UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Basic Data and Preliminary Density Profile from a Borehole Gravity Survey Made in the Cajon Pass Scientific Drillhole, California

by

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INTRODUCTION

This report presents a brief summary of the borehole gravity (BHG) method, a description of the data reduction and error estimate procedures, and a preliminary density profile for a borehole gravity (BHG) survey made in the Cajon Pass Scientific Drillhole (Federal 2-26) by the Geological Survey in July 1988. The Federal 2-26 well is located 4.3 km (2.7 mi) northeast of the San Andreas fault zone in sec. 26, T3N., R6W., S.B.B.&M., San Bernardino County, California (Fig. 1).

The rationale for drilling the Federal 2-26 well under the auspices of Deep Observation and Sampling of the Earth's Continental Crust, Inc. (DOSECC) and most of the scientific work accomplished during and after phase I drilling to 2,115 m (6,938 ft) are summarized in Geophysical Research Letters, v. 15, p. 933-1076, August 1988 Supplement. Scientific work is not published at this writing (December 1988) for drilling phase II during which the well was deepened to 3,510 m (ll,515 ft). The 1988 BHG survey had been originally planned for 1987 after phase I drilling, but was postponed until after phase II drilling due to delays in prior commitments.

The BHG survey in the Federal 2-26 well was made with the small diameter Geological Survey borehole gravity meter (La Coste & Romberg BHG meter #6) using the Geological Survey BHG well logging system (Robbins, 1979). A careful casing collar (CCL) survey was made to 3,437 m (11,275 ft) to tie depth measurements from the Geological Survey logging cable-measuring sheave system to that used for the cased-hole cement bond logs (Micro-Seismogram Log of WELEX). The natural gamma-ray traces from the cement bond logs were correlated to those of the gamma-gamma density log (Compensated Neutron-Litho Density Log of Schlumberger). In this way, depths for downhole gravity stations selected from the open-hole log suite were adjusted via natural gamma-ray curves to the cement band logs and, thence, via casing collars to the Geological Survey depth measuring system. Comparison of Geological Survey depth measurements with the driller's depth to the top of the 7 5/8-inch casing string and with a summation of the 7 5/8-inch casing tally measurements, the latter adjusted for elastic stretch and thermal expansion, showed differences of 0.03%, well within the range of accuracies considered acceptable for BHG surveys (Table 1).

Seventy-one valid downhole gravity stations were occupied between ground level and 2,576 m (8,451 ft). Twenty repeat downhole gravity measurements were made to monitor gravity meter drift and improve the precision of gravity differences measured over small-vertical intervals[1]. Most gravity stations were selected from independent downhole information to bracket intervals of confirmed or suspected distinct lithologic and(or) physical properties. Most closely spaced stations were selected in the intervals from 407 to 599 m (1,337 to 1,965 ft) and 2,446 to 2,576 m (8,026 to 8,451 ft). The shallower interval brackets the contact between underlying crystalline basement rocks and overlying sedimentary rocks, while the deeper interval corresponds to one of the zones of suspected faulting and fracturing within the basement. Stations were also occupied at 60-m intervals to a depth of 1,380 m to conform to the blocking interval for P-wave velocities from the VSP surveys (Rector, 1988).

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[1]Fiscal constraints prevented a more detailed survey above 2,576 m (8,451 ft) and measurements between 2,576 m (8,451 ft) and 3,437 m (11,275 ft). Also, equipment failure on the final survey day left gravity measurements between 1,139 m (3,737 ft) and 2,446 m (8,026 ft) without a gravity tie for drift control. In spite of this malfunction, documented behavior of the gravity meter during this day suggests very low, uniform drift, neglect of which over the above interval probably is not significant. It is hoped a later BHG survey can be made to tie these measurements, log deeper portions of the well, and fill in detail where needed above 2,576 m.

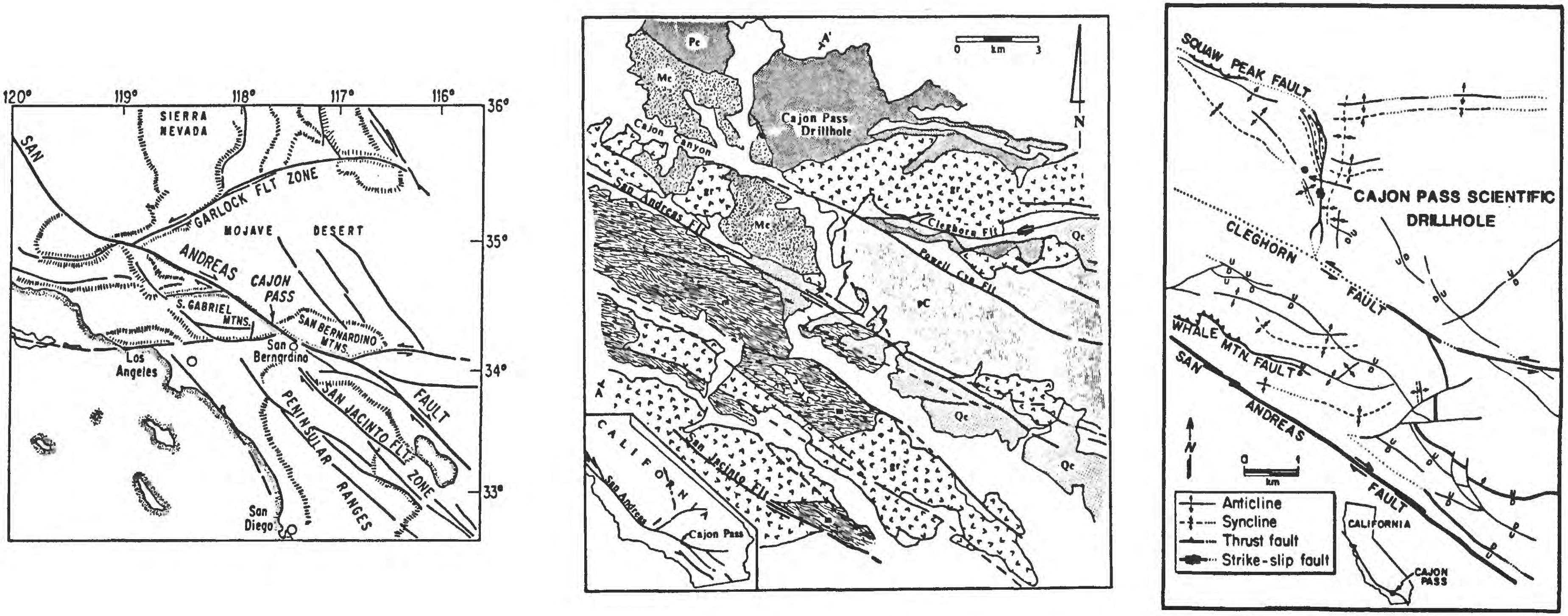

Figure 1. (A) Location of Cajon Pass, major faults and physiographic features in southern California (after Silver and James, 1988). (B) Generalized geologic map of the Cajon Pass area (after Rodgers, 1967). pC - Precambrian igneous and metamorphic complex; m - Pre-Cretaceous metamorphic rocks; gr - Mesozoic granitic rocks; Mc - Miocene nonmarine rocks; Pc - Pliocene nonmarine rocks; Qc - Pleistocene nonmarine rocks. (C) Simplified structural features of western San Bernardino Mountains (after Weldon, 1986) with location of Cajon Pass Scientific Drillhole (modified from Pezard and others, 1988). Dotted lines correspond to inferred extensions of exposed structures locally covered by Plio-Pleistocene deposits.

Table 1. Measurements to top of 7 5/8-inch casing and measured length of 7 5/8-inch casing string by driller and by Geological Survey during borehole gravity survey. (Depths are given in customary English units used in U.S. drilling and well logging industry).

	Driller	Geological Survey
Depth to top of 7 5/8-inch casing	5494	5495.7
Length of 7 5/8-inch casing string	5882.9 5886.1*	5887.6

*Corrected for elongation due to thermal expansion and elastic strain.

NOTE: The 7 5/8-inch casing string extends from 5,494 feet to 11,380 feet if one accepts the driller's depth to the casing top and includes 3.2 feet of lengthening due to thermal expansion and elastic strain. The top and bottom of the 7 5/8-inch casing string are about 1.7 feet deeper if one accepts the depth measurement to the casing top made for the borehole gravity survey. The absence of the casing tally for the 9 5/8-inch casing string prevents a more thorough analysis of absolute depths in the drillhole.

The BHG survey in the Federal 2-26 well, when fully interpreted, will provide accurate, large-volume measurements of in situ bulk density of the rocks surrounding the drillhole, and a profile of anomalous gravity and the anomalous vertical gradient of gravity down the well. Anomalous gravity effects appear to be measurable, particularly in the upper part of the drillhole, and should further elucidate the shape (and thus nature) of the sediment-basement rock boundary in the vicinity of the drillhole (Ehlig, 1988; Pezard and others, 1988; Silver and James, 1988). After further analysis, reliable rock density information will be available (1) from the top of the open-hole log suite at 250 m (822 ft) to the ground surface, (2) for some of the unreliable intervals of the gamma-gamma density log below 250 m, and (3) to aid the interpretation of surface gravity anomalies in the local area surrounding the drillhole. Integration of the BHG density data will help to provide a more accurate vertical stress profile that may or may not be a significant improvement to Healy and Zoback (1988).

The determination of large-volume BHG porosity information will depend on reliable matrix or grain density information from analysis of conventional logs (Anderson and others, 1988a, b) and rock samples (Silver and others, 1988; Silver and James, 1988). Independent measurements of matrix or intergranular porosity would be needed to quantitatively evaluate fracture porosity from BHG porosity (Beyer, 1987), although qualitative comparisons between BHG porosity and other fracture-sensitive measurements (Barton and Moos, 1988; Leary and others, 1988; Moos, 1988; Pezard and Luthi, 1988; Pezard and others, 1988) are simple and direct. Unfortunately, BHG porosity is especially sensitive to uncertainties in matrix density in low-porosity rocks (see Appendix A) and intergranular and fracture porosity mostly are very low in the crystalline basement section. The possibility that BHG density or porosity information will improve determinations of thermal conductivity (Lachenbruch and Sass, 1988; Williams and others, 1988) or elastic wave studies (e.g., Rector, 1988), or provide further evidence of mass-altering chemical processes (e.g., James and Silver, 1988), will have to await possible future collaborative efforts.

BASIC DATA AND PRELIMINARY DENSITY PROFILE

The following data set includes a small-scale plot of BHG apparent density and a tabulation of the basic borehole gravity data (see Fig. 2; Table 2). 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 the drillhole is vertical. Maximum likely errors in calculated density, due to measurement precision, are displayed as error bars on the plotted profile (Fig. 2). These error estimates do not include uncertainties due to anomalous gravity (ΔG_g) effects which are significant in the Federal 2-26 and will be evaluated in a future paper. Because no effort was made in this preliminary report to separate out anomalous gravity effects, BHG density values given in Figure 2 and Table 2 are not accurate for the rocks immediately surrounding the borehole, especially at shallow depths.

An explanation of columns 1 through 15 in Table 2 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.

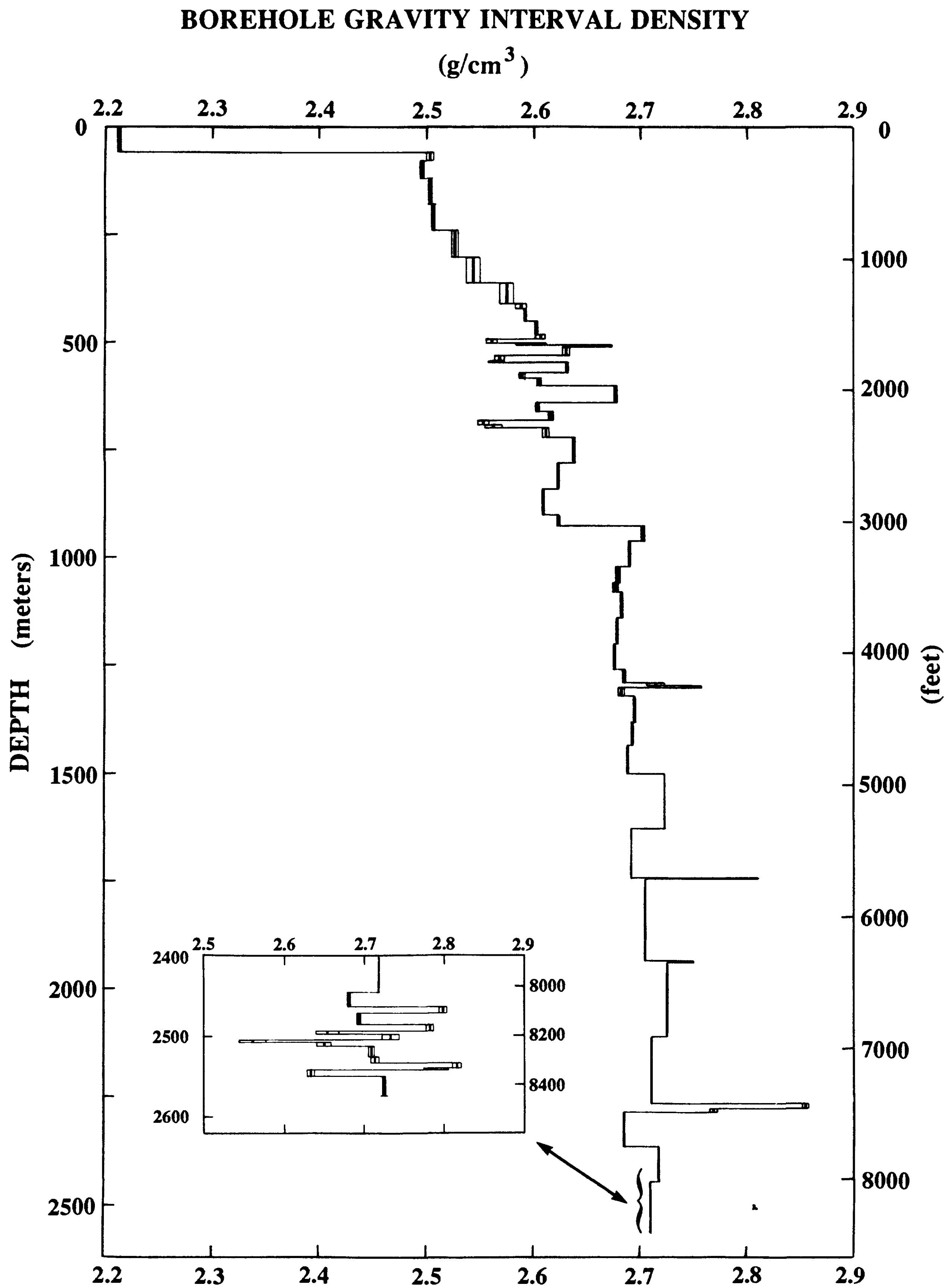

Figure 2. BHG (apparent) density profile from borehole gravity survey in Cajon Pass Scientific Drillhole. Density values do not have high absolute accuracy, especially at shallow depths, where unevaluated anomalous gravity effects presumably are significant.

Table 2. Basic data for BHG survey in Cajon Pass Scientific Drillhole. See pages 5, 9 and 10 for explanation.

USGS BOREHOLE GRAVITY SURVEY: DOSECC Cajon Pass Scientific Drill-hole (Federal 2-26)
LOCATION: 26-3N-6W San Bernardino Co California

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	3278.9	0.	3.234	0.	.001									0.
						7.304	.004	195.00	0.15	.03746	.094025	2.213	.002	
2	3083.9	195.0	3.774	7.304	.003									59.4
						1.808	.004	60.18	0.05	.03004	.094028	2.504	.004	
3	3023.7	255.2	3.933	9.112	.001									77.8
						4.083	.003	135.05	0.15	.03023	.094029	2.496	.002	
4	2888.7	390.2	4.277	13.195	.002									118.9
						5.911	.005	196.79	0.15	.03004	.094031	2.504	.002	
5	2691.9	587.0	4.743	19.106	.003									178.9
						5.901	.005	196.88	0.15	.02997	.094033	2.506	.002	
6	2495.0	783.9	5.174	25.007	.002									238.9
						5.795	.012	196.72	0.15	.02946	.094036	2.527	.003	
7	2298.3	990.1	5.572	30.802	.010									298.9
						5.718	.030	196.99	0.15	.02903	.094039	2.544	.007	
8	2101.3	1187.1	5.943	36.520	.020									358.9
						4.498	.023	159.34	0.15	.02823	.094041	2.575	.007	
9	1941.9	1346.2	6.225	41.018	.003									407.5
						1.046	.004	37.51	0.05	.02789	.094043	2.589	.006	
10	1904.4	1383.8	6.289	42.064	.001									418.9
						2.692	.002	96.89	0.05	.02778	.094044	2.593	.001	
11	1807.5	1480.6	6.451	44.756	.001									448.5
						2.750	.003	99.93	0.05	.02752	.094045	2.603	.002	
12	1707.6	1580.5	6.613	47.506	.002									478.9
						0.952	.003	34.72	0.05	.02742	.094047	2.607	.005	
13	1672.9	1615.2	6.668	48.458	.001									489.5
						0.882	.003	30.85	0.05	.02859	.094047	2.561	.006	
14	1642.0	1646.0	6.717	49.340	.002									498.9
						0.468	.005	16.93	0.05	.02764	.094047	2.598	.015	
15	1625.1	1662.9	6.743	49.808	.003									504.1
						0.377	.006	14.39	0.05	.02620	.094048	2.655	.020	
16	1610.7	1677.3	6.766	50.185	.003									508.5
						1.720	.005	64.16	0.05	.02681	.094048	2.631	.004	
17	1546.6	1741.4	6.864	51.905	.002									528.0
						1.017	.003	35.80	0.05	.02841	.094049	2.568	.005	
18	1510.8	1777.2	6.918	52.922	.001									538.9
						0.480	.002	16.85	0.05	.02848	.094049	2.565	.008	
19	1493.9	1794.0	6.943	53.402	.001									544.1
						2.145	.002	80.09	0.05	.02678	.094049	2.632	.002	
20	1413.8	1874.0	7.061	55.547	.001									568.5
						1.139	.002	40.87	0.05	.02787	.094050	2.590	.003	
21	1373.0	1914.8	7.121	56.686	.001									580.9
						1.621	.002	59.04	0.05	.02746	.094051	2.606	.002	
22	1313.9	1973.8	7.205	58.307	.001									598.9
						3.279	.002	127.97	0.15	.02562	.094052	2.677	.002	
23	1185.9	2101.6	7.383	61.586	.001									637.9
						1.893	.002	68.84	0.05	.02750	.094054	2.604	.002	
24	1117.1	2170.4	7.476	63.479	.001									658.9
						1.774	.003	65.27	0.05	.02718	.094054	2.617	.003	
25	1051.8	2235.6	7.562	65.253	.002									678.8
						0.920	.003	31.95	0.05	.02880	.094055	2.553	.005	
26	1019.9	2267.5	7.604	66.173	.001									688.6
						0.714	.004	25.00	0.05	.02856	.094056	2.563	.008	
27	994.9	2292.5	7.637	66.887	.003									696.2
						2.041	.005	74.75	0.05	.02730	.094056	2.612	.003	
28	920.1	2367.2	7.732	68.928	.002									719.0
						5.242	.003	196.82	0.15	.02663	.094057	2.638	.001	
29	723.3	2563.8	7.974	74.170	.001									779.0
						5.316	.002	196.80	0.15	.02701	.094060	2.623	.001	
30	526.5	2760.4	8.203	79.486	.001									838.9
						5.387	.002	196.78	0.15	.02738	.094062	2.609	.001	
31	329.7	2957.0	8.420	84.873	.001									898.9
						2.232	.002	82.64	0.05	.02701	.094065	2.624	.002	
32	247.1	3039.5	8.508	87.105	.001									924.1
						2.856	.002	114.30	0.15	.02499	.094066	2.703	.002	
33	132.8	3153.8	8.626	89.961	.001									958.9
						4.982	.003	196.86	0.15	.02531	.094068	2.690	.001	
34	-64.1	3350.5	8.819	94.943	.002									1018.9
						3.177	.004	124.15	0.15	.02559	.094070	2.679	.002	
35	-188.2	3474.4	8.936	98.120	.002									1056.8
						1.864	.004	72.67	0.05	.02565	.094072	2.677	.003	

Table 2.--Continued. Basic data for BHG survey in Cajon Pass Scientific Drillhole. See pages 5, 9 and 10 for explanation.

USGS BOREHOLE GRAVITY SURVEY: DOSECC Cajon Pass Scientific Drill-hole (Federal 2-26)
LOCATION: 26-3N-6W San Bernardino Co California

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
36	-260.9	3547.1	9.003	99.984	.002									1078.9
						5.024	.003	196.98	0.15	.02551	.094073	2.683	.001	
37	-457.9	3743.9	9.175	105.008	.001									1139.0
						5.038	.002	196.67	0.15	.02562	.094076	2.679	.001	
38	-654.5	3940.3	9.338	110.046	.001									1198.9
						5.056	.002	196.87	0.15	.02568	.094078	2.676	.001	
39	-851.4	4137.0	9.491	115.102	.001									1258.9
						2.406	.003	94.54	0.05	.02545	.094081	2.685	.002	
40	-945.9	4231.5	9.561	117.508	.002									1287.7
						0.468	.003	18.95	0.05	.02470	.094082	2.715	.009	
41	-964.9	4250.5	9.575	117.976	.001									1293.5
						0.406	.003	17.02	0.05	.02385	.094082	2.748	.010	
42	-981.9	4267.5	9.587	118.382	.002									1298.7
						1.694	.004	66.37	0.05	.02552	.094083	2.683	.003	
43	-1048.3	4333.8	9.635	120.076	.002									1318.9
						4.960	.003	196.82	0.15	.02520	.094083	2.695	.001	
44	-1245.1	4530.6	9.769	125.036	.001									1378.9
						4.425	.002	175.21	0.15	.02526	.094086	2.693	.001	
45	-1420.3	4705.7	9.882	129.461	.001									1432.3
						5.543	.003	218.49	0.15	.02537	.094088	2.689	.001	
46	-1638.8	4924.2	10.012	135.004	.002									1498.9
						10.251	.004	418.52	0.15	.02449	.094091	2.723	.001	
47	-2057.3	5342.8	10.234	145.255	.002									1626.5
						9.543	.003	377.20	0.15	.02530	.094097	2.692	.001	
48	-2434.5	5716.3	10.403	154.798	.001									1741.5
						0.142	.004	6.18	0.02	.02297	.094102	2.783	.028	
49	-2440.7	5722.5	10.405	154.940	.003									1743.4
						15.597	.004	624.73	0.15	.02497	.094102	2.705	.000	
50	-3065.4	6347.4	10.626	170.537	.001									1933.8
						0.216	.002	8.97	0.02	.02408	.094110	2.740	.011	
51	-3074.4	6356.4	10.628	170.753	.001									1936.5
						13.860	.003	566.94	0.15	.02445	.094111	2.726	.000	
52	-3641.3	6923.1	10.768	184.613	.002									2109.3
						12.626	.003	508.77	0.15	.02482	.094118	2.712	.001	
53	-4150.1	7430.6	10.850	197.239	.001									2264.4
						0.764	.002	36.11	0.05	.02116	.094125	2.855	.003	
54	-4186.2	7466.6	10.855	198.003	.001									2275.4
						0.698	.002	29.89	0.05	.02335	.094126	2.769	.004	
55	-4216.1	7496.4	10.858	198.701	.001									2284.5
						6.691	.003	262.50	0.15	.02549	.094126	2.686	.001	
56	-4478.6	7758.1	10.883	205.392	.002									2364.5
						6.616	.003	268.21	0.15	.02467	.094129	2.718	.001	
57	-4746.8	8025.3	10.898	212.008	.001									2446.3
						1.536	.002	59.96	0.05	.02562	.094133	2.681	.002	
58	-4806.8	8085.1	10.900	213.544	.001									2464.5
						0.557	.002	24.62	0.05	.02262	.094134	2.798	.005	
59	-4831.4	8109.6	10.900	214.101	.001									2472.0
						1.202	.002	47.51	0.05	.02530	.094134	2.693	.003	
60	-4878.9	8156.9	10.901	215.303	.001									2486.5
						0.599	.002	26.00	0.05	.02304	.094135	2.782	.005	
61	-4904.9	8182.8	10.902	215.902	.001									2494.5
						0.369	.004	14.03	0.05	.02630	.094135	2.654	.015	
62	-4918.9	8196.7	10.902	216.271	.003									2498.7
						0.534	.005	21.98	0.05	.02429	.094135	2.733	.011	
63	-4940.9	8218.7	10.902	216.805	.002									2505.4
						0.289	.003	10.07	0.05	.02870	.094136	2.560	.017	
64	-4951.0	8228.8	10.903	217.094	.001									2508.5
						0.473	.003	17.91	0.05	.02641	.094136	2.650	.009	
65	-4968.9	8246.5	10.903	217.567	.002									2514.0
						1.099	.003	44.13	0.05	.02490	.094136	2.709	.004	
66	-5013.0	8290.4	10.903	218.666	.001									2527.4
						0.598	.002	24.12	0.05	.02479	.094137	2.713	.005	
67	-5037.1	8314.6	10.903	219.264	.001									2534.8
						0.465	.002	20.96	0.05	.02218	.094137	2.815	.006	
68	-5058.1	8335.4	10.903	219.729	.001									2541.2
						0.138	.002	6.04	0.02	.02285	.094137	2.789	.016	
69	-5064.1	8341.4	10.903	219.867	.001									2543.0
						0.722	.002	26.90	0.05	.02684	.094137	2.633	.005	
70	-5091.1	8368.2	10.903	220.589	.001									2551.2
						1.988	.003	81.16	0.05	.02450	.094138	2.725	.002	
71	-5172.2	8449.0	10.902	222.577	.002									2575.9

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).

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 due to gravity reading quality, gravity meter repeatability and drift correction (column 6) (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.

Control 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

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

where ϕ 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 apparent 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, Appendix A. ρ_{error} is in g/cm^3.

Column 15

Depth of borehole gravity station relative to ground level (meters). Values are not corrected for borehole deviation from the vertical.

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. 3).

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; 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).

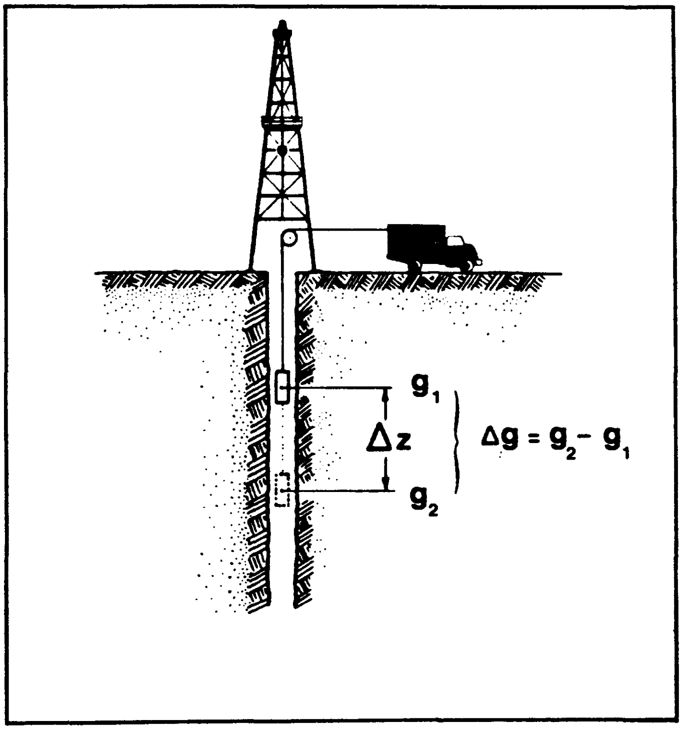

Figure 3. Schematic diagram showing measurement of gravity (Δg) and depth differences (Δz) in the borehole.

The second term on the right-hand side of eq. (1) 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 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, 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 ($\rho_g - \rho_f$) 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 (10-ft) interval are shown in Table 3. 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 3. 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 (in.)	(cm)	Formation volume investigated (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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