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In situ bulk density and porosity estimates from borehole gravity data in limestones of the Madison Group, test well no. 1, Crook County, Wyoming

by

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Introduction

In 1975 the U.S. Geological Survey, in cooperation with the Old West Regional Commission, prepared a plan of study (U.S. Geological Survey, 1975) for evaluating the water-supply potential of limestone of the Madison Group and associated rocks. To obtain better subsurface hydrologic and geologic information it was recognized that Madison Group test wells would have to be drilled. This report tabulates the results of in situ bulk density and porosity determinations from borehole gravity data obtained in the first of these wells, test well no. 1.

Location and Drilling History

The Madison Group test well no. 1 is located in the NE 1/4 SE 1/4 sec. 15, T. 57 N., R. 65 W., Crook County, Wyoming (fig. 1). The drill site is approximately 30 mi (48 km) north of Hulett, Wyoming, and 50 mi (80 km) northwest of Belle Fourche, South Dakota.

Test well no. 1 was spudded in the Fall River Formation of Early Cretaceous age on July 16, 1976, and bottomed 60 ft (18 m) below the top of Precambrian rocks 4,341 ft (1,323 m) below land surface on October 13, 1976 (Blankennagel and others, 1977). 13 3/8-in. diameter casing was set in the well from the surface to 1,490 ft (454 m), and 9 5/8-in. casing from 1,390 ft (424 m) to 2,320 ft (707 m). The remainder of the well is 7 7/8-in. diameter open hole. Twenty-two cores were taken from selected intervals totaling 650 ft (198 m), with core recovery totaling 607 ft (185

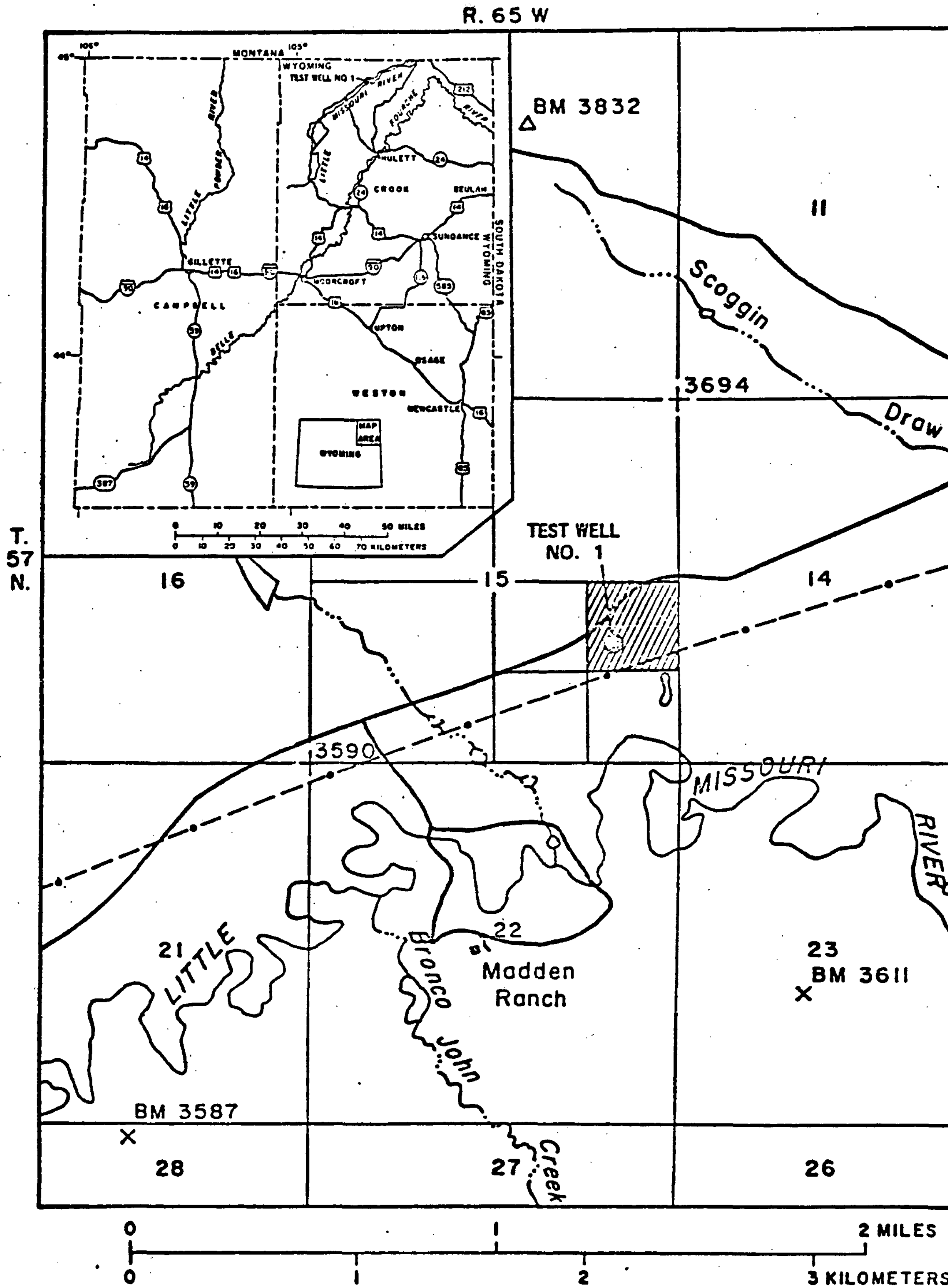

Figure 1.--Location of drilling site for Madison Group test well no. 1. (modified from Blankennagel and others, 1977)

m) (Blankennagel and others, 1977).

Stratigraphy

As previously noted, the rocks penetrated by the Madison Group test well no. 1 range in age from Early Cretaceous to Precambrian. The formation tops identified from well logs are shown in table 1. For a complete lithologic description of cuttings and cores the reader is referred to Blankennagel and others (1977, p. 35-48).

Borehole Gravity Data

Borehole gravity data were obtained by the U.S. Geological Survey in test well no. 1 during field studies conducted in June 1978. The U.S. Geological Survey-LaCoste and Romberg[1/] borehole gravity meter (McCulloh and others, 1967a; McCulloh and others, 1967b) was used in the logging program. The primary objective of this work was to obtain data for the determination of in situ formation densities and porosities utilizing an instrument not significantly affected by casing, borehole rugosity, or other near-borehole conditions.

[1/] Use of brand names in this report is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

Table 1. - Log tops, Madison Group test well No. 1, Crook County, Wyoming (modified from Blankennagel and others, 1977)

Stratigraphic Unit	Depth[1] ft	Depth[1] m
Sundance Formation	444	135
Hulett Sandstone Member	616	188
Gypsum Spring Formation	808	246
Spearfish Formation[2]	1294	394
Minnekahta Limestone	1500	457
Opeche Shale	1530	466
Minnelusa Formation		
Bell Sandstone unit (of drillers)	2280	695
Madison Group	2292	699
Mission Canyon Limestone	2482	757
Lodgepole Limestone	2754	839
Englewood Formation	3030	924
Stony Mountain Formation	3060	933
Red River Formation	3070	936
Winnipeg Formation		
Roughlock Sandstone Member[3]	3530	1076
Ice Box Shale member[3]	3542	1080
Deadwood Formation	3692	
Flathead Sandstone	4096	1248
Ellison (?) Formation[4]	4295	1309

[1]Datum for depth values is the Kelly bushing, 14 ft (3 m) above land surface.
[2]May include strata of Goose Egg Formation of some authors.
[3]Carlson (1958).
[4]Hosted and Wright (1923).

Table 2 records the data associated with each subsurface gravity station in the Madison Group test well. The column headings are explained in the following list:

Station number:	A numbering of borehole gravity stations in the order recorded.
Depth:	Depth of stations in feet and meters. Datum is the Kelly bushing elevation of 3,618 ft (1103 m) above sea level (14 ft (3 m) above land surface).
Time:	Greenwich mean time of each gravity reading.
Uncorrected gravity:	Observed gravity in milligals, referenced to an arbitrary base, uncorrected for tide, terrain, and drift effects.
Tide correction:	Theoretical correction for earth tides in milligals.
Terrain correction:	Terrain correction in milligals calculated for a density of 2.67 g/cm^3 out to a distance of 71,996 ft (21,944 m), corresponding to zone M of Hammer's terrain correction chart (Hammer, 1939).
Drift correction:	A correction for instrument drift derived from station reoccupations.
Corrected gravity:	Observed gravity in milligals, referenced to an arbitrary base, corrected for tide, terrain, and drift effects.

Table 2. Borehole gravity data, Madison Group Test well no. 1, Crook County, Wyoming. Logged June 24-25, 1978. Datum elevation 3618.0 ft (1102.8 m).

Station	Depth ft	Depth m	Time	Uncorrected Gravity	Tide correction	Terrain correction	Drift correction	Corrected Gravity
1	444.1	135.4	1646	94.906	- .041	- .176	- .032	94.657
2	13.7	4.2	1724	79.731	- .023	.075	- .011	79.772
3	444.1	135.4	1754	94.834	- .007	- .176	+ .006	94.657
4	525.0	160.0	1810	97.515	.002	- .143	+ .006	97.380
5	615.9	187.7	1826	100.549	.011	- .104	+ .006	100.462
6	700.0	213.4	1839	103.457	.019	- .068	+ .004	103.412
7	808.0	246.3	1853	107.093	.027	- .025	+ .003	107.098
8	1000.0	304.8	1906	112.698	.034	.046	0.000	112.778
9	1200.0	365.8	1919	118.680	.041	.113	- .002	118.832
10	1294.0	394.4	1934	121.308	.049	.141	- .005	121.493
11	1400.0	426.7	1945	124.127	.054	.172	- .007	124.346
12	1500.0	457.2	1956	126.863	.059	.200	- .009	127.113
13	1530.0	466.3	2005	127.534	.063	.208	- .010	127.795
14	1570.0	478.5	2015	128.535	.067	.218	- .012	128.808
15	1650.0	502.9	2031	131.559	.073	.239	- .014	131.857
16	1670.0	509.0	2039	132.340	.075	.244	- .016	132.643
17	1800.0	548.6	2053	136.756	.079	.276	- .019	137.092
18	2004.0	610.8	2107	142.975	.082	.324	- .023	143.358
19	2094.1	638.3	2119	145.495	.084	.344	- .025	145.898
20	2223.0	677.6	2131	148.855	.085	.372	- .025	149.287
21	2280.0	694.9	2137	150.528	.086	.385	- .022	150.977
22	2292.0	698.6	2145	150.782	.086	.387	- .020	151.235
23	2402.0	732.1	2154	153.592	.086	.410	- .017	154.071
24	2482.0	756.5	2202	155.719	.086	.426	- .013	156.218
25	2522.0	768.7	2210	156.823	.085	.434	- .011	157.331
26	2653.0	808.6	2221	160.682	.084	.460	- .008	161.218
27	2754.0	839.4	2231	163.387	.082	.480	- .004	163.945
28	2820.0	859.5	2241	165.100	.080	.492	- .001	165.671
29	2845.0	867.2	2250	165.721	.078	.497	+ .003	166.299
30	2900.0	883.9	2301	167.155	.075	.507	+ .006	167.743
31	2980.0	908.3	2312	169.285	.071	.522	+ .010	169.888
32	3028.0	922.9	2325	170.743	.067	.531	+ .014	171.335
33	3042.0	927.2	2337	171.128	.062	.533	+ .019	171.742
34	3060.1	932.7	2348	171.593	.057	.537	+ .022	172.209
35	3070.0	935.7	2356	171.862	.053	.538	+ .025	172.478
36	3102.0	945.5	0005	172.709	.048	.544	+ .027	173.328
37	3132.0	954.6	0014	173.567	.043	.550	+ .030	174.190
38	3272.1	997.3	0026	177.512	.037	.574	+ .034	178.157
39	3302.0	1006.4	0033	178.341	.033	.579	+ .035	178.988
40	3400.0	1036.3	0048	181.150	.024	.596	+ .038	181.808
41	3400.0	1036.3	0102	181.161	.015	.596	+ .039	181.811
42	3028.0	922.9	0121	170.773	.004	.531	+ .047	171.355
43	2653.0	808.6	0138	160.715	- .007	.460	+ .052	161.220
44	2223.0	677.6	0153	148.869	- .017	.372	+ .058	149.282
45	1650.0	502.9	0212	131.671	- .028	.239	+ .056	131.938
46	1500.0	457.2	0226	126.898	- .037	.200	+ .053	127.114
47	615.9	187.7	0251	100.567	- .050	- .104	+ .049	100.462

Density and Porosity Estimates

A detailed discussion of the relationship between subsurface gravity measurements and mass distributions within the earth is given by McCulloh (1966). Other literature on borehole-gravity-logging fundamentals and data interpretation include Smith (1950), Goodell and Fay (1964); Howell, Heintz, and Barry (1966); Beyer (1971); and Brown and others (1975).

In the absence of complicating factors, the in situ bulk density ( ), in grams per cubic centimeter between two observation points in a borehole, is given by the equation:

$$\rho = \frac{1}{4\pi k}(F - \Delta g/\Delta z), \qquad (1)$$

where k is the gravitational constant; F, the free-air vertical gradient of gravity; and $\Delta g/\Delta z$, the vertical gradient of gravity between discrete pairs of gravity measurements in the well. Assuming a "normal" free-air gravity gradient of 0.09406 mgal/ft, equation (1) becomes:

$$\rho = 3.686 - 39.185\ (\Delta g/\Delta z). \qquad (2)$$

Following an error analysis given by Schmoker (1977), the indeterminate density error for intervals where Δg is measured twice and averaged is:

$$\delta(\rho) = \pm\ 0.377/\Delta z, \qquad (3)$$

where Δz is the vertical separation (ft) of the borehole gravity measurements. For intervals where Δg is measured once, the density error is:

$$\delta(\rho) = \pm\ 0.461/\Delta z. \qquad (4)$$

An error in the assumed free-air gradient would bias all computed densities, but would not effect density changes from interval to interval.

Porosity values can also be computed from borehole gravity data using the equation:

$$\phi = (\rho-\rho_m)/(S_w\rho_w - \rho_m) \qquad (5)$$

where ρ is the bulk density calculated from equation 2, ρ_m is the grain density, S_w the water saturation, and ρ_w, the density of the interstitial water. Assuming no errors in ρ_m, S_w, and ρ_w, the indeterminate error in porosity is given by:

$$\delta(\phi) = \pm\ \delta(\rho)/S_w\rho_w - \rho_m) \qquad (6)$$

Table 3 shows the results of in situ bulk density and porosity calculations made from the gravity data obtained in the Madison test well. The bulk density values on this table were computed from equation (2). Equation (5) was used to obtain the porosity estimates. The value for the fluid saturation term in this equation (S_w) was assumed to be 1.0. A value of 1.0 g/cm^3 was also used for fluid density.

It should be noted that the bulk density and porosity values shown in table 3 are both dependent upon not only the accuracy of the borehole gravity data but also the accuracy of the assumed free-air gradient. For these calculations the so-called "normal" free-air gradient value of 0.09406 mgal/ft was used. An error of as little as 2 percent in this figure will result in an error of ± 0.074 g/cm^3 in the calculated density values and an error range of approximately ± 4 to ± 7 percent in the porosity values, dependent upon the matrix density assumed for the interval over which porosity calculations are made (Kososki, unpublished notes).

Table 3. Average bulk density and porosity estimates from borehole gravity data, Madison Group test well no. 1, Crook County, Wyoming.

BHGM Logged Interval ft	BHGM Logged Interval m	Bulk Density[1]	Matrix Density[2]	Porosity (percent)
13.7 - 444.1	4.2 - 135.4	2.33	2.40	5.0
441.1 - 525.0	135.4 - 160.0	2.37	2.50	8.7
525.0 - 615.9	160.0 - 187.7	2.36	2.50	9.3
615.9 - 700.0	187.7 - 213.4	2.31	2.63	19.6
700.0 - 808.0	213.4 - 246.3	2.35	2.63	17.2
808.0 - 1000.0	246.3 - 304.8	2.53	2.60	4.4
1000.0 - 1200.0	304.8 - 365.8	2.50	2.60	6.7
1200.0 - 1294.0	365.8 - 394.4	2.58	2.60	1.3
1294.0 - 1400.0	394.4 - 426.7	2.63	2.63	0.0
1400.0 - 1500.0	426.7 - 457.2	2.60	2.60	0.0
1500.0 - 1530.0	457.2 - 466.3	2.80	2.80	0.0
1530.0 - 1570.0	466.3 - 478.5	2.69	2.69	0.0
1570.0 - 1650.0	478.5 - 502.9	2.19	2.60	25.6
1650.0 - 1670.0	502.9 - 509.0	2.15	2.60	28.1
1670.0 - 1800.0	509.0 - 548.6	2.35	2.60	15.6
1800.0 - 2004.0	548.6 - 610.8	2.48	2.80	17.8
2004.0 - 2094.1	610.8 - 638.3	2.58	2.80	12.2
2094.1 - 2223.0	638.3 - 677.6	2.66	2.82	8.8
2223.0 - 2280.0	677.6 - 694.9	2.52	2.82	16.5
2280.0 - 2292.0	694.9 - 698.6	2.84	2.71	0.0
2292.0 - 2402.0	698.6 - 732.1	2.68	2.76	4.5
2402.0 - 2482.0	732.1 - 756.5	2.63	2.80	9.4
2482.0 - 2552.0	756.5 - 768.7	2.60	2.81	11.6
2552.0 - 2653.0	768.7 - 808.6	2.52	2.81	16.0
2653.0 - 2754.0	808.6 - 839.4	2.63	2.79	8.9
2754.0 - 2820.0	839.4 - 859.5	2.66	2.78	6.7
2820.0 - 2845.0	859.5 - 867.2	2.70	2.81	6.1
2845.0 - 2900.0	867.2 - 883.9	2.66	2.81	8.3
2900.0 - 2980.0	883.9 - 908.3	2.64	2.81	9.4
2980.0 - 3028.0	908.3 - 922.9	2.49	2.80	17.2
3028.0 - 3042.0	922.9 - 927.2	2.60	2.80	11.1
3042.0 - 3060.1	927.2 - 932.7	2.67	2.80	7.2
3060.1 - 3070.0	932.7 - 935.7	2.62	2.80	10.0
3070.0 - 3102.0	935.7 - 945.5	2.64	2.80	8.9
3102.0 - 3132.0	945.5 - 954.6	2.56	2.80	13.3
3132.0 - 3272.1	954.6 - 997.3	2.58	2.81	12.7
3272.1 - 3302.0	997.3 - 1006.4	2.60	2.82	12.1
3302.0 - 3400.0	1006.4 - 1036.3	2.56	2.82	14.3

[1]Bulk density values calculated from borehole gravity data using equation (2).
[2]Matrix density values based on core measurements and/or lithologic descriptions from well cuttings.

Table 4 and figure 2 compare the borehole-gravity-derived porosity estimates with measured core porosities. The cored intervals in the Madison Group test well no. 1 and the average porosity values obtained from core measurements over these intervals are shown in table 4. Since most of the intervals over which borehole gravity observations and the resulting porosity calculations were made do not coincide precisely with the cored intervals, a graphical comparison between the two data sets is shown in figure 2.

Table 4. Average matrix density and porosity estimates from core samples, Madison Group test well no. 1, Crook County, Wyoming. (modified from Blankennagel and others, 1977)

Formation	Cored Interval ft	Cored Interval m	Matrix Density g/cm^3	Porosity (percent)
Sundance	650.0 - 680.0	198.1 - 207.3	2.63	21.3
Minnekahta Ls.	1502.0 - 1528.0	457.8 - 465.7	2.76	7.5
Minnelusa-Amsden	2087.0 - 2117.0	636.1 - 645.3	2.82	5.3
Bell Sandstone	2280.0 - 2289.0	694.9 - 697.7	2.71	12.0
Madison Gp	2292.5 - 2335.0	698.8 - 711.7	2.75	3.5
	2335.0 - 2388.0	711.7 - 727.9	2.76	10.6
	2455.0 - 2474.0	748.3 - 754.1	2.82	4.8
Mission Canyon Ls.	2474.0 - 2500.0	754.1 - 762.0	2.81	14.0
Mission Canyon Ls.	2500.0 - 2513.0	762.0 - 766.0	2.81	12.2
Mission Canyon Ls.	2513.0 - 2525.0	766.0 - 769.6	2.80	21.5
Mission Canyon Ls.	2632.0 - 2646.0	802.2 - 806.5	2.82	20.9
Mission Canyon Ls.	2646.0 - 2676.0	806.5 - 815.6	2.79	24.6
Lodgepole Ls.	2760.0 - 2820.0	841.2 - 859.5	2.78	9.1
Lodgepole Ls.	2820.0 - 2845.0	859.5 - 867.2	2.81	10.7
Madison, Devonian & Stony Mountain	3015.0 - 3070.0	919.0 - 935.7	2.80	15.7
Red River	3102.0 - 3132.0	945.5 - 954.6	2.80	17.6
Red River	3272.0 - 3302.0	997.3 - 1006.4	2.82	13.8
Red River	3491.0 - 3521.0	1064.1 - 1073.2	2.76	2.2
Winnipeg	3610.0 - 3643.0	1100.3 - 1110.4	2.62	
Flathead Ss	4145.0 - 4175.0	1263.4 - 1272.5	2.67	15.6
Flathead Ss & Ellison?	4292.0 - 4326.0	1308.2 - 1318.6	2.65	6.1
Ellison?	4346.0 - 4355.0	1324.7 - 1327.4	2.89	1.4

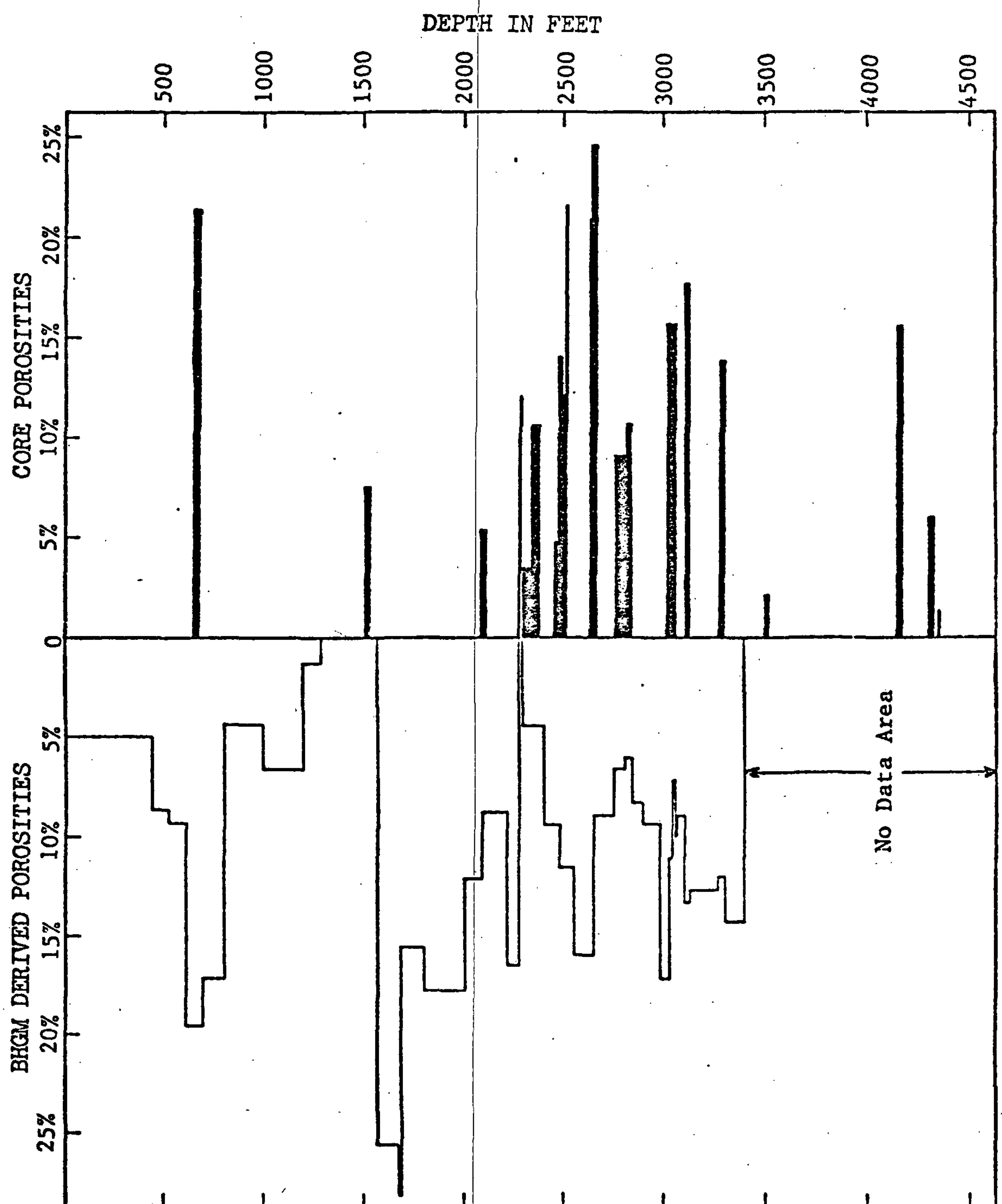

Figure 2.—Comparison of BHGM derived porosities and core porosities, Madison Group test well no. 1, Crook County, Wyoming

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