: 35°C/km

System/series, Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-10	-3115
Hiatus	10-20	0
Uinta Formation (part)	20-30	3115
Uinta Formation (part)	30-45	220
Green River Fm. (part)	45-49	1860
Wasatch Fm. (part)	49-51	370
Green River Fm. (part)	51-54	550
Wasatch Fm. (part)	54-57	2410
Fort Union Formation	57-60	1520
Hiatus	60-68	0
Williams Fork Fm.	68-73	4240
Mesaverde Group	73-76	1300
Mancos Shale (part)/Castlegate Ss.	76-80	750
Mancos Sh,/Frontier Fm./Mowry Sh.	80-97.5	3950
Dak/Cedar	97.5-112.5	60
Hiatus	112.5-140	0
Morrison Fm.	140-155	420
Hiatus	155-159	0
Sundance Fm.	159-162.5	120
Hiatus	162.5-163	0
Entrada Ss.	163-166	182
Hiatus	166-186	0
Glen Canyon Sandstone	186-207	183
Hiatus	207-212	0
Chinle Fm.	212-228	210
Hiatus	228-242.5	0
State Bridge Fm.	242.5-269	500
Hiatus	269-279	0
Maroon Fm.	279-305	2000
Morgan Fm.	305-322	2000
Hiatus	322-340	0
Madison Limestone	340-357	400

Texas Co., Wilson Creek Unit 20, sec. 34, T. 3 N., R. 94 W., Rio Blanco Co., CO, TD 12,702 ft
Geothermal gradient: 32°C/km

System/series, Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-10	-1800
Hiatus	10-36	0
Erosion	36-56	-4400
Paleocene	56-60	3000
Mesaverde Group (part)	60-69	3200
Hiatus	69-70	0
Mesaverde Group (part)	70-76	1100
Mancos Shale	76-89	4780
Frontier Fm.	89-90	160
Hiatus	90-95	0
Mowry Shale	95-97.5	220
Dak/Cedar	97.5-112.5	85
Hiatus	112.5-140	0
Morrison Fm.	140-154	525
Hiatus	154-157	0
Sundance Fm.	157-163	100
Entrada Ss.	163-167	70
Carmel Fm.	167-169	50
Hiatus	169-187.5	0
Glen Canyon Sandstone	187.5-207	290
Hiatus	207-212.5	0
Chinle Fm.	212.5-229	380
Hiatus	229-242	0

Table 2—Continued. Data used to construct burial curves for 12 locations in the Uinta-Piceance Province.

State Bridge Fm.	242-267	520
Hiatus	267-280	0
Weber Ss.	280-309	1150
Eagle Valley Evaporite	309-314	2280
Belden Shale	314-322.5	300
Hiatus	322.5-344	0
Leadville Limestone	344-360	490

CER Corp., MWX-1, sec. 34, T. 6 S., R. 94 W., Garfield Co., CO, TD 8,350 ft
Geothermal gradient: 43°C/km

System/series, Unit, or Event	Age Range (Ma)	Thickness (feet)
Uplift and erosion	0-10	-4700
Hiatus	10-35	0
Green River Fm.	35-42	4100
Wasatch Fm. (part)	42-47	600
Wasatch Fm. (part)	47-60	3900
Hiatus	60-66	0
Mesaverde Group	66-77	4300
Mancos Shale	77-88	5500
Frontier Fm./Mowry Shale	88-97	50
Dak/Cedar	97-112	50
Hiatus	112-139	0
Morrison Fm./Sundance Fm.	139-162	25
Hiatus	162-162.5	0
Entrada Ss.	162.5-165	150
Hiatus	165-186	0
Glen Canyon Sandstone	186-206	100
Hiatus	206-210	0
Chinle Fm.	210-229	500
Hiatus	229-278	0
Pennsylvanian strata	278-312	2600
Belden Shale	312-320	400

Pan American Petroleum, Baxter 4-25 (on the Douglas Creek Arch)

The area around the Pan American Petroleum, Baxter 4-25 well (fig. 10), located on the structurally high Douglas Creek arch, represents the shallowest burial history of all the areas that we reconstructed. Maximum burial was achieved between 20 and 10 Ma with approximately 3,000 ft of rock removed by erosion in this location since 10 Ma (table 2). Here, during maximum burial, strata near the Pennsylvanian-Permian horizon (Maroon Formation) were buried to more than 12,000 ft and reached temperatures in excess of 300°F; the base of the Mancos Shale was buried to about 10,000 ft and achieved temperatures approaching 275°F; the base of the Mesaverde Group/top of Mancos Shale was buried to about 6,500 ft and reached temperatures of nearly 200°F; and the lower part of the Green River Formation was buried to just over 4,000 ft and reached temperatures approaching 150°F.

Mobil Oil, 52-19-G (Deep Piceance Basin)

The reconstruction of the Mobil Oil, 52-19-G well, in the structural trough of the Piceance Basin (fig. 12), illustrates another area of deep burial in the Uinta-Piceance Province. Uplift and erosion starting about 10 Ma removed approximately 3,100 ft of section there (table 2). During maximum burial between 20 and 10 Ma, strata at approximately the Pennsylvanian-Permian horizon (Maroon Formation) were buried to 24,000 ft and reached temperatures as high as 500°F; the base of the Mancos Shale was buried to over 20,000 ft and achieved a temperature of around 425°F; the base of the Mesaverde Group/top of Mancos Shale was buried to greater than 16,000 ft and was subjected to temperatures of around 350°F; and the lower part of the Green River Formation was buried to around 6,000 ft and reached temperatures exceeding 150°F.

The four wells just discussed are summarized in the following chart. Reported depths and temperatures occurred at maximum burial between 20 and 10 Ma. Erosion estimates are since 10 Ma.

Well	Erosion	Phosphoria* Depth; Temp.	Mancos Sh. Depth; Temp.	Mesaverde Gp. Depth; Temp.	Green River Fm. Depth; Temp.
Shell, 1-11-B4 Brotherson	5,900 ft	35,000 ft; 525 °F	30,000 ft; 450 °F	25,000 ft; 400 °F	22,000 ft; 350 °F
Texaco, 2 Seep Ridge	4,000 ft	16,000 ft; 375 °F	14,000 ft; 325 °F	9,000 ft; 250 °F	8,000 ft; 200 °F
Pan American Petroleum, Baxter 4-25	3,000 ft	12,000 ft; 300 °F	10,000 ft; 275 °F	6,500 ft; 200 °F	4,000 ft; 150 °F
Mobil Oil, 52-19-G	3,100 ft	24,000 ft; 500 °F	20,000 ft; 425 °F	16,000 ft; 350 °F	6,000 ft; 150 °F

*Includes other Pennsylvanian-Permian source rocks.

Thermal Maturity Trends and Hydrocarbon Generation

This section describes thermal maturity trends and oil and gas generation history for the four key petroleum system source-rock horizons throughout the study area. Because of the large size of the study area, the following discussion is, by necessity, general. However, one can get a better idea of the thermal maturity, and oil and gas generation history of each horizon in specific areas by comparing the burial curve, maturity map, and timing of oil and gas generation data (table 3) for an area as discussed below.

Lower Part of the Green River Formation

Vitrinite reflectance trends for the lower part of the Green River Formation are shown in figure 15. The lower part of the Green River Formation is within the window for oil and gas generation (>0.60 percent R_o) over much of the deep trough of the Uinta Basin, but is immature elsewhere in the Uinta-Piceance Province, including the deep trough of the Piceance Basin.

The timing of oil and gas generation varies throughout the study area (fig. 16; table 3). The onset of oil and gas generation ranges from 0 Ma (immature) throughout all of the Piceance Basin and the southern part of the Uinta Basin, to 23 Ma in the deep northern part of the Uinta Basin (fig. 3; table 3). Rates of oil and gas generation peaked around 17 Ma in the deep trough of the Uinta Basin, then gradually slowed due to uplift and erosion. Significant oil and gas generation ceased at about 5 Ma. Some gas generation from the thermal cracking of oil is probably still occurring in the deepest, most mature part of the Uinta Basin, and is the cause of overpressuring encountered there.

Base of Mesaverde Group/Top of Mancos Shale

Vitrinite reflectance trends at the base of the Mesaverde Group/top of the Mancos Shale are illustrated in figure 17. The data used to construct this map are tabulated in table 1. Vitrinite reflectance of source rocks at this horizon ranges from <0.60 percent around the margins of the study area and on the Douglas Creek arch to >1.35 percent in the troughs of the basins. R_o values approach 2.0 percent in the deepest parts of both basins. These R_o trends suggest that the base of the Mesaverde/top of Mancos is mature for oil and thermogenic gas generation throughout most of the study area. In immature areas, where R_o is <0.60 percent, the possibility still exists for biogenic gas generation from coal beds.

The onset of oil and gas generation at the base of the Mesaverde/top of Mancos varies widely throughout the study area (fig. 18; table 3). Significant oil and gas generation began as early as 55 Ma, and peaked about 52 Ma in the structurally deepest part of the Piceance Basin. In the deep Uinta Basin, oil and gas generation began around 40 Ma and peaked at around 35 Ma (fig. 3; table 3). Due to uplift, erosion, and subsequent cooling, significant oil and gas generation from source rocks at this horizon ceased between 10 and 5 Ma in the Uinta Basin, and between 45 and 10 Ma in the deep Piceance Basin. It is conceivable that in the deep troughs of the basins some gas generation from kerogen, as well as from the cracking of oil to gas, could be occurring at the present time. Around the margins of the basins, and on the Douglas Creek arch, source rocks are immature, and significant oil and (or) thermogenic gas generation has not occurred.

Base of the Mancos Shale

Vitrinite reflectance trends at the base of the Mancos Shale are shown in figure 19. R_o at this horizon ranges from <0.60 percent around the southern part of the study area to as high as 4.0 percent in the deep troughs of the basins. The R_o values suggest that the base of the Mancos is mature (0.60–1.35 percent) to overmature (>1.35 percent) for oil generation over most of the study area.

The onset of oil and gas generation at the base of the Mancos Shale ranges from 20 Ma in the southwestern part of the study area, to 60 Ma along the trough of the Uinta Basin, to more than 70 Ma along the trough of the Piceance Basin (fig. 20; table 3). Peak oil and gas generation in the deep troughs of the Uinta and Piceance Basins occurred at 74 Ma and 50 Ma, respectively (figs. 14 and 3; table 3). Because of high thermal maturities in the deeper parts of the Uinta and Piceance Basins, oil generation ended as early as 43 Ma and 66 Ma, respectively. Gas generation from the cracking of oil and (or) from kerogen continued for some time after, and did

Table 3. Timing of oil and gas generation for the four petroleum system source rocks at the 12 locations throughout the Uinta-Piceance Province.

Shell, 1-11-B4 Brotherson

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	80	71	58	80	50	45
Mancos Shale	57	50	43	57	35	32
Mesaverde Group	42	35	10	42	26	10
Green River Fm.	23	17	5	23	17	5

Energy Reserve, 2 Indian Canyon

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	82	78	68	82	54	46
Mancos Shale	54	50	42	54	22	15
Mesaverde Group	25	22	5	25	22	5
Green River Fm.	Immature; little generation			Immature; little generation		

Mountain Fuel, 1 Keel Ranch

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	85	81	73	86	52	50
Mancos Shale	50	27	20	50	23	5
Mesaverde Group	24	17	5	24	17	5
Green River Fm.	Immature; little generation			Immature; little generation		

Pure Oil, 1-A Washboard

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	68	61	50	68	60	8
Mancos Shale	20	17	7	20	18	7
Mesaverde Group	Immature; little generation			Immature; little generation		
Green River Fm.	Immature; little generation			Immature; little generation		

Table 3—Continued. Timing of oil and gas generation for the four petroleum system source rocks at the 12 locations throughout the Uinta-Piceance Province.

Conoco, 22-1 Federal

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	75	72	49	75	42	35
Mancos Shale	53	49	35	53	27	20
Mesaverde Group	33	28	10	33	23	5
Green River Fm.	Immature; little generation			Immature; little generation		

Texaco, 2 Seep Ridge

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	73	71	40	73	30	20
Mancos Shale	49	37	27	49	36	5
Mesaverde Group	23	17	5	23	17	5
Green River Fm.	Immature; little generation			Immature; little generation		

Town of Green River, UT

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	88	82	74	88	82	32
Mancos Shale	40	37	33	40	37	33
Mesaverde Group	Immature; little generation			Immature; little generation		
Green River Fm.	Immature; little generation			Immature; little generation		

Pan American Petroleum, Baxter 4-25

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	73	68	30	73	18	0
Mancos Shale	35	22	5	35	22	5
Mesaverde Group	Immature; little generation			Immature; little generation		
Green River Fm.	Immature; little generation			Immature; little generation		

Table 3—Continued. Timing of oil and gas generation for the four petroleum system source rocks at the 12 locations throughout the Uinta-Piceance Province.

Shell Oil, Govt. 31-10

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	76	74	65	76	74	30
Mancos Shale	62	53	25	72	53	0
Mesaverde Group	18	Little generation		18	Little generation	
Green River Fm.	Immature; little generation			Immature; little generation		

Mobil Oil, 52-19-G

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	81	74	68	81	70	60
Mancos Shale	72	70	60	72	53	51
Mesaverde Group	55	52	45	55	47	10
Green River Fm.	Immature; little generation			Immature; little generation		

Texas Co., Wilson Creek Unit 20

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	82	79	56	82	59	56
Mancos Shale	58	56	42	58	56	42
Mesaverde Group	Immature; little generation			Immature; little generation		
Green River Fm.	Immature; little generation			Immature; little generation		

CER Corp., MWX-1

Petroleum System	Oil generation			Gas generation		
	Onset	Peak	End	Onset	Peak	End
Paleozoic	85	80	77	85	74	71
Mancos Shale	76	74	66	76	57	35
Mesaverde Group	51	50	27	51	39	20
Green River Fm.	Immature; little generation			Immature; little generation		

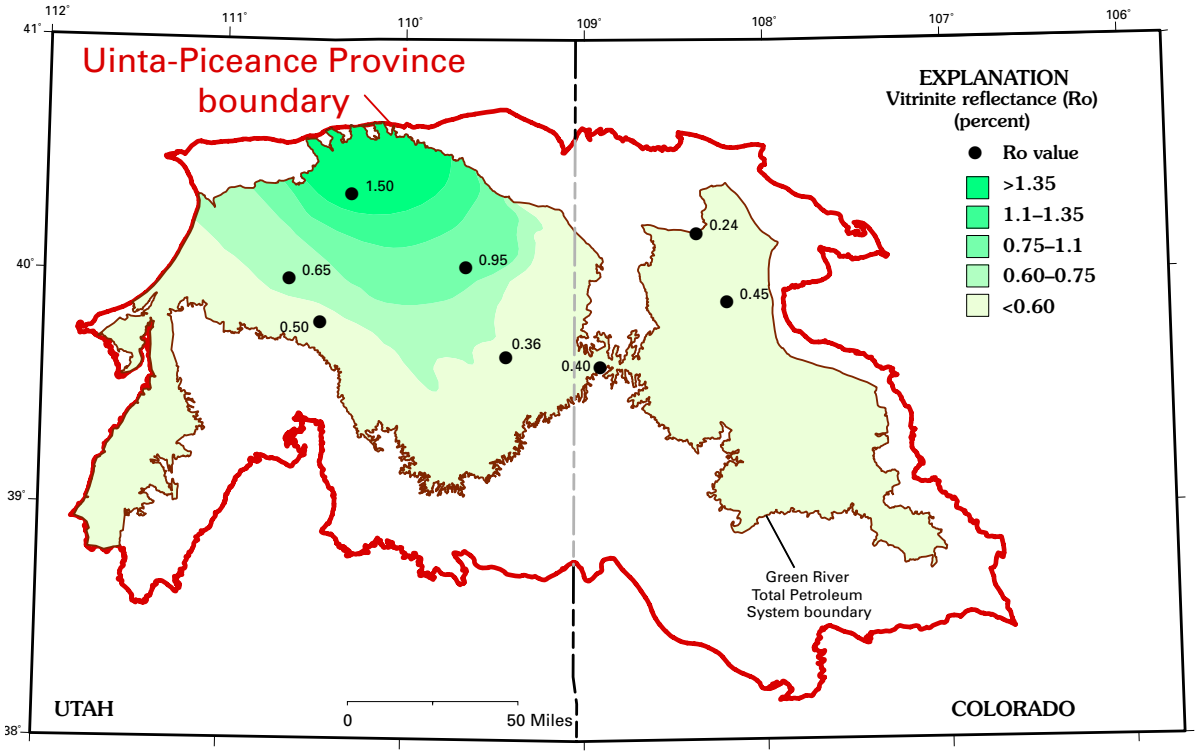


Figure 15. Vitrinite reflectance trends at horizon of lower part of Green River Formation.

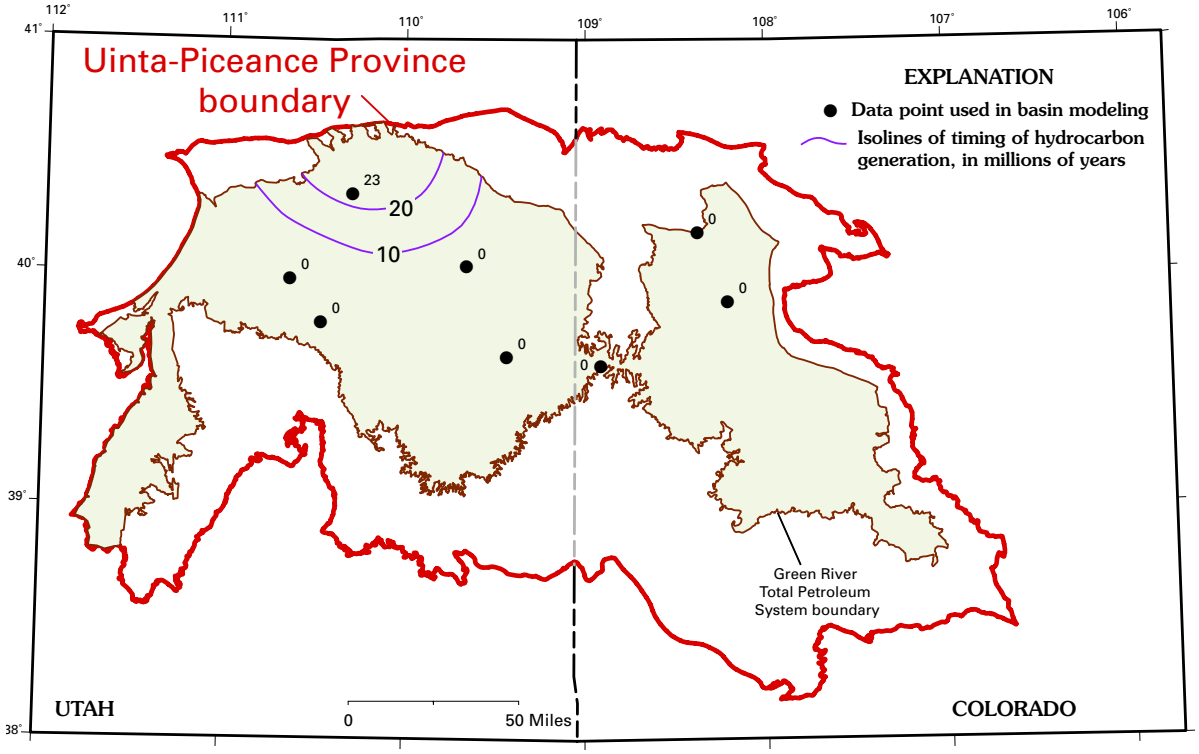


Figure 16. Time when significant oil and gas generation began for source rocks at horizon of lower part of Green River Formation.

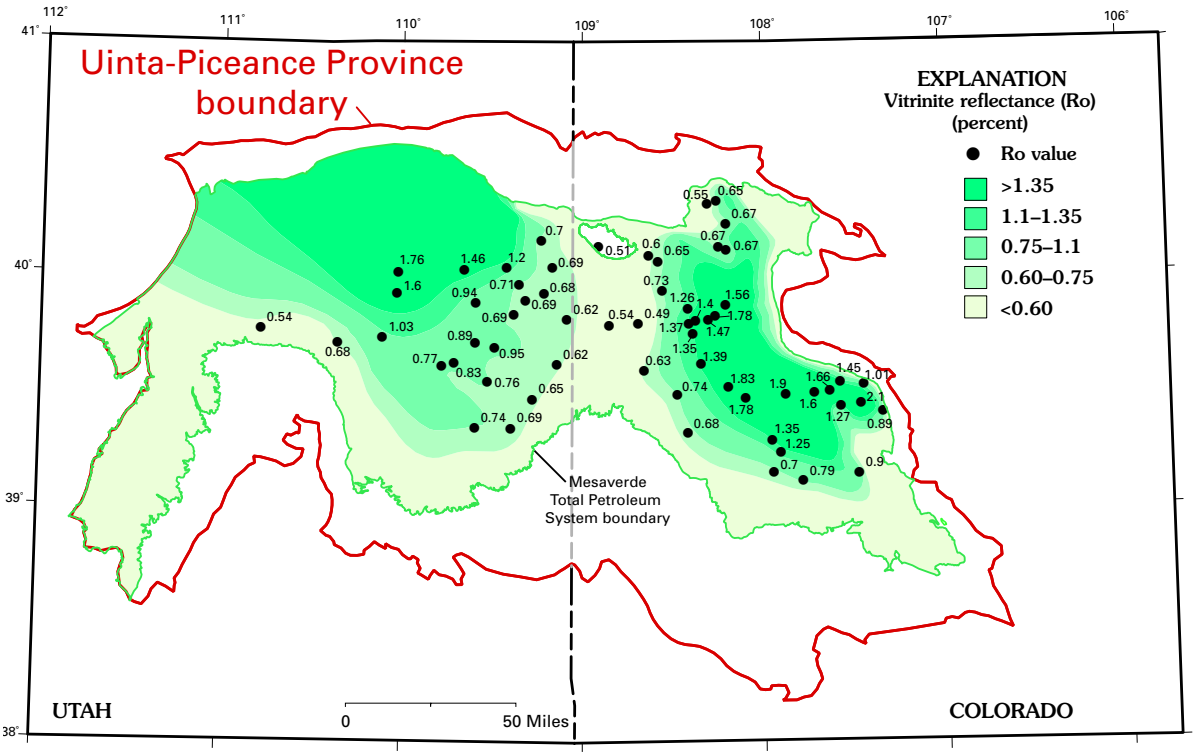


Figure 17. Vitrinite reflectance trends at horizon of base of Mesaverde Group/top of Mancos Shale.

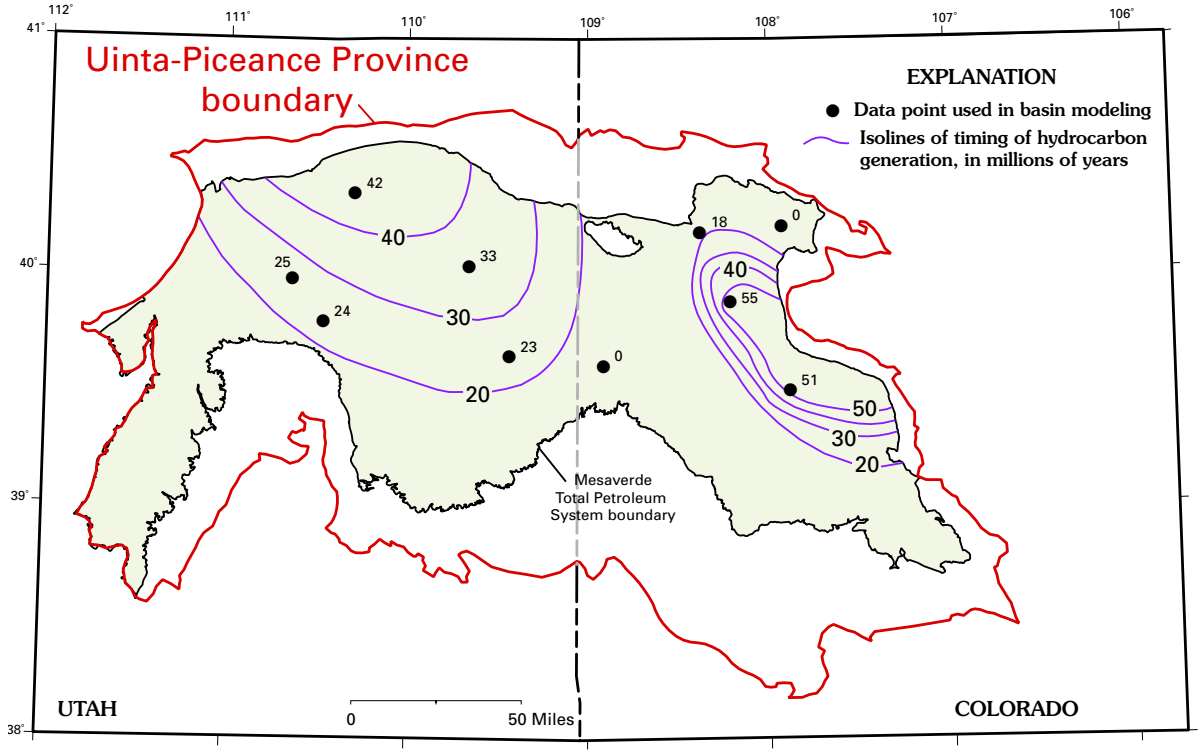


Figure 18. Time when significant oil and gas generation began for source rocks at horizon of base of Mesaverde Group/top of Mancos Shale.

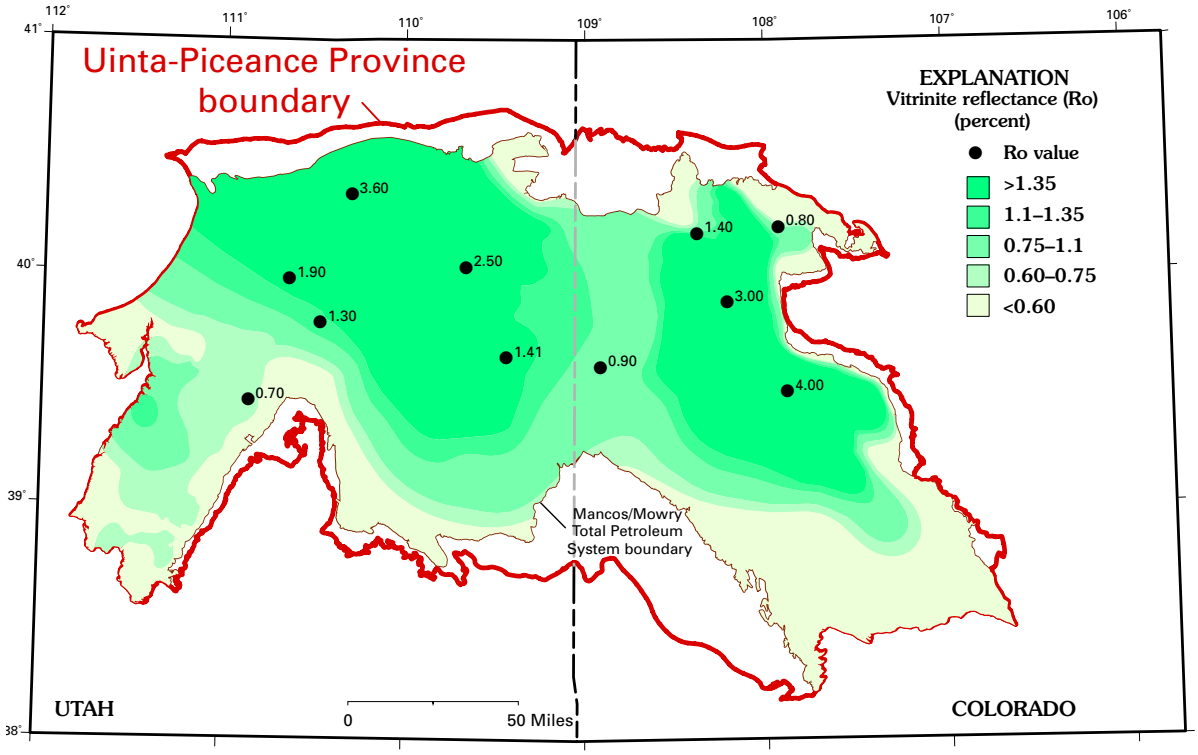


Figure 19. Vitrinite reflectance trends at horizon of base of Mancos Shale.

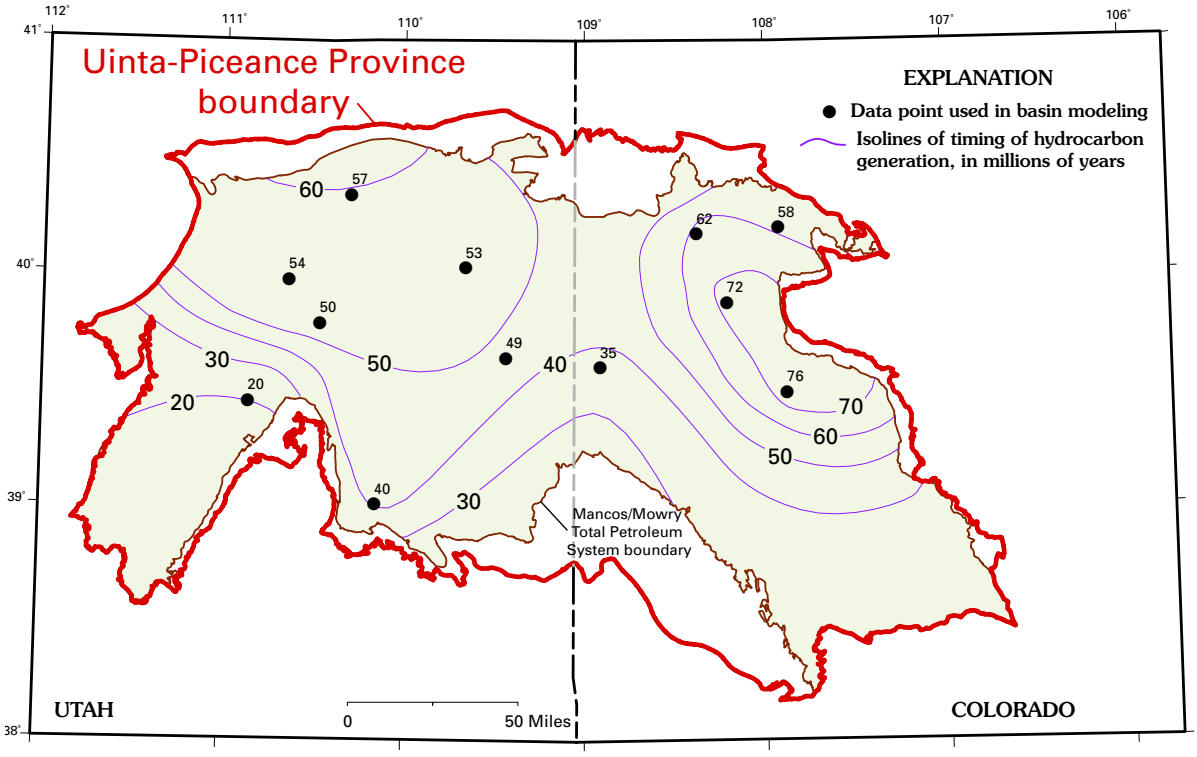


Figure 20. Time when significant oil and gas generation began for source rocks at horizon of base of Mancos Shale.

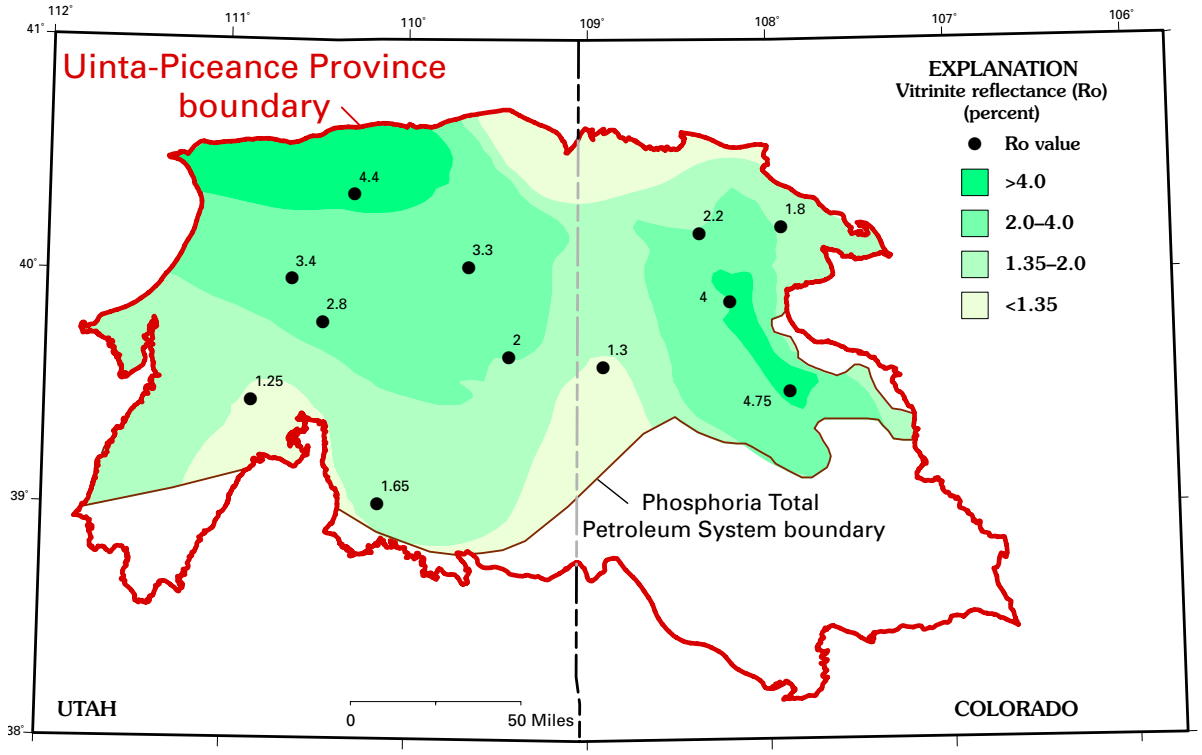


Figure 21. Vitrinite reflectance trends at horizon of base of Phosphoria Formation or other potential Pennsylvanian-Permian source rocks.

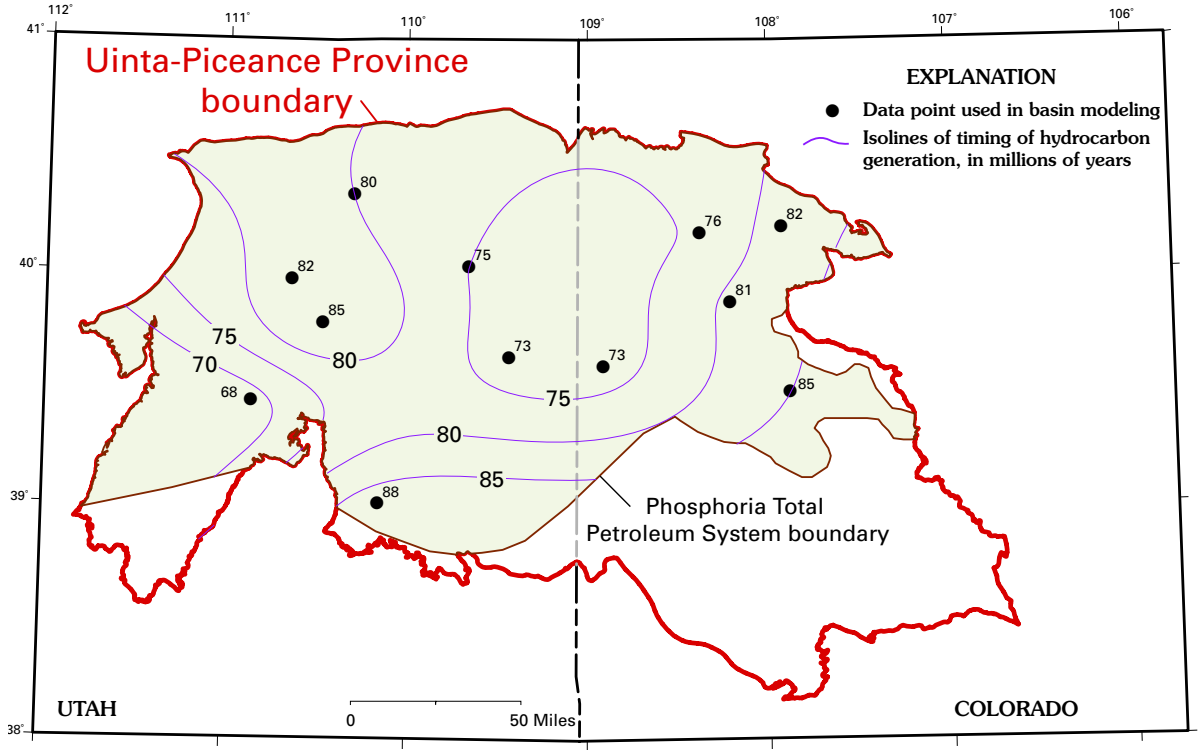


Figure 22. Time when significant oil and gas generation began for source rocks at horizon of Phosphoria Formation or other potential Pennsylvanian-Permian source rocks.

not end until either the oil and kerogen were exhausted, or uplift and erosion cooled the system, whichever occurred first (see table 3).

Base of Phosphoria Formation/Other Potential Pennsylvanian-Permian Source Rocks

Figure 21 illustrates R_o values at the base of the Phosphoria Formation or, where the Phosphoria is not present, other potential Pennsylvanian to Permian-age source rocks. R_o values for these strata range from <1.35 percent around the southern part of the study area to as high as 4.4 percent in the deep Uinta Basin (fig. 3) and 4.7 percent in the trough of the Piceance Basin (fig. 14). These high R_o values suggest that strata at this horizon are mature to overmature for oil generation and preservation over most of the study area. The R_o values also indicate that thermogenic gas generation from Type II kerogen as well as from the cracking of oil to gas (R_o>1.35 percent) occurred throughout much of the study area. Any Phosphoria oil that migrated into, was trapped, and was subsequently deeply buried in the study area would likely have been cracked to gas, except in structurally positive areas such as Rangely field and the Douglas Creek arch.

The onset of oil and gas generation at the base of the Phosphoria Formation or for other potential Pennsylvanian-Permian source rocks ranges from about 85 Ma to 70 Ma over much of the study area (fig. 22; table 3). Peak oil generation falls within the fairly narrow range of 82–61 Ma. Peak gas generation occurred at a later time, ranging from 82 Ma in the southwestern part of the study area to 18 Ma on the Douglas Creek arch. Because of the extremely high thermal maturities in the deep Uinta and Piceance Basins, oil generation ended as early as 73 Ma and 77 Ma, respectively. Gas generation from the cracking of oil and (or) from kerogen continued, and did not end until the oil and kerogen were exhausted (table 3). Some gas generation may still be occurring on structurally high areas such as the Douglas Creek arch.

Summary

Burial reconstructions, thermal maturity data, and hydrocarbon generation modeling have been used to characterize four petroleum system source rocks in the Uinta-Piceance Province. These data are necessary in order to define total petroleum systems and their associated assessment units, and in assessing the oil and gas resources of a basin. Results show that depth of burial, levels of thermal maturity, and the timing of oil and gas generation vary greatly depending on location in the province. The following summarizes our findings.

1. For the lower part of the Green River Formation, maximum depth of burial and maximum temperatures range from 4,000 ft and 150°F on the Douglas Creek arch to 22,000 ft and 350°F along the deep trough of the Uinta Basin. Vitrinite reflectance ranges from <0.60 percent on the Douglas Creek arch to 1.5 percent in the deep Uinta Basin. Hydrocarbon generation is confined to the deep trough of the Uinta Basin, where generation began about 23 Ma.

2. For the base of the Mesaverde Group/top of Mancos Shale, maximum depth of burial and associated temperatures range from 6,500 ft and 200°F on the Douglas Creek arch to 25,000 ft and 400°F in the northern part of the Uinta Basin. Vitrinite reflectance ranges from <0.60 percent on the Douglas Creek arch to 2.0 percent in the deep trough of the Uinta Basin. Hydrocarbon generation began about 55 Ma along the deep trough of the Piceance Basin, and 40 Ma along the deep trough of the Uinta Basin.

3. For the base of the Mancos Shale, maximum depth of burial and associated temperatures range from 10,000 ft and 275°F on the Douglas Creek arch to 30,000 ft and 450°F in the northern part of the Uinta Basin. Vitrinite reflectance ranges from 0.90 percent on the Douglas Creek arch to 3.6 percent in the deep Uinta Basin. Hydrocarbon generation began more than 60 Ma along the deep trough of the Uinta Basin, and more than 70 Ma along the deep trough of the Piceance Basin.

4. For the base of the Phosphoria or other potential Pennsylvanian-Permian source rocks, maximum depth of burial and associated temperatures range from 12,000 ft and 300°F on the Douglas Creek arch to 35,000 ft and 525°F in the northern part of the Uinta Basin. Vitrinite reflectance ranges from 1.3 percent on the Douglas Creek arch to >4.0 percent in the deep Uinta Basin. The onset of oil generation ranges from 85 to 70 Ma, with oil having been cracked to gas across most of the study area.

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