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Basic Data and Preliminary Density and Porosity Profiles from Three Borehole Gravity Surveys Made in the Kuparuk River and Prudhoe Bay Oil fields, Alaska

by

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INTRODUCTION

The first-ever high-precision borehole gravity (BHG) measurements through permafrost and possible gas hydrate-bearing sedimentary rocks were made by the Geological Survey on the Alaskan North Slope during 1987. Three borehole gravity (BHG) surveys were made as part of a study, sponsored by the Department of Energy, to investigate the distribution and physio-chemical environment of gas hydrate thought to occur in the shallow subsurface beneath parts of the Arctic coastal plain in the Prudhoe Bay-Kuparuk River region of Alaska. Two BHG surveys were made in plugged-back, idle wells in the Kuparuk River oil field, and one survey was made in a plugged-back, idle well at the west end of the Prudhoe Bay oil field (Fig. 1, Table 1).

The BHG surveys were undertaken, along with eight high-precision temperature surveys (Lachenbruch and others, 1988), to investigate selected formation properties (and the thermal regime) in the region where gas hydrate has been encountered in industry wells (Kvenvolden and McMenamin, 1980; Collett, 1983). The direct products of the BHG surveys are accurate, large-volume measurements of formation density and overburden stress through the interval of gas hydrate stability within and beneath the permafrost. Reliable large-volume estimates of formation porosity also can be calculated from the BHG data if accurate pore-fluid and grain (or matrix) density information is independently available. Interpretation of the BHG surveys to better understand the environment of gas-hydrate occurrence and the mass properties of permafrost will be the subject of future papers. This report presents only the basic data, density profiles and preliminary porosity values from the surveys. Appendix A provides a brief summary of the borehole gravity method.

BASIC DATA AND PRELIMINARY DENSITY AND POROSITY PROFILES

The following data set for each borehole gravity survey includes a density profile and a tabulation of the borehole gravity data (Figs. 2, 3, 4, 5, 6; Tables 2, 3, 4). Density values have been calculated with the assumptions that anomalous gravity effects are negligibly small, rock layers are horizontal and of great lateral extent, and boreholes are vertical. Maximum likely errors in calculated density, explained in Appendix A, are displayed as error bars on the plotted profiles. These error estimates do not include uncertainties due to anomalous gravity (ΔGg) effects which are believed to be negligibly small for the three BHG surveys in the Kuparuk River and Prudhoe Bay oil fields.

Preliminary porosity values have been calculated from the BHG density data with the simple assumption that grain (or matrix) density is 2.65 g/cm^3 and pore-fluid density is 1.00 g/cm^3. More accurate values of pore-fluid and grain (or matrix) density may be used in equation 3, Appendix A, to calculate revised values of porosity. Different assumptions about errors also can be used with equation 4, Appendix A, to calculate revised values of porosity error. More accurate porosity determinations will appear in a future paper.

An explanation of columns 1 through 20 of Tables 2, 3 and 4 follows:

Column 1

Sequential numbers for borehole gravity stations from shallow to deep.

Column 2

Elevation of borehole gravity station calculated from surveyed ground level elevation at well site (feet). Values are not corrected for borehole deviation from the vertical.

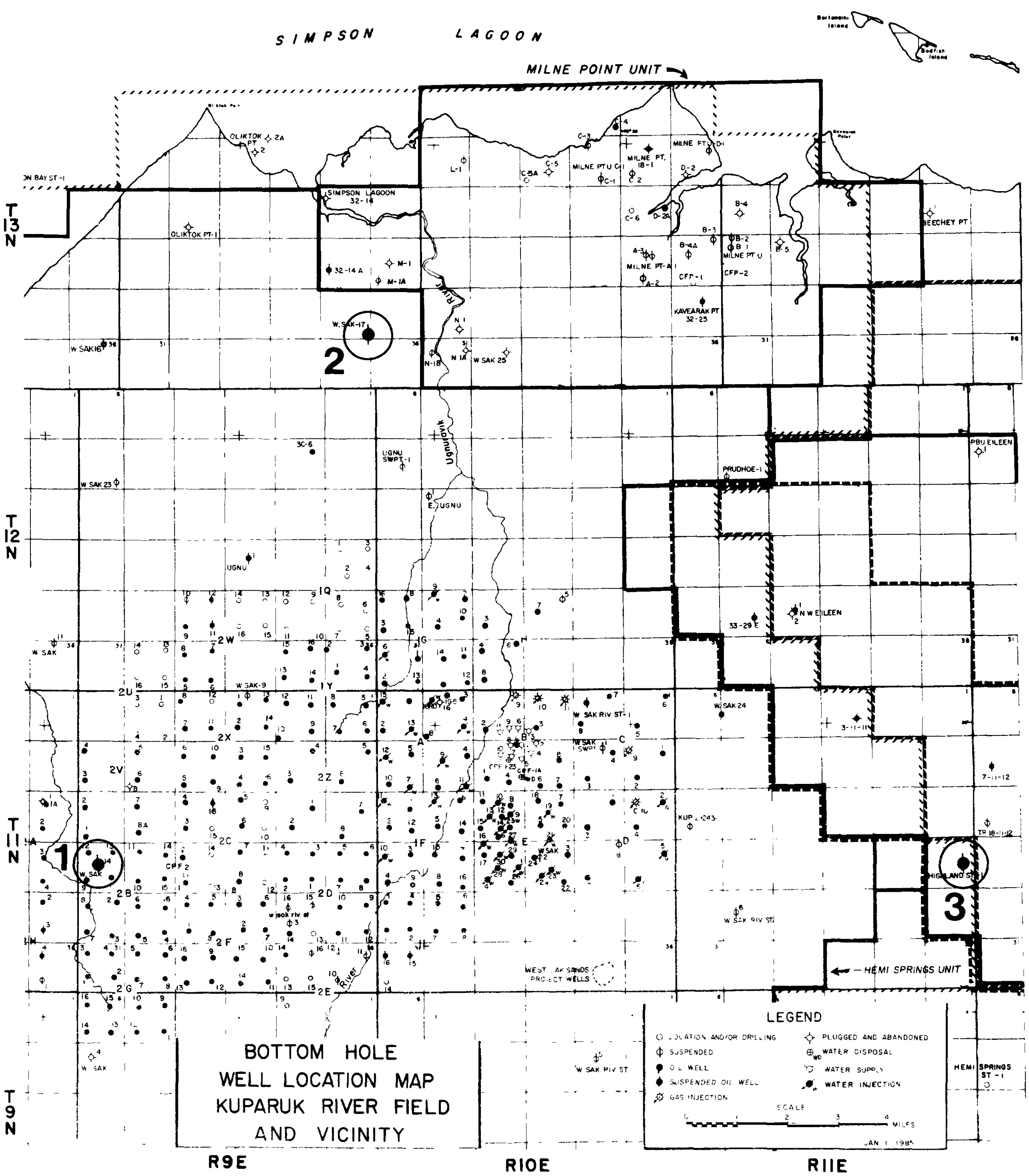

Figure 1. Index map of Kuparuk River, Milne Point and westernmost Prudhoe Bay oil fields showing locations of borehole gravity surveys: 1) West Sak 14, 2) West Sak 17, and 3) Highland State 1. Map modified from Alaska Oil and Gas Conservation Committee (1984).

Table 1. Surveyed intervals and number of gravity stations and readings for three wells in which borehole gravity measurements were made.

Well[1]	Interval Surveyed	Number of Gravity Stations	Number of Gravity Readings
West Sak 14 19-11N-9E, ADL 25655 API 50-029-20419	50-3,450 ft	77	124
West Sak 17 26-13N-9E, ADL 25519 API 50-029-20542	118-4,398 ft	70	136
Highland State 1 24-11N-11E, ADL 28245 API 50-029-20199	314-2,423 ft	34	69

[1]Includes well name and number, section-township-range, Alaska Division of Lands lease number, and American Petroleum Institute well number.

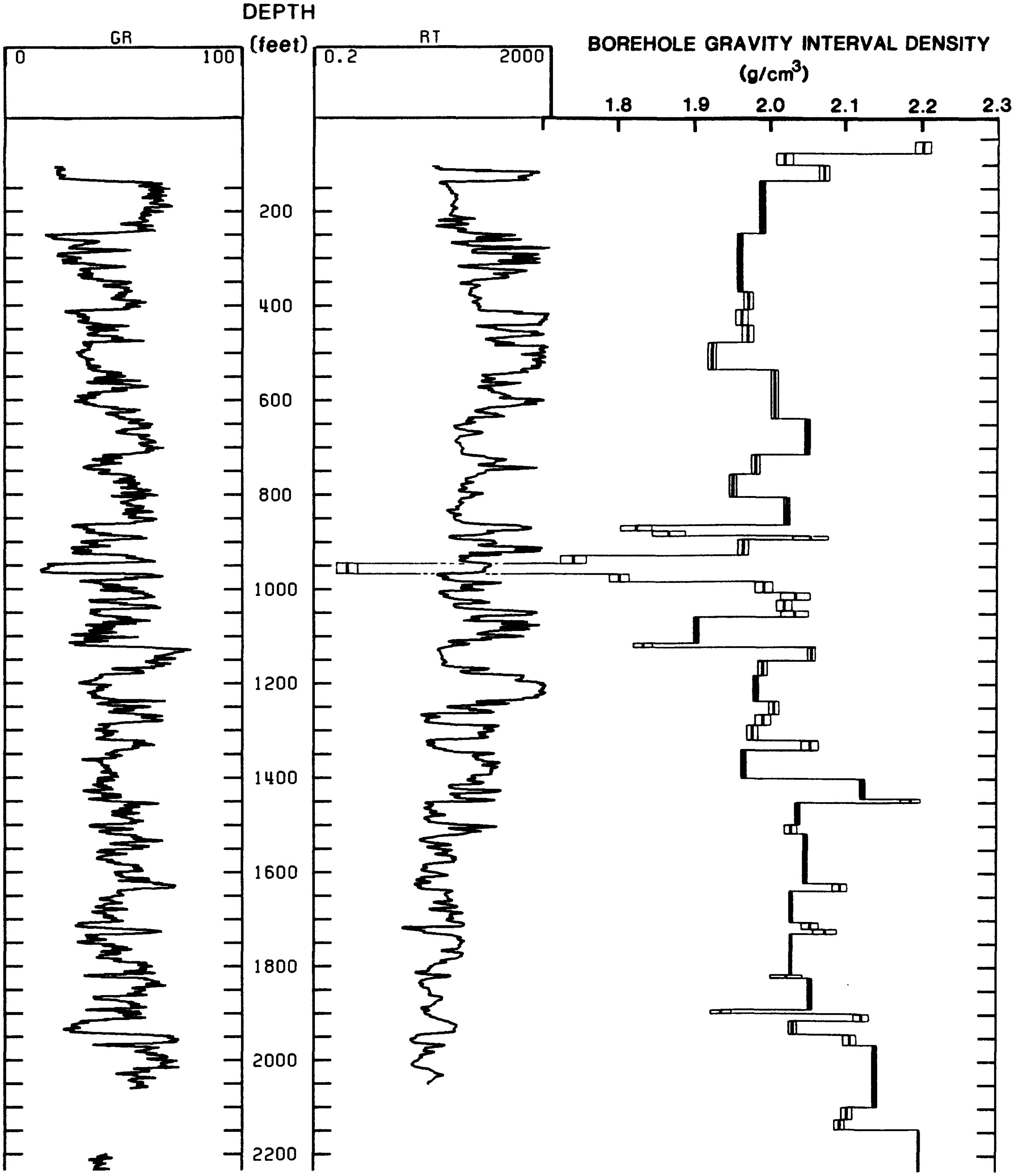

Figure 2. BHG interval density profile for West Sak 14 well, Kuparuk River oil field. Natural gamma ray (left) and resistivity (center) logs also are shown.

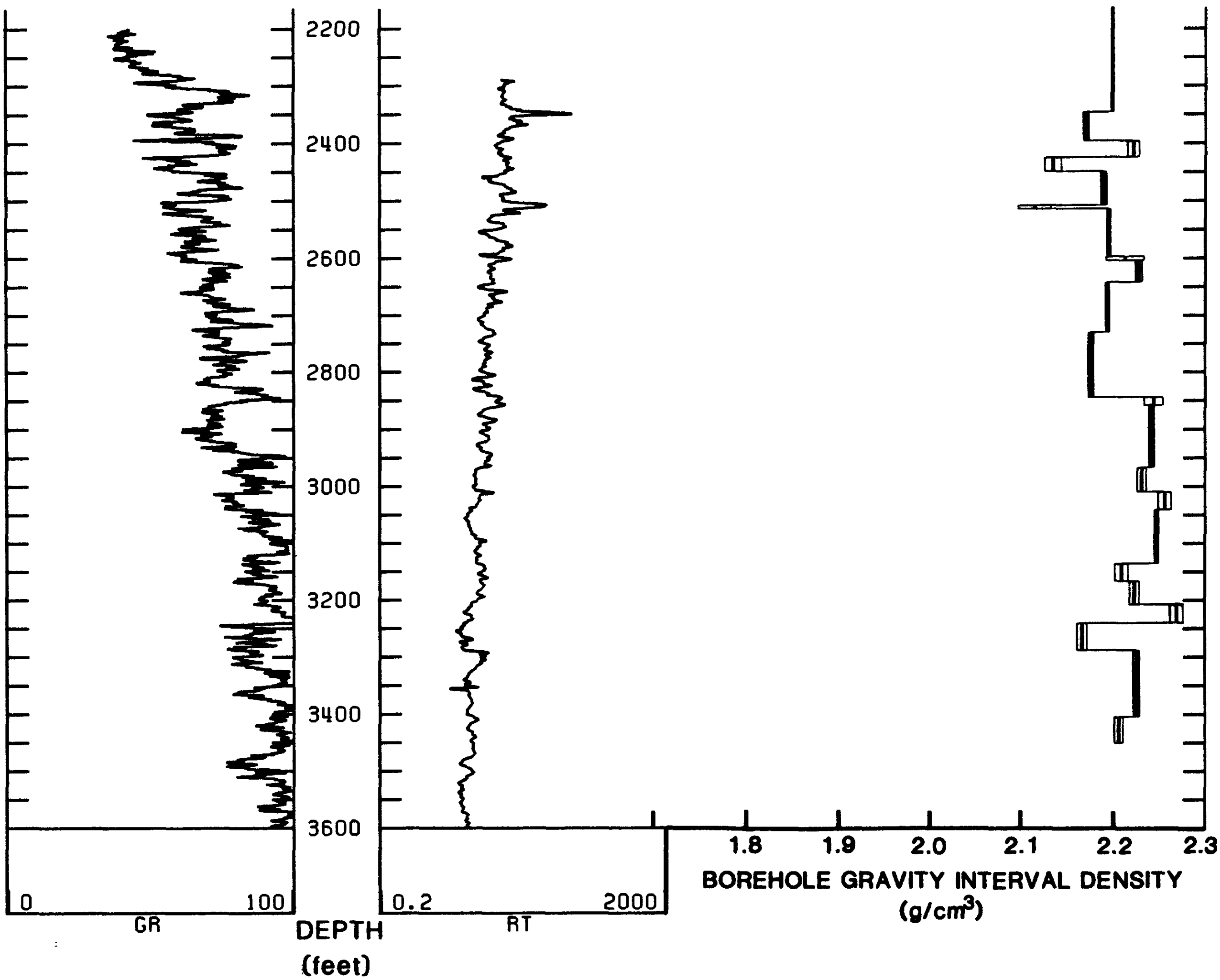

Figure 2.--Continued. BHG interval density profile for West Sak 14 well, Kuparuk River oil field. Natural gamma ray (left) and resistivity (center) logs also are shown.

Table 2. Basic data, assumptions and calculations acquired from the BHG survey in West Sak 14 well, Kuparuk River oil field. See pages 2, 17, 18 and 19 for explanation.

USGS BOREHOLE GRAVITY SURVEY: STANDARD ALASKA PRODUCTION CO. WEST SAK 14
LOCATION: 19-11N-9E Kuparuk River Unit Alaska

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	77.0	50.4	0.	0.	.002														
						0.943	.005	25.00	0.05	.03772	.093992	2.202	.011	2.65	.02	1.00	.02	27.2	1.9
2	52.0	75.4	0.	0.943	.003														
						1.059	.005	25.00	0.05	.04236	.093992	2.020	.011	2.65	.02	1.00	.02	38.2	1.9
3	27.0	100.4	0.	2.002	.002														
						1.379	.004	33.60	0.05	.04104	.093993	2.072	.007	2.65	.02	1.00	.02	35.0	1.6
4	-6.6	134.0	0.	3.381	.002														
						4.829	.005	111.98	0.15	.04312	.093993	1.990	.004	2.65	.02	1.00	.02	40.0	1.5
5	-118.6	246.0	0.	8.210	.003														
						5.441	.005	124.02	0.15	.04387	.093995	1.961	.004	2.65	.02	1.00	.02	41.7	1.4
6	-242.6	370.0	0.	13.651	.002														
						1.613	.004	37.00	0.05	.04359	.093996	1.972	.007	2.65	.02	1.00	.02	41.1	1.6
7	-279.6	407.0	0.	15.264	.002														
						1.446	.005	33.00	0.05	.04382	.093997	1.963	.009	2.65	.02	1.00	.02	41.6	1.7
8	-312.6	440.0	0.	16.710	.003														
						1.570	.005	36.00	0.05	.04361	.093997	1.971	.008	2.65	.02	1.00	.02	41.1	1.7
9	-348.6	476.0	0.	18.280	.002														
						2.599	.006	58.00	0.05	.04481	.093998	1.925	.006	2.65	.02	1.00	.02	44.0	1.5
10	-406.6	534.0	0.	20.879	.004														
						4.441	.007	104.00	0.15	.04270	.093999	2.007	.005	2.65	.02	1.00	.02	39.0	1.5
11	-510.6	638.0	0.	25.320	.003														
						3.161	.005	76.00	0.05	.04159	.094000	2.051	.004	2.65	.02	1.00	.02	36.3	1.4
12	-586.6	714.0	0.	28.481	.002														
						1.820	.004	42.00	0.05	.04333	.094001	1.982	.006	2.65	.02	1.00	.02	40.5	1.6
13	-628.6	756.0	0.	30.301	.002														
						2.161	.004	49.00	0.05	.04410	.094002	1.952	.005	2.65	.02	1.00	.02	42.3	1.5
14	-677.6	805.0	0.	32.462	.002														
						2.452	.004	57.99	0.05	.04228	.094002	2.024	.004	2.65	.02	1.00	.02	38.0	1.5
15	-735.6	863.0	0.	34.914	.002														
						0.569	.004	12.01	0.05	.04737	.094003	1.824	.021	2.65	.02	1.00	.02	50.0	2.5
16	-747.6	875.0	0.	35.483	.002														
						0.509	.004	11.00	0.05	.04628	.094003	1.867	.022	2.65	.02	1.00	.02	47.4	2.6
17	-758.6	886.0	0.	35.992	.002														
						0.332	.004	8.00	0.02	.04150	.094003	2.054	.024	2.65	.02	1.00	.02	36.1	2.6
18	-766.6	894.0	0.	36.324	.002														
						1.466	.004	33.50	0.05	.04376	.094003	1.966	.007	2.65	.02	1.00	.02	41.5	1.7
19	-800.1	927.0	0.	37.790	.002														
						0.841	.005	17.00	0.05	.04947	.094004	1.742	.017	2.65	.02	1.00	.02	55.0	2.3
20	-817.1	944.0	0.	38.631	.003														
						1.256	.005	22.00	0.05	.05709	.094004	1.444	.014	2.65	.02	1.00	.02	73.1	2.1
21	-839.1	966.0	0.	39.887	.002														
						0.767	.003	16.00	0.05	.04794	.094004	1.802	.013	2.65	.02	1.00	.02	51.4	2.0
22	-855.1	982.0	0.	40.654	.001														
						1.012	.005	23.50	0.05	.04306	.094005	1.993	.012	2.65	.02	1.00	.02	39.8	1.9
23	-878.6	1005.0	0.	41.666	.004														
						0.672	.006	16.00	0.05	.04200	.094005	2.035	.020	2.65	.02	1.00	.02	37.3	2.4
24	-894.6	1021.0	0.	42.338	.002														
						0.976	.004	23.03	0.05	.04238	.094005	2.020	.010	2.65	.02	1.00	.02	38.2	1.8
25	-917.6	1044.0	0.	43.314	.002														
						0.545	.004	12.97	0.05	.04202	.094005	2.034	.018	2.65	.02	1.00	.02	37.3	2.3
26	-930.6	1057.0	0.	43.859	.002														
						2.494	.003	55.00	0.05	.04534	.094006	1.904	.004	2.65	.02	1.00	.02	45.2	1.4
27	-985.6	1112.0	0.	46.353	.001														
						0.422	.002	8.95	0.02	.04715	.094006	1.833	.013	2.65	.02	1.00	.02	49.5	2.0
28	-994.5	1121.0	0.	46.775	.001														
						1.204	.002	29.05	0.05	.04145	.094006	2.056	.005	2.65	.02	1.00	.02	36.0	1.5
29	-1023.6	1150.0	0.	47.979	.001														
						1.336	.003	31.00	0.05	.04310	.094007	1.992	.007	2.65	.02	1.00	.02	39.9	1.6
30	-1054.6	1181.0	0.	49.315	.002														
						2.383	.003	55.00	0.05	.04333	.094007	1.983	.004	2.65	.02	1.00	.02	40.4	1.4
31	-1109.6	1236.0	0.	51.698	.001														
						1.196	.003	28.00	0.05	.04271	.094008	2.007	.007	2.65	.02	1.00	.02	39.0	1.6
32	-1137.6	1264.0	0.	52.894	.002														
						0.991	.004	23.00	0.05	.04309	.094008	1.992	.010	2.65	.02	1.00	.02	39.9	1.8
33	-1160.6	1287.0	0.	53.885	.002														
						1.412	.004	32.50	0.05	.04345	.094009	1.978	.007	2.65	.02	1.00	.02	40.7	1.7
34	-1193.1	1319.5	0.	55.297	.002														
						0.851	.004	20.50	0.05	.04151	.094009	2.054	.012	2.65	.02	1.00	.02	36.1	1.9
35	-1213.6	1340.0	0.	56.148	.002														
						2.623	.003	59.98	0.05	.04373	.094009	1.967	.003	2.65	.02	1.00	.02	41.4	1.4
36	-1273.6	1400.0	0.	58.771	.001														
						1.670	.002	42.02	0.05	.03974	.094010	2.123	.004	2.65	.02	1.00	.02	31.9	1.4
37	-1315.6	1442.0	0.	60.441	.001														
						0.305	.002	8.00	0.02	.03812	.094011	2.187	.014	2.65	.02	1.00	.02	28.1	2.0
38	-1323.6	1450.0	0.	60.746	.001														
						1.970	.002	47.00	0.05	.04192	.094011	2.038	.003	2.65	.02	1.00	.02	37.1	1.4
39	-1370.6	1497.0	0.	62.716	.001														
						0.803	.002	19.05	0.05	.04215	.094012	2.029	.008	2.65	.02	1.00	.02	37.6	1.7
40	-1389.7	1516.0	0.	63.519	.001														
						4.414	.002	105.95	0.15	.04166	.094012	2.048	.003	2.65	.02	1.00	.02	36.5	1.4
41	-1495.6	1622.0	0.	67.933	.001														
						0.648	.002	16.00	0.05	.04050	.094013	2.094	.010	2.65	.02	1.00	.02	33.7	1.8
42	-1511.6	1638.0	0.	68.581	.001														
						2.844	.002	67.50	0.05	.04213	.094013	2.030	.002	2.65	.02	1.00	.02	37.6	1.4
43	-1579.1	1705.0	0.	71.425	.001														
						0.581	.002	14.00	0.05	.04150	.094014	2.055	.011	2.65	.02	1.00	.02	36.1	1.9
44	-1593.1	1719.0	0.	72.006	.001														
						0.410	.002	10.00	0.05	.04100	.094015	2.074	.016	2.65	.02	1.00	.02	34.9	2.2

Table 2.--Continued. Basic data, assumptions and calculations acquired from the BHG survey in West Sak 14 well, Kuparuk River oil field. See pages 2, 17, 18 and 19 for explanation.

USGS BOREHOLE GRAVITY SURVEY: STANDARD ALASKA PRODUCTION CO. WEST SAK 14
LOCATION: 19-11N-9E Kuparuk River Unit Alaska

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
45	-1603.1	1729.0	0.	72.416	.001														
						3.687	.002	87.50	0.05	.04214	.094015	2.030	.002	2.65	.02	1.00	.02	37.6	1.3
46	-1690.6	1816.0	0.	76.103	.001														
						0.296	.003	7.00	0.02	.04229	.094016	2.024	.021	2.65	.02	1.00	.02	37.9	2.5
47	-1697.6	1823.0	0.	76.399	.002														
						2.780	.003	67.00	0.05	.04149	.094016	2.055	.003	2.65	.02	1.00	.02	36.1	1.4
48	-1764.6	1890.0	0.	79.179	.001														
						0.356	.002	8.00	0.02	.04449	.094017	1.938	.014	2.65	.02	1.00	.02	43.2	2.1
49	-1772.6	1898.0	0.	79.535	.001														
						0.596	.002	14.98	0.05	.03979	.094017	2.122	.010	2.65	.02	1.00	.02	32.0	1.8
50	-1787.6	1913.0	0.	80.131	.001														
						1.221	.002	29.02	0.05	.04207	.094017	2.032	.006	2.65	.02	1.00	.02	37.4	1.5
51	-1816.6	1942.0	0.	81.352	.001														
						0.883	.003	21.98	0.05	.04017	.094017	2.107	.009	2.65	.02	1.00	.02	32.9	1.8
52	-1838.6	1964.0	0.	82.235	.002														
						5.150	.004	130.99	0.15	.03932	.094018	2.140	.003	2.65	.02	1.00	.02	30.9	1.4
53	-1969.6	2096.0	0.	87.385	.002														
						1.047	.003	26.01	0.05	.04025	.094020	2.104	.008	2.65	.02	1.00	.02	33.1	1.7
54	-1995.6	2122.0	0.	88.432	.001														
						0.891	.002	22.00	0.05	.04050	.094020	2.094	.007	2.65	.02	1.00	.02	33.7	1.6
55	-2017.6	2144.0	0.	89.323	.001														
						7.642	.002	202.02	0.15	.03783	.094020	2.199	.001	2.65	.02	1.00	.02	27.4	1.3
56	-2219.6	2346.0	0.	96.965	.001														
						1.928	.002	50.00	0.05	.03856	.094023	2.170	.003	2.65	.02	1.00	.02	29.1	1.4
57	-2269.6	2396.0	0.	98.893	.001														
						1.043	.003	28.00	0.05	.03725	.094024	2.221	.007	2.65	.02	1.00	.02	26.0	1.6
58	-2297.6	2424.0	0.	99.936	.002														
						0.987	.004	25.00	0.05	.03948	.094024	2.134	.009	2.65	.02	1.00	.02	31.3	1.8
59	-2322.6	2449.0	0.	100.923	.002														
						2.246	.003	59.00	0.05	.03807	.094024	2.189	.003	2.65	.02	1.00	.02	27.9	1.4
60	-2381.6	2508.0	0.	103.169	.001														
						0.240	.002	6.00	0.02	.04000	.094025	2.114	.018	2.65	.02	1.00	.02	32.5	2.3
61	-2387.6	2514.0	0.	103.409	.001														
						3.148	.003	83.00	0.05	.03793	.094025	2.195	.002	2.65	.02	1.00	.02	27.6	1.4
62	-2470.6	2597.0	0.	106.557	.002														
						0.262	.003	6.99	0.02	.03748	.094026	2.213	.021	2.65	.02	1.00	.02	26.5	2.5
63	-2477.6	2604.0	0.	106.819	.001														
						1.410	.002	38.01	0.05	.03710	.094026	2.227	.004	2.65	.02	1.00	.02	25.6	1.5
64	-2515.6	2642.0	0.	108.229	.001														
						3.360	.003	88.50	0.05	.03797	.094027	2.193	.002	2.65	.02	1.00	.02	27.7	1.3
65	-2604.1	2730.0	0.	111.589	.002														
						4.400	.003	114.49	0.15	.03843	.094028	2.175	.003	2.65	.02	1.00	.02	28.8	1.4
66	-2718.6	2844.0	0.	115.989	.001														
						0.514	.002	14.01	0.05	.03669	.094030	2.244	.011	2.65	.02	1.00	.02	24.6	1.9
67	-2732.6	2858.0	0.	116.503	.001														
						3.967	.003	107.99	0.15	.03673	.094030	2.242	.003	2.65	.02	1.00	.02	24.7	1.4
68	-2840.6	2966.0	0.	120.470	.002														
						1.591	.004	42.99	0.05	.03701	.094031	2.231	.005	2.65	.02	1.00	.02	25.4	1.5
69	-2883.6	3009.0	0.	122.061	.002														
						1.130	.004	31.07	0.05	.03637	.094032	2.256	.007	2.65	.02	1.00	.02	23.9	1.7
70	-2914.7	3040.0	0.	123.191	.002														
						3.475	.004	94.95	0.05	.03660	.094032	2.247	.002	2.65	.02	1.00	.02	24.4	1.4
71	-3009.6	3135.0	0.	126.666	.002														
						1.164	.004	30.98	0.05	.03757	.094033	2.209	.007	2.65	.02	1.00	.02	26.7	1.7
72	-3040.6	3166.0	0.	127.830	.002														
						1.563	.004	42.00	0.05	.03721	.094034	2.223	.005	2.65	.02	1.00	.02	25.9	1.5
73	-3082.6	3208.0	0.	129.393	.002														
						1.154	.004	32.02	0.05	.03604	.094034	2.269	.007	2.65	.02	1.00	.02	23.1	1.6
74	-3114.6	3240.0	0.	130.547	.002														
						1.856	.005	47.99	0.05	.03868	.094035	2.166	.006	2.65	.02	1.00	.02	29.3	1.6
75	-3162.6	3288.0	0.	132.403	.003														
						4.309	.005	115.97	0.15	.03716	.094036	2.226	.004	2.65	.02	1.00	.02	25.7	1.4
76	-3278.6	3404.0	0.	136.712	.002														
						1.737	.004	46.14	0.05	.03765	.094037	2.206	.005	2.65	.02	1.00	.02	26.9	1.5
77	-3324.7	3450.1	0.	138.449	.002														

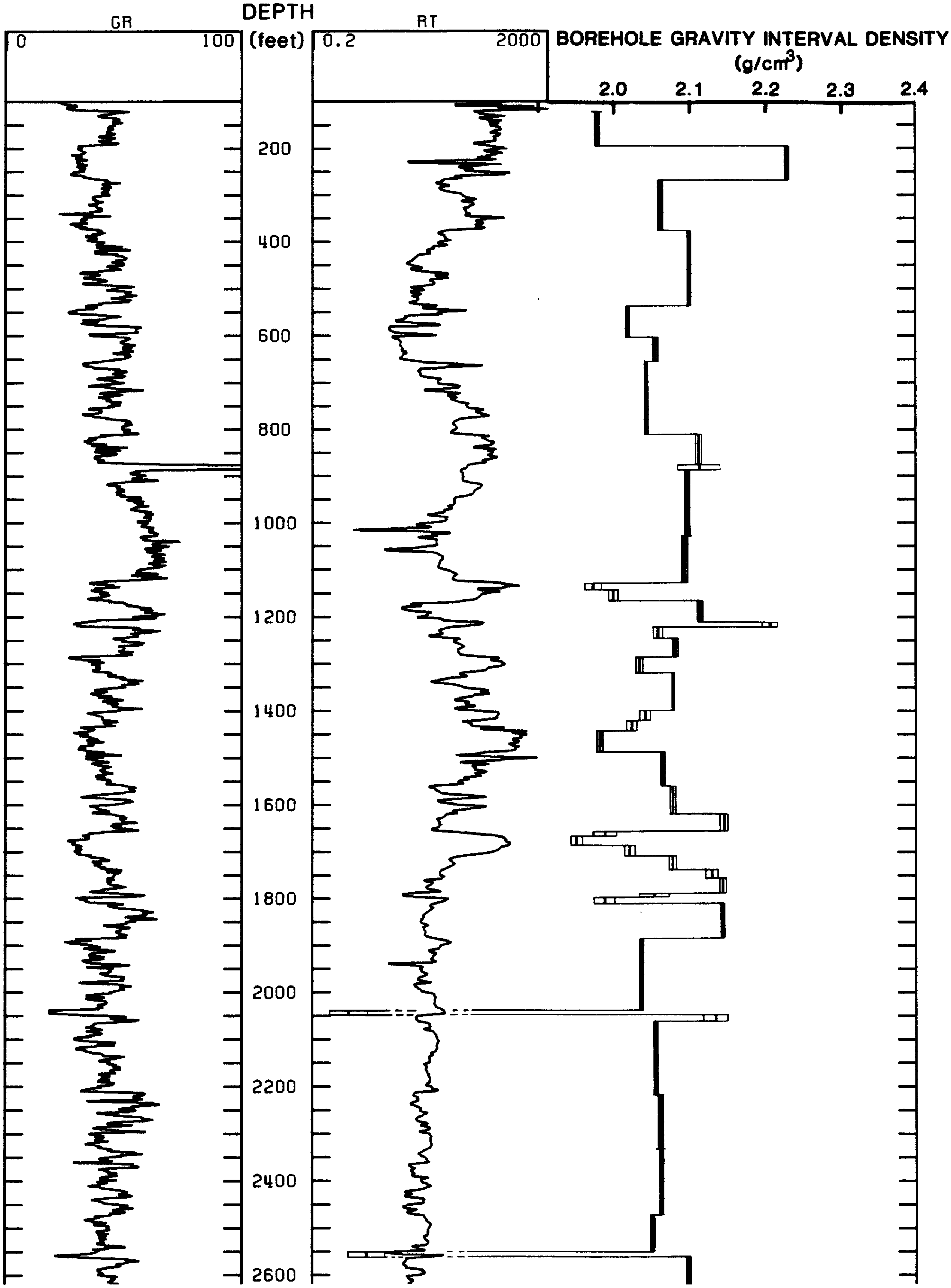

Figure 3. BHG interval density profile for West Sak 17 well, Kuparuk River oil field. Natural gamma ray (left) and resistivity (center) logs also are shown.

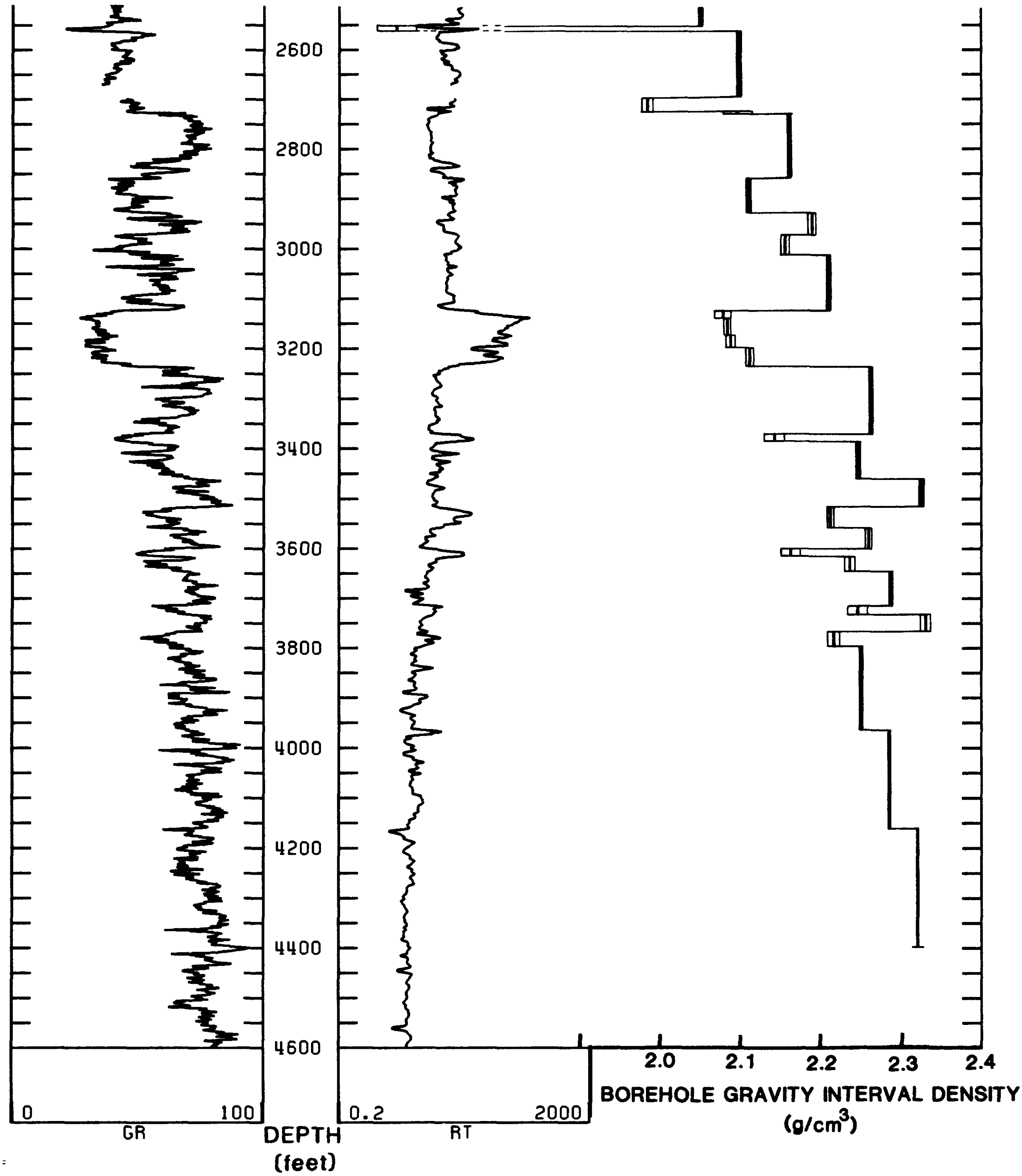

Figure 3.--Continued. BHG interval density profile for West Sak 17 well, Kuparuk River oil field. Natural gamma ray (left) and resistivity (center) logs also are shown.

Table 3. Basic data, assumptions, and calculations acquired from the BHG survey in West Sak 17 well, Kuparuk River oil field. See pages 2, 17, 18 and 19 for explanation.

USGS BOREHOLE GRAVITY SURVEY: STANDARD ALASKA PRODUCTION CO. WEST SAK 17
LOCATION: 26-13N-9E Kuparuk River Unit Alaska

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	-57.4	117.9	0.	0.	.002														
						3.237	.004	74.52	0.05	.04344	.093994	1.978	.003	2.65	.02	1.00	.02	40.7	1.4
2	-132.0	192.2	0.	3.237	.002														
						2.720	.004	73.50	0.05	.03701	.093995	2.230	.003	2.65	.02	1.00	.02	25.5	1.4
3	-205.5	265.6	0.	5.957	.002														
						4.456	.004	107.93	0.15	.04129	.093996	2.062	.004	2.65	.02	1.00	.02	35.6	1.4
4	-313.4	373.2	0.	10.413	.002														
						6.514	.004	161.57	0.15	.04032	.093997	2.100	.002	2.65	.02	1.00	.02	33.3	1.4
5	-474.9	534.4	0.	16.927	.002														
						2.842	.003	67.02	0.05	.04240	.093999	2.019	.003	2.65	.02	1.00	.02	38.3	1.4
6	-542.0	601.3	0.	19.769	.001														
						2.112	.003	50.93	0.05	.04147	.094000	2.055	.004	2.65	.02	1.00	.02	36.0	1.4
7	-592.9	652.1	0.	21.881	.002														
						6.557	.004	156.95	0.15	.04178	.094001	2.043	.003	2.65	.02	1.00	.02	36.8	1.4
8	-749.9	808.6	0.	28.438	.002														
						2.623	.005	65.55	0.05	.04002	.094003	2.112	.004	2.65	.02	1.00	.02	32.6	1.5
9	-815.4	874.0	0.	31.061	.003														
						0.440	.006	11.00	0.05	.04000	.094004	2.113	.028	2.65	.02	1.00	.02	32.5	2.9
10	-826.4	885.0	0.	31.501	.003														
						5.696	.007	141.03	0.15	.04039	.094004	2.098	.004	2.65	.02	1.00	.02	33.5	1.4
11	-967.4	1025.7	0.	37.197	.004														
						4.048	.005	99.99	0.15	.04048	.094006	2.094	.004	2.65	.02	1.00	.02	33.7	1.5
12	-1067.4	1125.5	0.	41.245	.001														
						0.611	.002	14.01	0.05	.04361	.094007	1.972	.012	2.65	.02	1.00	.02	41.1	1.9
13	-1081.4	1139.4	0.	41.856	.001														
						1.029	.002	23.98	0.05	.04291	.094007	1.999	.007	2.65	.02	1.00	.02	39.4	1.6
14	-1105.4	1163.3	0.	42.885	.001														
						1.821	.002	45.55	0.05	.03998	.094008	2.114	.003	2.65	.02	1.00	.02	32.5	1.4
15	-1151.0	1208.8	0.	44.706	.001														
						0.375	.002	9.97	0.02	.03761	.094008	2.207	.011	2.65	.02	1.00	.02	26.9	1.9
16	-1160.9	1218.8	0.	45.081	.001														
						0.994	.002	24.01	0.05	.04140	.094009	2.058	.007	2.65	.02	1.00	.02	35.9	1.6
17	-1184.9	1242.7	0.	46.075	.001														
						1.631	.002	39.98	0.05	.04079	.094009	2.082	.004	2.65	.02	1.00	.02	34.4	1.5
18	-1224.9	1282.6	0.	47.706	.001														
						1.428	.002	33.97	0.05	.04204	.094009	2.034	.005	2.65	.02	1.00	.02	37.4	1.5
19	-1258.9	1316.5	0.	49.134	.001														
						3.312	.002	81.02	0.05	.04088	.094010	2.079	.002	2.65	.02	1.00	.02	34.6	1.3
20	-1339.9	1397.3	0.	52.446	.001														
						0.879	.002	21.01	0.05	.04184	.094011	2.041	.008	2.65	.02	1.00	.02	36.9	1.7
21	-1360.9	1418.3	0.	53.325	.001														
						0.931	.002	22.01	0.05	.04230	.094011	2.023	.007	2.65	.02	1.00	.02	38.0	1.7
22	-1382.9	1440.2	0.	54.256	.001														
						1.974	.003	45.50	0.05	.04338	.094012	1.981	.004	2.65	.02	1.00	.02	40.6	1.5
23	-1428.4	1485.7	0.	56.230	.002														
						3.007	.004	72.93	0.05	.04123	.094012	2.065	.003	2.65	.02	1.00	.02	35.4	1.4
24	-1501.4	1558.4	0.	59.237	.002														
						2.456	.004	60.05	0.05	.04090	.094013	2.078	.004	2.65	.02	1.00	.02	34.7	1.5
25	-1561.4	1618.3	0.	61.693	.002														
						1.410	.003	35.99	0.05	.03918	.094014	2.146	.005	2.65	.02	1.00	.02	30.6	1.5
26	-1597.4	1654.2	0.	63.103	.001														
						0.433	.002	10.02	0.05	.04322	.094014	1.988	.016	2.65	.02	1.00	.02	40.2	2.2
27	-1607.4	1664.3	0.	63.536	.001														
						0.907	.002	20.53	0.05	.04418	.094015	1.950	.008	2.65	.02	1.00	.02	42.4	1.7
28	-1628.0	1684.4	0.	64.443	.001														
						0.932	.002	22.00	0.05	.04236	.094015	2.021	.007	2.65	.02	1.00	.02	38.1	1.7
29	-1650.0	1706.7	0.	65.375	.001														
						1.226	.002	29.97	0.05	.04091	.094015	2.078	.005	2.65	.02	1.00	.02	34.7	1.5
30	-1679.9	1736.6	0.	66.601	.001														
						0.715	.002	18.06	0.05	.03959	.094016	2.130	.009	2.65	.02	1.00	.02	31.5	1.7
31	-1698.0	1754.6	0.	67.316	.001														
						1.272	.002	32.44	0.05	.03921	.094016	2.144	.005	2.65	.02	1.00	.02	30.6	1.5
32	-1730.4	1787.0	0.	68.588	.001														
						0.312	.003	7.51	0.02	.04154	.094016	2.053	.020	2.65	.02	1.00	.02	36.2	2.4
33	-1737.9	1794.5	0.	68.900	.002														
						0.606	.003	14.02	0.05	.04323	.094016	1.987	.014	2.65	.02	1.00	.02	40.2	2.1
34	-1752.0	1808.5	0.	69.506	.001														
						2.920	.003	74.45	0.05	.03922	.094016	2.144	.003	2.65	.02	1.00	.02	30.7	1.4
35	-1826.4	1882.8	0.	72.426	.002														
						6.421	.004	153.01	0.15	.04196	.094017	2.037	.003	2.65	.02	1.00	.02	37.2	1.4
36	-1979.4	2035.5	0.	78.847	.002														
						0.519	.004	10.00	0.05	.05190	.094020	1.648	.026	2.65	.02	1.00	.02	60.7	2.8
37	-1989.4	2045.4	0.	79.366	.002														
						0.552	.004	13.99	0.05	.03946	.094020	2.135	.017	2.65	.02	1.00	.02	31.2	2.2
38	-2003.4	2059.4	0.	79.918	.002														
						6.451	.004	155.52	0.15	.04148	.094020	2.056	.003	2.65	.02	1.00	.02	36.0	1.4
39	-2158.9	2214.6	0.	86.369	.002														
						4.816	.004	116.53	0.15	.04133	.094022	2.062	.003	2.65	.02	1.00	.02	35.7	1.4
40	-2275.4	2331.0	0.	91.185	.002														
						5.821	.004	140.96	0.15	.04130	.094024	2.063	.003	2.65	.02	1.00	.02	35.6	1.4
41	-2416.4	2471.7	0.	97.006	.002														
						3.311	.004	79.58	0.05	.04161	.094025	2.051	.003	2.65	.02	1.00	.02	36.3	1.4
42	-2496.0	2551.1	0.	100.317	.002														
						0.534	.004	10.41	0.05	.05130	.094026	1.672	.025	2.65	.02	1.00	.02	59.3	2.7
43	-2506.4	2561.5	0.	100.851	.002														
						5.312	.004	131.51	0.15	.04039	.094027	2.099	.003	2.65	.02	1.00	.02	33.4	1.4
44	-2637.9	2694.7	0.	106.163	.002														
						1.217	.003	28.09	0.05	.04333	.094028	1.984	.007	2.65	.02	1.00	.02	40.4	1.6

Table 3.--Continued. Basic data, assumptions, and calculations acquired from the BHG survey in West Sak 17 well, Kuparuk River oil field. See pages 2, 17, 18 and 19 for explanation.

USGS BOREHOLE GRAVITY SURVEY: STANDARD ALASKA PRODUCTION CO. WEST SAK 17
LOCATION: 26-13N-9E Kuparuk River Unit Alaska

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
45	-2666.0	2722.6	0.	107.380	.001														
						0.239	.002	5.91	0.02	.04043	.094029	2.097	.019	2.65	.02	1.00	.02	33.5	2.3
46	-2671.9	2728.5	0.	107.619	.001														
						5.042	.003	129.98	0.15	.03879	.094029	2.161	.003	2.65	.02	1.00	.02	29.6	1.4
47	-2801.9	2857.8	0.	112.661	.002														
						2.789	.004	69.57	0.05	.04009	.094031	2.111	.003	2.65	.02	1.00	.02	32.7	1.4
48	-2871.5	2927.1	0.	115.450	.002														
						1.655	.004	43.45	0.05	.03809	.094031	2.189	.005	2.65	.02	1.00	.02	27.9	1.5
49	-2914.9	2970.3	0.	117.105	.002														
						1.577	.004	40.50	0.05	.03894	.094032	2.156	.006	2.65	.02	1.00	.02	30.0	1.6
50	-2955.4	3010.6	0.	118.682	.002														
						4.228	.003	112.58	0.15	.03756	.094033	2.210	.003	2.65	.02	1.00	.02	26.7	1.4
51	-3068.0	3122.8	0.	122.910	.001														
						0.610	.002	14.91	0.05	.04091	.094034	2.079	.011	2.65	.02	1.00	.02	34.6	1.9
52	-3082.9	3137.6	0.	123.520	.001														
						1.390	.002	34.09	0.05	.04077	.094034	2.084	.005	2.65	.02	1.00	.02	34.3	1.5
53	-3117.0	3171.6	0.	124.910	.001														
						1.016	.002	24.98	0.05	.04067	.094035	2.088	.006	2.65	.02	1.00	.02	34.1	1.6
54	-3142.0	3196.5	0.	125.926	.001														
						1.540	.003	38.44	0.05	.04006	.094035	2.112	.005	2.65	.02	1.00	.02	32.6	1.5
55	-3180.4	3234.8	0.	127.466	.002														
						4.924	.003	135.97	0.15	.03621	.094036	2.262	.002	2.65	.02	1.00	.02	23.5	1.4
56	-3316.4	3370.3	0.	132.390	.001														
						0.590	.003	15.02	0.05	.03928	.094037	2.143	.013	2.65	.02	1.00	.02	30.8	2.0
57	-3331.4	3385.2	0.	132.980	.002														
						2.711	.004	74.01	0.05	.03663	.094038	2.246	.003	2.65	.02	1.00	.02	24.5	1.4
58	-3405.4	3459.0	0.	135.691	.002														
						1.923	.003	55.58	0.05	.03460	.094039	2.326	.003	2.65	.02	1.00	.02	19.7	1.4
59	-3461.0	3514.4	0.	137.614	.001														
						1.612	.003	42.98	0.05	.03751	.094039	2.212	.004	2.65	.02	1.00	.02	26.5	1.5
60	-3504.0	3557.2	0.	139.226	.002														
						1.526	.003	42.04	0.05	.03630	.094040	2.259	.004	2.65	.02	1.00	.02	23.7	1.5
61	-3546.0	3599.2	0.	140.752	.001														
						0.618	.003	15.94	0.05	.03877	.094041	2.163	.012	2.65	.02	1.00	.02	29.5	1.9
62	-3561.9	3615.0	0.	141.370	.002														
						1.072	.003	29.05	0.05	.03690	.094041	2.236	.007	2.65	.02	1.00	.02	25.1	1.6
63	-3591.0	3644.0	0.	142.442	.001														
						2.455	.003	68.99	0.05	.03559	.094041	2.287	.003	2.65	.02	1.00	.02	22.0	1.4
64	-3660.0	3712.8	0.	144.897	.002														
						0.657	.004	17.93	0.05	.03664	.094042	2.246	.013	2.65	.02	1.00	.02	24.5	2.0
65	-3677.9	3730.7	0.	145.554	.002														
						1.171	.004	33.97	0.05	.03447	.094042	2.331	.007	2.65	.02	1.00	.02	19.3	1.6
66	-3711.9	3764.5	0.	146.725	.002														
						1.122	.004	29.99	0.05	.03741	.094043	2.216	.008	2.65	.02	1.00	.02	26.3	1.7
67	-3741.9	3794.4	0.	147.847	.002														
						6.158	.004	168.55	0.15	.03654	.094043	2.250	.002	2.65	.02	1.00	.02	24.2	1.3
68	-3910.4	3962.5	0.	154.005	.002														
						7.053	.004	197.92	0.15	.03564	.094045	2.285	.002	2.65	.02	1.00	.02	22.1	1.3
69	-4108.4	4159.8	0.	161.058	.002														
						8.289	.004	238.64	0.15	.03473	.094048	2.321	.002	2.65	.02	1.00	.02	20.0	1.3
70	-4347.0	4397.8	0.	169.347	.002														

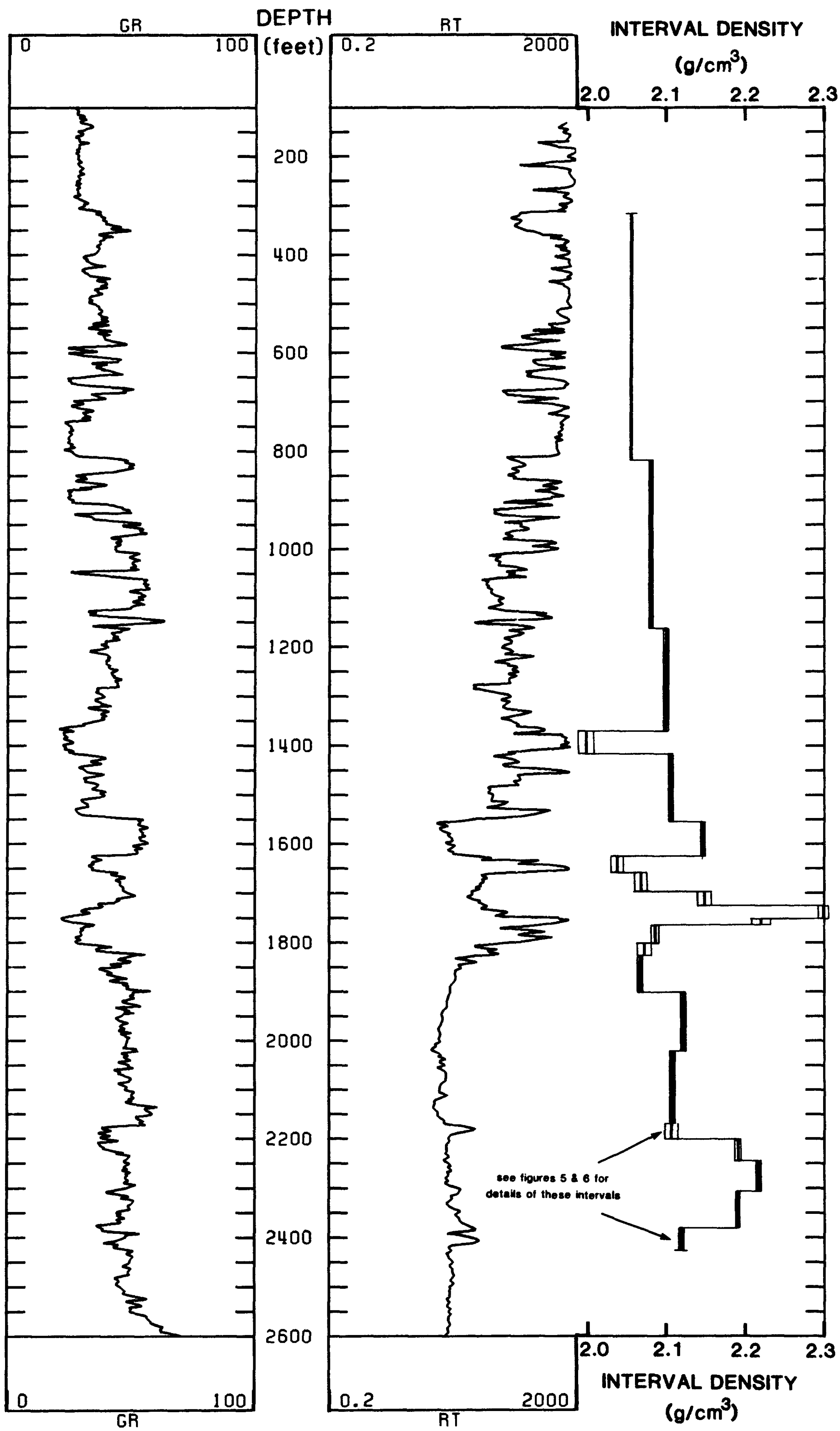

Figure 4. BHG interval density profile for Highland State 1, west end Prudhoe Bay oil field. Natural gamma ray (left) and resistivity (center) logs also are shown.

Table 4. Basic data, assumptions, and calculations acquired from the BHG survey in Highland State 1 well, west end Prudhoe Bay oil field. See pages 2, 17, 18 and 19 for explanation.

USGS BOREHOLE GRAVITY SURVEY: ARCO Alaska Inc. Highland State 1
LOCATION: 24-11N-11E Prudhoe Bay Unit Alaska

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	-259.0	314.0	0.	0.	.005														
						20.957	.015	505.04	0.15	.04150	.093997	2.054	.002	2.65	.02	1.00	.02	36.1	1.3
2	-764.0	818.3	0.	20.957	.010														
						14.057	.017	344.06	0.15	.04086	.094003	2.079	.003	2.65	.02	1.00	.02	34.6	1.4
3	-1108.1	1161.6	0.	35.014	.007														
						8.435	.013	208.95	0.15	.04037	.094008	2.099	.004	2.65	.02	1.00	.02	33.4	1.4
4	-1317.0	1370.0	0.	43.449	.006														
						1.978	.010	46.04	0.05	.04296	.094011	1.997	.010	2.65	.02	1.00	.02	39.6	1.8
5	-1363.1	1416.1	0.	45.427	.004														
						5.527	.005	137.44	0.15	.04021	.094011	2.105	.003	2.65	.02	1.00	.02	33.0	1.4
6	-1500.5	1553.0	0.	50.954	.001														
						2.765	.003	70.58	0.05	.03918	.094013	2.146	.003	2.65	.02	1.00	.02	30.6	1.4
7	-1571.1	1623.6	0.	53.719	.002														
						1.417	.005	33.79	0.05	.04194	.094014	2.038	.008	2.65	.02	1.00	.02	37.1	1.7
8	-1604.9	1657.1	0.	55.136	.003														
						1.552	.006	37.69	0.05	.04118	.094015	2.067	.008	2.65	.02	1.00	.02	35.3	1.7
9	-1642.6	1694.8	0.	56.688	.003														
						1.152	.005	29.44	0.05	.03913	.094015	2.147	.009	2.65	.02	1.00	.02	30.5	1.8
10	-1672.0	1724.0	0.	57.840	.002														
						0.919	.003	26.04	0.05	.03529	.094016	2.298	.007	2.65	.02	1.00	.02	21.4	1.6
11	-1698.1	1750.0	0.	58.759	.001														
						0.450	.002	12.06	0.05	.03731	.094016	2.219	.013	2.65	.02	1.00	.02	26.1	2.0
12	-1710.1	1762.1	0.	59.209	.001														
						1.545	.003	37.95	0.05	.04071	.094016	2.086	.005	2.65	.02	1.00	.02	34.2	1.5
13	-1748.1	1799.8	0.	60.754	.002														
						1.067	.004	25.98	0.05	.04107	.094017	2.072	.009	2.65	.02	1.00	.02	35.0	1.8
14	-1774.0	1825.8	0.	61.821	.002														
						3.046	.005	73.92	0.05	.04121	.094017	2.066	.004	2.65	.02	1.00	.02	35.4	1.4
15	-1848.0	1899.5	0.	64.867	.003														
						4.780	.005	120.09	0.15	.03980	.094018	2.121	.004	2.65	.02	1.00	.02	32.0	1.4
16	-1968.1	2019.0	0.	69.647	.002														
						5.936	.006	147.96	0.15	.04012	.094020	2.109	.003	2.65	.02	1.00	.02	32.8	1.4
17	-2116.0	2166.3	0.	75.583	.004														
						0.145	.007	4.00	0.02	.03625	.094022	2.260	.076	2.65	.02	1.00	.02	23.6	5.8
18	-2120.0	2170.3	0.	75.728	.003														
						0.163	.004	4.01	0.02	.04064	.094022	2.089	.047	2.65	.02	1.00	.02	34.0	4.1
19	-2124.0	2174.3	0.	75.891	.001														
						0.170	.002	3.97	0.02	.04282	.094022	2.003	.028	2.65	.02	1.00	.02	39.2	2.9
20	-2128.0	2178.2	0.	76.061	.001														
						0.160	.002	3.99	0.02	.04011	.094022	2.109	.027	2.65	.02	1.00	.02	32.8	2.9
21	-2132.0	2182.2	0.	76.221	.001														
						0.164	.002	4.03	0.02	.04069	.094022	2.087	.027	2.65	.02	1.00	.02	34.2	2.9
22	-2136.0	2186.3	0.	76.385	.001														
						0.173	.004	4.00	0.02	.04324	.094022	1.987	.048	2.65	.02	1.00	.02	40.2	4.1
23	-2140.0	2190.3	0.	76.558	.003														
						0.152	.004	4.01	0.02	.03791	.094022	2.195	.046	2.65	.02	1.00	.02	27.6	4.0
24	-2144.0	2194.3	0.	76.710	.001														
						0.164	.002	3.99	0.02	.04110	.094022	2.071	.028	2.65	.02	1.00	.02	35.1	2.9
25	-2148.0	2198.3	0.	76.874	.001														
						1.715	.003	45.02	0.05	.03809	.094022	2.188	.004	2.65	.02	1.00	.02	28.0	1.5
26	-2193.0	2243.0	0.	78.589	.002														
						2.280	.004	61.00	0.05	.03738	.094023	2.216	.004	2.65	.02	1.00	.02	26.3	1.4
27	-2254.0	2303.8	0.	80.869	.002														
						2.815	.003	73.98	0.05	.03805	.094023	2.190	.003	2.65	.02	1.00	.02	27.9	1.4
28	-2328.0	2377.5	0.	83.684	.001														
						0.205	.002	4.99	0.02	.04107	.094024	2.072	.022	2.65	.02	1.00	.02	35.0	2.6
29	-2333.0	2382.5	0.	83.889	.001														
						0.283	.002	7.01	0.02	.04037	.094024	2.099	.016	2.65	.02	1.00	.02	33.4	2.2
30	-2340.0	2389.5	0.	84.172	.001														
						0.556	.002	14.00	0.02	.03972	.094025	2.125	.008	2.65	.02	1.00	.02	31.8	1.7
31	-2354.0	2403.5	0.	84.728	.001														
						0.247	.002	6.02	0.02	.04102	.094025	2.074	.018	2.65	.02	1.00	.02	34.9	2.3
32	-2360.0	2409.5	0.	84.975	.001														
						0.232	.002	5.98	0.02	.03881	.094025	2.161	.018	2.65	.02	1.00	.02	29.7	2.3
33	-2366.0	2415.3	0.	85.207	.001														
						0.311	.002	8.01	0.02	.03882	.094025	2.160	.014	2.65	.02	1.00	.02	29.7	2.0
34	-2374.0	2423.3	0.	85.518	.001														

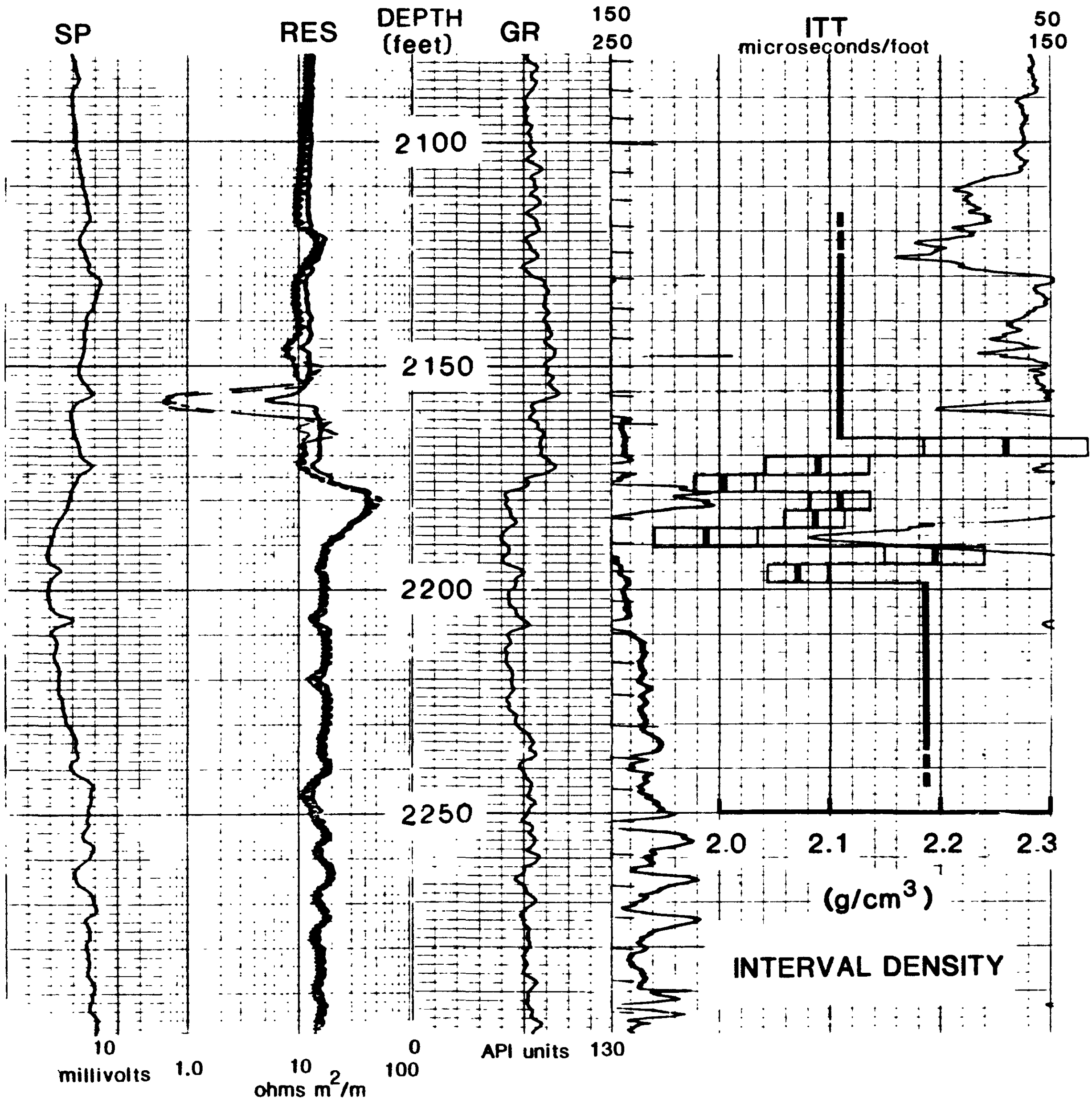

Figure 5. Detail of BHG interval density profile for Highland State 1 between 2166 and 2198 feet. Spontaneous potential, resistivity, natural gamma ray and interval transit time logs also are shown.

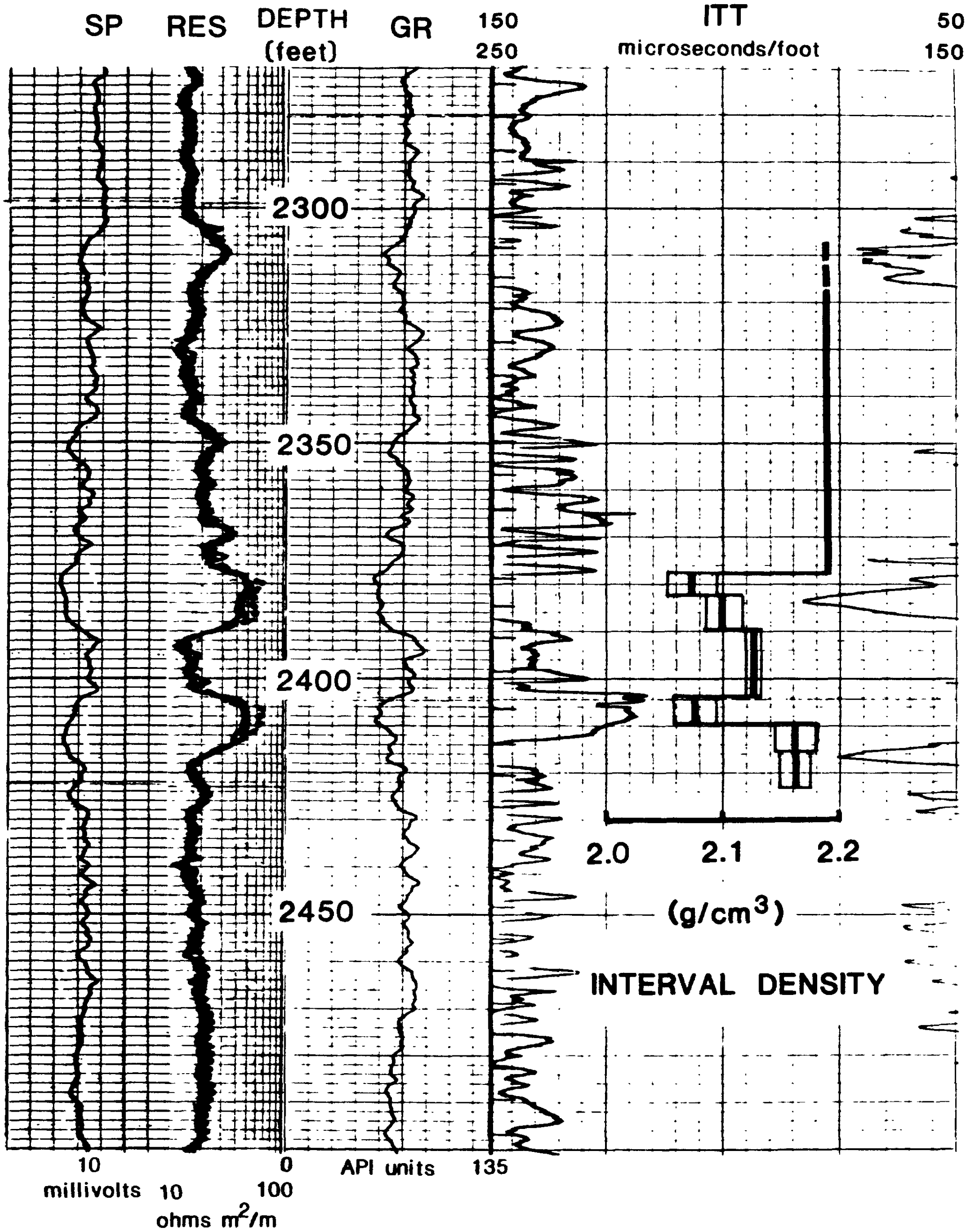

Figure 6. Detail of BHG interval density profile for Highland State 1 between 2377 and 2423 feet. Spontaneous potential, resistivity, natural gamma ray and interval transit time logs also are shown.

Column 3

Measured depth of borehole gravity station adjusted to depth scale of open-hole well logs (feet)

Column 4

Terrain corrections calculated out through Hayford-Bowie zone O using variable terrain density (Beyer and Corbato, 1972) (milligals) (not needed for Kuparuk River and Prudhoe Bay region).

Column 5

Relative gravity with uppermost station set equal to zero (milligals). Corrections for tidal gravity, instrument drift and terrain have been applied.

Column 6

Estimated uncertainty in gravity value in column 5 based on quality of reading(s) at station and drift behavior of gravity meter (milligals).

Column 7

Gravity difference (Δg) between successive stations (milligals).

Column 8

Uncertainty in gravity difference (Δg_{error}) that is the sum of gravity reading uncertainties (column 6) due to gravity reading quality, gravity meter repeatability and drift correction (milligals).

Column 9

Depth difference (Δz) between successive borehole gravity stations (feet). Values are not corrected for borehole deviation from the vertical.

Column 10

Estimated uncertainty (Δz_{error}) in depth difference (feet). Δz_{error} is estimated to be .02 feet for $\Delta z < 10$ feet, .05 feet for $10 < \Delta z < 100$ feet and .15 feet for $\Delta z > 100$ feet.

Column 11

Interval vertical gradient ($\Delta g / \Delta z$) milligals/foot).

Column 12

Theoretical free-air vertical gradient (F) for latitude and elevation of borehole gravity station (milligals/foot). Values are calculated from

$$F = .094112 - .000134 \sin^2\theta - .134 \times 10^{-7}h$$

where θ is latitude and h is elevation in feet. Equation is from Heiskanen and Moritz (1967) with constants of the 1967 Geodetic Reference System.

Column 13

BHG density (ρ) calculated from

$$\Delta g/\Delta z = F - 4\pi k\rho$$

where k is the gravitational constant (g/cm^3). Assuming a mean value for F, this equation becomes

$$\rho = 3.680 - 39.127\ (\Delta g/\Delta z)$$

Column 14

Maximum likely error in BHG density (ρ_{error}). See equation 2 in Appendix A. ρ_{error} is in g/cm^3.

Column 15

Assumed grain (or matrix) density (ρ_g) (g/cm^3).

Column 16

Assumed uncertainty of 0.02 in grain density ($\rho_{g\ error}$) (g/cm^3).

Column 17

Assumed pore-fluid density (ρ_f) (g/cm^3).

Column 18

Assumed uncertainty of 0.02 in pore fluid density ($\rho_{f\ error}$) (g/cm^3).

Column 19

BHG (apparent) porosity (ϕ) calculated from

$$\phi = 100(\rho_g-\rho)/(\rho_g-\rho_f) \qquad (\%)$$

where ρ_g is set equal to 2.65 g/cm^3 and ρ_f is set equal to 1.00 g/cm^3

Column 20

Maximum likely error in BHG (apparent) porosity (ϕ) due to uncertainties in BHG density (ρ), grain density (ρ_g) and pore-fluid density (ρ_f). See equation 4 in Appendix A. ϕ_{error} is in porosity percent.

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APPENDIX A: The Borehole Gravity Method

Smith (1950) recognized that borehole gravity measurements are responsive primarily to the vertical density variations in the rocks traversed by the survey and secondarily to lateral rock density variations (anomalous density structure) of detectable magnitudes that may occur in the region surrounding the surveyed well. However, the development of a reliable borehole gravity meter with high precision came much later and the use of surveys for reservoir evaluation soon followed (Howell and others, 1966; McCulloh and others, 1967a, 1967b, 1968).

Borehole gravity surveys are conducted by stopping and reading the borehole gravity meter at a series of downhole stations. These stations are selected from examination of well logs usually to bracket distinct units in a manner that meets the survey objectives. This technique leads to a set of gravity difference (Δg) and depth difference (Δz) measurements that constitute the interval vertical gradient of gravity ($\Delta g/\Delta z$) between successive stations (Fig. 7).

In a practical sense, the factors that affect measurements of $\Delta g/\Delta z$ are given by the following equation:

$$\Delta g/\Delta z = F - 4\pi k\rho + \Delta G_g + \Delta G_t + \Delta G_b \qquad \text{(McCulloh, 1966)} \qquad (1)$$

F is the so-called free-air vertical gradient that varies from the equator to either pole by less than 0.2% and with elevation by about 0.01% per 1,000 feet or 0.05% per kilometer (Hammer, 1970;

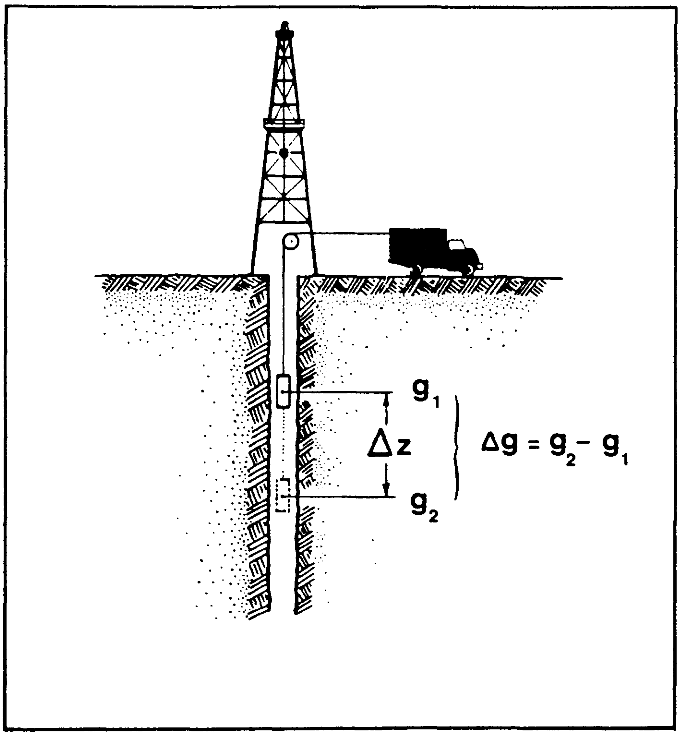

Figure 7. Schematic diagram showing measurement of gravity (Δg) and depth differences (Δz) in the borehole.

Robbins, 1981). These variations generally are negligible for borehole gravity surveys and F usually is assumed to be constant (.09406 mGal/ft or .30859 mGal/m).

The second term on the right-hand side of eq. (l) involves the constant coefficient $4\pi k$ which equals .025558 (units of feet, mGal, g/cm^3) or .083850 (units of meters, mGal, g/cm^3) when the Newtonian gravitational constant k equals $6.6726 \times 10^{-8} cm^3 sec^{-2} g^{-1}$ (Luther and Towler, 1982). The last factor, ρ, in this term is the BHG (apparent) density that is discussed in the following paragraph. Anomalous gravity effects caused by lateral density variations in the area of the well, as well as more regional anomalous effects that usually are negligible or very small, are represented by the gradient term ΔG_g in eq. (1). Corrections for gravitational effects due to the borehole (ΔG_b) and topography (ΔG_t) usually are not needed or can be easily calculated with high accuracy (Beyer and Corbato, 1972; Beyer, 1979).

In many geologic settings BHG (apparent) density ρ is the only significant factor that affects $\Delta g/\Delta z$ because the formations surrounding the borehole are level (or nearly so) and possess relatively uniform densities in lateral directions. In such areas, borehole gravity data are easily converted to highly accurate and unique BHG density profiles. The word "apparent" is omitted from BHG density in this case because the BHG densities are believed to accurately represent the densities of the rocks penetrated by the well. In cases where ΔG_g, ΔG_b and(or) ΔG_t are significant but ignored in the calculation of ρ, BHG (apparent) density is used.

BHG density is the gravitational average density of the horizontal layer between each pair of gravity measurements and, in theory, can be caused by groups of beds in which density is reasonably constant in a horizontal direction for radial distances of at least five to ten times the interval thickness Δz. Under these circumstances ρ can be considered a linear average of any vertical variations of density over the Δz interval. Error in ρ is related to survey errors in depth (Δz_{error}) and gravity (Δg_{error}) difference measurements and is given by the following equation:

$$\rho_{error} = 1/4\pi k \, (\Delta g/\Delta z) \, (\Delta z_{error}/\Delta z + \Delta g_{error}/\Delta g) \qquad (g/cm^3) \qquad (2)$$

Lateral density variations (the ΔG_g term) may be significant where, for example, folded strata, faults, unconformities, intrusions, ice wedges or lateral variations in lithology, porosity, or pore fluids (due to selective depositional or postdepositional processes) intersect or occur within detectable distances of the borehole. Analysis of the borehole gravity data in these cases is more difficult because equal density surfaces generally are poorly known and may be complex in shape. Separation of normal and anomalous components of the BHG survey and development of density models from independent geological and geophysical data to fit the "anomalous" part of the BHG survey are necessary steps to a more complete interpretation. Anomalous or "structural" effects usually (but not always) are small or change slowly with depth so that high relative accuracy between proximal intervals is seldom affected.

A very important application of borehole gravity surveys is the accurate and representative evaluation of formation or reservoir total porosity in the vicinity of the well. BHG porosities are calculated from BHG densities using the familiar equation for porosity:

$$\phi = 100(\rho_g - \rho)/(\rho_g - \rho_f) \qquad (3)$$

where ϕ = total porosity (percent), ρ = BHG density (g/cm^3), ρ_g = average grain or matrix density of the solid constituents of the rocks contained in the interval (g/cm^3), and ρ_f = average density of the pore fluids contained in the interval (g/cm^3). If ρ is provided from the borehole gravity survey, ρ_g and ρ_f must be estimated from independent data in order to calculate BHG porosity ϕ.

Accurate determination of BHG porosity requires an understanding of the effects of errors in the three variables on the right side of equation (3). An error equation is

$$\phi_{error} = \frac{100}{(\rho_g - \rho_f)}\left[(1-\phi)\,|\rho_{g_{error}}| + \phi\,|\rho_{f_{error}}| + |\rho_{error}|\right] \qquad (4)$$

where $\rho_{g_{error}}$, $\rho_{f_{error}}$, and ρ_{error} represent the errors or uncertainties in the values of grain density, pore-fluid density, and BHG density, respectively, expressed in g/cm^3. ϕ is given fractionally. ϕ_{error} is the resultant error or uncertainty in calculated BHG porosity expressed in porosity percent. Absolute values of $\rho_{g_{error}}$, $\rho_{f_{error}}$, and ρ_{error} are summed in equation (4) to give the maximum error case. In practice, the signs of these three errors may cause some compensation so that ϕ_{error} is actually less than estimated from equation (4). Note that the magnitude of each error on the right side depends on the inverse value of (ρ_g - ρ_f) which, for practically all economically important sedimentary rocks, ranges from about 0.77 to 0.35 (g/cm^3)$^{-1}$. Also, $\rho_{g_{error}}$ is larger in lower porosity rocks than in higher porosity rocks and the converse is true for $\rho_{f_{error}}$. Careful borehole gravity surveying and the acquisition of sufficient independent downhole data to describe mineralogy and pore fluids almost always will cause ϕ_{error} to be less than 3 and frequently less than 1.5 porosity percent.

Density and porosity profiles calculated from BHG densities are particularly important because of the large volume of formation investigated and high relative or absolute accuracy that is inherent and unique to the borehole gravity method. Comparative radial distances from the borehole and corresponding rock volumes investigated by conventional cores, gamma-gamma log, neutron log, sonic log, and borehole gravity meter over a 3-m (l0-ft) interval are shown in Table 5. There is no doubt that the borehole gravity meter provides a unique glimpse of the rocks surrounding the borehole and can be very important for formation and reservoir analysis where conventional logs give faulty or ambiguous results.

Suggested references for the theory and mechanics of borehole gravity surveys are Smith (1950), Beyer (1971, 1983), and Rasmussen (1973, 1975). Applications of borehole gravity surveys include formation evaluation, reservoir engineering, evaluation of well log and core analyses, surface gravity and seismic studies, and engineering or rock property investigations. Useful references for applications include Smith (1950), McCulloh (1966), McCulloh and others (1968), Jageler (1976), Bradley (1976), Beyer and Clutsom (1978), Schmoker (1979), Robbins (1979), Tucci and others (1983), and Beyer (1987a, b).

Table 5. Radial distances investigated (to encompass 90% of the effects) by gamma-gamma neutron, and acoustical type logs, and borehole gravity survey with corresponding formation volumes over a 10-ft vertical interval. Beyer (1987a).

Logging method[1]	Radial distance investigated for 90% effect		Formation volume investigated	
	(in.)	(cm)	(ft^3)	(m^3)
Conventional 5.25-in. (13-cm) core	2.6	(6.6)	1.5	(.04)
Gamma-gamma log	8	(20)	17	(0.5)
Neutron log	14	(36)	40	(1.1)
Sonic log	18	(46)	59	(1.7)
Borehole gravity survey	600	(1500)	78,532	(2,224)

[1]Borehole radius is assumed to be 6 in. and gamma-gamma, neutron, and acoustical logs are assumed to investigate one-half of the circular annulus around the borehole. Conventional 5.25-in. core is included for comparison. Investigative radii of gamma-gamma, neutron, and acoustical logs, chosen very liberally, are from Sherman and Locke (1975), Antkiw (1976), Jageler (1976), Baker (1984), and Bateman (1985).

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