U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Thermal maturity data used for the assessment of gas resources in the Wind River Basin, Wyoming

by

Vito F. Nuccio, Thomas M. Finn, and Ronald C. Johnson [1]

Open-File Report 96-064

[1] USGS, Denver, CO

THERMAL MATURITY DATA USED FOR THE ASSESSMENT OF GAS RESOURCES IN THE WIND RIVER BASIN, WYOMING

by
Vito F. Nuccio, Thomas M. Finn, and Ronald C. Johnson

INTRODUCTION

The Wind River Basin, Wyoming (fig. 1), contains significant resources of natural gas in low-permeability (tight) sandstone reservoirs. From 1993 through 1995 the U.S. Geological Survey conducted a geological characterization and assessment of the tight gas resources of this basin for the Department of Energy. One of the major factors used in assessing the tight gas resources in the Wind River Basin was the thermal maturity of the source rocks. Vitrinite reflectance (R_o) was used to define levels of thermal maturity. By knowing thermal maturity, we can reconstruct the thermal history of the basin, characterize the petroleum potential of the source rocks, and assess the gas resources. The purpose of this report is to present all of the vitrinite reflectance data generated for this project represented in the form of (1) tabulated data, (2) thermal maturity maps of the basin, (3) regional cross sections, and (4) vitrinite reflectance profiles.

METHODS

Vitrinite, a maceral derived from woody plant material, is common in coal and carbonaceous shale. Vitrinite reflectance (R_o) is a measurement of the proportion of light reflected from a polished vitrinite grain. It is related to the degree of thermal maturity of the rock and can be directly converted to coal rank.

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 at which hydrocarbon begins to be generated, and it probably begins over a range of R_o values (and temperatures) depending on the specific type of organic matter. In addition, several models have been developed relating the generation of hydrocarbons to types of kerogen and thermal maturity (Tissot and others, 1974; Dow, 1977; Waples, 1980, 1985).

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 depending on the model one chooses. Dow (1977) uses 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) use 0.70 percent R_o.

Type II kerogen occurs mainly in marine rocks, but can occur in lacustrine rocks as well, and generates oil and gas during catagenesis. Waples (1985) states that oil generation begins over a range of R_o values of about 0.45 to 0.50 percent for high-sulfur kerogen to 0.60 percent for "typical" type II kerogen.

Huminite and vitrinite, or Type III kerogen, is oxygen-rich and hydrogen-poor, occurs mainly in terrestrial, marginal-lacustrine, or marginal-marine rocks, and generates mostly 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: these are 0.73 percent and 1.10 percent. An R_o of about 0.73 percent represents the maturity required for the onset of significant gas

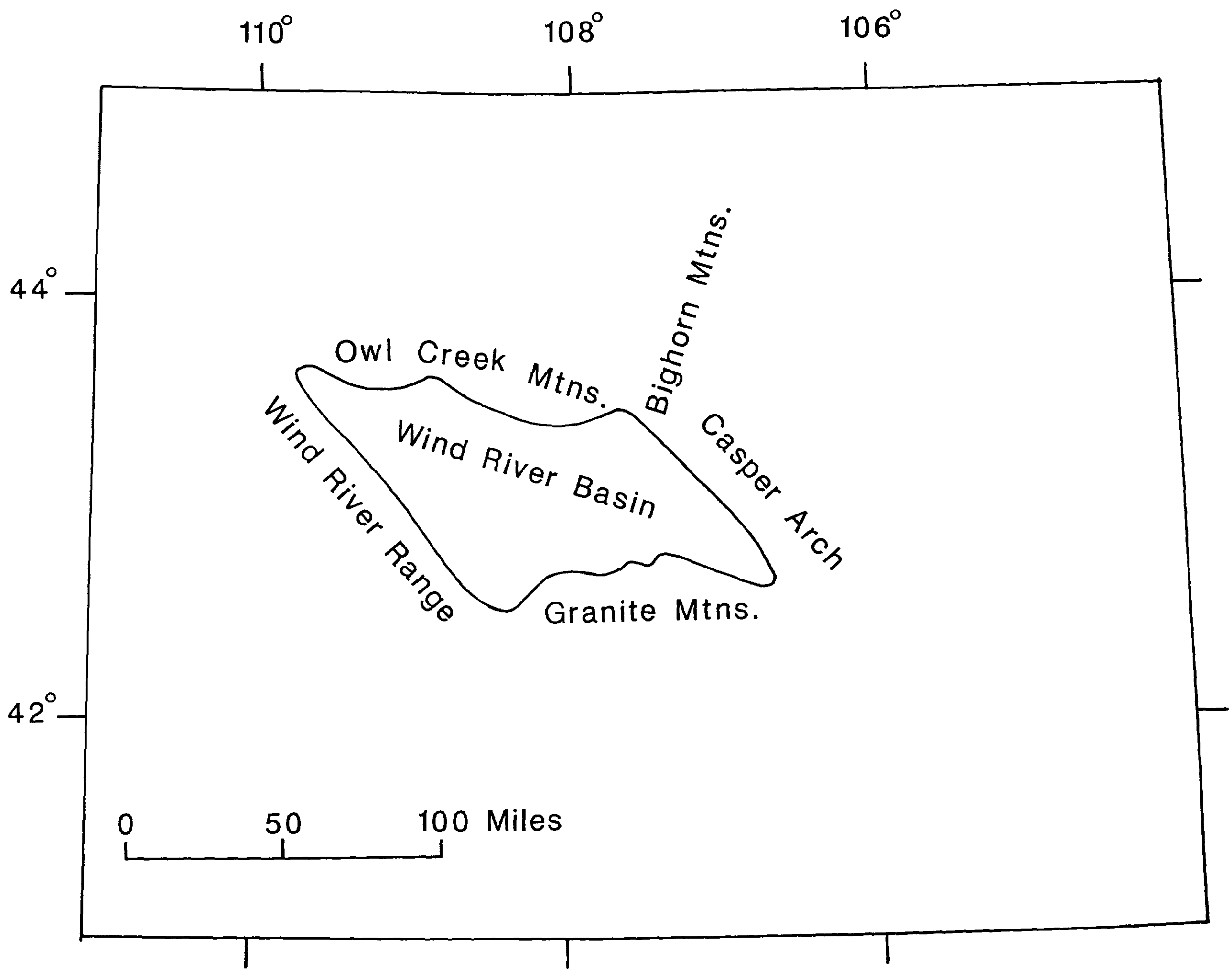


Figure 1--Index map showing general location of the Wind River Basin, Wyoming.

generation (Juntgen and Karweil, 1966; Juntgen and Klein, 1975). Gas accumulations found in rocks with an R_o less than 0.73 percent contain either early biogenic gas or gas migrated from more mature source rocks; biogenic gas can be generated at levels of maturity as low as those for peat (0.20 percent R_o). In the Piceance and Uinta basins, it appears that low-permeability Mesaverde rocks have negligible gas production where the Mesaverde has an R_o of less than 0.73 percent (Johnson, 1989; Johnson and others, 1987; Nuccio and others, 1992). 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 R_o (Dow, 1977) or 4.0 percent R_o (Waples, 1980).

Three hundred and seventy-three vitrinite reflectance samples were utilized for the Wind River Basin Tight Gas Project. The samples were prepared for R_o analysis by crushing, mounting in epoxy on a microscope slide, and polishing. The mean random R_o (from randomly oriented indigenous vitrinite grains) was determined using plane-polarized incident white light and a 546 nm monochromatic filter, in immersion oil, on a reflected light microscope with a nonrotating stage (Bostick, 1979; Bustin, 1986).

Most of the vitrinite reflectance data for this project are scattered in various publications, although some have not been previously published. Table 1 lists all of the vitrinite reflectance data for the project and is presented as samples 1 through 373. Samples 1 through 96 are from Nuccio, and others (1993); samples 97 through 296 are from Pawlewicz (1993); samples 297 through 344 are previously unpublished data of V.F. Nuccio; samples 345 through 361 are from Nuccio (1994), and Nuccio and Finn (1994); and samples 362 through 373 are from Katz and Liro (1993).

THERMAL MATURITY OF POTENTIAL SOURCE ROCKS

Mowry Shale. The organic-rich marine shales (TOC values in the 2.0 percent range) of the Upper Cretaceous Mowry Shale (fig. 2) are potential source rocks for petroleum throughout the Wind River Basin (Hagen and Surdam, 1984; Burtner and Warner, 1984, 1986; Johnson and others, in press). Although only two Mowry samples were analyzed for this study (see table 1), the thermal maturity of the Mowry can be estimated using the R_o map of the top of the Teapot Sandstone Member of the Mesaverde Group (fig. 3). The trend is likely similar to that of the Teapot, however, more mature due to increased depth of burial. Based on the Teapot maturity trend, the Mowry is mature for oil and thermogenic gas generation throughout most of the basin.

Frontier Formation. The Upper Cretaceous Frontier Formation (fig. 2) is a series of regressive marine sandstone, nonmarine sandstone, and marine shale, and some thin coal beds. Hagen and Surdam (1984) found that shales in the Frontier were rich enough (TOC values from around 0.50 to 1.60 percent) in Type II and III organic matter to be potential source rocks for both oil and gas, and it is likely that much of the hydrocarbons found in the Frontier were derived from these shales. The thermal maturity of the Frontier can also be estimated by extrapolation the R_o map of the Teapot Sandstone Member. Based on the Teapot maturity trend, the Frontier is mature for oil and thermogenic gas generation throughout most of the basin. In the shallowest parts of the basin, along outcrop, the Frontier has R_o values as low as 0.45 percent (see table 1). In these areas, the thin coal beds and carbonaceous shales could have the potential for biogenic gas generation.

Cody Shale. The thick Upper Cretaceous Cody Shale (fig. 2) consists of marine shales and sandstones, and locally, some thin coal beds. The Cody Shale is likely similar to the Mancos Shale in the Piceance basin, where shales contain significant amounts (up to

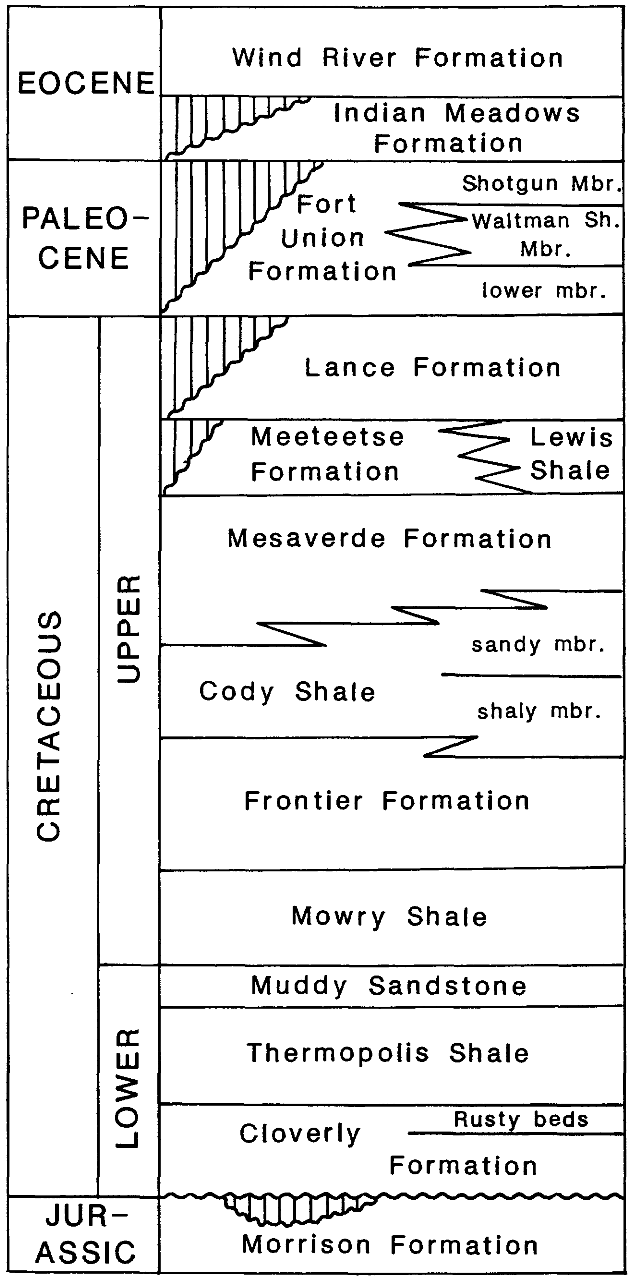


Figure 2--Generalized stratigraphic column for Cretaceous, Paleocene, and Eocene units of the Wind River Basin.

Table 1--Vitrinite reflectance data for the Wind River Basin, Wyoming. ["n" is the number of measurements for that sample; Ro is the mean of the measurements for that sample].

Sample No.	*Well name or outcrop No.*	*Location Section-Township-Range*	*Depth (in feet)*	*Ro (in percent)*	*"n"*	*Formation*
1	90-WR-CB-9	NE1/4 23-33N-99W	outcrop	0.74	7	Frontier
2	90-WR-CB-10	SE1/4 SE1/4 31-33N-98W	outcrop	0.53	30	Frontier
3	90-1A	NW1/4 20-6N-1E	outcrop	0.45	13	Meeteetse
4	90-2	NW1/4 18-6N-1E	outcrop	0.52	45	Mesaverde
5	90-3	NE1/4 NW1/4 33-6N-1W	outcrop	0.43	35	Frontier
6	90-6	NW1/4 NW1/4 1-5N-2W	outcrop	0.51	31	Frontier
7	90-7	NW1/4 SE1/4 8-5N-1W	outcrop	0.67	7	Frontier
8	90-8	NE1/4 NW1/4 32-5N-1E	outcrop	0.48	45	Frontier
9	90-9	SW1/4 SW1/4 9-5N-1E	outcrop	0.52	9	Mesaverde
10	90-10	NW1/4 NE1/4 32-5N-1E	outcrop	0.5	45	Mesaverde
11	90-11	SE1/4 NE1/4 32-5N-1E	outcrop	0.46	41	Mesaverde
12	90-12	NW1/4 SE1/4 32-5N-1E	outcrop	0.38	3	Mesaverde
13	90-13	SE1/4 SE1/4 32-5N-1E	outcrop	0.49	35	Mesaverde
14	90-20	NW1/4 NW1/4 29-6N-2E	outcrop	0.41	3	Mesaverde
15	90-28	NW1/4 20-6N-1E	outcrop	0.52	31	Meeteetse
16	90-29	NW1/4 20-6N-1E	outcrop	0.46	41	Meeteetse
17	90-WR-CB-1	SW1/4 NW1/4 8-6N-1E	outcrop	0.34	3	Meeteetse
18	90-WR-CB-2	SE1/4 NE1/4 8-6N-1E	outcrop	0.38	11	Meeteetse
19	90-WR-CB-3	SE1/4 15-6N-1E	outcrop	0.53	41	Mesaverde
20	90-WR-CB-4	NE1/4 NE1/4 3-5N-1E	outcrop	0.43	41	Fort Union
21	90-WR-CB-5	SE1/4 36-7N-1W	outcrop	0.47	15	Mesaverde
22	86-WR-7	3-33N-88W	outcrop	0.52	45	Frontier
23	86-WR-9	16-34N-88W	outcrop	0.38	13	Cody Shale
24	86-WR-10	28-34N-89W	outcrop	0.58	35	Mesaverde
25	86-WR-11	12-34N-91W	outcrop	0.89	45	Mesaverde
26	86-WR-13	26-34N-95W	outcrop	0.56	2	Cody Shale
27	86-WR-14	4-33N-94W	outcrop	0.44	51	Cody Shale
28	86-WR-15	14-33N-94W	outcrop	0.78	41	Cody Shale
29	86-WR-25	5-31N-98W	outcrop	0.58	51	Frontier
30	32-3	6-35N-85W	outcrop	0.55	47	Lance
31	32-37A	32-33N-94W	outcrop	0.45	31	Frontier
32	32-38	33-33N-94W	outcrop	0.54	75	Frontier
33	32-39	14-33N-94W	outcrop	0.84	55	Cody Shale
34	32-44	16-33N-81W	outcrop	0.44	39	Cody Shale
35	91CB-WRIR-3	13-3N-1W	outcrop	0.47	31	Frontier
36	92-WY-11A	NE1/4 NE1/4 13-6N-1W	outcrop	0.45	25	Mesaverde
37	92-WY-11F	NE1/4 NE1/4 13-6N-1W	outcrop	0.42	25	Mesaverde
38	92-WY-11J	NE1/4 NE1/4 13-6N-1W	outcrop	0.46	15	Mesaverde
39	92-WY-11N	NE1/4 NE1/4 13-6N-1W	outcrop	0.43	35	Mesaverde
40	92-WY-11T	NE1/4 NE1/4 13-6N-1W	outcrop	0.47	25	Mesaverde

Sample No.	Well name or outcrop No.	Location Section-Township-Range	Depth (in feet)	Ro (in percent)	"n"	Formation
41	92-WY-11X	SE1/4 SE1/4 12-6N-1W	outcrop	0.43	25	Mesaverde
42	92-WY-11Y	SE1/4 SE1/4 12-6N-1W	outcrop	0.42	25	Mesaverde
43	92-WY-11Z	SE1/4 SE1/4 12-6N-1W	outcrop	0.41	15	Mesaverde
44	92-WY-12A	SE1/4 SW1/4 36-7N-1W	outcrop	0.42	25	Mesaverde
45	92-WY-12B	SE1/4 SW1/4 36-7N-1W	outcrop	0.43	35	Mesaverde
46	TV-1	NE1/4 NW1/4 16-33N-83W	outcrop	0.77	26	Mesaverde
47	TV-2	SW1/4 SW1/4 16-33N-82W	outcrop	0.39	25	Cody Shale
48	TV-4	SW1/4 SE1/4 32-33N-82W	outcrop	0.5	15	Mesaverde
49	TV-5	SW1/4 SE1/4 32-33N-82W	outcrop	0.81	41	Mesaverde
50	TV-6	SE1/4 16-32N-82W	outcrop	0.44	31	Mesaverde
51	TV-8	SE1/4 36-36N-86W	outcrop	0.42	17	Fort Union
52	TV-9	C 14-35N-85W	outcrop	0.45	40	Meeteetse
53	TV-10	C-14-35N-85W	outcrop	0.46	40	Meeteetse
54	TV-11	SW1/4 30-35N-84W	outcrop	0.46	41	Mesaverde
55	TV-12	SW1/4 30-35N-84W	outcrop	0.4	15	Mesaverde
56	TV-13	NE1/4 5-34N-84W	outcrop	0.4	40	Lance
57	TV-14	NE1/4 5-34N-84W	outcrop	0.39	40	Lance
58	TV-15	SE1/4 25-37N-87W	outcrop	0.48	41	Lance
59	TV-16	SE1/4 25-37N-87W	outcrop	0.47	40	Lance
60	TV-17	NW1/4 30-37N-86W	outcrop	0.39	22	Meeteetse
61	TV-18	SW1/4 30-37N-86W	outcrop	0.48	40	Meeteetse
62	TV-23	NW1/4 10-34N-88W	outcrop	0.41	41	Meeteetse
63	TV-24	NW1/4 10-34N-88W	outcrop	0.39	34	Meeteetse
64	TV-25	NW1/4 10-34N-88W	outcrop	0.43	40	Meeteetse
65	TV-27	SE1/4 35-35N-91W	outcrop	0.4	30	Fort Union
66	TV-28	SW1/4 4-34N-90W	outcrop	0.36	36	Fort Union
67	TV-92-1	C 13-37N-87W	outcrop	0.42	30	Meeteetse
68	TV-92-2	C 13-37N-87W	outcrop	0.36	32	Mesaverde
69	TV-92-5	C 13-37N-87W	outcrop	0.42	30	Cody Shale
70	TV-92-10	SW1/4 32-36N-85W	outcrop	0.45	35	Mesaverde
71	TV-92-11	SW1/4 32-36N-85W	outcrop	0.52	30	Mesaverde
72	TV-92-13	SW1/4 32-36N-85W	outcrop	0.35	2	Meeteetse
73	TV-92-14	SW1/4 32-36N-85W	outcrop	0.43	30	Meeteetse
74	TV-92-15	SW1/4 32-36N-85W	outcrop	0.4	30	Meeteetse
75	TV-92-16	SW1/4 32-36N-85W	outcrop	0.45	30	Meeteetse
76	TV-92-17	SE1/4 31-36N-85W	outcrop	0.47	32	Lance
77	TV-92-18	SE1/4 31-36N-85W	outcrop	0.46	30	Lance
78	TV-92-44	S1/2 15-32N-85W	outcrop	0.49	17	Mesaverde
79	TV-92-45	NW1/4 35-33N-86W	outcrop	0.4	35	Meeteetse
80	TV-92-46	NW1/4 35-33N-86W	outcrop	0.43	2	Meeteetse
81	TV-92-65	NW1/4 4-33N-87W	outcrop	0.48	31	Meeteetse
82	TV-92-66	NE1/4 13-33N-87W	outcrop	0.46	30	Meeteetse
83	TV-92-70	NE1/4 23-33N-99W	outcrop	0.61	12	Frontier

Sample No.	*Well name or outcrop No.*	*Location Section-Township-Range*	*Depth (in feet)*	*Ro (in percent)*	*"n"*	*Formation*
84	TV-92-71	NE1/4 23-33N-99W	outcrop	0.57	25	Frontier
85	TV-92-91	SE1/4 14-33N-94W	outcrop	0.57	8	Frontier
86	TV-92-95	NW1/4 6-33N-92W	outcrop	0.39	31	Fort Union
87	TV-92-96	E1/2 19-34N-92W	outcrop	0.54	32	Fort Union
88	TV-92-97	SW1/4 17-34N-92W	outcrop	0.4	30	Fort Union
89	TV-92-98	S1/2 22-34N-92W	outcrop	0.29	30	Fort Union
90	TV-92-100	NE1/4 11-34N-91W	outcrop	0.45	23	Mesaverde
91	TV-92-101	NE1/4 12-34N-91W	outcrop	0.51	31	Mesaverde
92	TV-92-111	SW1/4 22-33N-95W	outcrop	0.55	4	Fort Union
93	92-WY-13	NW1/4 NW1/4 33-34N-98W	outcrop	0.42	30	Mesaverde
94	92-WY-14	C NE1/4 10-33N-98W	outcrop	0.41	32	Mesaverde
95	92-WY-19A	NW1/4 SW1/4 13-3N-1W	outcrop	0.47	30	Mesaverde
96	USGS CBM-1	29-1S-6E	outcrop	0.33	30	Mesaverde
97	Bridger #1-20	20-2N-4E	4,985	0.58		Shotgun Mbr.
98			5,380	0.65		Shotgun Mbr.
99			6,015	0.56		Shotgun Mbr.
100			6,650	0.64		Shotgun Mbr.
101			7,005	0.72		L. Fort Union
102			7,195	0.66		L. Fort Union
103			9,665	0.77		Lance
104			10,425	0.76		Lance
105			10,880	0.77		Meeteetse
106			11,470	0.79		Meeteetse
107			12,565	1.07		Mesaverde
108			12,995	1.11		Mesaverde
109	Amoco #8-22	22-2N-2E	5,025	0.6		Fort Union
110	Shoshone-		6,025	0.67		Fort Union
111	Arapahoe Tribal		7,025	0.56		Meeteetse
112			8,025	0.58		Mesaverde
113			9,025	0.65		Mesaverde
114			10,025	1.16		Cody Shale
115			11,025	1.08		Cody Shale
116			12,025	1.42		Cody Shale
117	Amoco #1-14	14-2N-3E	6,030	0.62		Shotgun Mbr.
118	Shoshone-		7,025	0.67		L. Fort Union
119	Arapahoe Tribal		8,025	0.66		L. Fort Union
120			9,025	0.73		Lance
121			10,025	0.75		Lance
122			11,025	0.78		Meeteetse
123			12,025	0.81		Mesaverde

Sample No.	Well name or outcrop No.	Location Section-Township-Range	Depth (in feet)	Ro (in percent)	"n"	Formation
124	Amoco #1-14		13,025	0.83		Mesaverde
125	(cont.)		14,025	0.96		Cody Shale
126			15,025	1.23		Cody Shale
127			16,075	1.26		Cody Shale
128	Shell 33X-10	10-3N-2E	5,560	0.6		L. Fort Union
129			7,100	0.6		Lance
130			8,060	0.64		Meeteetse
131			8,435	0.64		Meeteetse
132			9,435	0.62		Mesaverde
133			10,170	0.66		Mesaverde
134			10,555	0.74		Mesaverde
135			10,760	0.66		Mesaverde
136	Exxon Tribal	15-3N-3E	11,225	0.63		Meeteetse
137	15-1 Ocean Lake		11,507	0.86		Meeteetse
138			11,925	0.9		Meeteetse
139			13,215	1.15		Mesaverde
140			13,305	1.17		Mesaverde
141			13,410	1.14		Mesaverde
142			13,660	1.28		Mesaverde
143			13,835	1.26		Mesaverde
144	Michigan-	24-4N-4E	6,755	0.8		L. Eocene
145	Wisconsin		6,905	0.66		L. Eocene
146	Pipeline #1-24		7,880	0.87		Shotgun Mbr.
147	Tribal		8,820	0.96		Shotgun Mbr.
148			9,835	1.19		Shotgun Mbr.
149			10,275	1.22		Shotgun Mbr.
150			11,670	1.62		L. Fort Union
151			12,960	1.77		Lance
152			14,420	2.08		Lance
153			14,950	2.06		Lance
154			17,275	2.62		Mesaverde
155			17,960	2.89		Mesaverde
156	Dome #6-1	6-4N-5E	8,375	0.77		Shotgun Mbr.
157	Shoshone-		8,405	0.71		Shotgun Mbr.
158	Arapahoe		8,825	0.79		Shotgun Mbr.
159			8,855	0.78		Shotgun Mbr.
160			9,990	0.97		Shotgun Mbr.
161			10,135	1.05		Shotgun Mbr.

Sample No.	Well name or outcrop No.	Location Section-Township-Range	Depth (in feet)	Ro (in percent)	"n"	Formation
162	Dome #6-1		10,325	1.09		Shotgun Mbr.
163	(cont.)		10,725	1.18		Shotgun Mbr.
164			11,505	1.25		L. Fort Union
165			12,005	1.44		L. Fort Union
166			12,105	1.4		L. Fort Union
167			14,490	1.76		Lance
168			15,185	1.88		Lance
169			15,255	2		Lance
170			15,475	1.91		Lance
171	Emanuel #1	7-5N-2E	3,250	0.63		Lance
172	Tribal A		3,355	0.56		Lance
173			4,665	0.64		Meeteetse
174			5,460	0.59		Meeteetse
175			5,645	0.67		Meeteetse
176	Coastal #1	26-5N-3E	5,220	0.46		L. Eocene
177	Owl Creek		5,500	0.58		L. Eocene
178			6,350	0.6		L. Eocene
179			7,000	0.62		L. Eocene
180			8,000	0.62		Shotgun Mbr.
181			8,045	0.67		Shotgun Mbr.
182			8,680	0.67		Shotgun Mbr.
183			9,000	0.64		Shotgun Mbr.
184			9,230	0.68		Shotgun Mbr.
185			10,000	0.67		Shotgun Mbr.
186			11,000	0.83		L. Fort Union
187			15,000	1.3		Lance
188			15,500	1.36		Meeteetse
189			16,460	1.8		Meeteetse
190			17,815	1.98		Mesaverde
191			18,000	2		Mesaverde
192			18,395	2.08		Mesaverde
193			21,000	2.31		Cody Shale
194			22,000	2.12		Cody Shale
195			23,000	2.42		Frontier
196	Sun #1	15-33N-86W	5,060	0.43		Cody Shale
197	Ranch Federal		5,690	0.43		Cody Shale
198			6,140	0.43		Cody Shale
199			6,470	0.44		Cody Shale
200			6,860	0.44		Cody Shale
201			7,190	0.5		Cody Shale

Sample No.	Well name or outcrop No.	Location Section-Township-Range	Depth (in feet)	Ro (in percent)	"n"	Formation
202	Sun #1		7,400	0.54		Cody Shale
203	(cont.)		7,640	0.5		Cody Shale
204			7,910	0.56		Cody Shale
205			8,279	0.65		Cody Shale
206			8,600	0.75		Cody Shale
207			8,915	0.9		Cody Shale
208			9,220	0.75		Frontier
209			9,330	0.96		Frontier
210			9,530	0.95		Frontier
211			10,030	0.74		Mowry Shale
212			10,220	0.94		Mowry Shale
213			10,320	1.03		Muddy Sandstone
214			10,370	1.07		Muddy Sandstone
215			10,425	1.15		Muddy Sandstone
216	Pan American	20-35N-86W	2,415	0.53		L. Fort Union
217	#1 USA		2,625	0.61		L. Fort Union
218	Birdsong		3,960	0.47		Lance
219			4,370	0.55		Lance
220			7,345	0.48		Meeteetse/Lewis
221			7,525	0.6		Mesaverde
222			7,805	0.61		Mesaverde
223			8,165	0.65		Fales/Wallace Cr.
224	Pan American	18-37N-88W	4,135	0.53		Waltman Shale
225	#1 Hoagland		4,315	0.48		Waltman Shale
226			4,645	0.55		Waltman Shale
227			10,325	1.04		Lance
228			10,595	1.09		Lance
229			10,785	0.93		Lance
230			10,825	1.19		Lance
231	Mobil	14-37N-94W	7,325	0.76		L. Fort Union
232	#F-33-14G		7,475	0.71		L. Fort Union
233			7,685	0.82		L. Fort Union
234			8,170	0.81		L. Fort Union
235			9,010	0.84		L. Fort Union
236			9,765	0.88		Lance
237			11,085	1.16		Lance
238			11,285	1.21		Lance
239			12,020	1.29		Meeteetse
240			12,120	1.24		Meeteetse
241			12,520	1.11		Meeteetse

Sample No.	*Well name or outcrop No.*	*Location Section-Township-Range*	*Depth (in feet)*	*Ro (in percent)*	*"n"*	*Formation*
242	Monsanto	6-38N-89W	5,845	0.76		L. Fort Union
243	#1-6 Cevin		6,095	0.8		L. Fort Union
244			6,415	0.77		L. Fort Union
245			6,745	0.82		L. Fort Union
246			7,105	0.86		L. Fort Union
247	Monsanto	5-38N-90W	7,875	0.97		L. Fort Union
248	#1-5 Bighorn		8,115	0.99		L. Fort Union
249			8,305	1.05		L. Fort Union
250			8,603	1.07		Lance
251			8,985	1.28		Lance
252			9,200	1.3		Lance
253			9,680	1.34		Lance
254			9,810	1.38		Lance
255			10,030	1.41		Lance
256			10,790	1.58		Lance
257			10,940	1.54		Lance
258			11,300	1.59		Lance
259			11,690	1.76		Lance
260			11,940	1.82		Lance
261			12,220	1.81		Lance
262			12,310	1.73		Lance
263			12,610	1.64		Lance
264			12,860	1.77		Lance
265			13,380	2.03		Meeteetse
266			13,470	1.76		Meeteetse
267			13,610	2.02		Meeteetse
268			13,830	2.11		Meeteetse
269			14,240	2.04		Meeteetse
270			14,720	2.02		Meeteetse
271			14,960	2.07		Mesaverde
272			15,200	2.35		Mesaverde
273			15,440	2.09		Mesaverde
274			15,680	2.27		Mesaverde
275			15,890	2.07		Mesaverde
276			16,130	2.08		Cody Shale
277			16,370	2.6		Cody Shale
278			16,610	2.3		Cody Shale
279			18,310	2.53		Cody Shale
280			18,550	2.51		Cody Shale
281			18,910	2.68		Cody Shale
282			19,150	2.64		Cody Shale
283			19,180	2.89		Cody Shale

Sample No.	*Well name or outcrop No.*	*Location Section-Township-Range*	*Depth (in feet)*	*Ro (in percent)*	*"n"*	*Formation*
284	Monsanto		19,540	2.71		Cody Shale
285	#1-5 Bighorn		19,900	3.32		Cody Shale
286	(cont.)		20,200	2.87		Frontier/Cloverly
287			20,320	3.33		Frontier/Cloverly
288			20,470	2.9		Frontier/Cloverly
289			20,800	3.32		Frontier/Cloverly
290			21,040	3.32		Frontier/Cloverly
291			21,400	3.56		Frontier/Cloverly
292			23,110	3.92		pre-Cretaceous
293			24,610	4.14		pre-Cretaceous
294	Union #F-14	14-35N-86W	12,530	0.67		Mesaverde
295	Key Spring		12,540	0.68		Mesaverde
296			12,558	1.93		Mesaverde
297	Coastal Bullfrog	8-36N-86W	5,425	0.56	40	L. Fort Union
298	3-8-36-86		6,470	0.63	40	L. Fort Union
299			9,730	0.71	50	Lance
300			10,275	0.69	40	Lance
301			10,415	0.78	40	Lance
302			10,860	0.75	41	Meeteetse
303			11,115	0.82	40	Meeteetse
304			11,795	0.78	40	Mesaverde
305			12,280	0.73	36	Mesaverde
306	Monsanto	16-39N-90W	7,105	0.71	41	L. Fort Union
307	1-16 State		10,510	0.99	40	Lance
308			12,115	1.25	40	Lance
309			12,350	1.27	41	Lance
310			16,610	2.08	40	Meeteetse
311			17,260	2.3	40	Meeteetse
312			18,510	2.72	40	Mesaverde
313	Monsanto 1-29	29-38N-88W	7,655	0.83	40	L. Fort Union
314	MDU Freedom		8,700	0.9	40	L. Fort Union
315			12,960	1.67	40	Lance
316			13,655	1.91	40	Lance
317			17,275	2.62	40	Lance
318			17,775	2.82	40	Lance
319			18,185	2.83	40	Meeteetse
320			18,825	3.07	41	Meeteetse
321			19,815	3.26	41	Mesaverde
322			20,320	3.32	40	Mesaverde

Sample No.	*Well name or outcrop No.*	*Location Section-Township-Range*	*Depth (in feet)*	*Ro (in percent)*	*"n"*	*Formation*
323	Adams 1-17	17-37N-90W	7,325	0.92	40	L. Fort Union
324	OAB		8,645	1.11	40	L. Fort Union
325			9,215	1.11	40	L. Fort Union
326			10,130	1.36	40	Lance
327			10,825	1.49	40	Lance
328			15,160	2.44	40	Meeteetse
329			16,260	2.77	40	Mesaverde
330	Dome 1-29	29-37N-91W	6,275	0.86	30	Waltman Shale
331	Moneta		7,405	0.85	40	L. Fort Union
332			8,150	0.92	40	L. Fort Union
333			9,335	1.2	40	Lance
334			12,290	1.7	40	Lance
335			13,350	1.88	46	Meeteetse
336			14,460	2.13	40	Mesaverde
337	Inexco 1-15	15-36N-91W	5,420	0.71	41	L. Fort Union
338	Hanagan		5,550	0.76	40	L. Fort Union
339			6,030	0.8	40	L. Fort Union
340			7,340	0.85	40	L. Fort Union
341			8,200	0.87	41	Lance
342			9,730	0.94	36	Lance
343			10,480	1.13	40	Meeteetse
344			11,680	1.29	40	Mesaverde
345	Larry Barnes Pet.	15-37N-94W	3,270	0.61	30	L. Eocene
346	Carvner Federal		4,525	0.67	32	L. Eocene
347	#22-15		4,665	0.67	30	Shotgun Mbr.
348			4,865	0.64	30	Shotgun Mbr.
349			5,025	0.66	30	Shotgun Mbr.
350			5,330	0.68	30	Shotgun Mbr.
351			5,535	0.62	30	Shotgun Mbr.
352			5,705	0.63	30	Shotgun Mbr.
353			6,065	0.71	30	Shotgun Mbr.
354			7,550	0.67	30	Waltman Shale
355			7,745	0.75	30	L. Fort Union
356			7,905	0.9	30	L. Fort Union
357			8,125	0.9	30	L. Fort Union
358			8,225	0.8	30	L. Fort Union
359			8,585	0.89	30	L. Fort Union
360			8,725	0.89	30	L. Fort Union
361			9,055	0.9	30	Lance

Sample No.	*Well name or outcrop No.*	*Location Section-Township-Range*	*Depth (in feet)*	*Ro (in percent)*	*"n"*	*Formation*
362	Diamond	21-38N-93W	7,250	0.55		Wastman Shale
363	Shamrock 1 Shoshoni		9,250	0.73		Waltman Shale
364	Oil Development	20-37N-90W	4,500	0.63		Waltman Shale
365	of Texas		5,100	0.63		Waltman Shale
366	Brown Fed. 1		5,400	0.7		Waltman Shale
367			6,100	0.75		Waltman Shale
368			6,750	0.7		Waltman Shale
369	Chorney (Helis)	27-39N-93W	5,750	0.53		Waltman Shale
370	2 Bonneville		6,250	0.47		Waltman Shale
371	Unit		7,250	0.52		Waltman Shale
372			7,800	0.65		Waltman Shale
373			8,250	0.73		Waltman Shale

3.36 percent TOC) of types II and III kerogen, and have generated oil and gas (Johnson and Rice, 1990). The thermal maturity of the Cody Shale ranges from 0.30-0.40 percent R_o along outcrop (Nuccio and others, 1993) to 2.0-3.0 percent R_o in the deep, northwestern part of the basin (see table 1). The overall maturity pattern of the Cody Shale should be similar to that of the Teapot Sandstone Member of the Mesaverde Group (fig. 3), although actual maturity levels are greater due to increased depth of burial. The richness and kerogen types in the Cody Shale combined with the large range in thermal maturity make it a potential source rock for oil, biogenic gas (near the periphery of the basin), and thermogenic gas.

Mesaverde Group. The Upper Cretaceous nonmarine to nearshore-marine Mesaverde Group (fig. 2) in the Wind River Basin comprises a sequence of sandstone, siltstone, shale, carbonaceous shale, and coal. The shales and siltstones are gray to brown and are commonly carbonaceous containing type III kerogen. The coal beds, also containing type III kerogen, have been mined in several locations in the basin, and are a potential source for both biogenic and thermogenic methane gas throughout the basin. The thermal maturity of the Mesaverde ranges from the 0.30-0.60 percent Ro along outcrop to nearly 3.0 percent in the northern part of the basin. Figure 3 illustrates the thermal maturity trends of the Teapot Sandstone Member of the Mesaverde Group, which represents the top of the Mesaverde.

Meeteetse Formation/Lewis Shale. The Upper Cretaceous Meeteetse Formation (fig. 2) consists of interbedded sandstone, siltstone, shale, carbonaceous shale, and coal. It is largely equivalent to, and intertongues with, the Lewis Shale in the eastern and northern parts of the Wind River Basin. Coal beds of minable thickness are present locally in the Meeteetse Formation throughout the basin. The thermal maturity of most Meeteetse/Lewis samples along outcrop is between 0.30-0.50 percent R_o (see table 1). Vitrinite reflectance values in the 2.0-3.0 percent range are found in the northern, deepest part of the basin. Figure 3, the thermal maturity map of the Teapot Sandstone Member of the Mesaverde Group, can be considered representative of thermal maturity trends for the Meeteetse Formation and Lewis Shale. Based on their R_o values, coals in the shallower parts of the basin could contain biogenic gas, whereas those in the deeper parts have the potential to generate thermogenic gas.

Lance Formation. The Upper Cretaceous Lance Formation (fig. 2) comprises a series of interbedded white, gray, and buff, fine- to coarse-grained, in part conglomeratic sandstone; gray to black shale and claystone; and minor brown to black carbonaceous shale and coal (Keefer, 1965). The thickness of the Lance ranges from zero feet in the southern and western margins of the basin, to more than 5,000 ft in the northern and eastern parts. R_o of carbonaceous shale and coal samples average 0.46 percent along outcrop (table 1; Nuccio and others, 1993); however in the northern, deepest part of the basin R_o for the Lance are as high as 2.82 percent (table 1). The overall maturity pattern of the Lance Formation should again be similar to that of the Teapot Sandstone Member of the Mesaverde Group (fig. 3), although actual maturity levels are lower due to less overall depth of burial. The carbonaceous shales and coal beds of the Lance Formation have the potential to generate primarily biogenic methane gas near the margins of the basin, and thermogenic gas throughout the deeper, more thermally mature areas of the basin.

Fort Union Formation. The Fort Union Formation is generally divided into three members; the lower unnamed member, the Waltman Shale Member, and the Shotgun Member (fig. 2). The Waltman Shale Member grades laterally into the Shotgun Member in the western and southern parts of the Wind River Basin, and, where the Waltman Shale Member is absent, the contact between the lower unnamed member and Shotgun Member is difficult to define and the formation is often undifferentiated. The lower unnamed member of the Fort Union consists of white to gray, fine- to coarse-grained, massive to crossbedded sandstone interbedded with dark-gray to black shale, claystone, siltstone, brown carbonaceous shale, and thin to thick coal beds. The Waltman Shale Member is characterized by chocolate-brown and gray, silty and shaley claystone with a few thin sandstone beds (Keefer, 1965). The Waltman Shale Member contains appreciable amounts of organic matter (TOC values as high as 6.21 percent; Katz and Liro, 1993), including thin, black, shiny coal laminae near the top and bottom. Organic content analyses and retorting procedures in the early 1960's (Keefer, 1965; p. A28) and recent studies by Katz and Liro (1993), Palacas and others (1993; 1994), Nuccio and Finn (1994), and unpublished organic geochemistry data by J.G. Palacas (U.S. Geological Survey, personal commun., 1994), indicate that the Waltman Shale Member is a good potential source rock for both oil and gas in the Wind River Basin. The Shotgun Member is a series of even-bedded soft claystone, siltstone, shale, and sandstone. Some thin, brown carbonaceous shales and thin coal beds crop out as dark bands on the light-colored slopes.

Figure 4 is an R_o map of the base of the Waltman Shale Member of the Fort Union Formation. The level of thermal maturity of the Fort Union Formation ranges from very immature (0.29 percent R_o) in outcrops in the southern part of the basin, to mature (>1.10 percent R_o) in the northern deep part of the basin. The Fort Union Formation in the deeper parts of the basin has reached the proper level of thermal maturity (>0.60 percent R_o) for both oil and thermogenic gas generation. In the structurally shallower areas of the basin, levels of thermal maturity decrease, and, where R_o values are <0.60 percent, the Fort Union Formation is considered, for purposes of this study, to be immature for significant oil or thermogenic gas generation. However, coals in the Fort Union in these areas of low thermal maturity may have the potential for biogenic gas generation and/or production.

REGIONAL THERMAL MATURITY MAPS

R_o of Top of Teapot Sandstone Member

The R_o map of the top of the Teapot Sandstone Member of the Mesaverde Group shows a general trend of increasing maturity from south to north (fig. 3). This trend generally follows the structural configuration of the basin (see structure contour maps in Johnson and others, in press), which indicates that thermal maturation is related to basin movement and the related burial history. In some areas, however, the R_o contours cut across structure, indicating that thermal maturation continued to increase during, or for some time after (well into the Tertiary) structural movement (this will be discussed later). Toward the deepest, northern part of the basin, thermal maturation at the top of the Teapot horizon probably continued to increase during or after final uplift and erosion (10-15 Ma). On the flanks of the basin, however, maturity trends may have been achieved prior to final uplift.

Five R_o contours, and three zones of hydrocarbon generation are illustrated in Figure 3. The 0.60 R_o contour shows the lower limit for oil generation at the horizon of the Teapot Sandstone Member. In the areas with R_o values less than 0.60, one would not expect generation of oil or thermogenic gas. In these areas, however, the possibility of biogenic gas from coal beds and carbonaceous shales does exist. The areas between an R_o of greater than 0.60 up to around 1.30-1.40 are in the oil generation window; the area where thermal maturity is optimum for oil generation from types II and III kerogen. The area between 0.73 and 1.10 percent R_o is where one would expect to begin encountering thermogenic gas generation and accumulation at this horizon. The area with R_o values

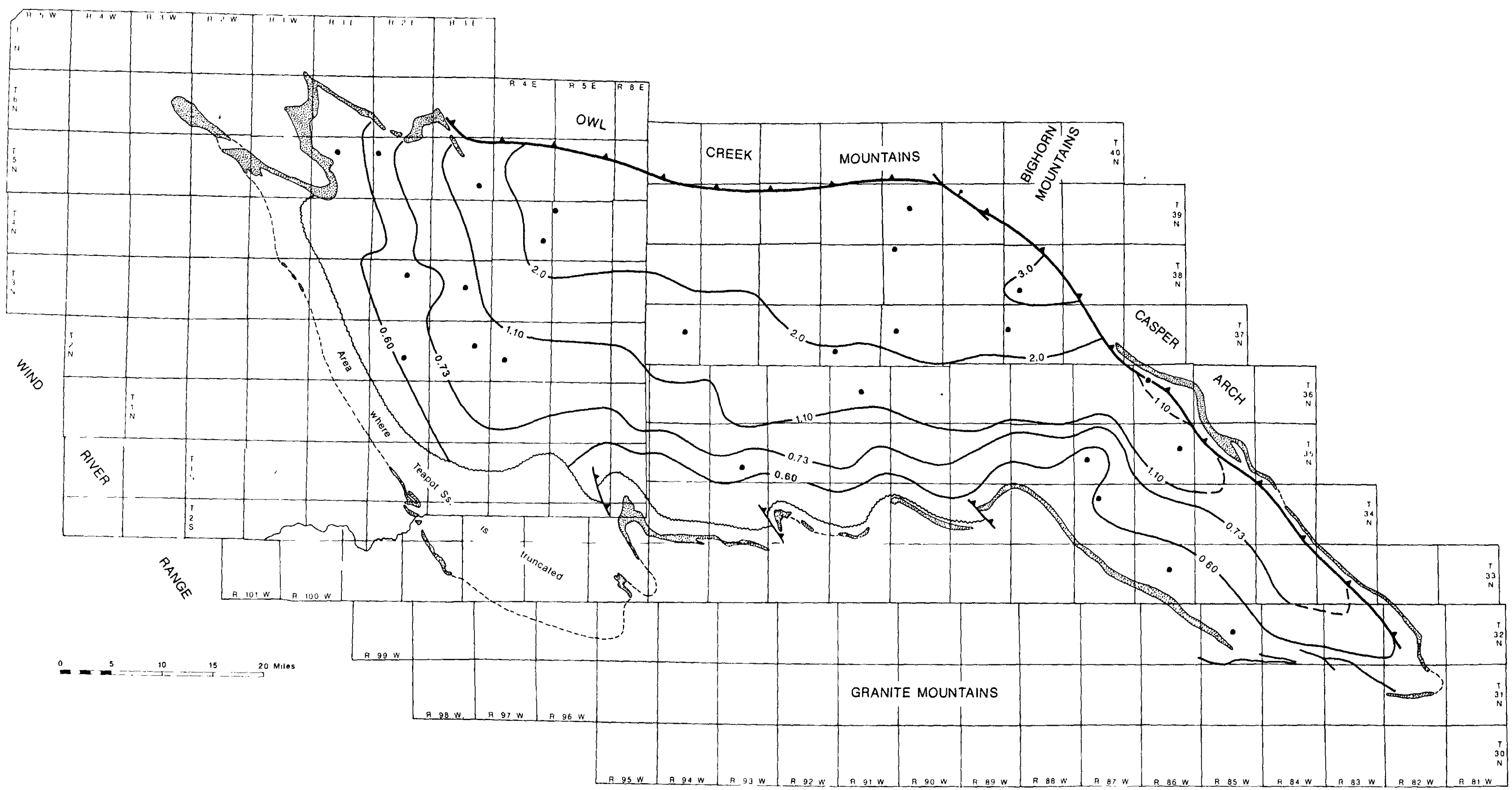


Figure 3--Isoreflectance map from vitrinite reflectance (R_o) showing thermal maturity of the top of the Cretaceous Teapot Sandstone Member of the Mesaverde Formation in the Wind River Basin, WY. Contours of note are 0.73 percent R_o (onset of significant thermogenic gas generation), and 1.10 percent R_o (area of maximum thermogenic gas generation).

greater than 1.10 percent is the zone of maximum thermogenic gas generation and expulsion. The upper limit of gas generation in the northern and deepest, largely undrilled, part of the basin is not known, however, the areas with R_o values in the 2.0 to greater than 3.0 percent R_o range have potential for thermogenic gas generation.

The Teapot Sandstone Member of the Mesaverde Group and adjacent strata have greater than 0.73 percent R_o over large areas of the Wind River Basin. Except at the margins of the basin, where subsidence and burial depths were less, gas was probably being generated as Tertiary sediments were being deposited, and continued until 10-15 Ma when uplift and erosion caused a regional cooling. This gas was likely trapped in tight sandstone reservoirs throughout the generation history of strata at this, and adjacent horizons.

R_o of Base of Waltman Shale Member

The R_o map of the base of the Waltman Shale Member of the Fort Union Formation shows a general trend of increasing maturity from south to north (fig. 4). This trend generally follows the structural configuration of the basin (see structure contour map of the base of the Waltman in Johnson and others, in press), which indicates that most of the thermal maturation preceded final structural movement. As with the Teapot Sandstone discussed earlier, in some areas (deeper parts of the basin), R_o contours cut across structure, indicating that thermal maturation continued to increase during, or for some time after (well into the Tertiary) structural movement. Toward the deepest, northern part of the basin, thermal maturation at the base of the Waltman horizon probably continued to increase during or after final uplift and erosion (10-15 Ma). On the flanks of the basin, however, present maturity trends may have been achieved prior to final uplift.

Three R_o contours, and three zones of hydrocarbon generation are illustrated in Figure 4. The 0.60 R_o contour shows the lower limit for oil generation at the horizon of the Waltman Shale Member. In the areas with R_o values less than 0.60, one would not expect generation of oil and thermogenic gas. In these areas, however, biogenic gas from coal beds and carbonaceous shales could be generated. In Figure 4, the areas between an R_o of 0.60 to 1.10 and greater are in the oil generation window, the area where thermal maturity is optimum for oil generation from types II and III kerogen. The area between 0.73 and 1.10 percent R_o is where one would expect to begin encountering thermogenic gas generation and accumulation. The area with R_o values greater than 1.10 percent is the zone of maximum thermogenic gas generation and expulsion.

The base of the Waltman Shale Member of the Fort Union Formation and adjacent strata have greater than 0.73 percent R_o over large areas of the Wind River Basin, although not as large as for the Teapot Sandstone Member of the Mesaverde Group. This is a direct result of less depth of burial (several thousands of feet), hence lower thermal maturity at the Waltman horizon, and the lesser aereal extent of Waltman source rocks. Except at the margins of the basin where subsidence and burial depths were less, gas was probably being generated as upper Tertiary sediments were being deposited and continued until 10-15 Ma when uplift and erosion caused a regional cooling. In the deepest parts of the basin, both oil and gas generation from Waltman shales likely continued after 10 -15 Ma and may still be generating today (Nuccio and Finn, 1994). This gas is likely trapped in sandstone reservoirs above the base of the Waltman. It should be noted here that gases produced from the Waltman Shale are distinct (isotopically lighter) than those gases produced from deeper, more mature sources. Johnson and others (in press) believe that mature, isotopically heavier gases, generated in the deeper Cretaceous Mesaverde Formation have migrated vertically into shallower, marginally mature to immature Cretaceous and Tertiary

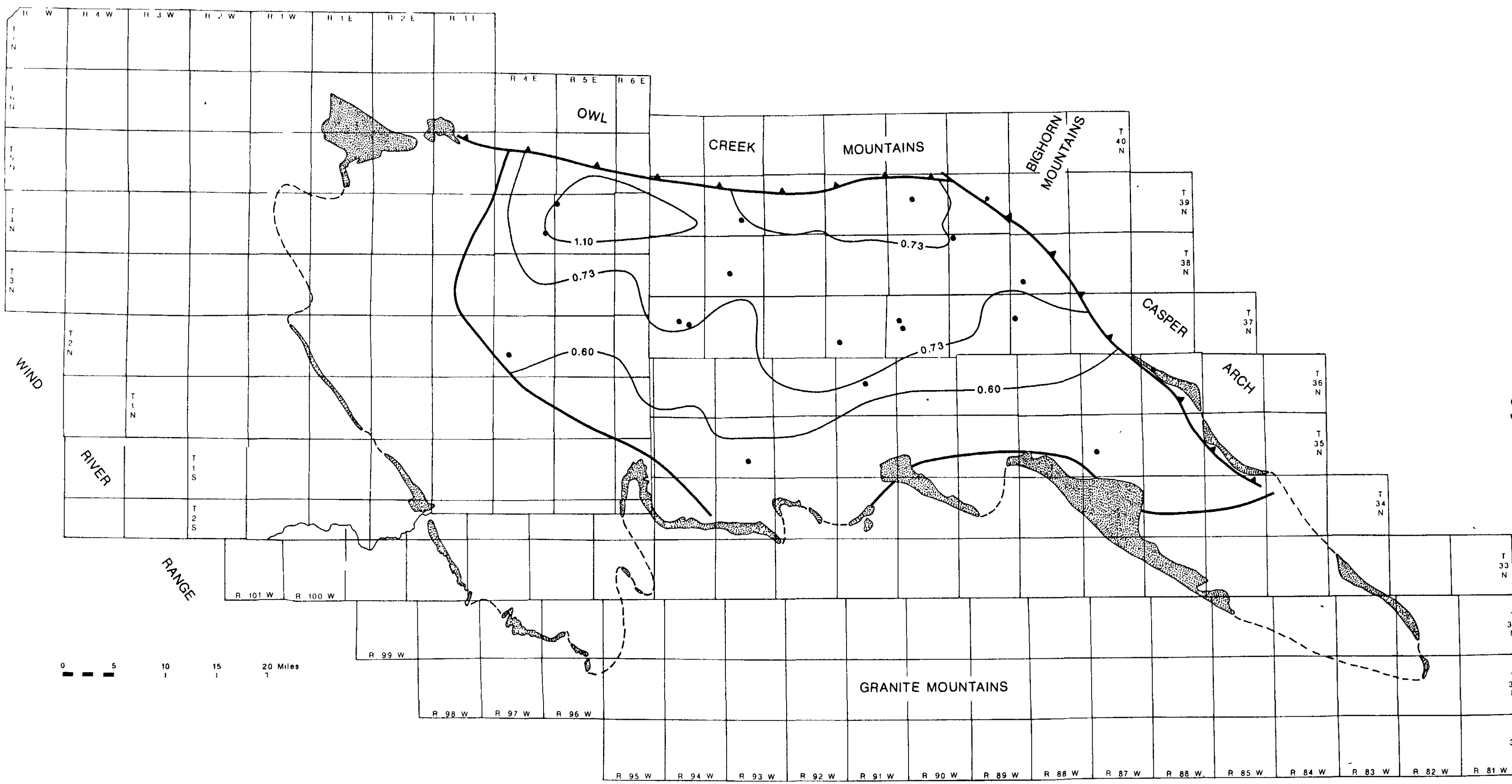


Figure 4--Isoreflectance map from vitrinite reflectance (R_o) showing thermal maturity of the base of the Paleocene Waltman Shale Member of the Fort Union Formation in the Wind River Basin, WY. Contours of note are 0.73 percent R_o (onset of significant thermogenic gas generation), and 1.10 percent R_o (area of maximum thermogenic gas generation).

reservoirs. Johnson and others (in press) further believe that the Waltman Shale Member acts as a seal, and where present, does not allow the deeper, more mature gases to migrate vertically into it.

Elevation to 1.10 percent R_o

The elevation to the 1.10 percent R_o line; the threshold for maximum gas generation is shown by Figure 5. The 1.10 percent R_o line cuts across formation boundaries, rising stratigraphically to the north and west. For example, in the southernmost part of the basin, 1.10 percent R_o occurs in the Upper Cretaceous Muddy Sandstone, at an elevation of around -3,500 ft. (table 1), whereas in the northern part of the basin 1.10 percent R_o occurs at the base of the Paleocene Waltman Shale Member of the Fort Union Formation at an elevation of approximately -5,000 ft (fig. 4; table 1). The reason for this can be related to the structural movement and variations of burial depth in the basin. After final uplift, there was more erosion near the flanks of the basin than in the structural center of the basin. In the center of the basin, where the effect of uplift and erosion was less, and sediment continued to accumulate, the rocks continued to mature causing the 1.10 percent R_o line to rise to stratigraphically higher positions.

Assuming no migration, this map is a useful exploration tool for approximating the elevation (easily converted to depth) and production formation for optimum thermogenic gas generation.

Elevation to 0.73 percent R_o

The elevation to the 0.73 percent R_o line, the threshold for significant gas generation is shown by Figure 6. Similar to the 1.10 percent R_o line, the 0.73 percent R_o line cuts across formation boundaries, rising stratigraphically to the north and west. In the southernmost part of the basin, 0.73 percent R_o occurs in the Upper Cretaceous Frontier Formation, at an elevation of about -2,000 ft. (table 1; fig. 6), whereas in the northern part of the basin 0.73 percent R_o occurs in Fort Union Formation at an elevation of about -2,000 to -3,000 ft (fig. 4, and 6; table 1). Again, this can be related to the structural movement and variations of burial depth in the basin. In the trough of the basin where uplift and erosion was less and sediment accumulation was uninterupted, the rocks continued to mature causing the 0.73 percent R_o line to rise to stratigraphically higher positions.

Figure 6 is useful in approximating the elevation (easily converted to depth) and formation to drill to encounter the onset of significant thermogenic gas generation.

REGIONAL CROSS SECTIONS

Three cross sections were constructed to generally depict the structure, stratigraphy, and thermal maturity across the Wind River Basin (see fig. 7 for locations of cross sections). The three cross sections, A-A', B-B', and C-C' (fig. 8), illustrate changes in facies, thickness, and thermal maturity of Cretaceous and Tertiary strata from outcrop areas in the southern parts of the basin, to the structurally deep parts of the basin. Wells containing vitrinite data were incorporated in the cross sections wherever possible.

The cross sections are used to approximate areas where the Cretaceous and Tertiary formations grade from immature ($<$0.73 percent R_o) to mature ($>$0.73 percent R_o) for thermogenic gas resources. For all three cross sections, Cretaceous and Tertiary strata become more thermally mature, and R_o lines rise stratigraphically from south to north, approaching the structurally deep part of the basin. As mentioned previously, this is related to structural movement and variations of burial depth in the basin. Vitrinite reflectance

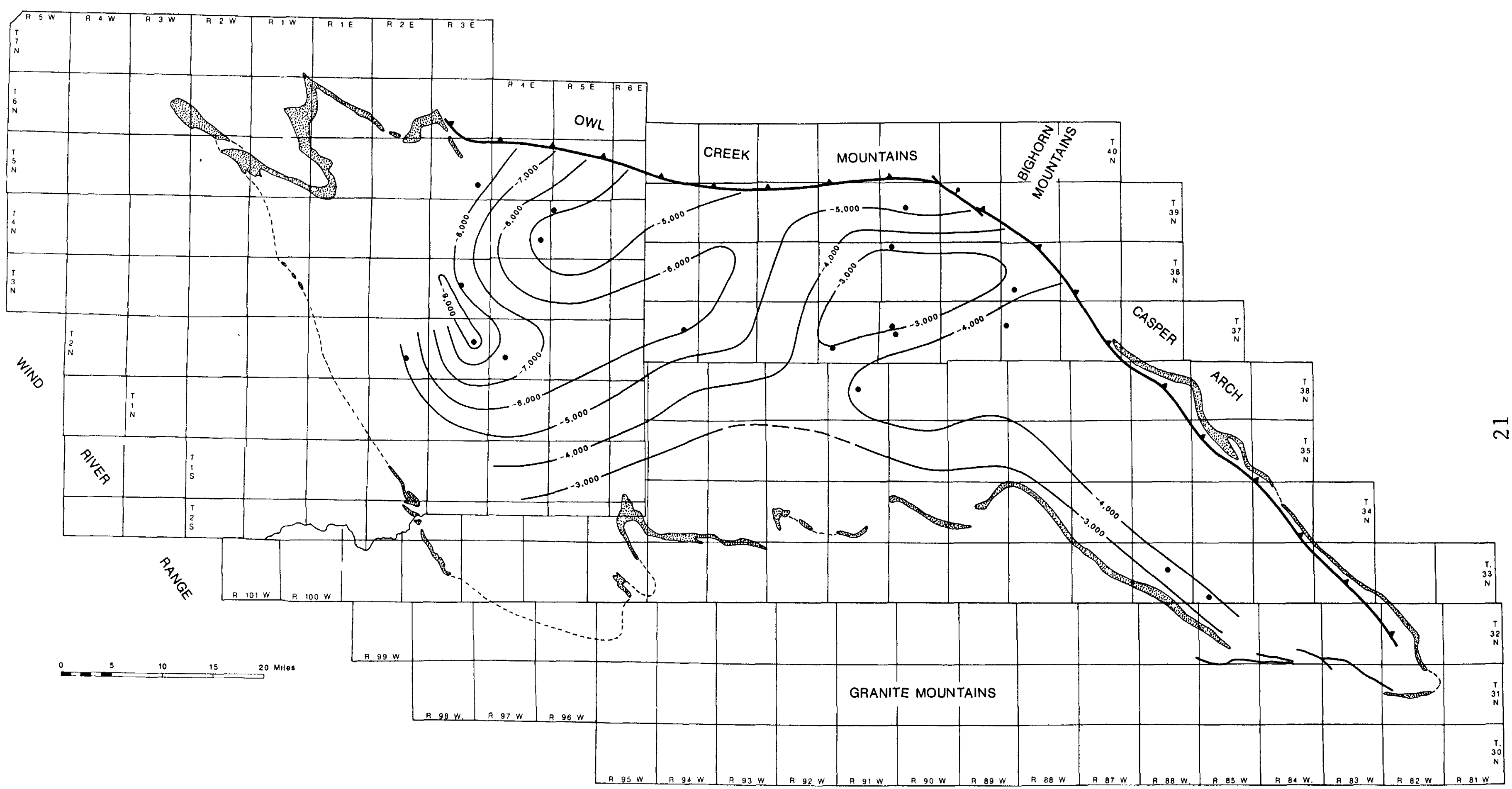


Figure 5--Map showing elevation to 1.10 percent R_o line (maximum thermogenic gas generation) in the Wind River Basin, WY. The 1.10 percent R_o line cuts across formation boundaries, rising stratigraphically to the north and west. This map is useful in approximating the elevation one would have to drill to encounter the threshold for maximum thermogenic gas generation.

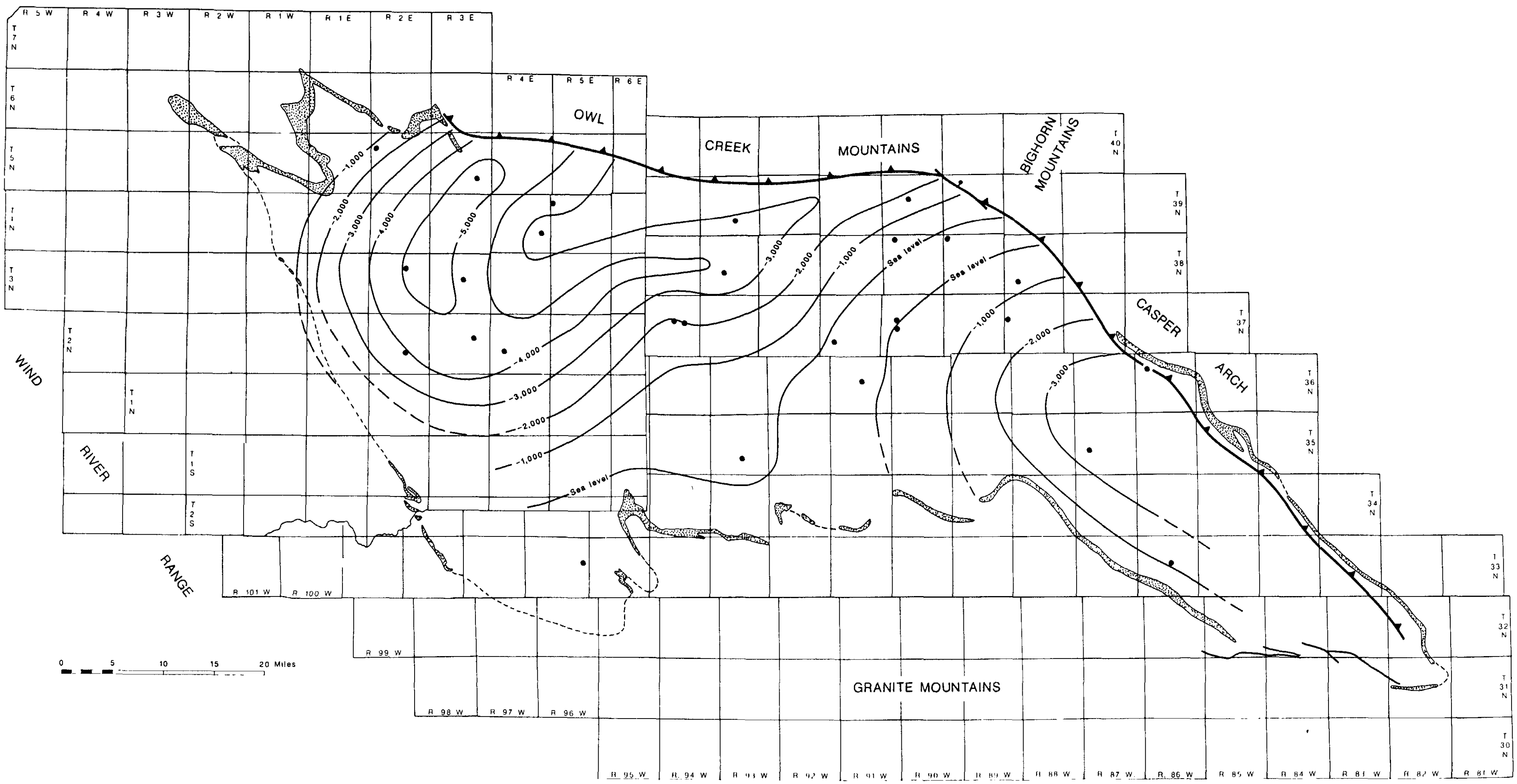


Figure 6-- Map showing elevation to 0.73 percent R_o line (onset of thermogenic gas generation) in the Wind River Basin, WY. The 0.73 percent R_o line cuts across formation boundaries, rising stratigraphically to the north and west. This map is useful in approximating the elevation one would have to drill to encounter the onset of thermogenic gas generation.

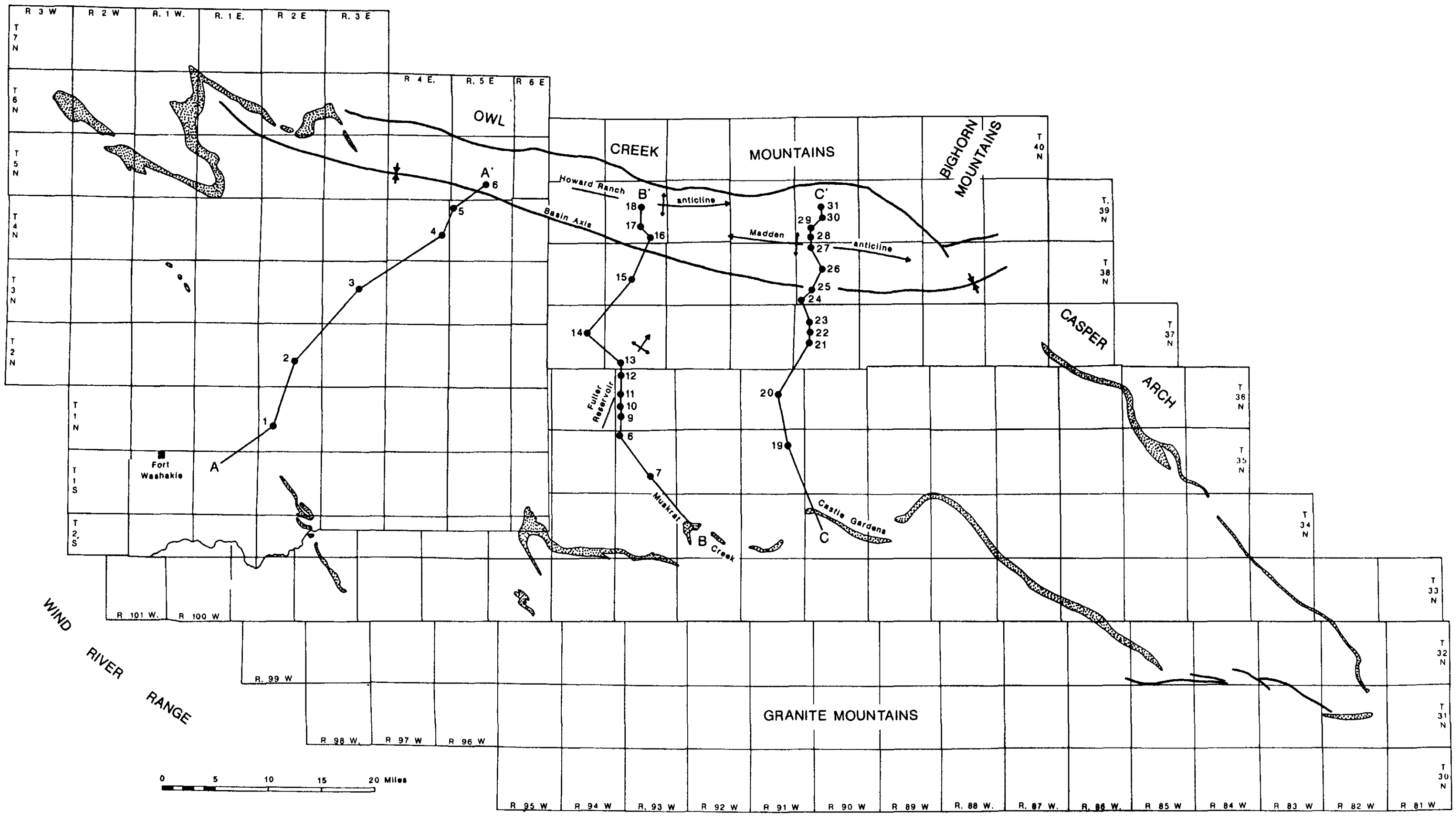
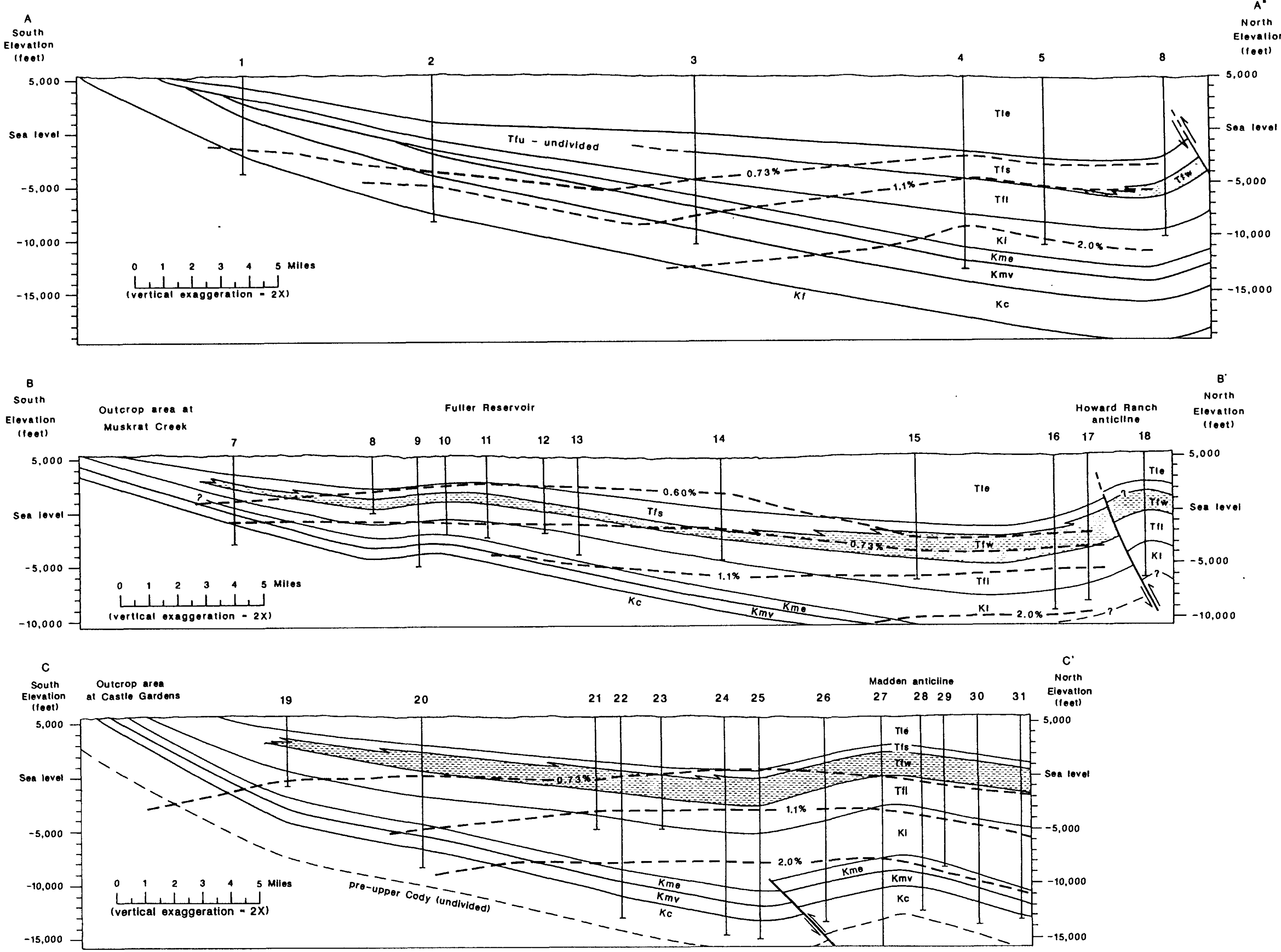


Figure 7--Index map of the Wind River Basin, WY, showing locations of lines of section A-A', B-B', C-C'. Well numbers on map correspond to those on the cross sections.



re 8--Cross sections A-A', B-B', C-C', illustrating the structure, stratigraphy and thermal maturity across the Wind River Basin, WY. Lines of section are shown on Figure 7. Abbreviations used are as follow: Tle-lower Eocene; Tfu-Fort Union Formation; Tfs-Shotgun Member of the Fort Union Formation; Tfw-Waltman Shale Member of the Fort Union Formation; Tfl-lower Member of the Fort Union Formation; Kl-Lance Formation; Kme-Meeteetse Formation; Kmv-Mesaverde Formation; Kc-Cody Shale; Kf-Frontier Formation.

lines do not always parallel structure, and in most cases, cut across structure. After final structural movement, the flanks of the basin were eroded to older stratigraphic levels than in the structural center of the basin. Toward the center of the basin where uplift and erosion were less, sediments continued to accumulate until about 15 Ma (time of maximum depth, burial, and temperature), and rocks matured at a faster rate than structural movement. This combination of events caused (1) R_o lines to cut across structure, and (2) an apparent rise of R_o lines to stratigraphically younger positions. Barker and Crysdale (1993) came to a similar conclusion. They stated that comparison of structure sections with isorank lines indicated that thermal maturation was mostly post-tectonic. Barker and Crysdale (1993) further stated that subhorizontal isorank lines suggest that thermal maturation mostly occurred after (1) folding of the Upper Cretaceous rocks during Laramide deformation, (2) uplift of the Wind River Range and subsidence of the Wind River Basin about 50 Ma, and (3) deposition of Eocene rocks.

Cross section A-A'

Cross section A-A', the westernmost of the three lines of section (fig. 7), extends from an outcrop near Fort Washakie, WY, and trends northeastward to the trough of the basin (fig. 8). Near the outcrop in the southern part of the cross section, the stratigraphic section shown (Cretaceous Cody Shale through Tertiary Eocene strata) is immature for any significant thermogenic gas generation (<0.73 percent R_o). Some of the shales in the Cody Shale may be within the oil window, and carbonaceous shales and coals in stratigraphically higher Cretaceous and Tertiary strata have potential for biogenic gas generation.

Northeastward, near well 3 of cross section A-A', thermal maturity of the stratigraphic section has increased dramatically. In this area, the Mesaverde Group and Cody Shale have R_o values >1.10 percent, and are interpreted to be in the zone of maximum thermogenic gas generation and expulsion. The Lance and Meeteetse Formations are in the zone of thermogenic gas generation (0.73 to 1.10 percent R_o), and the Fort Union is within the zone of biogenic gas generation.

In one of the deepest parts of the basin, between wells 5 and 6, the entire stratigraphic section shown (Cody Shale through Fort Union) is within the range of thermogenic gas generation (>0.73 percent R_o). The interval between the lower Member of the Fort Union Formation down through the Cody Shale is in the zone of maximum thermogenic gas generation (>1.10 percent R_o). In this same area of the basin, the oil-prone Waltman Shale Member of the Fort Union Formation is in the oil generation window (0.60 to 1.30 percent R_o).

Cross section B-B'

Cross section B-B' (fig. 7), outlines the structure, stratigraphy, and thermal maturity of the central part of the Wind River Basin (fig. 8). Cross section B-B' extends from the outcrop area around Muskrat Creek in the southern part of the basin northward, to the Howard Ranch anticline north of the axis of the basin (fig. 8). Near the outcrop in the southern part of the cross section, the stratigraphic section shown (Cretaceous Mesaverde Group through Tertiary Eocene strata) is immature in relation to oil generation (0.60 percent R_o) and significant thermogenic gas generation (<0.73 percent R_o). R_o values for the Fort Union Formation in this area range from 0.29 to 0.54 percent (Nuccio and Finn, 1994). Some of the coals in the Mesaverde Group and Fort Union Formation have potential conditions for biogenic gas generation.

Northward, near Fuller Reservoir and wells 9 through 12 on the cross section, the thermal maturity of the stratigraphic section has increased. In this area, the Mesaverde

Group and Cody Shale have R_o values of about 1.10 percent, and are in the zone of maximum thermogenic gas generation and expulsion. The Lance and Meeteetse Formations are in the zone of thermogenic gas generation (0.73 to 1.10 percent R_o) and the Fort Union is within the zone of biogenic gas generation. The Waltman Shale Member of the Fort Union Formation in this area is within the oil generation window (>0.60 percent R_o), (Nuccio and Finn, 1994).

Near the axis of the basin and between wells 15 and 16, rocks including the Cody Shale through the middle of the Waltman Shale Member of the Fort Union is within the range of thermogenic gas generation (>0.73 percent R_o). The interval between the lower Member of the Fort Union Formation down through the Cody Shale is in the zone of maximum thermogenic gas generation (>1.10 percent R_o). In this area of the basin, the oil-prone Waltman Shale Member of the Fort Union is present, and is in the oil generation window (0.60 to 1.30 percent R_o).

Cross section C-C'

Cross section C-C' (fig. 7) extends from the outcrop at Castle Gardens and trends northward defining the slope of the south flank of the basin, and the Madden anticline (fig. 8). At Castle Gardens, in the southern part of the cross section, the stratigraphic section shown (Cretaceous Cody Shale through Tertiary Eocene strata) is thermally immature for oil (<0.60 percent R_o) and significant thermogenic gas generation (<0.73 percent R_o). R_o values for the Fort Union Formation at Castle Gardens range from 0.36 to 0.40 percent (Nuccio and Finn, 1994). Carbonaceous shales and coals in Cretaceous and Tertiary strata in this area could have the potential for biogenic gas generation.

Trending northward toward the axis of the basin, near wells 24 and 25 on the cross section C-C', the thermal maturity of the stratigraphic section has increased greatly. This area is one of the deepest and most thermally mature parts of the basin. Here, the entire stratigraphic section shown (Cody Shale through Fort Union) is within the range of thermogenic gas generation (>0.73 percent R_o). The interval between the lower member of the Fort Union Formation down through the Cody Shale is in the zone of maximum thermogenic gas generation (>1.10 percent R_o). In this same area of the basin, the oil-prone Waltman Shale Member of the Fort Union Formation is in the oil generation window (0.60 to 1.30 percent R_o); see Nuccio and Finn (1994) for complete discussion.

Cross section C-C' clearly illustrates how R_o lines cut across structure. Approaching the trough of the basin, where sedimentation continued for the longest period of time, the isoreflectance lines rise stratigraphically and cut across the syncline. This crosscutting relationship indicates that thermal maturation continued during, or for a period of time after, structural downwarp. In the area of the Madden anticline, the R_o lines dip stratigraphically, and parallel structure on the northern flank. This parallel relationship suggests that maximum thermal maturation was established prior to uplift of the Madden anticline, and the strata (especially on the northern flank) did not experience increased temperatures after that time.

VITRINITE REFLECTANCE PROFILES

Vitrinite reflectance was plotted as a function of depth on semilogarithmic graphs for 26 wells throughout the Wind River Basin (see appendix). The R_o values for these wells are presented in Table 1. For the purpose of assessing gas, vitrinite reflectance profiles were used to determine the thermal maturity and hydrocarbon potential for source rocks throughout the basin. The profiles indicate in which unit important hydrocarbon thresholds occur. The profiles also allow extrapolation of thermal maturity to units with no data, or units not penetrated by the well bore.

These profiles can also be used to determine the erosional history in the area of the well. It is assumed that the vitrinite reflectance of surface rocks is approximately 0.20 to 0.30 percent. In areas where the burial-erosional history is not well understood, extrapolating a best fit line through the R_o data to 0.20 to 0.30 percent R_o yields an estimate of erosion. Problems including "kinks" in the profile may change the slope of the best fit line, and surface intercept, causing an error in estimating the amount of erosion (Law and others, 1989). In the Wind River Basin, well documented geological relationships and controls have been established to reconstruct a good burial and erosional history in the region (see Johnson and others, in press; Nuccio and Finn, 1994). Also, Barker and Crysdale (1993) compared erosion calculated from vitrinite reflectance profiles with erosion reconstructed from geological observations and found only a loose relationship. Therefore, vitrinite reflectance profile estimates of erosion are not considered in this report.

Vitrinite reflectance profiles can also be used to compare thermal history between different areas within the Wind River Basin. Vitrinite reflectance generally increases logarithmically with depth; the steeper slope of the line, the slower the rate of increase in vitrinite reflectance (maturity) with depth. Wells having less steeply sloped R_o profiles either have, or have had, higher geothermal gradients or have been subjected to a certain temperature or burial depth for a longer period of time than wells with steeply-sloped profiles.

In their burial and thermal reconstructions for four wells in the deeper parts of the Wind River Basin, Barker and Crysdale (1993) used variable heat flow models. Although heat flow changed at various times in the past, the heat flow at any given time for the four wells was fairly consistent throughout the basin. It should also be noted that present-day heat flow (Hinckley and Heasler, 1987), and geothermal gradients (Pawlewicz, 1993) vary across the basin in response to ground-water flow and structure. Assuming the thermal history throughout the basin was not drastically different from area to area, the observed differences in the slope of the profiles probably result mostly from differences in the burial histories.

For the most part, wells in the most shallow-buried areas of the Wind River Basin have steeper-sloped vitrinite reflectance profiles than those near the deep trough indicating they were not buried as deeply or for as long a period of time. There are exceptions to this relationship, however. For example, the Sun Ranch, Fed. #1 well in the southeastern part of the basin has a moderate slope (middle Cody Shale through Muddy Sandstone) to its R_o profile. This same stratigraphic section is at a depth of 5,000 to 9,000 ft, one of the shallowest parts of the basin, and where one would expect the vitrinite reflectance profile to have a steeply-sloped trending profile. This area may have experienced a late heating event where the strata achieved present levels of maturity during or after structural uplift and erosion. This heating was probably caused by fracturing and associated flow of hot fluids and is likely localized because other wells in the shallow margins of the basin have steeply-sloped trending profiles.

REFERENCES

Anders, D.E., and Gerrild, P.M., 1984, Hydrocarbon generation in lacustrine rocks of Tertiary age, Uinta Basin, Utah--organic carbon, pyrolysis yield, and light hydrocarbons, *in* Jane Woodward, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Denver, Rocky Mountain Association of Geologists, p. 513-529.

Barker, C.E., and Crysdale, B.L., 1993, Burial and temperature history of gas generation from coaly organic matter in the Late Cretaceous Mesaverde Formation and associated rocks in the deeper portions of the Wind River Basin, Wyoming, *in* Stroock, Betty, and Andrew, Sam, eds., Jubilee Anniversary field conference: Casper, Wyoming Geological Association, p. 235-258.

Bostick, N.H., 1979 Microscopic measurements of the level of catagenesis of solid organic matter in sedimentary rocks to aid in exploration for petroleum and to determine former burial temperatures--a review, *in* Scholle, P.A., and Schluger, P.R., eds., Aspects of diagenesis: Society of Economic Paleontologists and Mineralogists, Special Publication Number 26, p. 17-43.

Burtner, R.L., and Warner, M.A., 1984, Hydrocarbon generation in Lower Cretaceous Mowry and Skull Creek Shales of the northern Rocky Mountain area, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Denver, Rocky Mountain Association of Geologists, p. 449-467.

Burtner, R.L., and Warner, M.A., 1986, Relationship between illite/smectite diagenesis and hydrocarbon generation in Lower Cretaceous Mowry and Skull Creek Shales of the northern Rocky Mountain area: Clays and Clay Minerals, v. 34, no. 4, p. 390-402.

Bustin, R.M., 1986, Organic maturity of Late Cretaceous and Tertiary coal measures, Canadian Arctic Archipelago: International Journal of Coal Geology, v. 6, p. 71-106.

Dow, W.G., 1977, Kerogen studies and geological interpretations: Journal of Geochemical Exploration, v. 7, p. 79-99.

Hagen, E.S., and Surdam, R.C., 1984, Maturation history and thermal evolution of Cretaceous source rocks of the Bighorn Basin, Wyoming and Montana, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon Source Rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 321-338.

Hinckley, B.S., and Heasler, H.P., 1987, Geothermal resources of the Wind River Basin: Geological Survey of Wyoming Report of Investigations 38, 30 p.

Johnson, R.C., 1989, Geologic history and hydrocarbon potential of Late Cretaceous-age, low permeability reservoirs, Piceance basin, western Colorado: U.S. Geological Survey Bulletin 1787-E, p. E1-E51.

Johnson R.C., and Rice, D.D., 1990, Occurrence and Geochemistry of natural gases, Piceance basin, northwest Colorado: American Association of Petroleum Geologists Bulletin, v. 74, p. 805-829.

Johnson, R.C., Crovelli, R.A., Spencer, C.W., and Mast, R.F., 1987, An assessment of gas resources in low-permeability sandstones of the Upper Cretaceous Mesaverde Group, Piceance basin, Colorado: U.S. Geological Survey Open-File Report 87-357, 165 p.

Johnson, R.C., Keefer, W.R., Finn, T.M., and Szmajter, R.J., in press, Natural gas resources in low-permeability Upper Cretaceous and Paleocene rocks, Wind River Basin, Wyoming: U.S. Geological Survey Open-File Report.

Juntgen, H., and Karweil, J., 1966, Gasbildung und gasspeicherung in steinkohlenflozen, Part I and II: Erdol and Kohle, Erdgas, Petrochemie, v. 19, p. 251-258, 339-344.

Juntgen, H., and Klein, J., 1975, Entstehung von erdgas gus kohligen sedimenten: Erdol and Kohle, Erdgas, Petrochemie, Erganzungsband, v. 1, p. 52-69.

Katz, B.J., and Liro, L.M., 1993, The Waltman Shale Member, Fort Union Formation, Wind River Basin: A Paleocene clastic lacustrine source system, *in* Keefer, W.R., Metzger, W.J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Cheyenne, Wyoming Geological Association Special Symposium 1993, p. 163-174.

Keefer, W.R., 1965, Stratigraphy and geologic history of the uppermost Cretaceous, Paleocene, and lower Eocene Rocks in the Wind River Basin, Wyoming: U.S. Geological Survey Professional Paper 495-A, 77 p.

Law, B.E., Nuccio, V.F., and Barker, C.E., 1989, Kinky vitrinite reflectance profiles; evidence of paleopore pressure in low-permeability gas-bearing sequences in Rocky Mountain foreland basins: American Association of Petroleum Geologists Bulletin, v. 73, no. 8, p. 999-1010.

Meissner, F.F., 1984, Cretaceous and Lower Tertiary coals as source for gas accumulation in the Rocky Mountain area, *in* Jane Woodward, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain Region: Denver, Rocky Mountain Association of Geologists, p. 401-432.

Nuccio, V.F., Schmoker, J.W., and Fouch, T.D., 1992, Thermal maturity, porosity, and lithofacies relationships applied to gas generation and production in Cretaceous and Tertiary low-permeability (tight) sandstones, Uinta Basin, Utah, *in* Fouch, T.D., Nuccio, V.F., and Chidsey, T.C., Jr., eds, Hydrocarbon and mineral resources of the Uinta Basin, Utah and Colorado: Salt Lake City, Utah Geological Association Guidebook 20, p. 77-93.

Nuccio, V.F., Finn, T.M., and Pawlewicz, M.J., 1993, Surface vitrinite reflectance study of the Wind River Basin, central Wyoming, *in* Keefer, W.R., Metzger, W.J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Cheyenne, Wyoming Geological Association Special Symposium 1993, p. 307-317.

Nuccio, V.F., 1994, Vitrinite reflectance data for the Paleocene Fort Union and Eocene Wind River Formations, and burial history of a drill hole located in central Wind River Basin, Wyoming: U.S. Geological Survey Open-File Report 94-220, 42 p.

Nuccio, V.F., and Finn, T.M., 1994, Structural and thermal history of the Paleocene Fort Union Formation, central and eastern Wind River Basin, with emphasis on petroleum potential of the Waltman Shale Member, *in* Flores, R.M., Mehring, K.T., Jones, R.W., and Beck, T.L., eds., Organics and the Rockies Field Guide: Laramie, Wyoming State Geological Survey, Public Information Circular no. 33, p. 53-68.

Palacas, J.G., Flores, R.M., Keighin, C.W., and Anders, D.E., 1993, Organic geochemical typing of oils in the Wind River Basin, Wyoming: [abst] American Association of Petroleum Geologists 1993 Annual Convention Program, p. 162.

Palacas, J.G., Flores, R.M., Keighin, C.W., and Anders, D.E., 1994, Origin of oil in oil-saturated sandstones of the Fort Union Formation (Paleocene), Castle Gardens and Signor Ridge areas, Wind River Basin, Wyoming, *in* Flores, R.M., Mehring, K.T., Jones, R.W., and Beck, T.L., eds., Organics and the Rockies Field Guide: Laramie, Wyoming State Geological Survey, Public Information Circular no. 33, p.83-97.

Pawlewicz, M.J., 1993, Vitrinite reflectance and geothermal gradients in the Wind River Basin, central Wyoming, *in* Keefer, W.R., Metzger, W.J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Cheyenne, Wyoming Geological Association Special Symposium 1993, p. 295-305.

Tissot, B.P., and Welte, D.H., 1984, Petroleum formation and occurrence, second edition: Berlin, Springer-Verlag, 699 p.

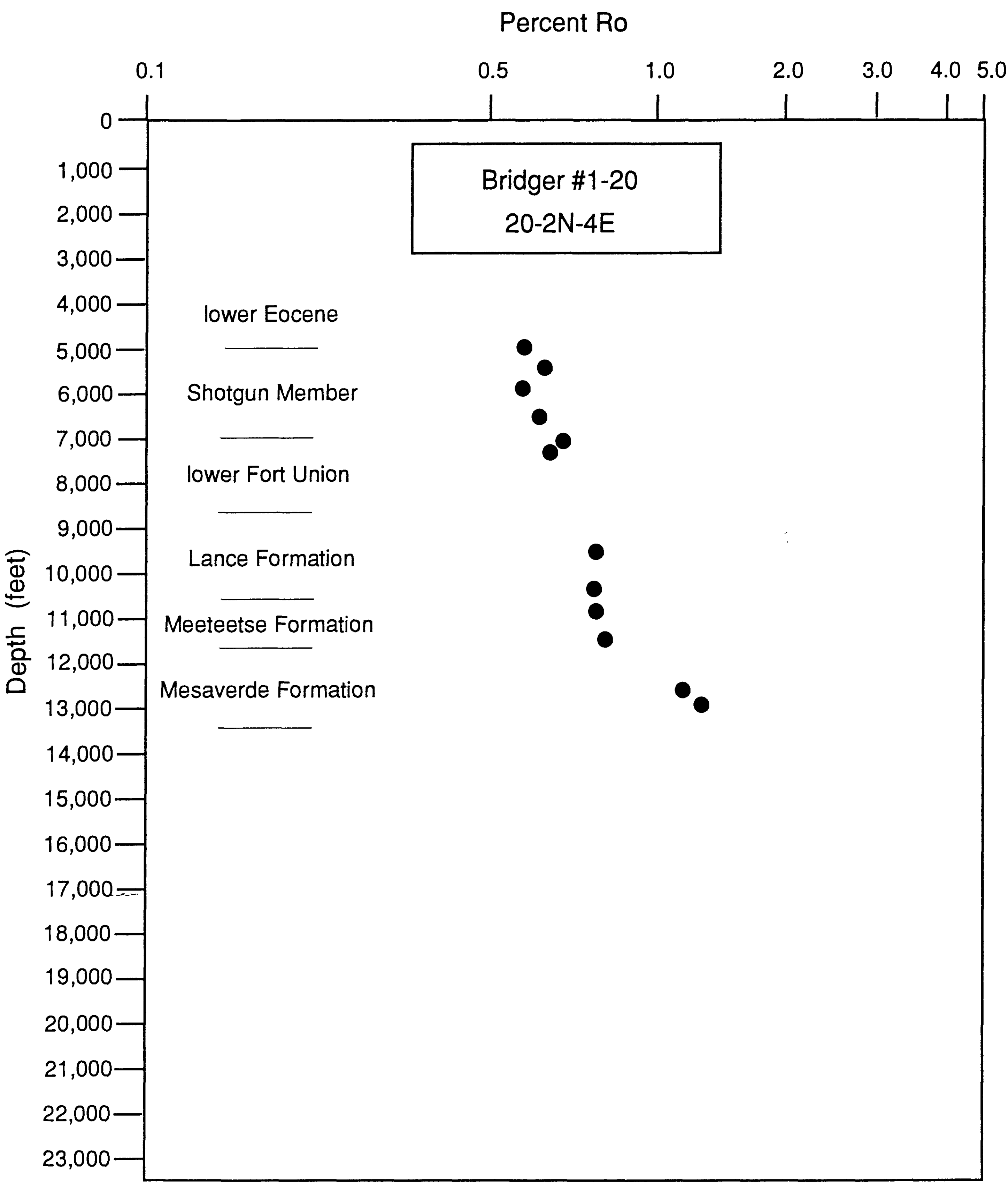
Tissot, B.P., Durand, B., Espitalie, J., and Combaz, A., 1974, Influence of nature and diagenesis of organic matter in formation of petroleum: American Association of Petroleum Geologists Bulletin, v. 58, p. 499-506.

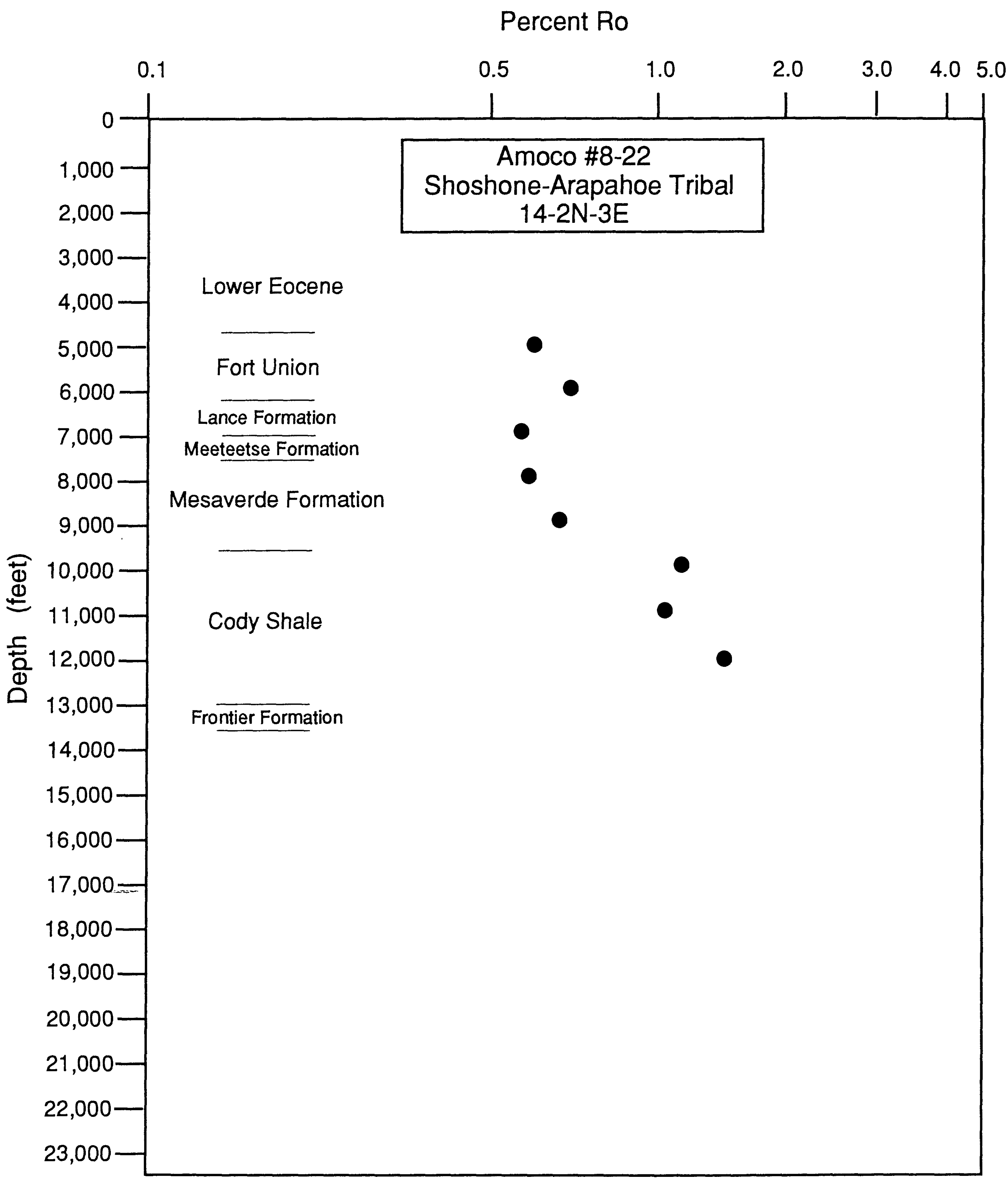
Waples, D.W., 1980, Time and temperature in petroleum formation: application of Lopatin's method to petroleum exploration: American Association of Petroleum Geologists Bulletin, v. 64, p. 916-926.

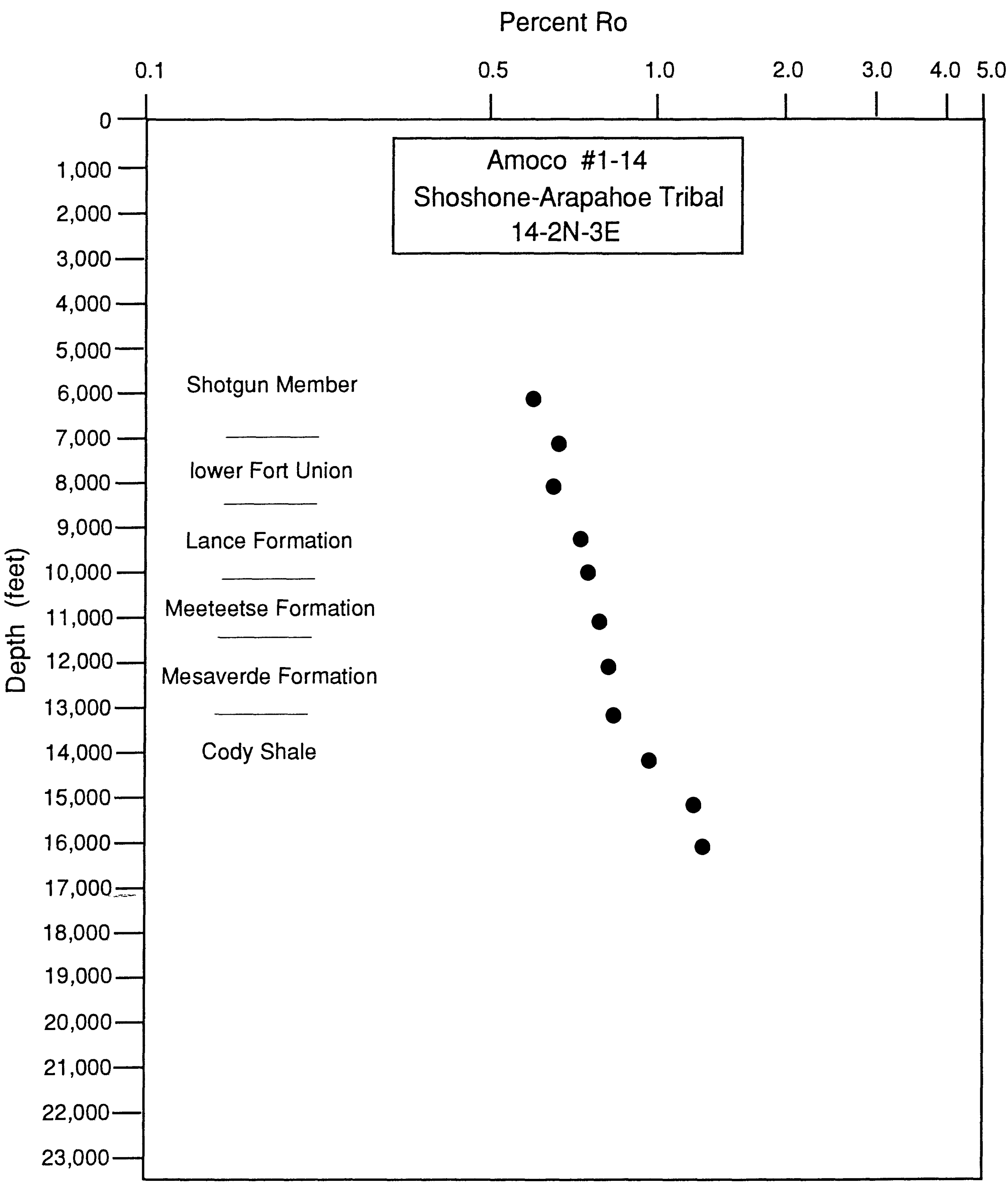
Waples, D.W., 1985, Geochemistry in petroleum exploration: Boston, International Human Resources Development Corporation, 232 p.

APPENDIX

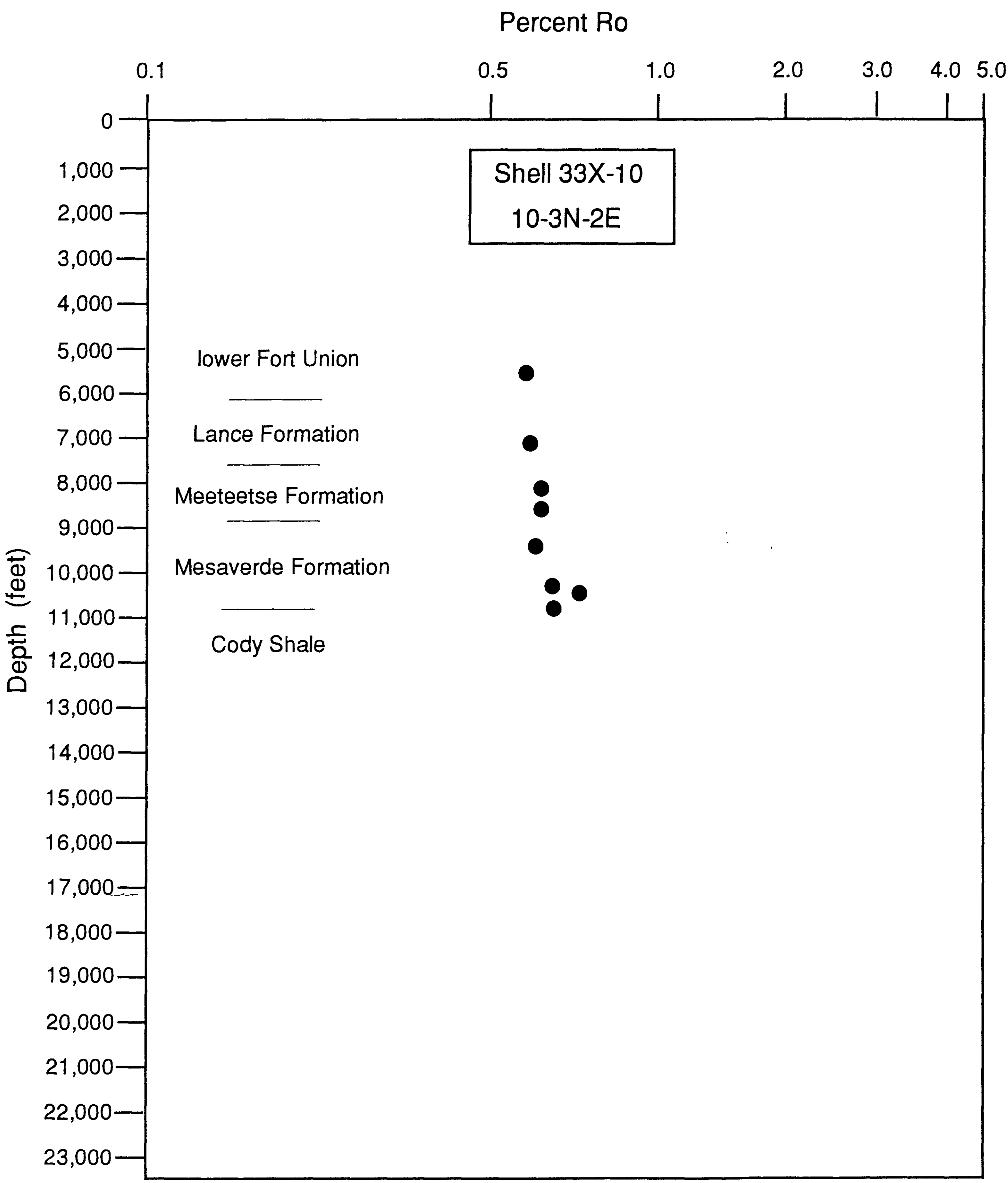
Vitrinite Reflectance Profiles


Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Bridger #1-20
20-2N-4E
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
lower Eocene
Shotgun Member
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation

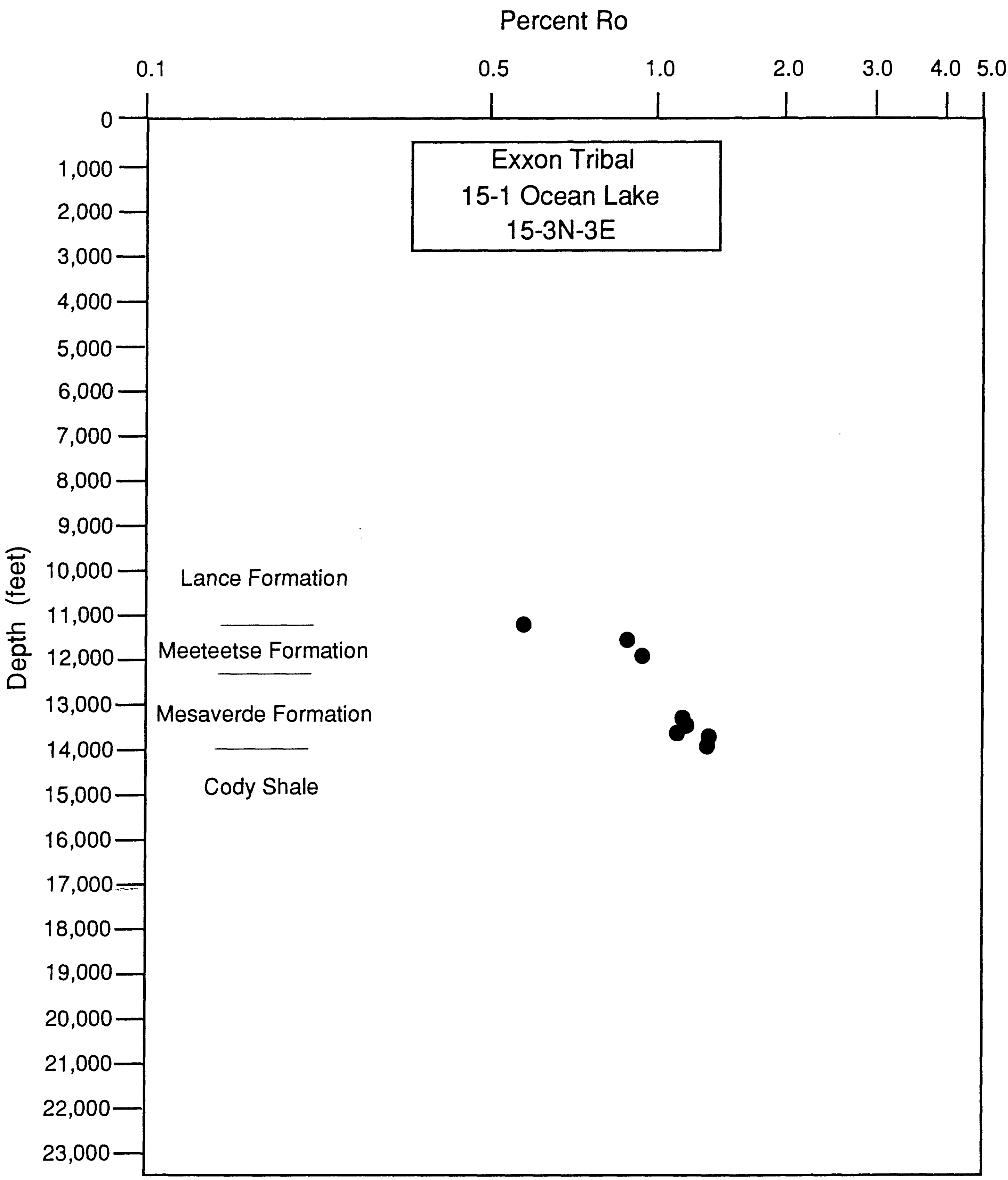

Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Amoco #8-22
Shoshone-Arapahoe Tribal
14-2N-3E
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Lower Eocene
Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation
Cody Shale
Frontier Formation



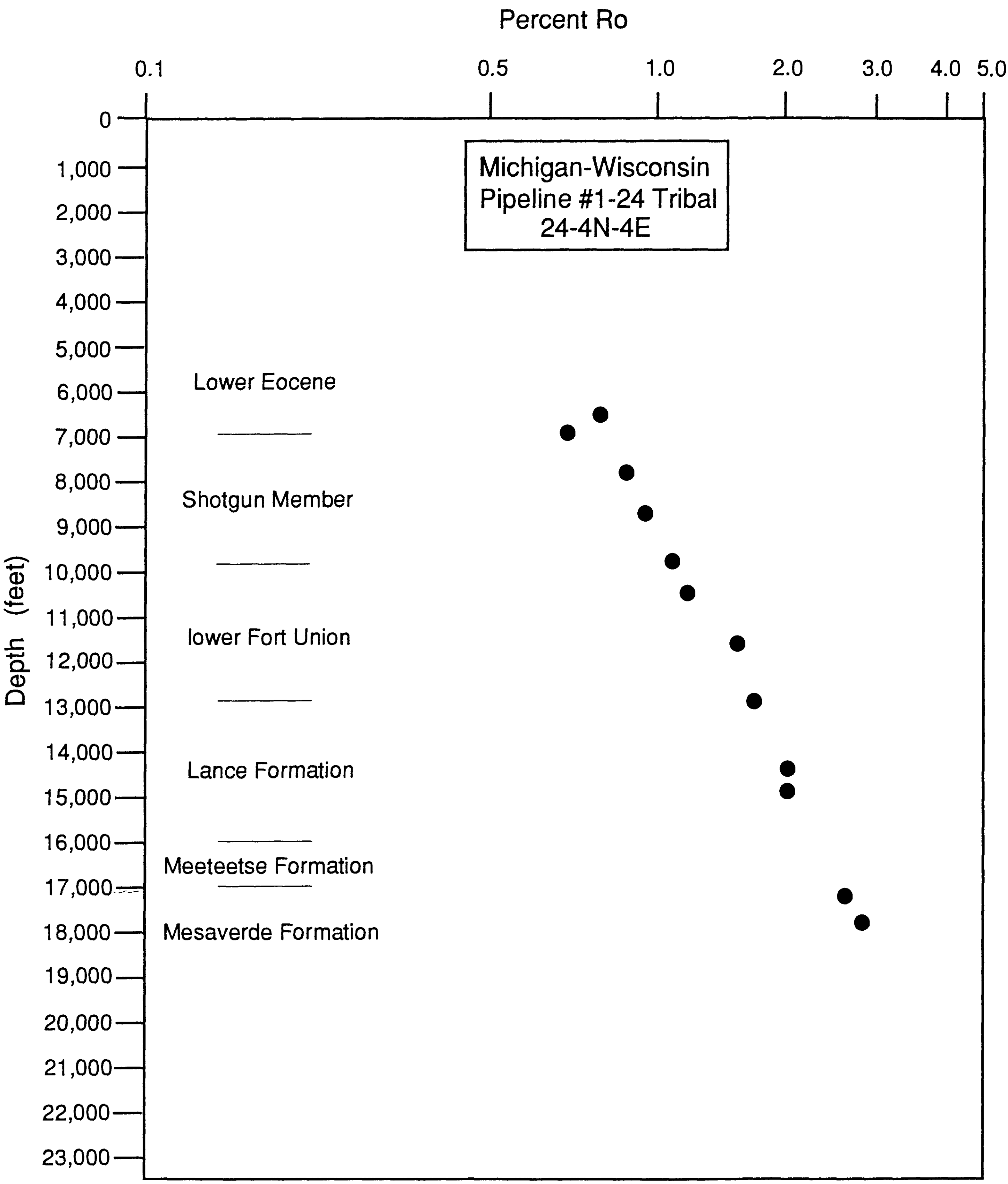
Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Amoco #1-14
Shoshone-Arapahoe Tribal
14-2N-3E
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Shotgun Member
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation
Cody Shale

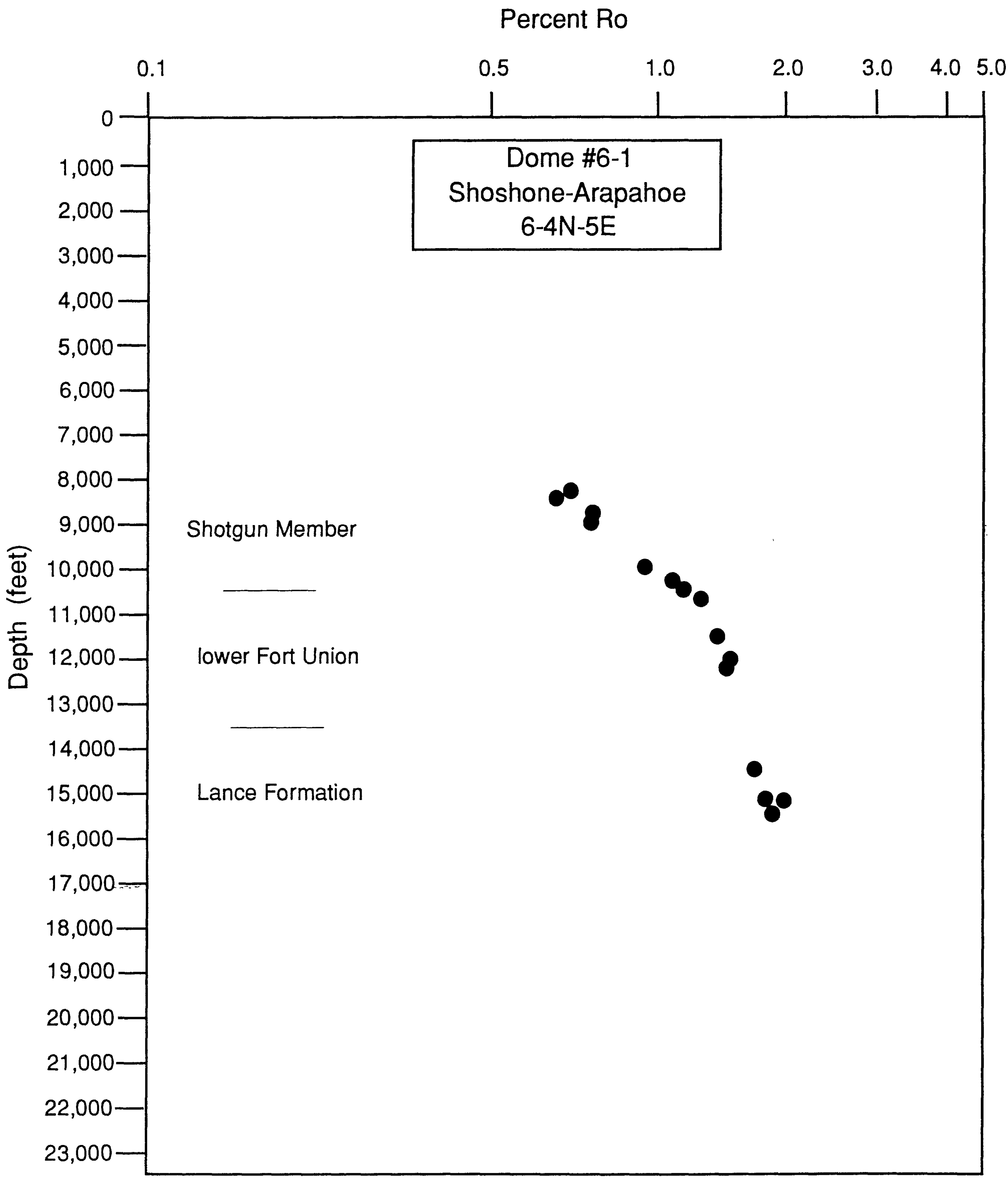


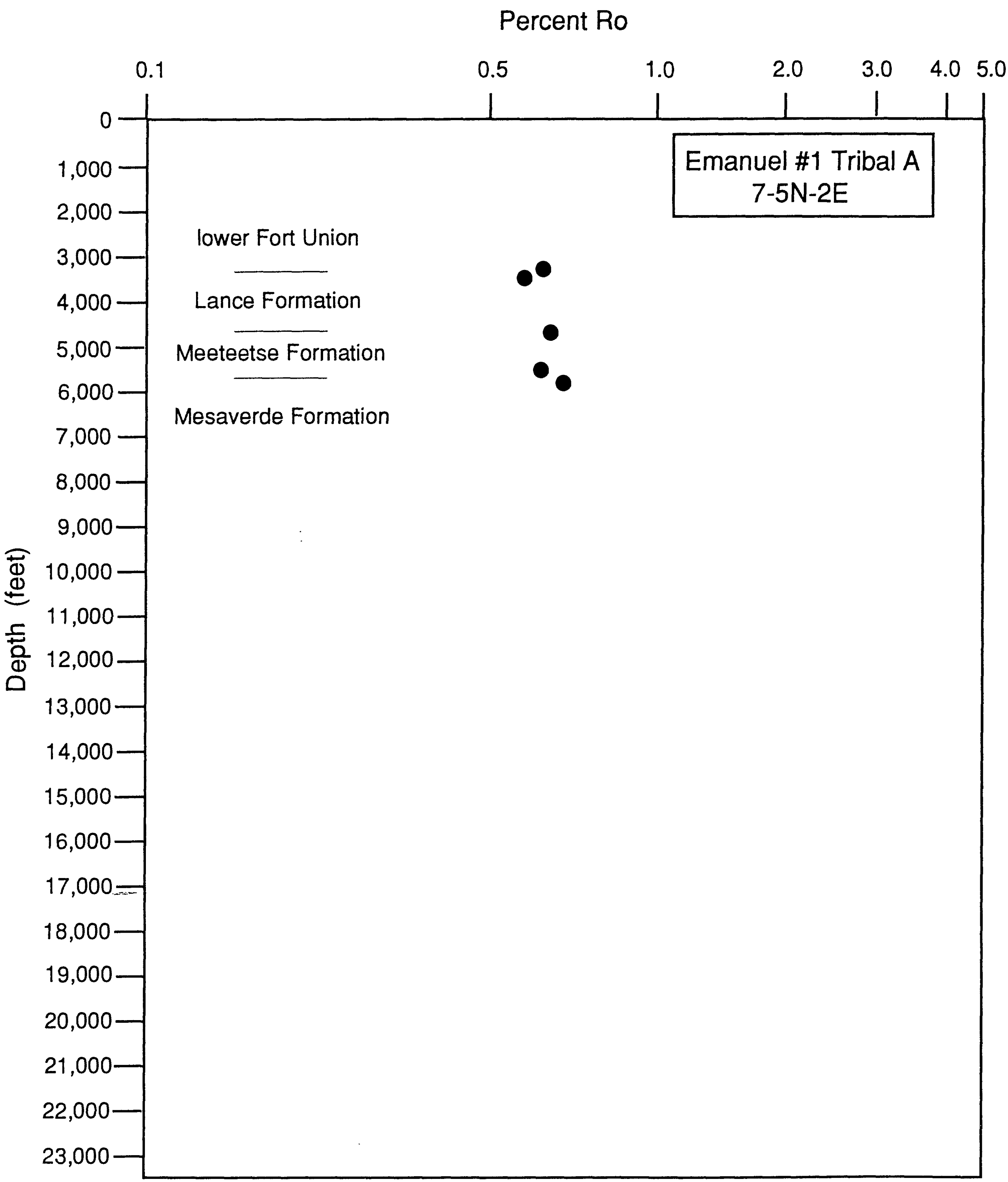
Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Shell 33X-10
10-3N-2E
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Depth (feet)
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation
Cody Shale

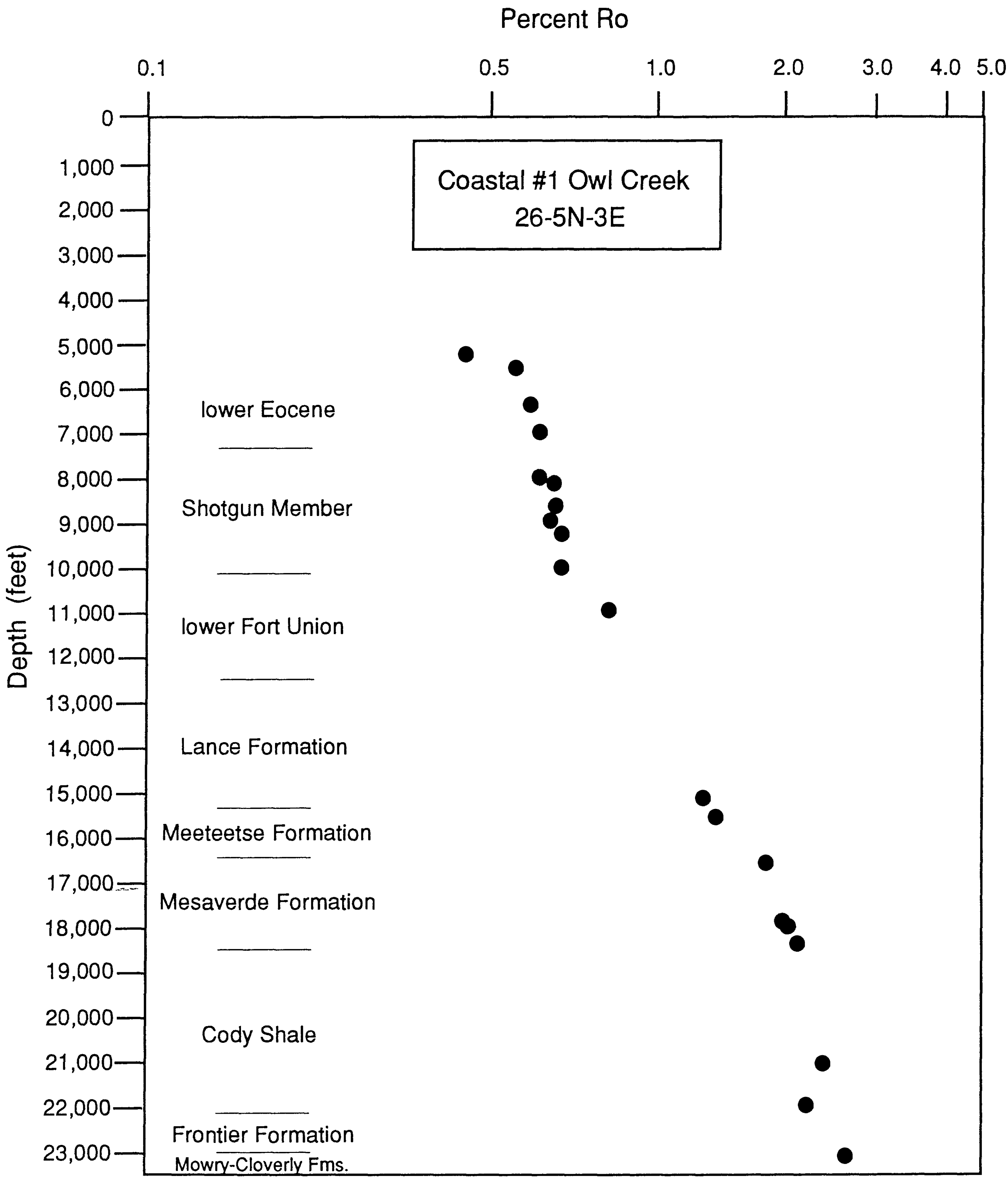


Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Exxon Tribal
15-1 Ocean Lake
15-3N-3E
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Lance Formation
Meeteetse Formation
Mesaverde Formation
Cody Shale

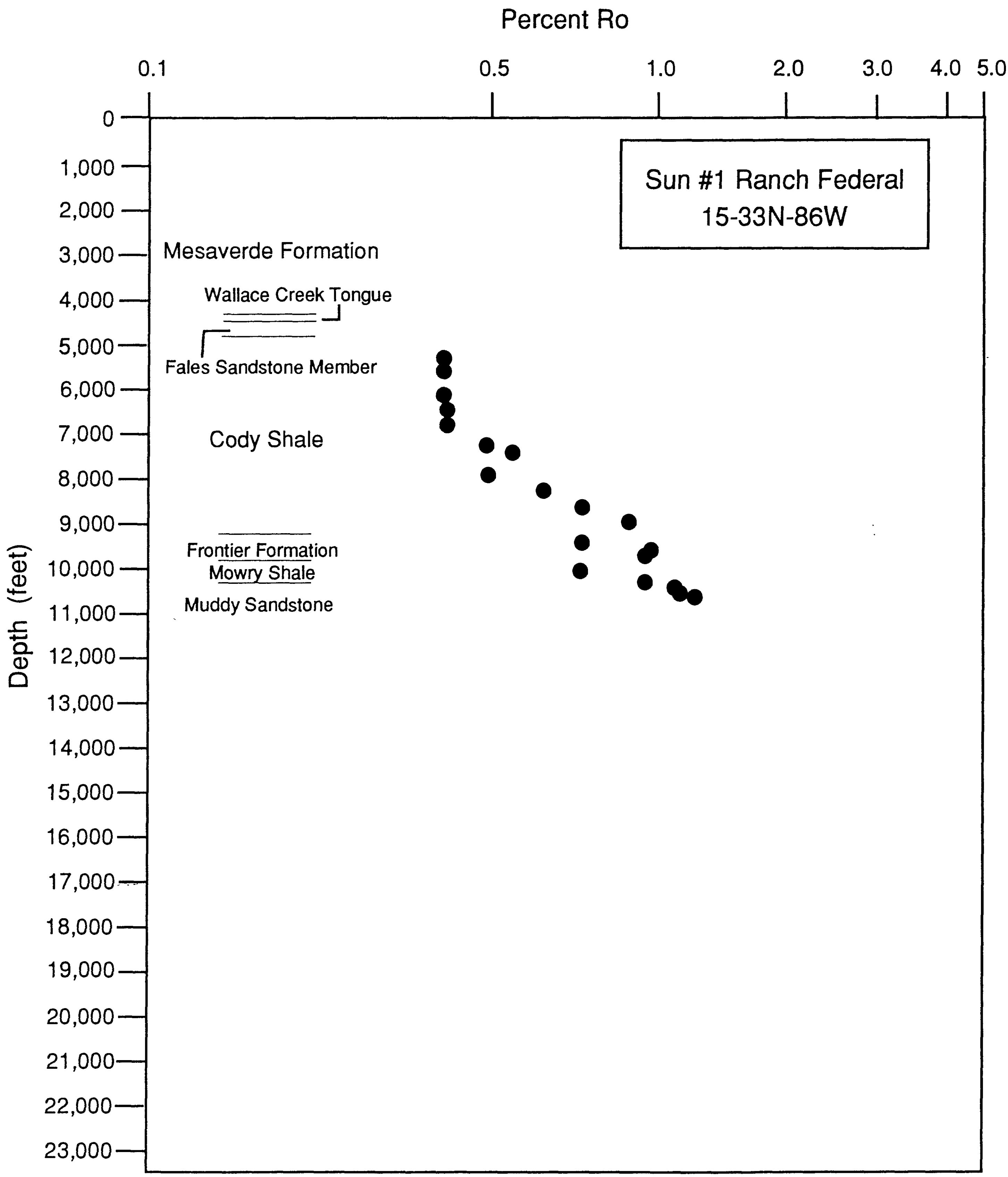

Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Michigan-Wisconsin
Pipeline #1-24 Tribal
24-4N-4E
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Lower Eocene
Shotgun Member
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation

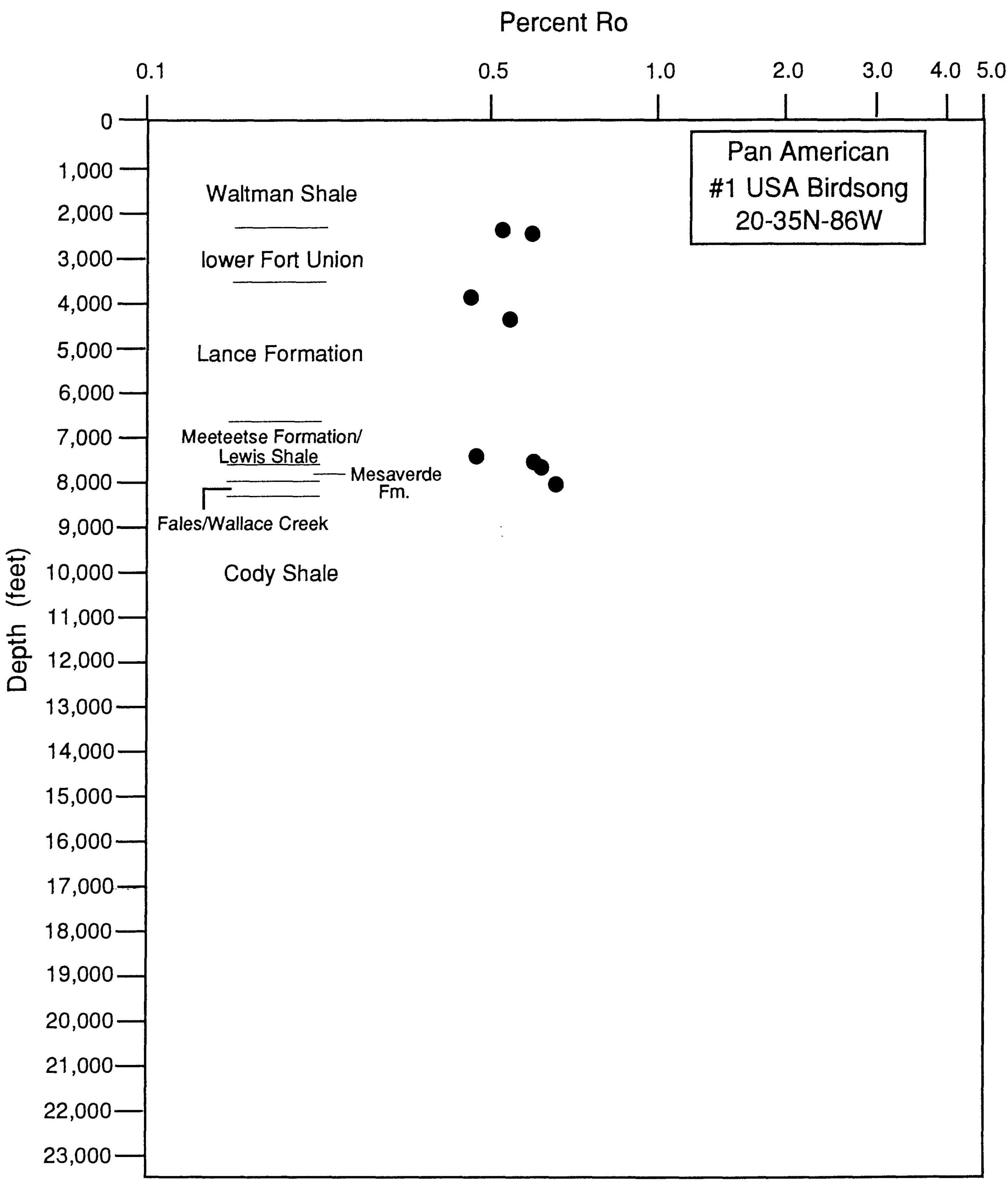

Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Dome #6-1
Shoshone-Arapahoe
6-4N-5E
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Shotgun Member
lower Fort Union
Lance Formation

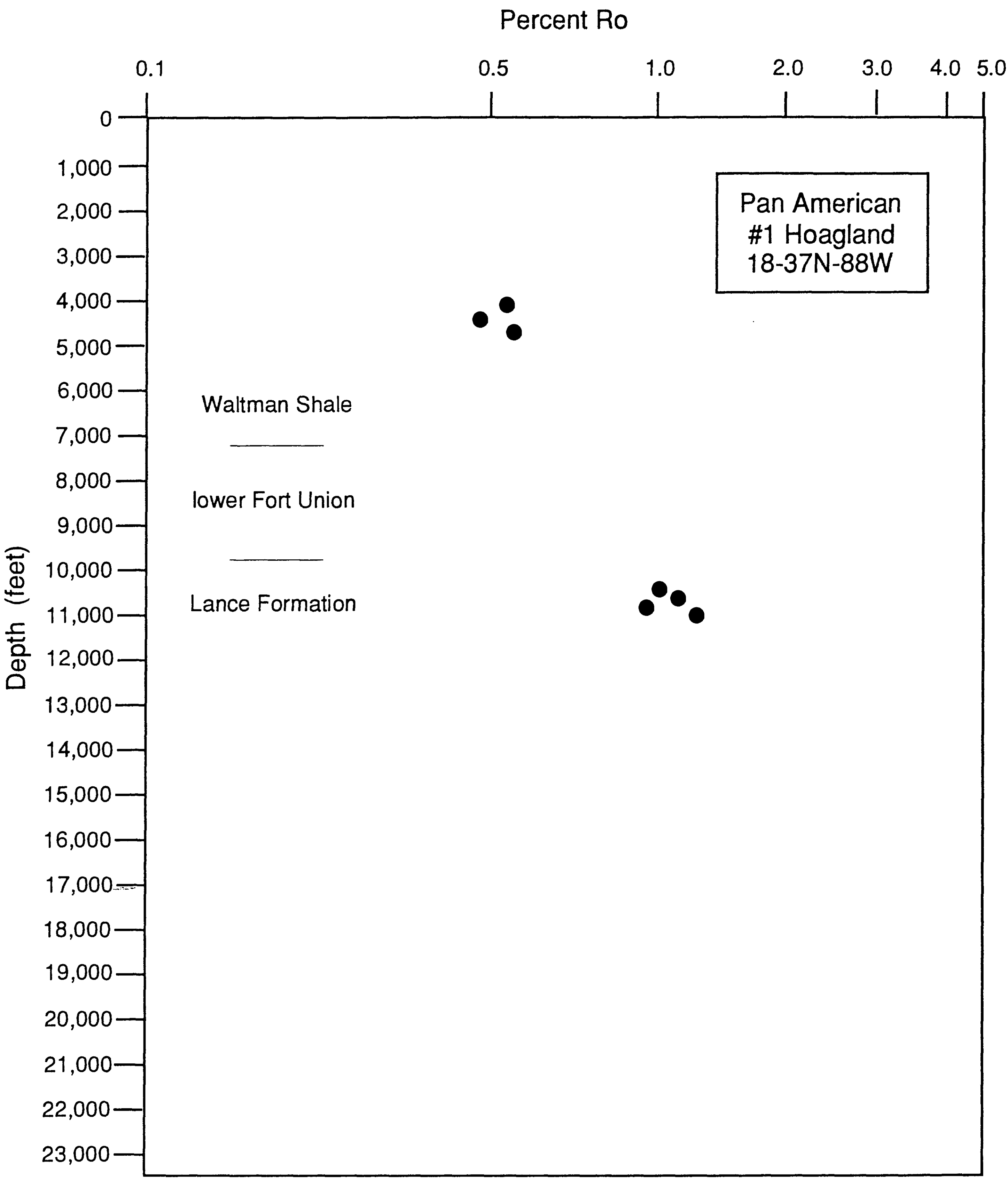

Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Emanuel #1 Tribal A
7-5N-2E
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000



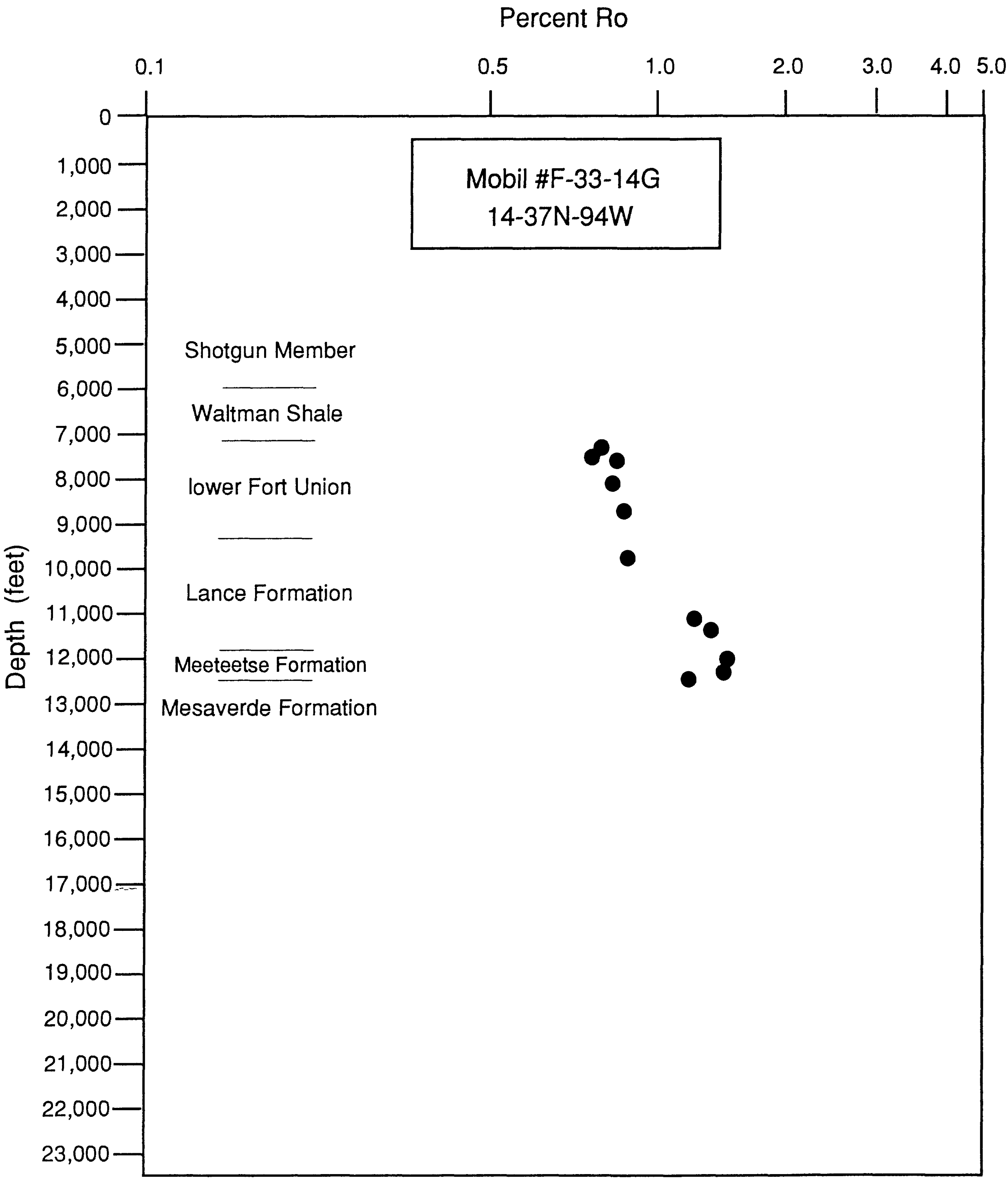
Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Coastal #1 Owl Creek
26-5N-3E
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
lower Eocene
Shotgun Member
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation
Cody Shale
Frontier Formation
Mowry-Cloverly Fms.


Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Sun #1 Ranch Federal
15-33N-86W
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Mesaverde Formation
Wallace Creek Tongue
Fales Sandstone Member
Cody Shale
Frontier Formation
Mowry Shale
Muddy Sandstone

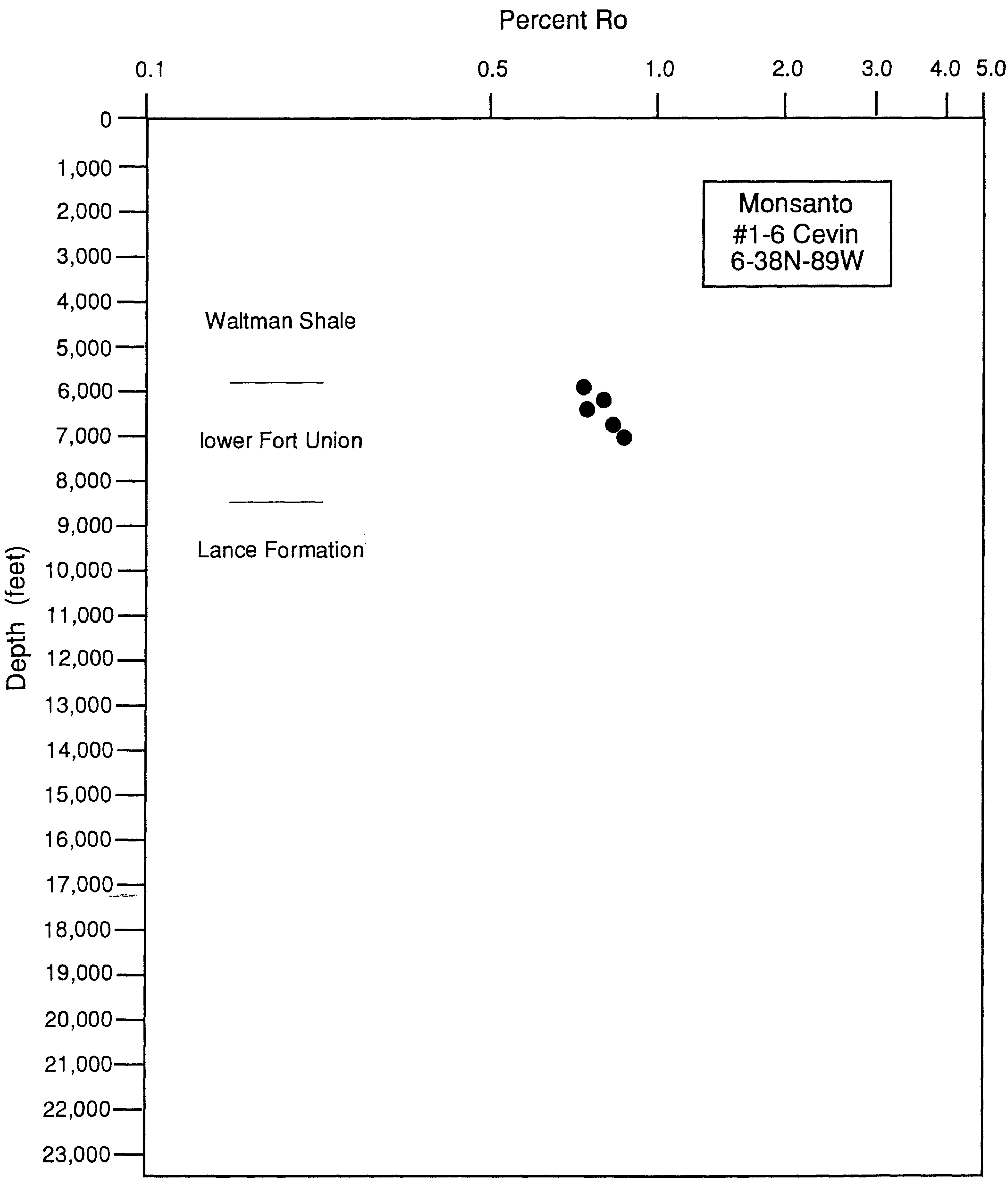

Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Pan American
#1 USA Birdsong
20-35N-86W
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Waltman Shale
lower Fort Union
Lance Formation
Meeteetse Formation/
Lewis Shale
Mesaverde
Fm.
Fales/Wallace Creek
Cody Shale

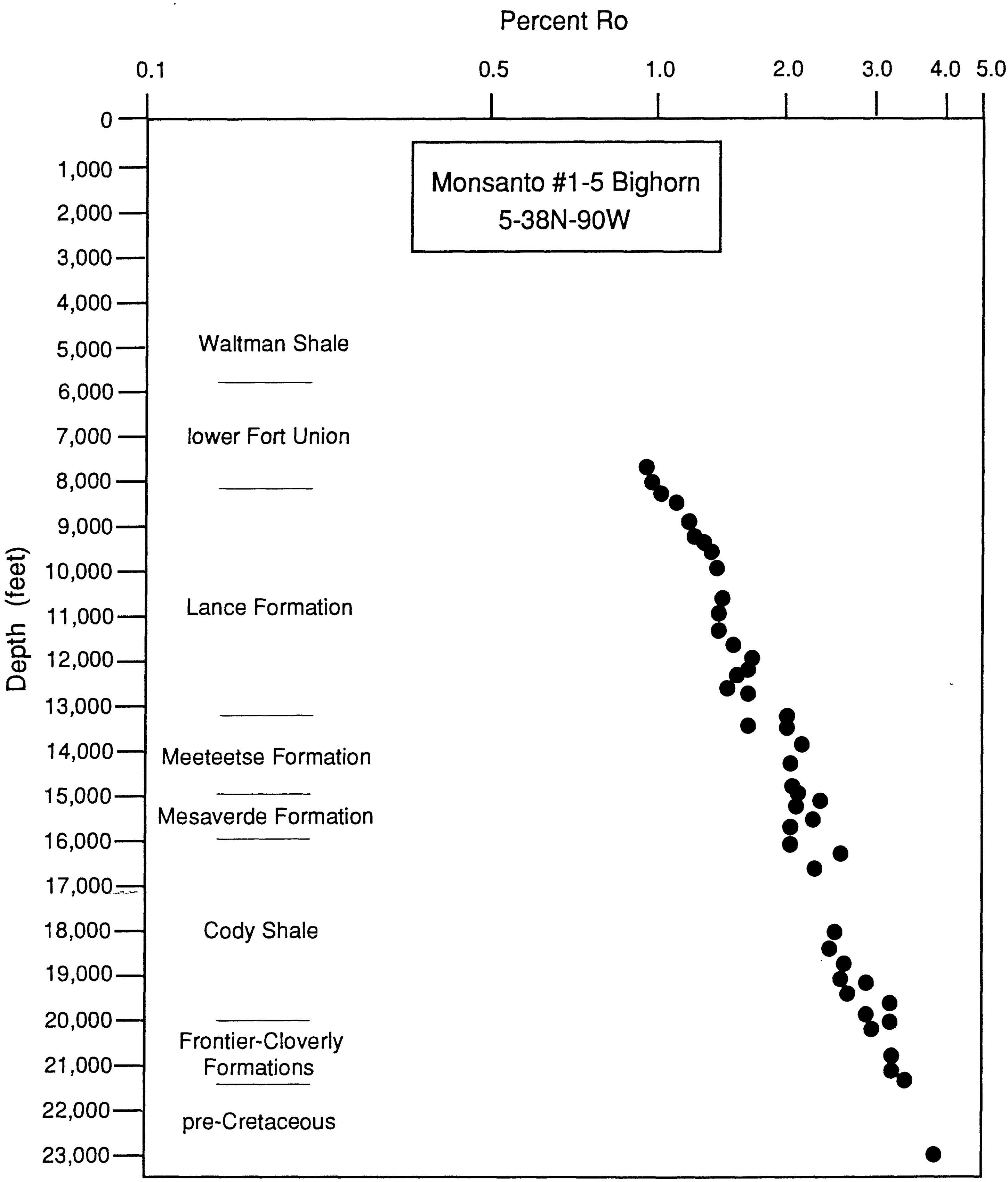


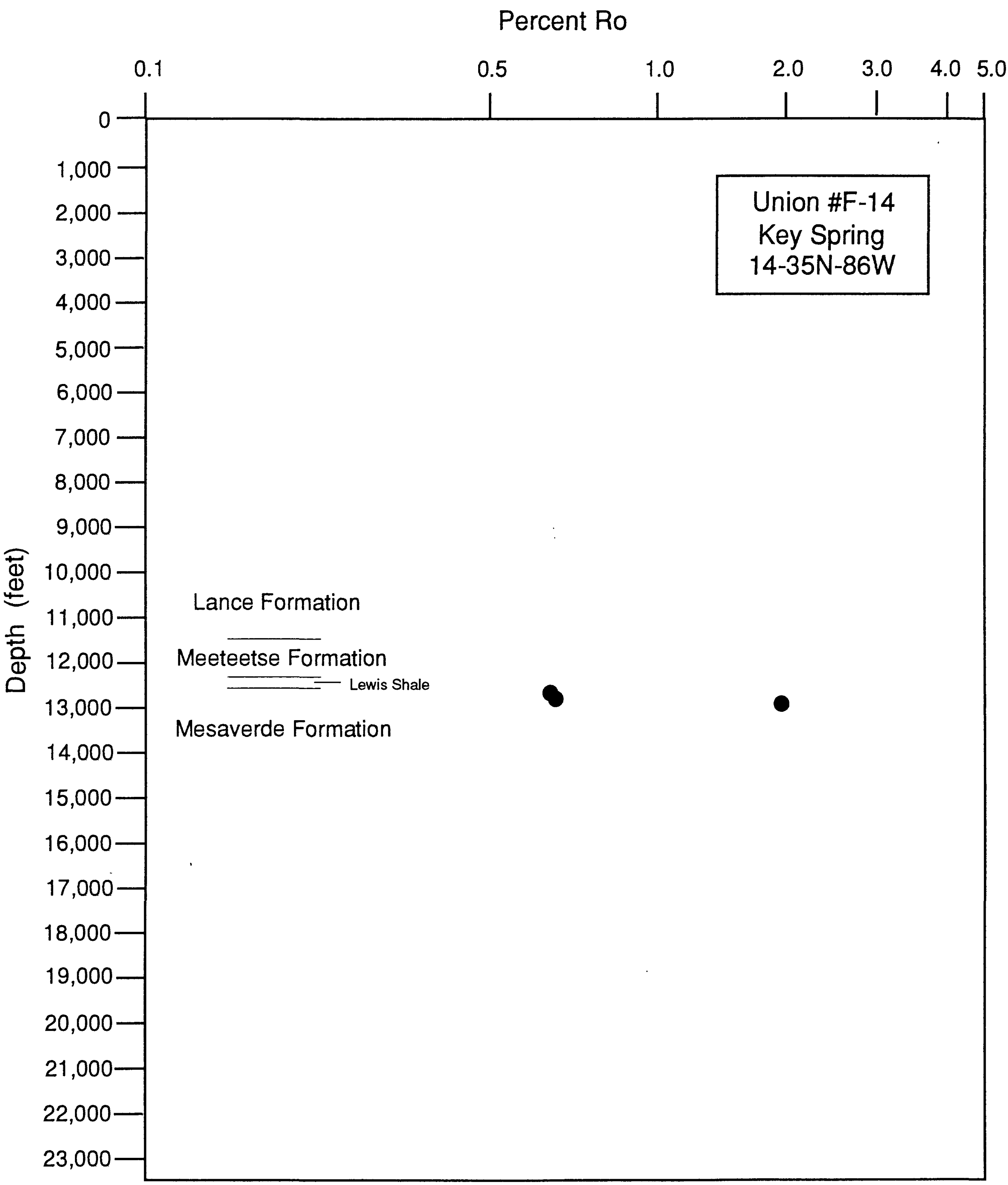
Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Depth (feet)
Pan American
#1 Hoagland
18-37N-88W
Waltman Shale
lower Fort Union
Lance Formation



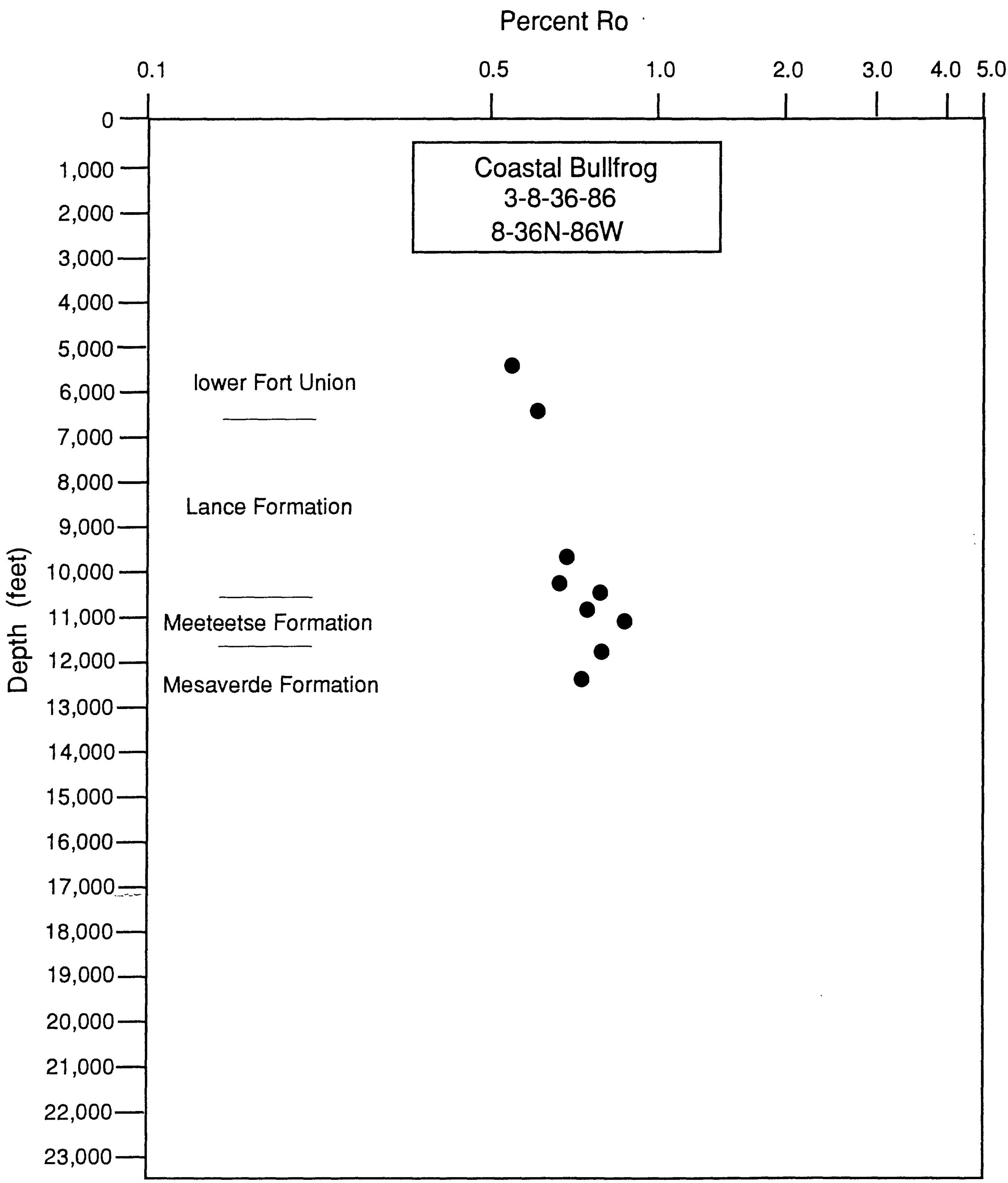
Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Mobil #F-33-14G
14-37N-94W
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Shotgun Member
Waltman Shale
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation

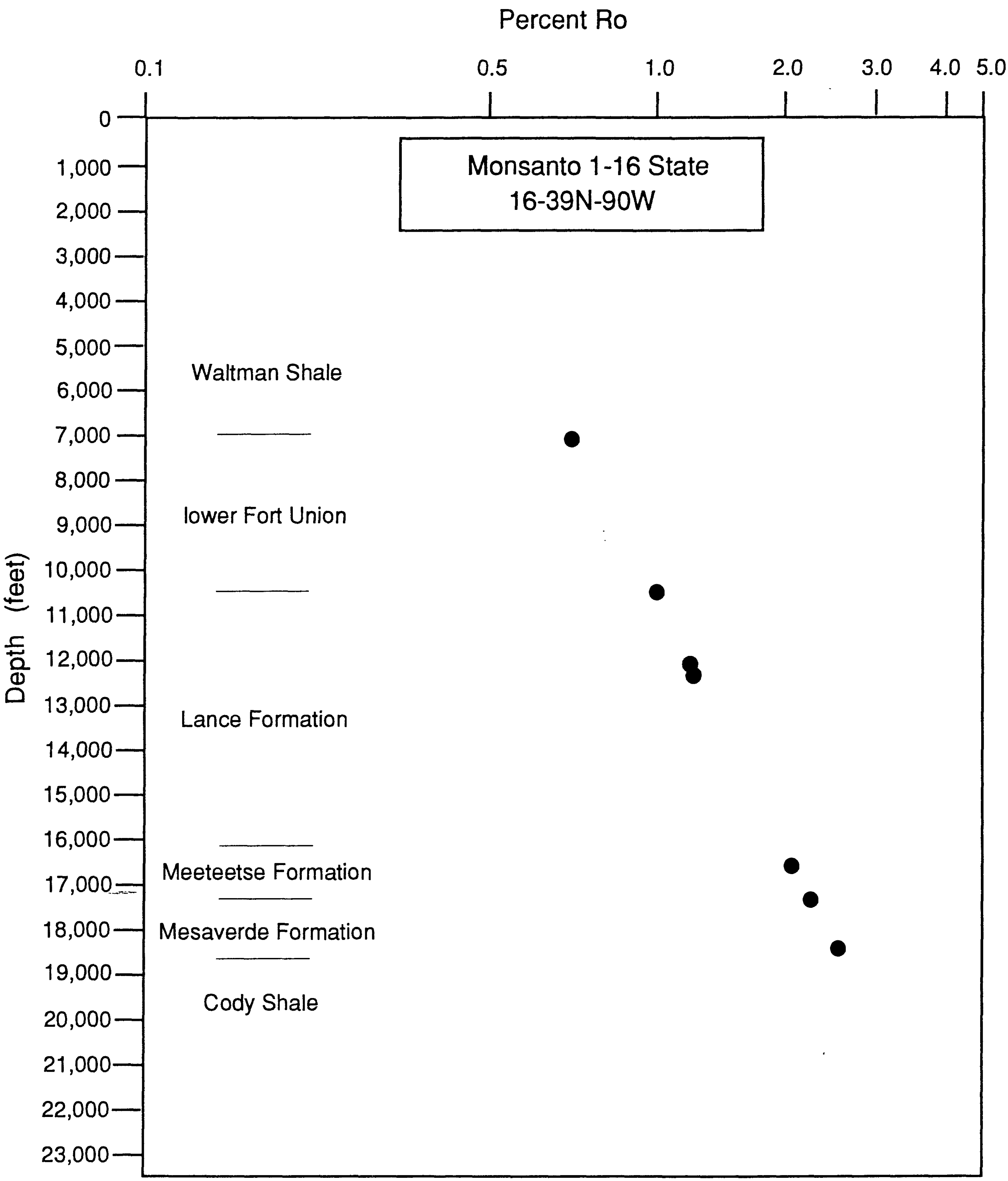

Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Monsanto
#1-6 Cevin
6-38N-89W
Waltman Shale
lower Fort Union
Lance Formation

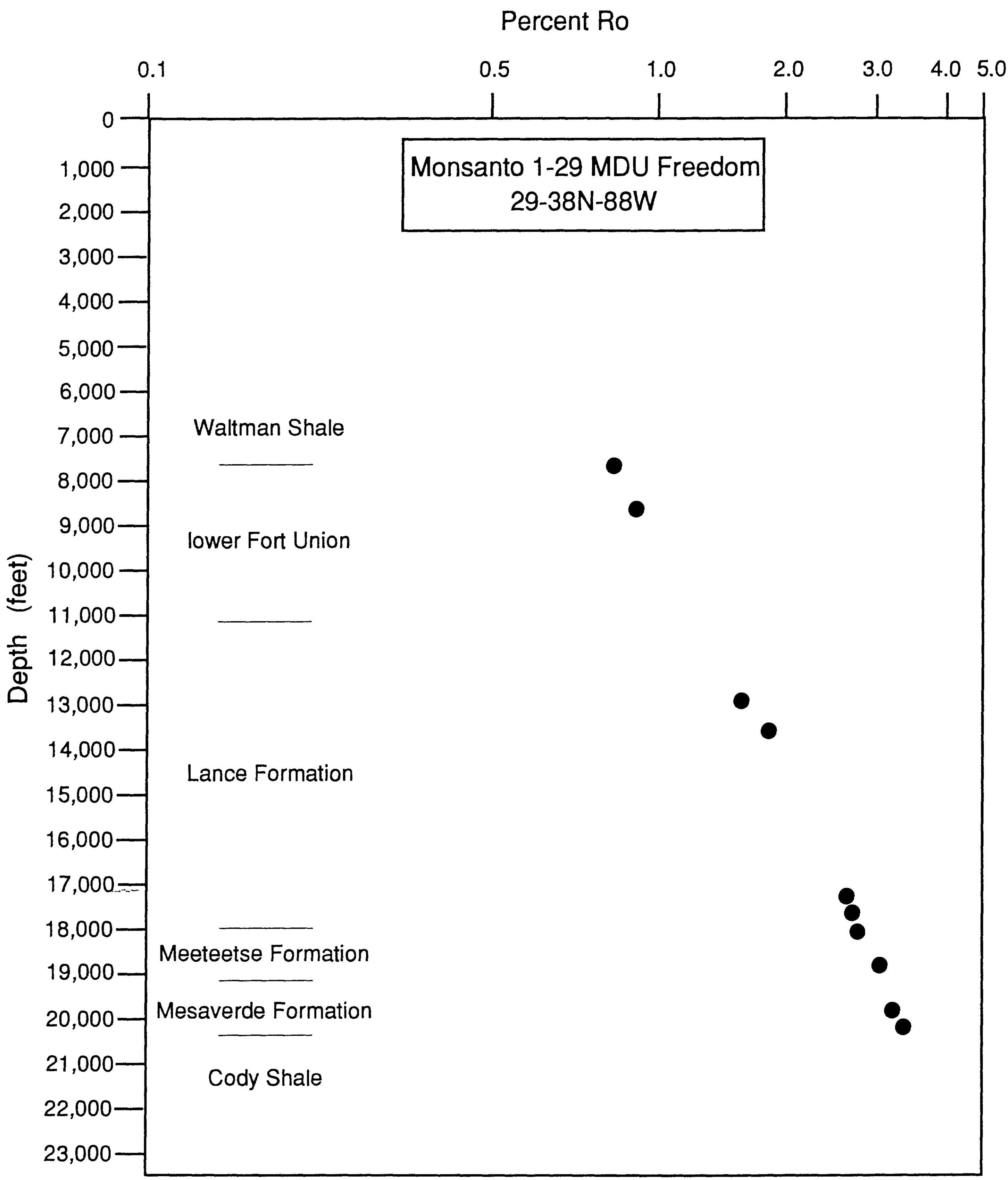

Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Monsanto #1-5 Bighorn
5-38N-90W
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Waltman Shale
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation
Cody Shale
Frontier-Cloverly
Formations
pre-Cretaceous



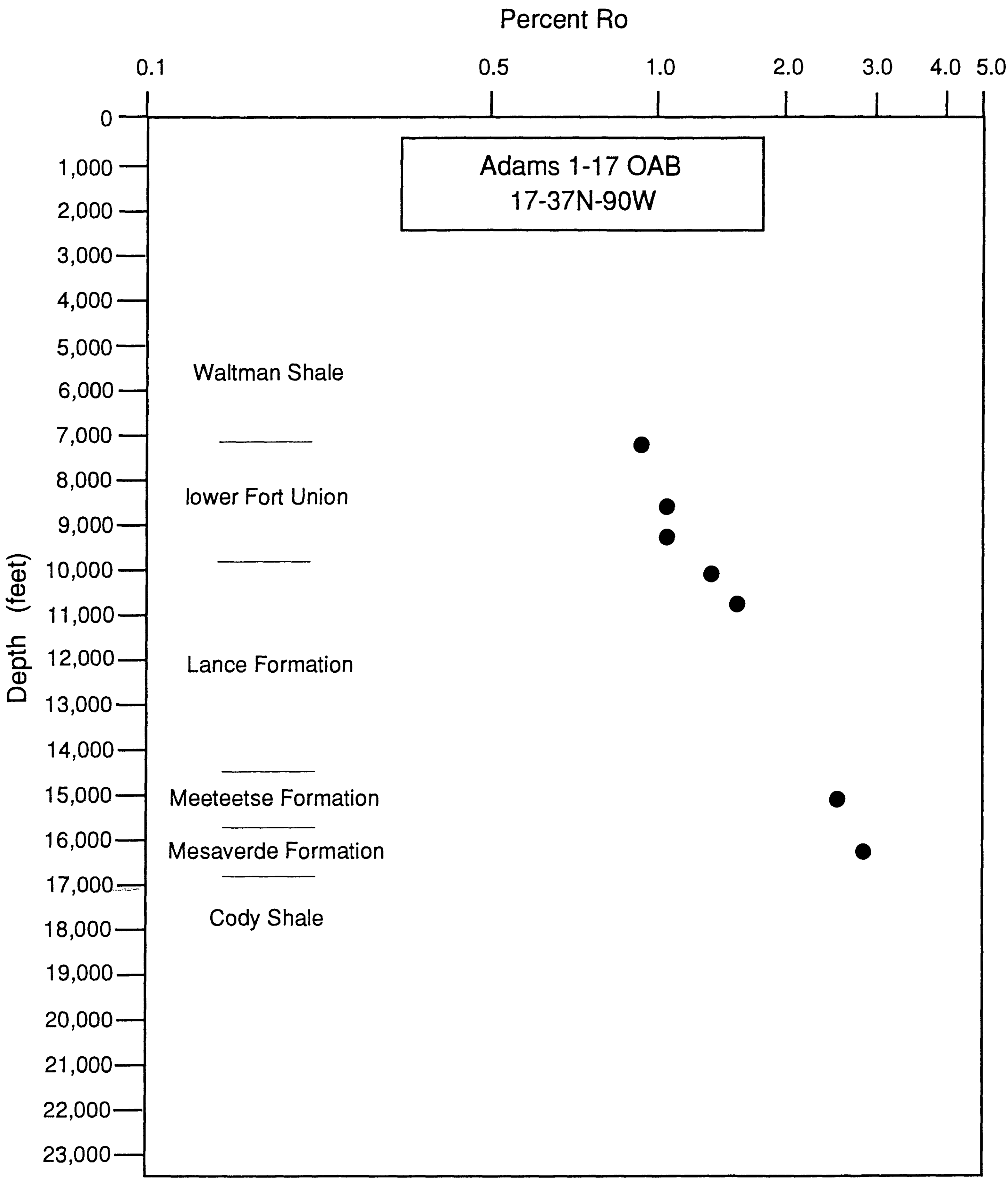
Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Union #F-14
Key Spring
14-35N-86W
Lance Formation
Meeteetse Formation
Lewis Shale
Mesaverde Formation

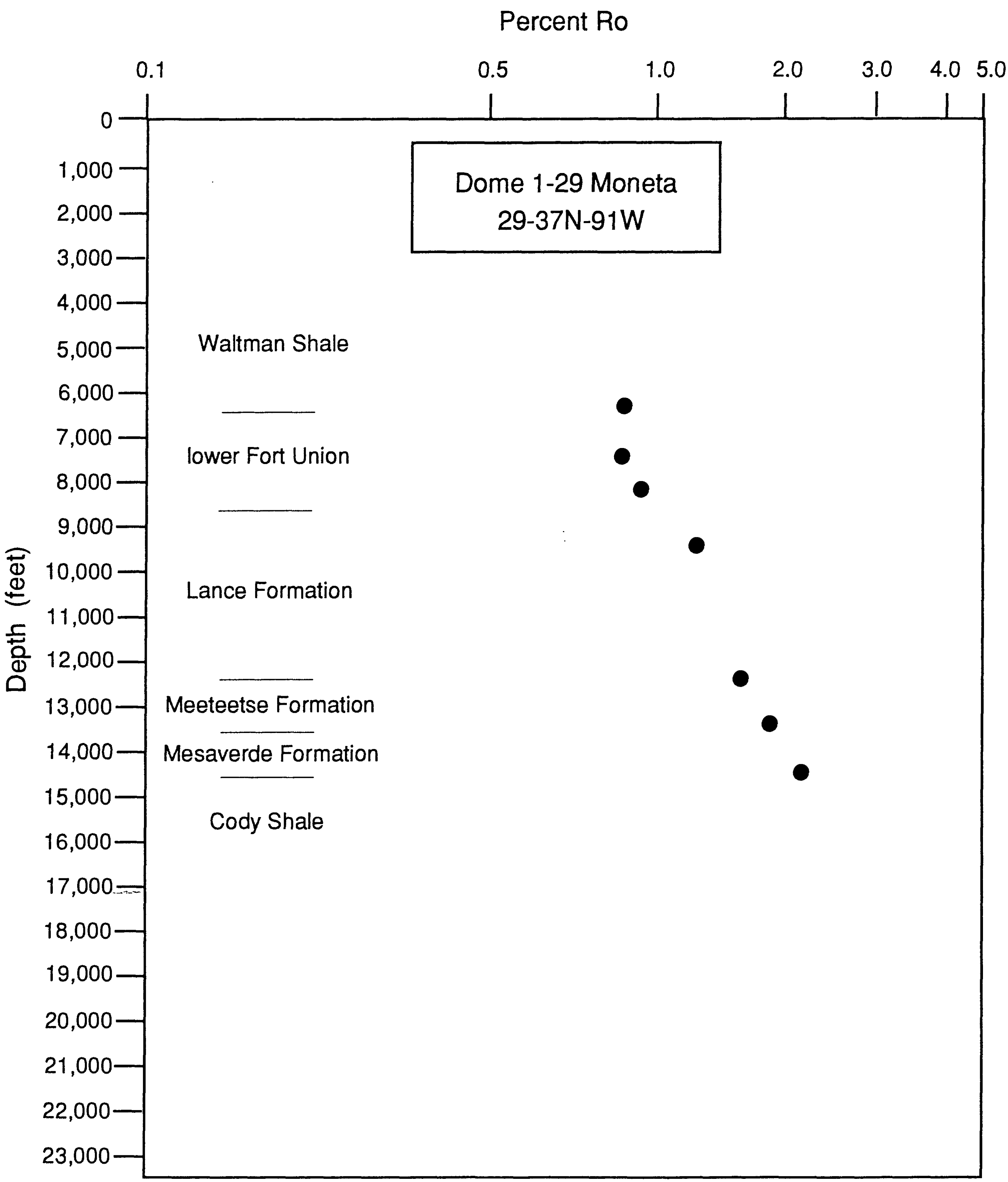

Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Coastal Bullfrog
3-8-36-86
8-36N-86W
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation


Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Monsanto 1-16 State
16-39N-90W
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Depth (feet)
Waltman Shale
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation
Cody Shale

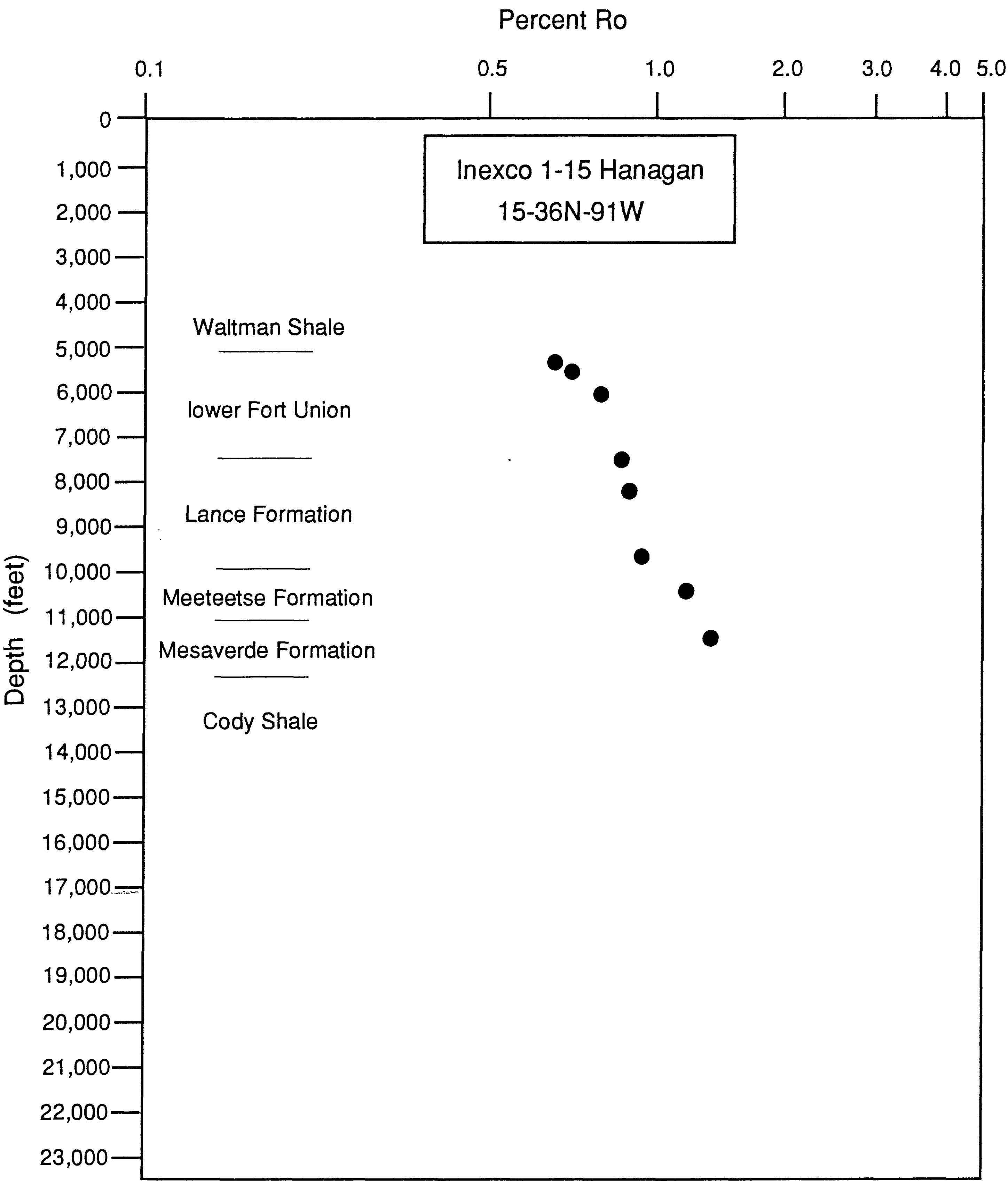


Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Monsanto 1-29 MDU Freedom
29-38N-88W
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Depth (feet)
Waltman Shale
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation
Cody Shale

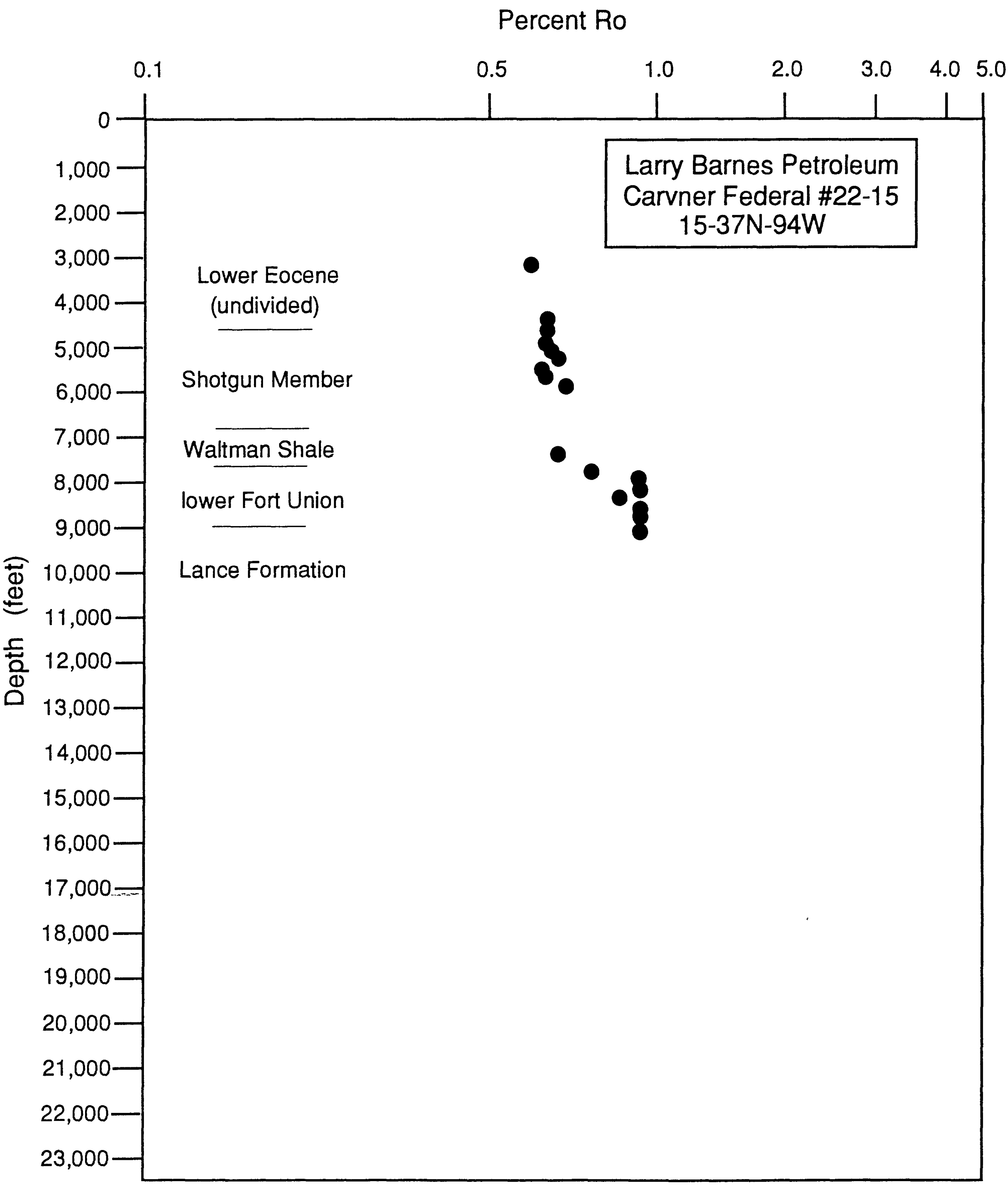

Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Adams 1-17 OAB
17-37N-90W
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Waltman Shale
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation
Cody Shale



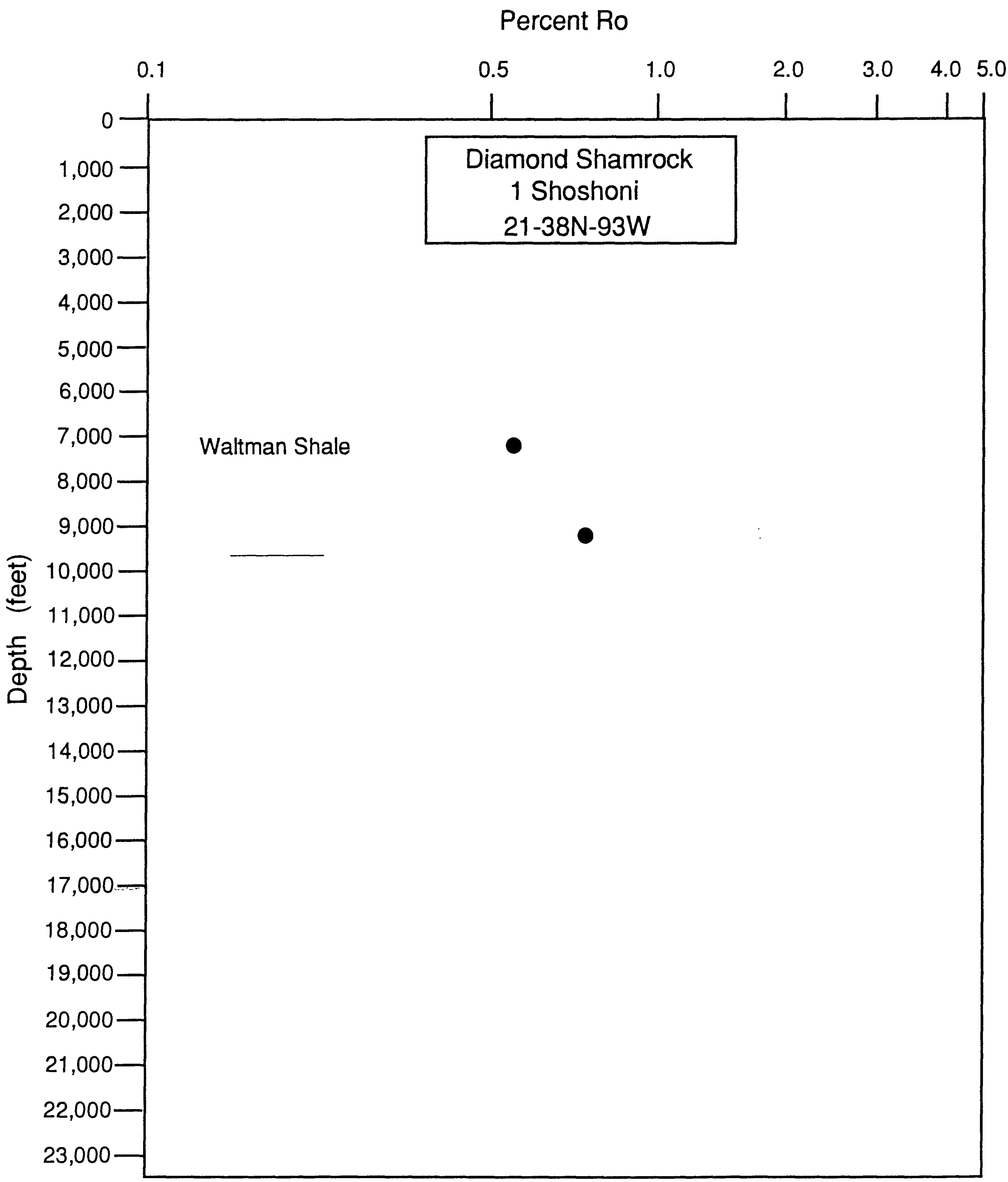
Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Dome 1-29 Moneta
29-37N-91W
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Waltman Shale
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation
Cody Shale



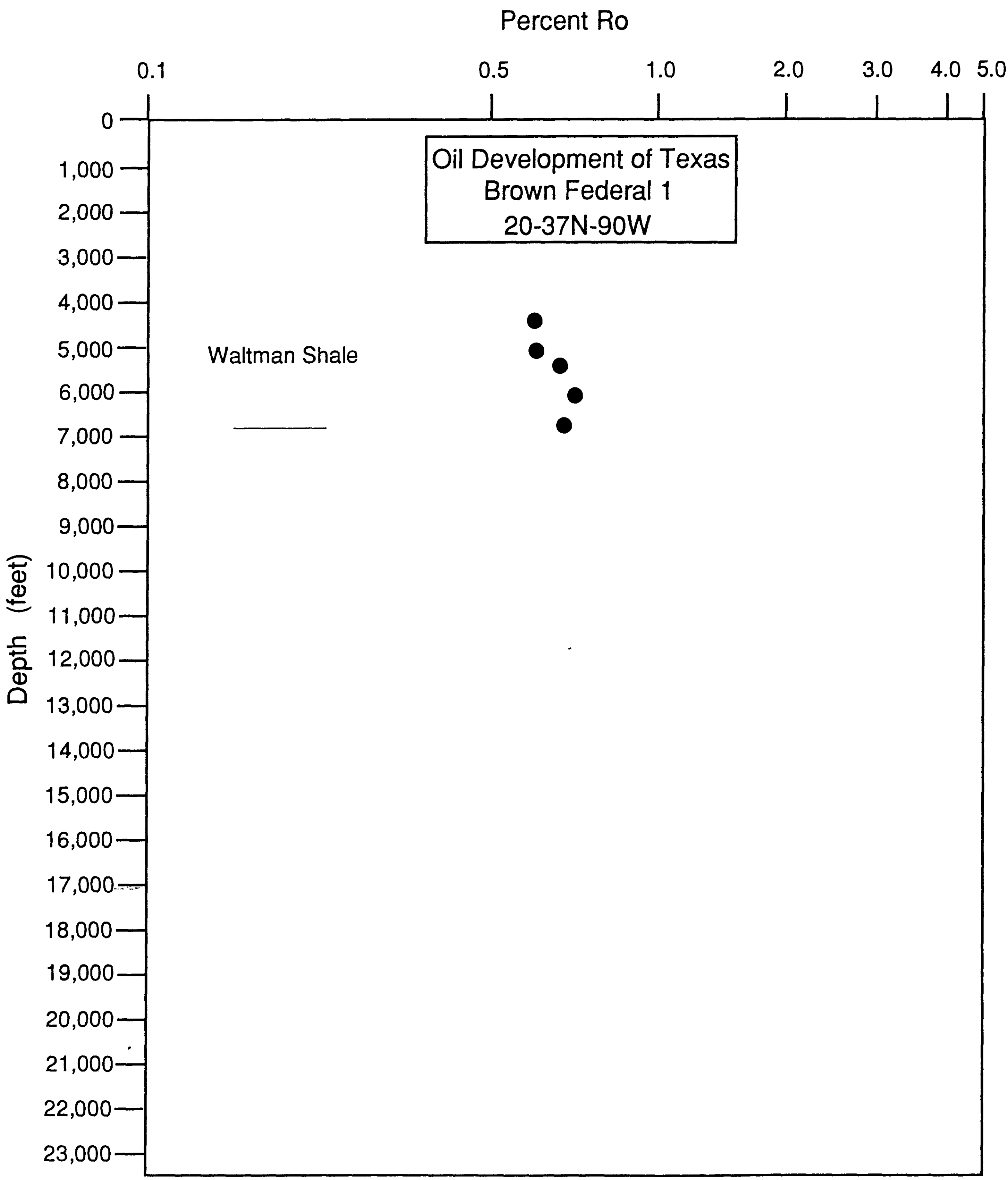
Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Inexco 1-15 Hanagan
15-36N-91W
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Waltman Shale
lower Fort Union
Lance Formation
Meeteetse Formation
Mesaverde Formation
Cody Shale

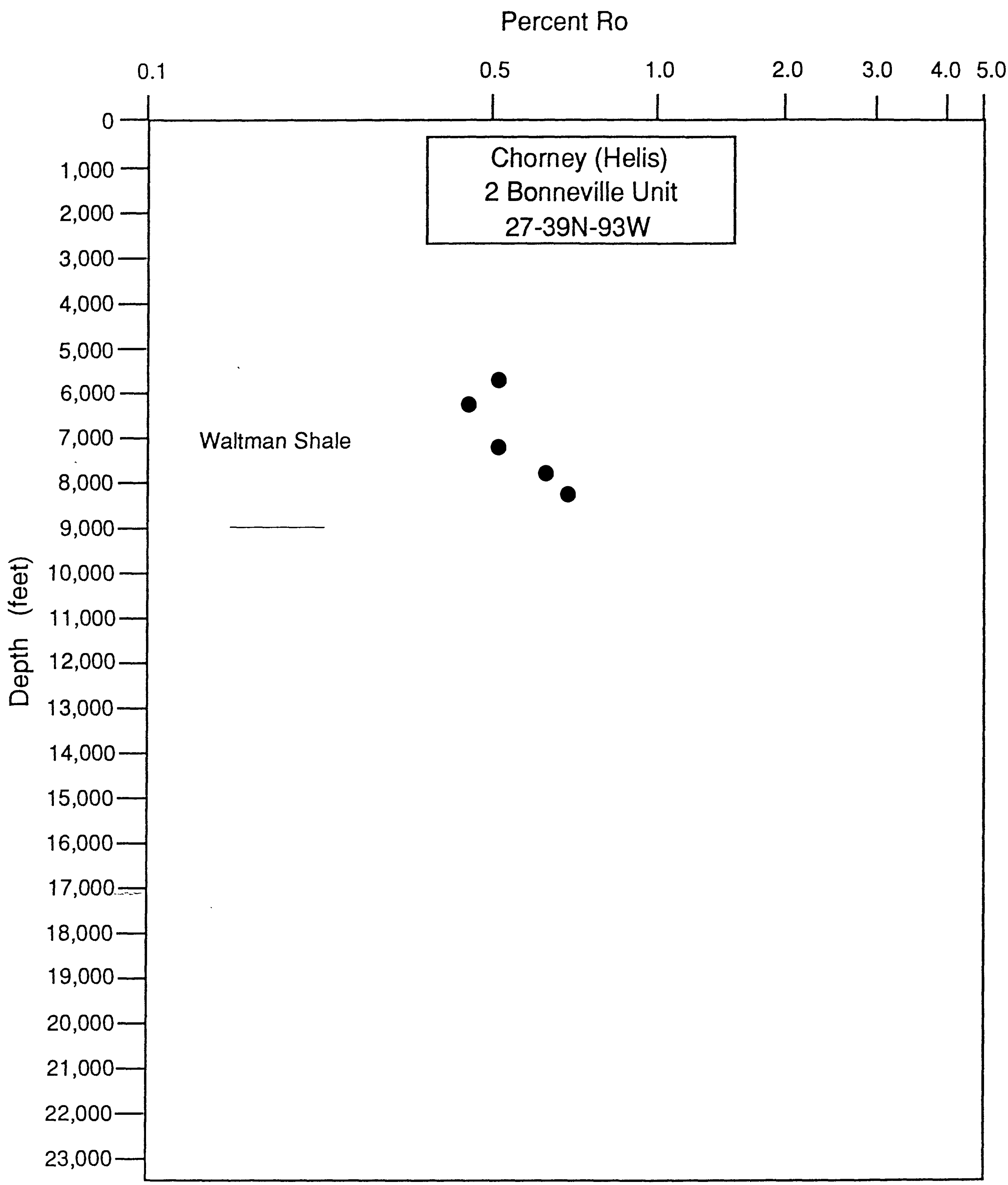


Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Depth (feet)
Larry Barnes Petroleum
Carvner Federal #22-15
15-37N-94W
Lower Eocene
(undivided)
Shotgun Member
Waltman Shale
lower Fort Union
Lance Formation



Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Diamond Shamrock
1 Shoshoni
21-38N-93W
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Waltman Shale


Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Oil Development of Texas
Brown Federal 1
20-37N-90W
Waltman Shale
Depth (feet)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000


Percent Ro
0.1
0.5
1.0
2.0
3.0
4.0
5.0
Chorney (Helis)
2 Bonneville Unit
27-39N-93W
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
Depth (feet)
Waltman Shale