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In-situ bulk-density estimates from borehole gravity data in the Madison Group test well no. 3, Yellowstone 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 limestones of the Madison Group and associated rocks. To obtain better subsurface hydrologic and geologic information several test wells that penetrate the Madison Group were drilled. This report tabulates the results of in-situ bulk-density determinations from borehole gravity data obtained in the Madison Group test well no. 3.

Location and Drilling History

Test well no. 3 is located in NW 1/4 SE 1/4 sec. 35, T. 2 N., R. 27 E., Yellowstone County, Montana (fig. 1). The drill site is approximately 15 mi (24 km) northeast of Billings, Montana, and about 1 1/2 mi (2 km) from Huntley, Montana.

Test well no. 3 was spudded in alluvium on August 15, 1978, and bottomed 48 ft (15 m) below the top of Precambrian rocks 7,175 ft (2,187 m) below land surface on November 16, 1978 (Blankennagel and others, 1979). 13 3/8-in. (0.34 m) diameter casing was set in the well from the surface to 979 ft (298 m), 9 5/8-in. (0.24 m) casing from 810 ft (247 m) to 4,298 ft (1,310 m), and 7-in. casing from 4,115 ft (1,254 m) to 5,942 ft (1,811 m). Twenty cores were taken from selected intervals totaling 594.8 ft (181.3 m), with core recovery totaling 520.3 ft (158.6 m) (Blankennagel and others, 1979).

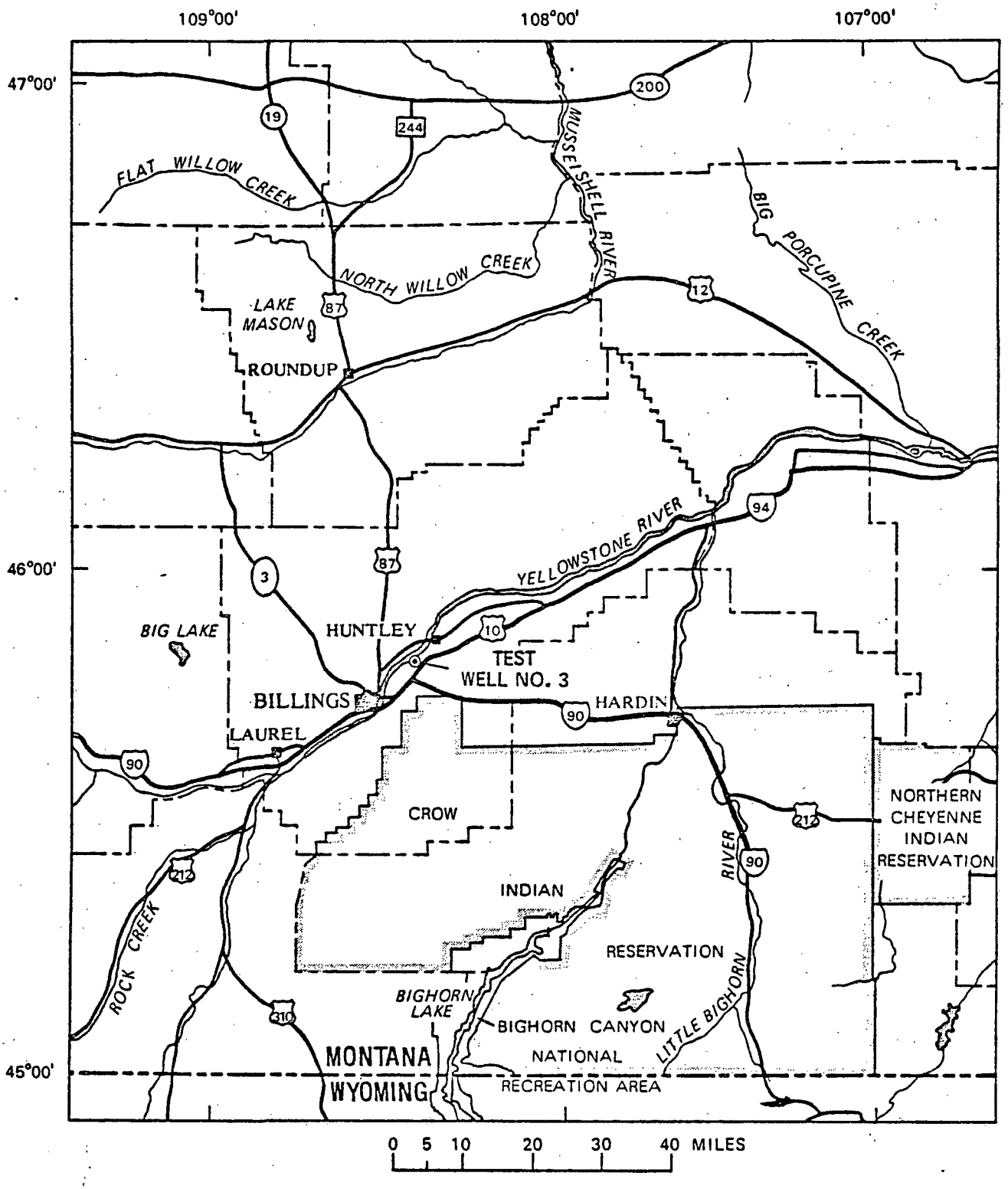

Figure 1.--Location of Madison Group test well no. 3, (from Blankennagel and others, 1979)

Stratigraphy

The rocks penetrated by the Madison Group test well no. 3 range in age from Quaternary 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 Blankennagel and others (1979, p. 36-54).

Borehole Gravity Data

Borehole gravity data were obtained by the U.S. Geological Survey in test well no. 3 in October, 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.

[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. 3, Yellowstone County, Montana (modified from Blankennagel and others, 1979)

Formation and age	Log Depth[1] ft	m
CRETACEOUS		
Eagle	245	74.7
Telegraph Creek	700	213.4
Shannon	789	240.5
Colorado	823	250.9
Niobrara	938	285.9
Frontier	1796	547.4
(Normal fault, 90′ cut out)	2143	653.2
Mowry	2216	675.4
Muddy	2457	748.9
Muddy (?)	2833	863.5
Skull Creek	2866	879.7
Dakota (silt)	2993	912.3
Dakota (sand)	3123	951.9
Kootenai	3208	977.8
Lakota	3390	1033.3
JURASSIC		
Morrison	3442	1049.1
Swift	3650	1112.5
Rierdon	3788	1154.6
(Normal fault, 90′ cut out)	3830	1167.4
Piper (shale)	3876	1181.4
Piper (limestone)	3942	1201.5
TRIASSIC AND PERMIAN		
Spearfish	4046	1233.2
PENNSYLVANIAN		
Tensleep	4128	1258.2
Amsden	4178	1273.5
MISSISSIPPIAN		
Madison (upper part)	4300	1310.6
Madison (Lodgepole)	4986	1519.7
DEVONIAN		
Undifferentiated rocks	5368	1636.2
ORDOVICIAN		
Stony Mountain	5612	1710.5
Red River	5724	1744.7
CAMBRIAN		
Snowy Range	5963	1817.5
Dry Creek	6454	1967.2
Pilgrim	6535	1991.9
Gros Ventre	6642	2024.5
Flathead	7073	2155.9
PRECAMBRIAN		
Gneiss	7142	2176.9

[1]Datum for depth values is the Kelly bushing, 15.5 ft (4.7 m) 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:	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. 3, Yellowstone County, Montana

Logged October 17-18, 1979. Datum elevation 3039.8 ft (926.5 m)

Station	Depth ft	Depth m	Time GMT	Uncorrected Gravity	Tide correction	Terrain correction	Drift correction	Corrected Gravity
1	907.0	276.5	1902	43.912	.013	2.293	.070	46.288
2	1284.5	391.5	1922	54.733	.005	2.620	.068	57.426
3	1765.0	538.0	1942	68.414	- .004	2.955	.067	71.432
4	3359.0	1023.8	2025	114.397	- .025	3.725	.063	118.160
5	3411.0	1039.7	2033	115.970	- .029	3.747	.062	119.750
6	4097.0	1248.8	2058	133.914	- .041	3.987	.058	137.918
7	4129.5	1258.7	2106	134.650	- .045	3.997	.057	138.659
8	4147.0	1264.0	2111	135.111	- .047	4.003	.057	139.124
9	4154.5	1266.3	2116	135.295	- .050	4.005	.056	139.306
10	4160.5	1268.1	2121	135.470	- .052	4.007	.055	139.480
11	4196.5	1279.1	2128	136.302	- .055	4.018	.054	140.319
12	4269.0	1301.2	2134	138.012	- .058	4.041	.053	142.048
13	4302.5	1311.4	2141	138.952	- .060	4.052	.051	142.995
14	4310.5	1313.8	2148	139.129	- .063	4.054	.050	143.170
15	4332.5	1320.5	2155	139.696	- .066	4.061	.048	143.739
16	4345.5	1324.5	2200	140.066	- .068	4.065	.047	144.110
17	4367.5	1331.2	2208	140.588	- .070	4.071	.045	144.634
18	4384.5	1336.4	2215	141.038	- .072	4.077	.043	145.086
19	4469.5	1362.3	2223	143.066	- .075	4.102	.041	147.134
20	4489.5	1368.4	2234	143.429	- .078	4.108	.038	147.497
21	4514.5	1376.0	2241	143.895	- .079	4.115	.036	147.967
22	4534.5	1382.1	2247	144.269	- .080	4.121	.034	148.344
23	4634.5	1412.6	2302	146.469	- .083	4.150	.029	150.565
24	4724.5	1440.0	2313	148.473	- .084	4.176	.026	152.591
25	4734.5	1443.1	2319	148.667	- .084	4.179	.024	152.786
26	4755.6	1449.5	2325	149.094	- .085	4.185	.022	153.216
27	4787.5	1459.2	2333	149.827	- .085	4.194	.019	153.955
28	4806.5	1465.0	2339	150.266	- .085	4.199	.017	154.397
29	4825.7	1470.9	2347	150.784	- .084	4.204	.014	154.918
30	4833.5	1473.3	2353	151.018	- .084	4.206	.012	155.152
31	4856.5	1480.3	2400	151.572	- .083	4.213	.009	155.711
32	4874.5	1485.7	0009	152.028	- .082	4.218	.005	156.169
33	4934.5	1504.0	0017	153.464	- .081	4.234	.001	157.618
34	4934.5	1504.0	0021	153.470	- .080	4.234	- .001	157.623
35	4787.5	1459.2	0032	149.856	- .078	4.194	- .019	153.953
36	4489.5	1368.4	0044	143.519	- .075	4.108	- .038	147.514
37	4302.5	1311.4	0057	139.110	- .071	4.052	- .051	143.040
38	4129.5	1258.7	0106	134.795	- .068	3.997	- .057	138.667
39	3359.0	1023.8	0131	114.572	- .058	3.725	- .063	118.176
40	907.0	276.5	0230	44.100	- .031	2.293	- .070	46.292

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 and others (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 in feet 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.--In-situ bulk densities computed from borehole gravity data, Madison Group test well no. 3, Yellowstone County, Montana

BHGM Logged Interval ft	BHGM Logged Interval m	Δg	Bulk Density g/cm^3
907.0 - 1284.5	276.5 - 391.5	11.138	2.53
1284.5 - 1765.0	391.5 - 538.0	14.006	2.54
1765.0 - 3359.0	538.0 - 1023.8	46.728	2.54
3359.0 - 3411.0	1023.8 - 1039.7	1.590	2.49
3411.0 - 4097.0	1039.7 - 1248.8	18.168	2.65
4097.0 - 4129.5	1248.8 - 1258.7	0.741	2.79
4129.5 - 4147.0	1258.7 - 1264.0	0.465	2.64
4147.0 - 4154.5	1264.0 - 1266.3	0.182	2.73
4154.5 - 4160.5	1266.3 - 1268.1	0.174	2.55
4160.5 - 4196.5	1268.1 - 1279.1	0.839	2.77
4196.5 - 4269.0	1279.1 - 1301.2	1.729	2.75
4269.0 - 4302.5	1301.2 - 1311.4	0.947	2.58
4302.5 - 4310.5	1311.4 - 1313.8	0.175	2.83
4310.5 - 4332.5	1313.8 - 1320.5	0.569	2.67
4332.5 - 4345.5	1320.5 - 1324.5	0.371	2.57
4345.5 - 4367.5	1324.5 - 1331.2	0.524	2.75
4367.5 - 4384.5	1331.2 - 1336.4	0.452	2.64
4384.5 - 4469.5	1336.4 - 1362.3	2.048	2.74
4469.5 - 4489.5	1362.3 - 1368.4	0.363	2.97
4489.5 - 4514.5	1368.4 - 1376.0	0.470	2.95
4514.5 - 4534.5	1376.0 - 1382.1	0.377	2.95
4534.5 - 4634.5	1382.1 - 1412.6	2.221	2.82
4634.5 - 4724.5	1412.6 - 1440.0	2.026	2.80
4724.5 - 4734.5	1440.0 - 1433.1	0.195	2.92
4734.5 - 4755.6	1433.1 - 1449.5	0.430	2.89
4755.6 - 4787.5	1449.5 - 1459.2	0.739	2.78
4787.5 - 4806.5	1459.2 - 1465.0	0.442	2.77
4806.5 - 4825.7	1465.0 - 1470.9	0.521	2.62
4825.7 - 4833.5	1470.9 - 1473.3	0.234	2.51
4833.5 - 4856.5	1473.3 - 1480.3	0.559	2.73
4856.5 - 4874.5	1480.3 - 1485.7	0.458	2.69
4874.5 - 4934.5	1485.7 - 1504.0	1.449	2.74

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