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In-Situ bulk density estimates and interval vs. borehole gravity data in the Madison Group test well no. 2, Custer County, Montana

by

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This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards.

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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 determinations from borehole gravity data obtained in the Madison Group test well no. 2.

Location and Drilling History

Test well no. 2 is located in the SE 1/4 SE 1/4 sec. 18, T. 1 N., R. 54 E., Custer County, Montana (fig. 1). The drill site is approximately 6 mi (10 km) northeast of Powderville, Montana, and 55 mi (89 km) southeast of Miles City, Montana.

Test well no. 2 was spudded in the Skull Creek Formation of Late Cretaceous age on November 17, 1976, and bottomed 94 ft (29 m) below the top of Precambrian rocks 9,378 ft (2,858 m) below land surface on March 23, 1977 (Brown and others, 1977). A 13 3/8-in. (0.34 m) diameter casing was set in the well from the surface to 4,661 ft (1,421 m), and 9 5/8-in. (0.24 m) casing from 4,519 ft (1,377 m) to 6,487 ft (1,977 m). It is 8 1/2-in. (0.22 m) open hole from 6,487 ft (1,977 m) to 8,422 ft (2,567 m). The well is sealed off below 8,422 ft (2,567 m) by two cement plugs--one from 9,378 ft (2,858 m) to 9,084 ft (2,769 m) and the other from 8,884 ft (2,708 m) to 8,422 ft (2,567

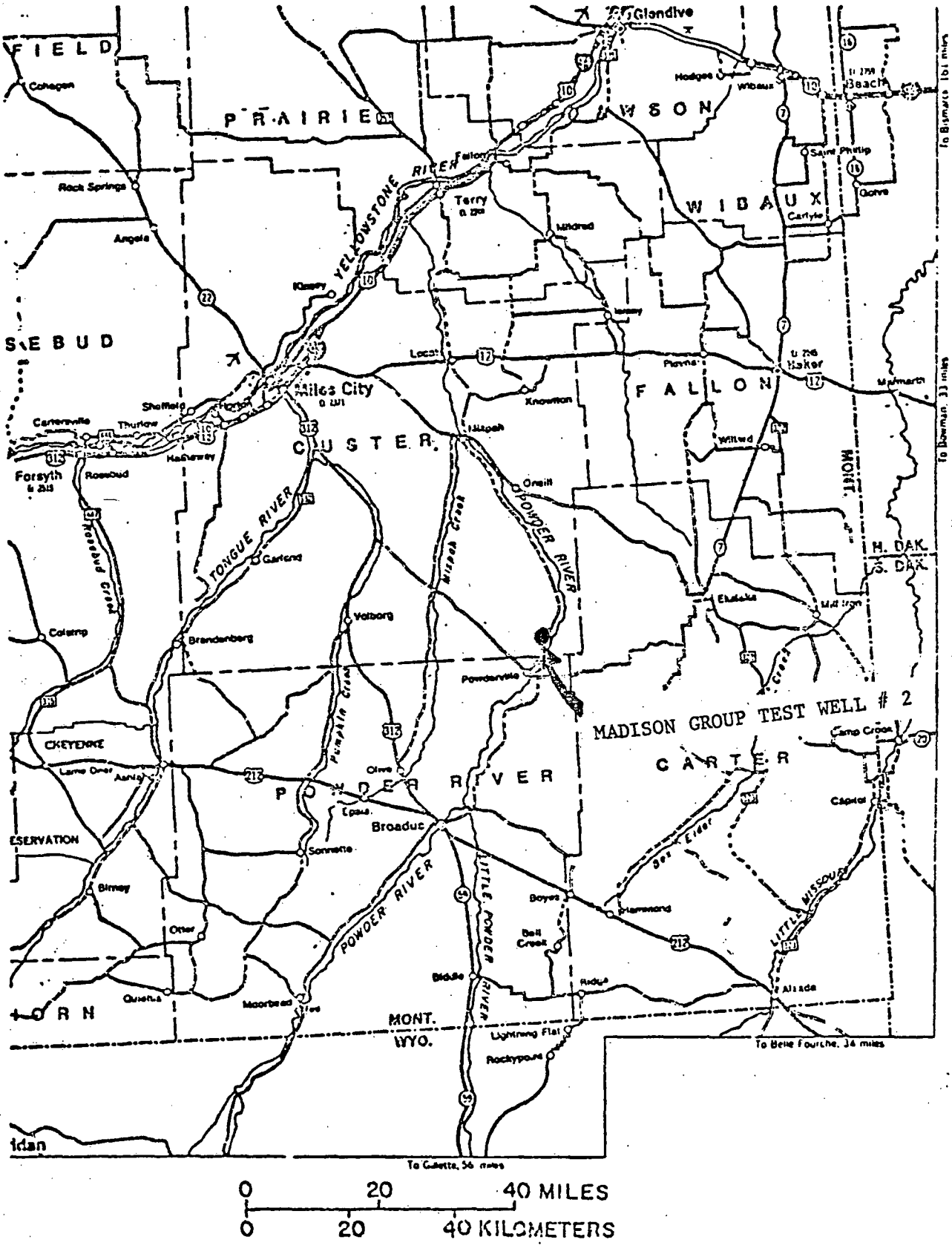

Figure 1.--Location of drilling site for Madison Group test well no. 2 (Brown and others, 1977).

m) below land surface--to isolate the upper part from Cambrian sandstones that contain saline water and gas shows. Nineteen cores were taken from selected intervals totaling 754 ft (230 m), with core recovery totaling 722.4 ft (220.2 m) (Brown and others, 1977).

Stratigraphy

The rocks penetrated by the Madison Group test well no. 2 range in age from Late Cretaceous to Precambrian. The formation tops identified from well logs are shown in table 1. A complete lithologic description of cuttings and cores is given by Brown and others (1977, p. 35-53).

Borehole Gravity Data

Borehole gravity data were obtained by the U.S. Geological Survey in test well no. 2 in June 1979 using the U.S. Geological Survey-LaCoste and Romberg[1] borehole gravity meter (McCulloh and others, 1967a; McCulloh and others, 1967b). The primary objective of this work was to obtain data for the determination of in-situ formation densities utilizing an instrument not significantly affected by casing, borehole rugosity, or other near-borehole conditions. Unfortunately, due to caving problems, logging operations were not possible below a depth of 4,372 ft (1,333 m), a depth well above the Madison Group objective.

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[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. 2, Custer County, Montana* (Brown and others, 1977).

Formation and age	Log Depth[1]	
	ft	m
CRETACEOUS		
Bearpaw Shale	420	128
Judith River	1168	356
Clagget	1284	391
Eagle	1672	510
Shannon Sandstone Member	1840	561
Telegraph Creek	1852	564
Niobrara	2764	842
Greenhorn	3406	1038
Mowry	4081	1244
Newcastle	4282	1305
Skull Creek	4388	1337
Colorado Silt	4556	1389
Logger TD	4656	1419
Driller TD	4682	1427
Strap	4677	1426
Dakota	4680	1426
JURASSIC		
Morrison	4926	1501
Swift	5095	1553
Spearfish	5692	1735
Minnekahta	6024	1836
Opeche	6034	1839
Minnelusa	6094	1857
MISSISSIPPIAN		
Madison	6484	1976
Logger TD	6567	2002
Driller TD	6559	1999
M-12	6640	2024
M-8.5	6742	2055
Lodgepole	7182	2189
M-3	7374	2248
DEVONIAN		
Three Forks-Jefferson	7662	2335
SILURIAN		
Interlake	7846	2391
ORDOVICIAN		
Stony Mountain-Gunton Member	7977	2431
Penitentiary Shale Member	8050	2454
Red River	8106	2471
Roughlock Sandstone	8558	2608
Icebox Shale	8623	2628
Winnipeg Sandstone	8667	2642
CAMBRIAN		
Deadwood	8676	2644
Gros Ventre Shale	8876	2705
Flathead Sandstone	9224	2811
PRECAMBRIAN	9300	2835
Total Depth	9394	2863

[1]Depths are from kelly bushing (2,809 ft above sea level), 16 ft above land surface

The data associated with each subsurface gravity station in the Madison Group test well is recorded in table 2. 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.
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 mg/m^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:	No drift correction applied.
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. 2, Custer County, Montana*

[Logged June 26, 1979. Datum elevation 2793 (851 m).]

Station	Depth ft	Depth m	Time GMT	Uncorrected Gravity	Tide correction	Terrain correction	Corrected Gravity
1	1062.0	323.7	0648	43.741	- .049	0.386	44.078
2	1092.0	332.8	0656	44.816	- .048	0.401	45.169
3	1152.0	351.1	0714	46.968	- .045	0.430	47.353
4	1268.0	386.5	0728	51.043	- .044	0.486	51.485
5	1284.0	391.4	0742	51.597	- .043	0.493	52.047
6	1656.0	504.7	0754	64.626	- .042	0.664	65.248
7	1672.0	509.6	0802	65.230	- .042	0.671	65.859
8	1824.0	556.0	0814	70.218	- .042	0.736	70.912
9	1836.0	559.6	0822	70.607	- .042	0.742	71.307
10	1852.0	564.5	0829	71.142	- .042	0.748	71.848
11	1953.0	595.3	0837	74.435	- .043	0.791	75.183
12	1983.0	604.4	0843	75.377	- .043	0.803	76.137
13	2748.0	837.6	0858	99.831	- .044	1.092	100.879
14	3390.0	1033.3	0916	120.268	- .047	1.301	121.522
15	3904.0	1189.9	0929	136.862	- .049	1.448	138.261
16	3944.0	1202.1	0935	138.159	- .050	1.459	139.568
17	4065.0	1239.0	0944	142.014	- .051	1.491	143.454
18	4094.0	1247.9	0949	142.962	- .052	1.498	144.408
19	4234.0	1290.5	0956	147.675	- .054	1.534	149.137
20	4266.0	1300.3	1002	148.658	- .055	1.547	150.150
21	4284.0	1305.8	1008	149.237	- .056	1.547	150.728
22	4314.0	1314.9	1014	150.150	- .057	1.554	151.647
23	4327.0	1318.9	1019	150.540	- .058	1.557	152.039
24	4339.0	1322.5	1025	150.926	- .060	1.560	152.426
25	4353.0	1326.8	1030	151.381	- .061	1.564	152.884
26	4372.0	1332.6	1038	152.046	- .062	1.568	153.552
27	4372.0	1332.6	1043	152.053	- .064	1.568	153.557
28	4284.0	1305.8	1051	149.224	- .065	1.547	150.706
29	3390.0	1033.3	1111	120.213	- .069	1.301	121.445
30	1062.0	323.7	1149	43.692	- .076	0.386	44.002

Density 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 includes Smith (1950), Goodell and Fay (1964); Howell, Heintz, and Barry (1966); and Beyer (1971).

In the absence of complicating factors, the in situ bulk density (ρ), in megagrams per cubic meter, 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 measured 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:

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

According to Schmoker (1978), 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.

Table 3 shows in-situ bulk-densities computed from equation (2) using the borehole gravity data of Table 2.

The bulk-density values shown in table 3 depend not only upon the accuracy of the borehole gravity data but also upon the accuracy of the assumed free-air gradient. In this report the so-called "normal" free-air gradient value of 0.09406 mgal/ft was used.

Table 3.--*Average bulk density estimates from borehole gravity data, Madison Group test well no. 2, Custer County, Montana*

BHGM Logged Interval		Δg	Bulk Density
ft	m		g/cm^3
1062.0 - 1092.0	323.7 - 332.8	1.091	2.26
1092.0 - 1152.0	332.8 - 351.1	2.184	2.26
1152.0 - 1268.0	351.1 - 386.5	4.132	2.29
1268.0 - 1284.0	386.5 - 391.4	0.562	2.31
1284.0 - 1656.0	391.4 - 504.7	13.201	2.30
1656.0 - 1672.0	504.7 - 509.6	0.611	2.19
1672.0 - 1824.0	509.6 - 556.0	5.053	2.38
1824.0 - 1836.0	556.0 - 559.6	0.395	2.40
1836.0 - 1852.0	559.6 - 564.5	0.541	2.36
1852.0 - 1953.0	564.5 - 595.3	3.335	2.39
1953.0 - 1983.0	595.3 - 604.4	0.954	2.44
1983.0 - 2748.0	604.4 - 837.6	24.742	2.42
2748.0 - 3390.0	837.6 - 1033.3	20.643	2.43
3390.0 - 3904.0	1033.3 - 1189.9	16.739	2.41
3904.0 - 3944.0	1189.9 - 1202.1	1.307	2.41
3944.0 - 4065.0	1202.1 - 1239.0	3.886	2.43
4065.0 - 4094.0	1239.0 - 1247.9	0.954	2.40
4094.0 - 4234.0	1247.9 - 1290.5	4.729	2.36
4234.0 - 4266.0	1290.5 - 1300.3	1.013	2.45
4266.0 - 4284.0	1300.3 - 1305.8	0.578	2.43
4284.0 - 4314.0	1305.8 - 1314.9	0.919	2.49
4314.0 - 4327.0	1314.9 - 1318.9	0.392	2.50
4327.0 - 4339.0	1318.9 - 1322.5	0.387	2.42
4339.0 - 4353.0	1322.5 - 1326.8	0.458	2.40
4353.0 - 4372.0	1326.8 - 1332.6	0.668	2.31

References

Beyer, L. A., 1971, The vertical gradient of gravity in vertical and near-vertical boreholes: Stanford University Ph.D. thesis, 217 p.

Brown, D. L., Blankennagel, R. K., Busby, J. F., and Lee, R. W., 1977, Preliminary data for Madison Limestone test well no. 2, SE 1/4 SE 1/4 sec. 18, T. 1 N., R. 54 E., Custer County, Montana: U.S. Geological Survey Open-File Report 77-863, 135 p.

Goodell, R. R., and Fay, C. H., 1964, Borehole gravity meter and its application: Geophysics, v. 29, no. 5, p. 774-782.

Hammer, S., 1939, Terrain corrections for gravimeter stations: Geophysics, v. 4, no. 3, p. 184-193.

Howell, L. G., Heintz, K. O., and Barry, A., 1966, The development and use of a high-precision downhole gravity meter: Geophysics, v. 31, no. 4, p. 764-772.

McCulloh, T. H., 1966, The promise of precise borehole gravimetry in petroleum exploration and exploitation: U.S. Geological Survey Circular 531, 12 p.

McCulloh, T. H., LaCoste, L. J. B., Schoellhamer, J. E., and Pampeyan, E. H., 1967a, The U.S. Geological Survey-LaCoste and Romberg precise borehole gravimeter system--Instrumentation and support equipment, *in* Geological Survey research 1967: U.S. Geological Survey Professional Paper 575-D, p. D92-D100.

McCulloh, T. H., Schoellhamer, J. E., Pampeyan, E. H., and Parks, H. B., 1967b, The U.S. Geological Survey-LaCoste and Romberg precise borehole gravimeter system--Test results, *in* Geological Survey research 1967: U.S. Geological Survey Professional Paper 575-D, p. D101-D112.

Schmoker, J. W., 1978, Accuracy of borehole gravity data: Geophysics, v. 43, no. 3, p. 538-542.

Smith, N. J., 1950, The case for gravity data from boreholes: Geophysics, v. 15, no. 4, p. 606-636.

U.S. Geological Survey, 1975, Plan of study of the hydrology of the Madison Limestone and associated rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Open-File Report 75-631, 35 p.