U. S. DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

Basic Data and Preliminary Density Profile from a Borehole Gravity Survey Made in the 341-11P Well, Kettleman North Dome Oil Field, Kings County, California

by

L. A. Beyer[1], F. G. Clutsom[2] and F. V. Grubb[3]

Open-File Report

95-54

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or with the North American Stratigraphic Code. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

[1]U.S. Geological Survey, 345 Middlefield Rd., MS 999, Menlo Park, CA 94025-3591

[2]U.S. Geological Survey, MS 964, Federal Center, Box 25046, Denver, CO 80225-0046

[3]U.S. Geological Survey, 2255 North Gemini Dr., Flagstaff, AZ 86001-1698

1995

INTRODUCTION

This report presents (1) a short description of the Kettleman North Dome oil field, (2) a brief summary of the 341-11P well drilled between October 1989 and February 1990, and (3) the preliminary density profile and tabulation of basic data for a borehole gravity (BHGM) survey made by the Geological Survey in the 341-11P well during October 30 and November 5, 6, and 7, 1992. A brief summary of the borehole gravity (BHGM) method and a description of the data reduction and error estimate procedures also is included.

KETTLEMAN NORTH DOME OIL FIELD

Kettleman North Dome oil field is located about 21 mi (35 km) south-southeast of the town of Coalinga along the central west side of the San Joaquin basin, California (Fig. 1). The Kettleman field is a giant multi-zoned oil and gas accumulation in a deeply eroded long, narrow, asymmetrical, post-Pliocene anticlinal uplift with flank dips up to 40° and an original productive area of nearly 14,000 acres (Sullivan, 1966) (Fig. 2). The Kettleman field ranks eighth in oil production (458 MMbbls), first in associated gas production (2.950 Tcf), and fifth in cumulative production plus estimated reserves of oil and gas (950 MM barrels oil equivalent) in the San Joaquin basin through 1990 (California Division of Oil and Gas, 1991). Production figures since 1960 indicate near depletion today, based on the largely primary production practices applied since that time. The California Division of Oil and Gas (1991) estimates that, at the end of 1990, only .21% of producible oil and .59% of producible gas remain in the field. However, produced hydrocarbons as a fraction of original oil in place is not available, and may be a smaller than expected fraction due to poor conservation practices during the early production history of the field.

Over 90% of the produced oil and gas is from the thick sequence of fluvial, deltaic, shelf, slope and submarine fan sandstones of the Oligocene and Miocene Temblor Formation (discovered in 1928) that are productive at depths of about 6,000 to 9,000 feet (Sullivan, 1966; Kuespert, 1985) (Fig. 3). Remaining production comes from underlying, thinner Oligocene and Miocene sandstones (Vaqueros sands of local usage) discovered in 1938, lower Eocene sandstones (upper McAdams sands of local usage presumably equivalent to the Domengine or Avenal Sandstone) discovered in 1938, and upper Paleocene sandstones (lower McAdams sands of local usage of the Lodo Formation) discovered in 1940. These sandstones occur at depths approaching 12,000 feet in flank locations on the anticline. Minor amounts of oil also have been produced in several widely separated wells from naturally fractured intervals of the Eocene Kreyenhagen Shale which is located between the "Vaqueros" and "McAdams" zones (D. B. Wagner, personal communication, 1992). Above the Temblor reservoirs, oil staining or local partial saturation has been reported in sandstones and siltstones of the Reef Ridge Shale and McLure Shale Member of the Monterey Formation, and minor tar sands noted in the Miocene and Pliocene Etchegoin Formation. No production tests for oil or gas have been made of intervals above the Temblor Formation.

Early development and production practices were not conducive to the maintenance of reservoir pressure or maximum primary recovery (Sullivan, 1966). Temblor reservoir pressures today generally are low (~500 psi) except for isolated sands (~1,500 to 2,000 psi). Water encroachment generally is not a serious problem in Temblor sands but does occur in the "Vaqueros" and upper "McAdams" reservoirs.

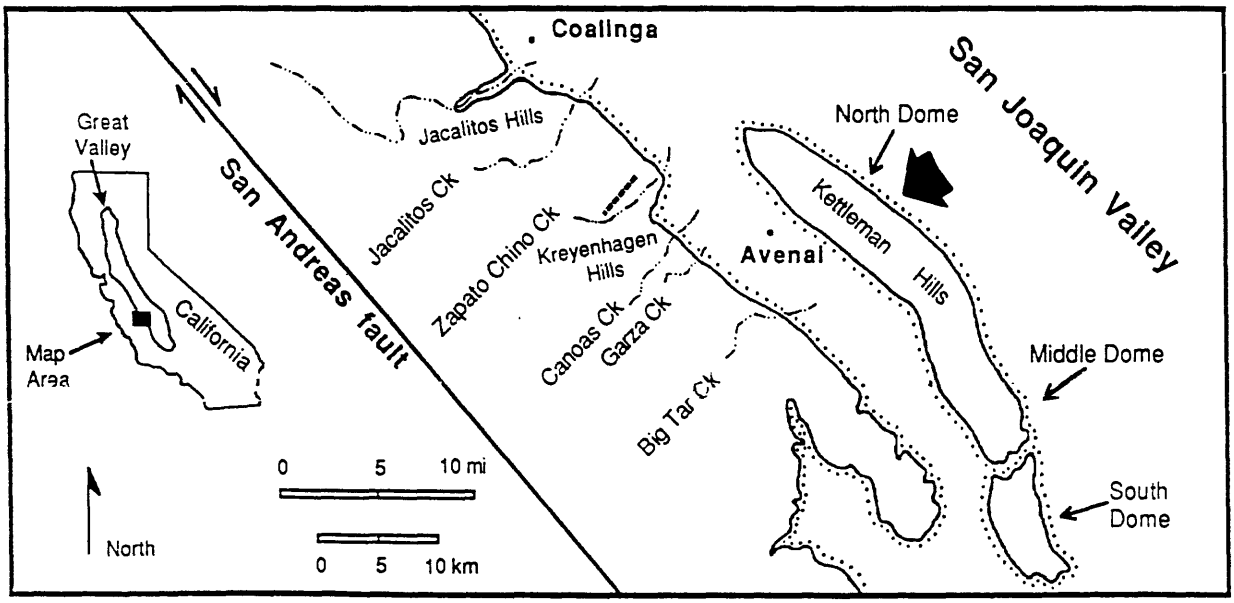

Figure 1. Location of Kettleman Hills North Dome, California (adapted from Loomis, 1992a).

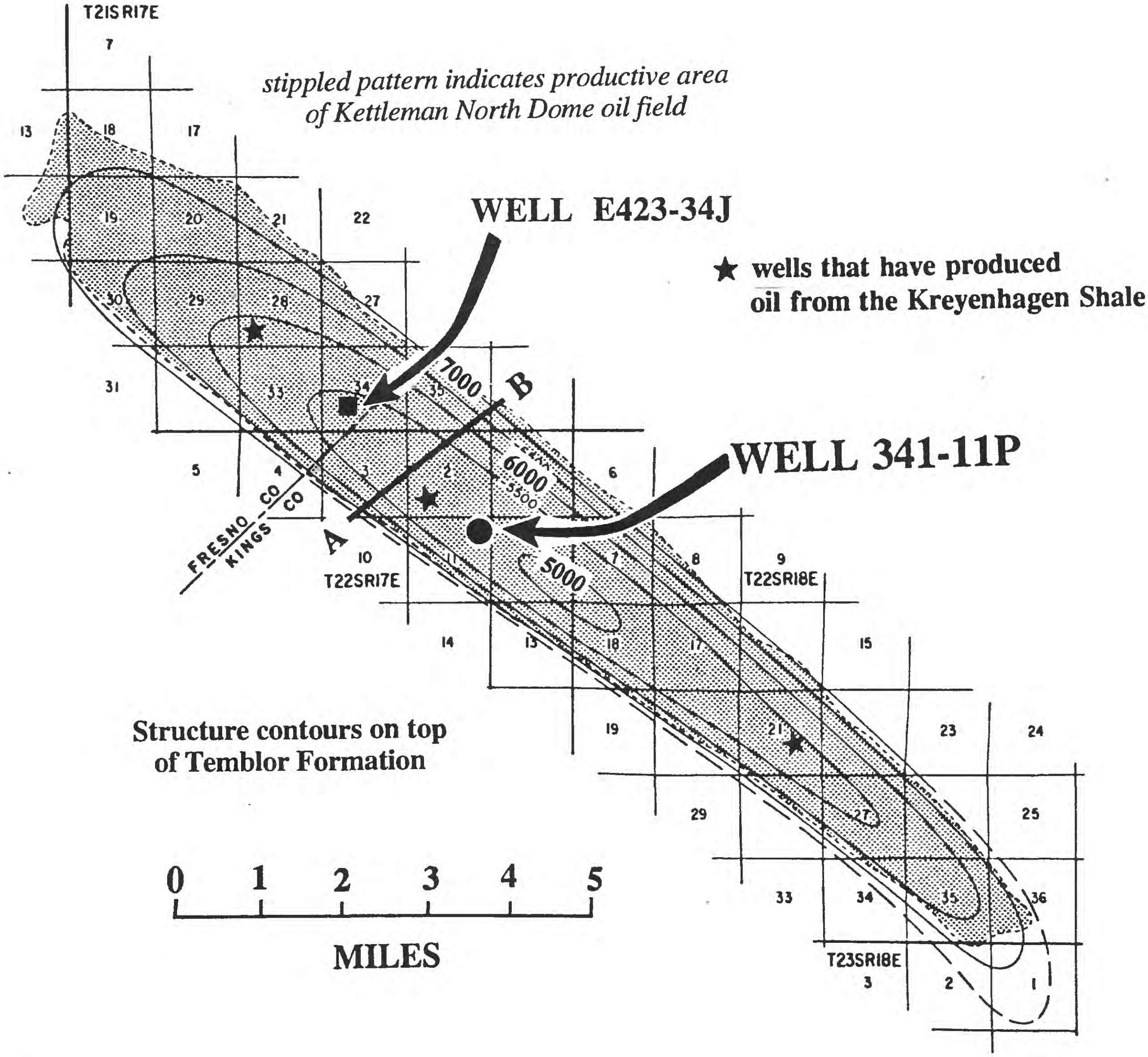

Figure 2. Generalized structure contour map on top of Temblor Formation, Kettleman North Dome oil field, California (California Division of Oil and Gas, 1973). Contour interval is 500 ft. Locations of cross section AB (Fig. 3) and wells 341-11P and E423-34J also are shown. See Fig. 3 for contoured horizon in cross section.

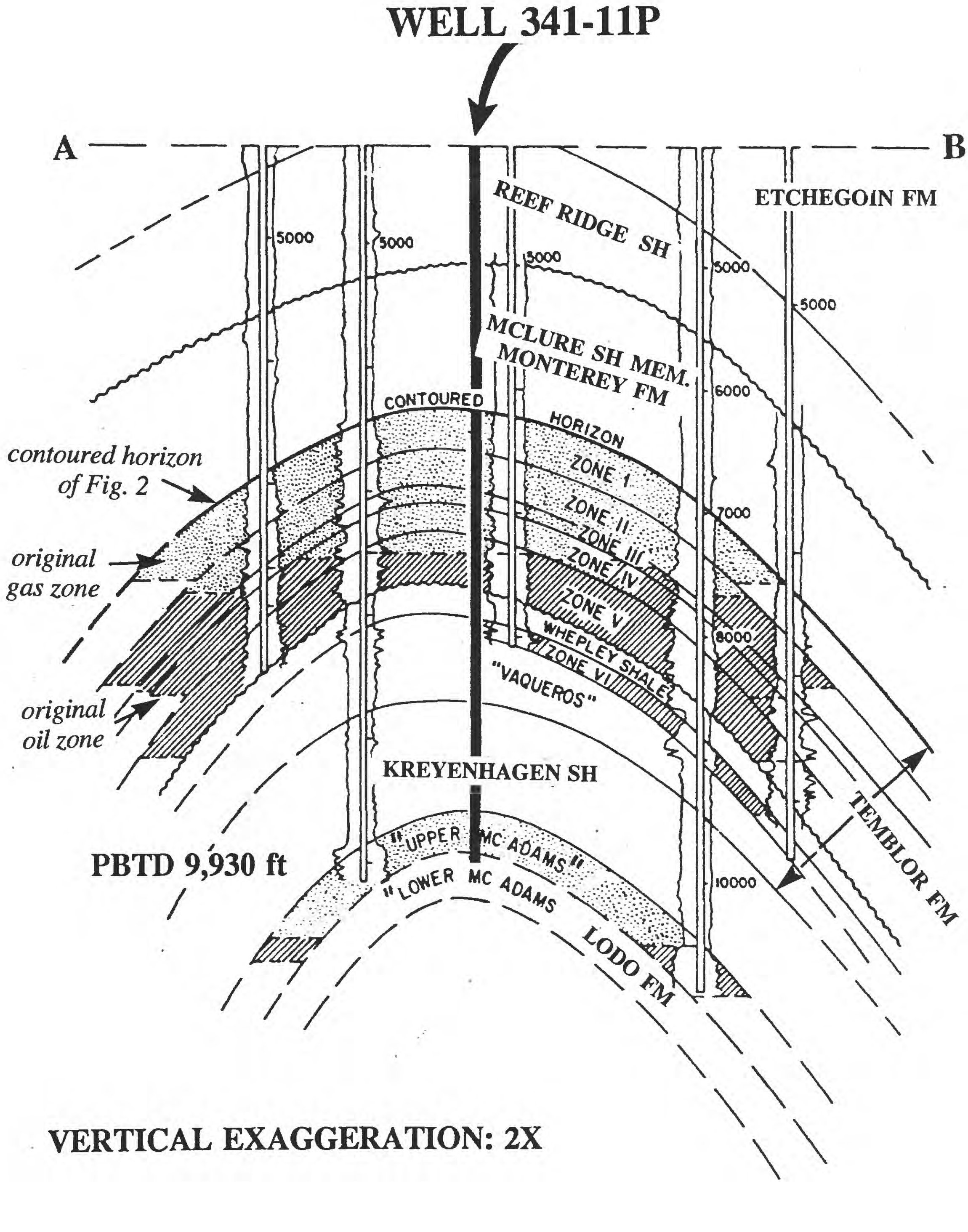

Figure 3. Transverse cross section AB across Kettleman North Dome oil field, California (Sullivan, 1966). Well 341-11P is projected into this section from one mile to the southeast (see Fig. 2).

Extensive conventional core was cut during the first several decades of field development. Unfortunately, few wells have been drilled in recent decades and practically all open-hole well logs pre-date 1965. In early 1992 the Kettleman field had 45 producing wells and 202 shut-in wells. Mechanical problems exist with many of the older wells, often due to the unstable "sloughing shale" zone of the McClure Formation that overlies the Temblor Formation. A state-mandated well abandonment program is pending for an unspecified number of the shut-in wells. The U. S. Government is the royalty owner of every other section of the field.

An excellent foundation for further work in the Kettleman North Dome field is provided by the wide variety of published studies of the field and surrounding area. These studies include conventional surface and subsurface geology (Gester and Galloway, 1933; Goudkoff, 1934; Woodring and others, 1940; Sullivan, 1966), provenance, depositional facies and sedimentary history of the Temblor Formation (Bent, 1985; Kuespert, 1985), diagenetic mineralogy of the oil reservoir sandstones (Merino, 1975a), isotopic composition of field brines (Kharaka and others, 1973), hydrodynamics, and water-rock and membrane geochemistry of the aqueous system (Kharaka and Berry, 1974; Merino, 1975b), description and discussion of abnormally high pore-fluid pressures (Berry, 1973; Yerkes and others, 1990), comparison of faunal and geochemical techniques to evaluate the Pliocene and Pleistocene paleoenvironment (Stanton and Dodd, 1970; Dodd and Stanton, 1975), chronostratigraphic studies (Loomis, 1992a, 1992b), a detailed surface gravity anomaly map (Boyd, 1948), deeper crustal structure and a nearby COCORP seismic profile (Wentworth and others, 1984; Fielding and others, 1984; Namson and Davis, 1988), and earthquake seismicity studies following the New Idria-Coalinga-Kettleman Hills earthquake series (1982-1985) (Ekström and others, 1992; Stein and Ekström, 1992).

THE 341-11P WELL

Surface location of the 341-11P well is 823 ft south and 218 ft west from the northeast corner of sec. 11, T22S., R17E., M.D.B.&M., Kings County, California (Fig. 2). Chevron USA Inc. spudded this well in the Miocene and Pliocene Etchegoin Formation as the first deep test in the Kettleman Hills North Dome oil field in more than two decades (Fig. 4). The 341-11P well was drilled as a gas delineation test of the "lower McAdams sands" brought about by gas demands for steam drives in the nearby Coalinga oil field and by a successful 1988 recompletion in the "lower McAdams" in the E423-34J well located 2.08 mi (3.36 km) north-northwestward along the Kettleman anticlinal axis (Figs. 2 and 3). Secondary objectives included (1) "upper McAdams", "Vaqueros", and Temblor undrained production, (2) testing of the hydrocarbon-bearing, high pressure fractured Kreyenhagen Shale, and (3) acquisition of a modern set of logs, cores, and drilling data from the entire hydrocarbon-bearing section of the field. The well reached a total depth of 10,457 ft (3,187 m) measured depth (MD) or 10,394 ft (3,168 m) true vertical depth on January 25, 1990, after intentional inclinations of as much as 14° 45′ (from about 8,968 to about 9,095 ft MD).

Drillstem tests of perforated intervals of the "lower McAdams sands" between 9,942 and 10,410 ft MD failed to find zones of economic gas production. Further tests suggested by oil and gas shows in mud and ditch samples from shallower zones, especially in the Kreyenhagen Shale, were not undertaken. The cost to drill and test the well was approximately $3.9 million.

When Chevron announced in late 1991 that the 341-11P well was to be abandoned, the senior author negotiated an agreement with Chevron for the U. S. Geological Survey to assume ownership of the well for scientific studies. The 341-11P well was partially abandoned, with

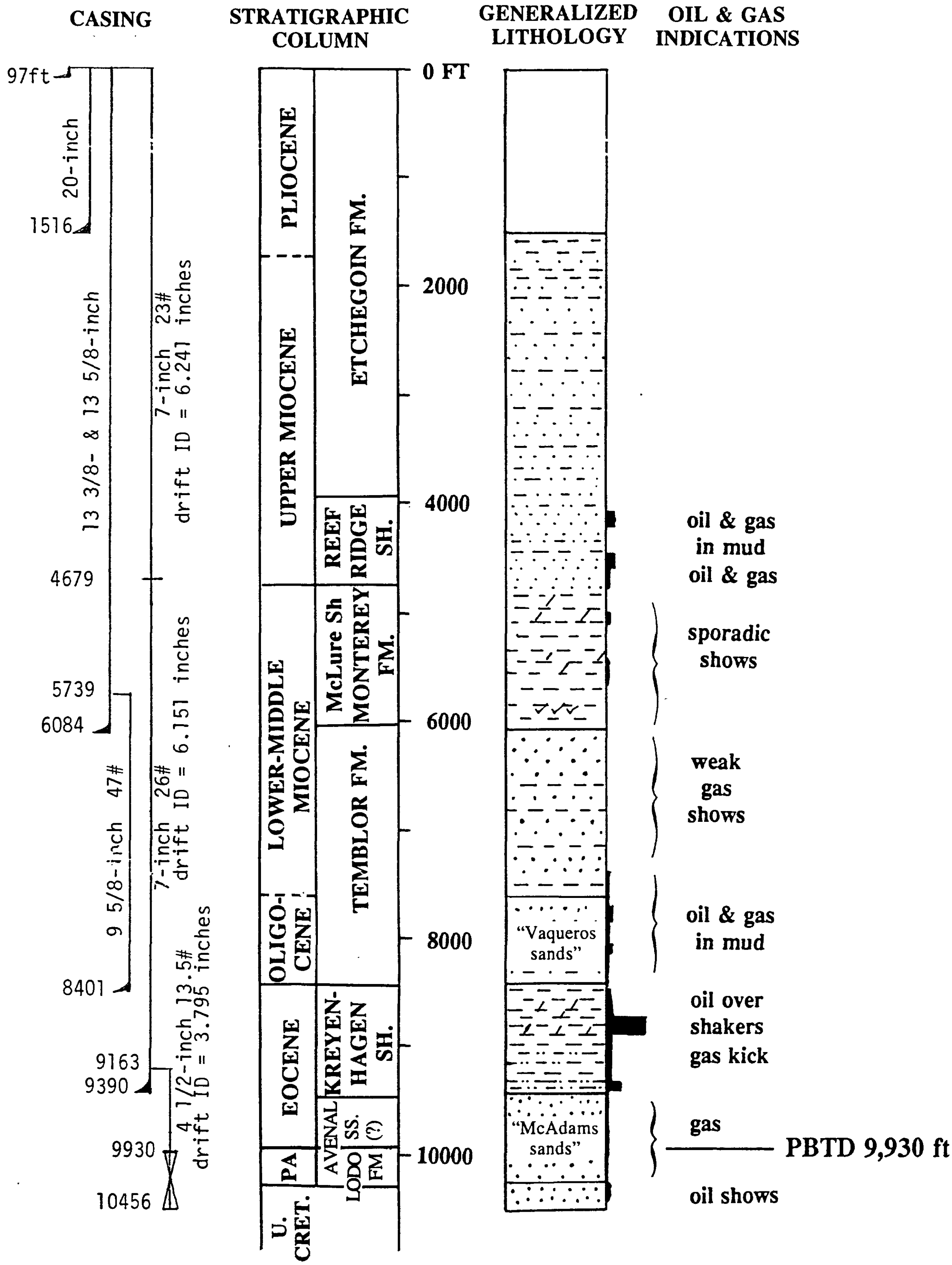

Figure 4. Casing, stratigraphic and generalized lithologic columns, and oil and gas indications of 341-11P well.

approval by the California Division of Oil and Gas, by cementing off perforations below 9,942 ft, filling the casing with cement from TD to 9,384 ft, then drilling out and scrapping the casing to a depth of 9,930 ft. The transfer of ownership agreement stipulated that the Geological Survey would not perforate the casing or conduct any studies that would cause fluids to enter the wellbore from the formation, or vice versa. The Geological Survey's portion of the direct cost of this partial abandonment was $19,240 which was paid to Chevron from the Deep Crustal Studies Program. The legal agreement setting conditions and performance for the transfer of ownership of the well from Chevron to the Geological Survey was signed March 18, 1992, and was approved by the California Division of Oil and Gas on June 9, 1992. At the senior author's request the Geological Survey received from Chevron a complete set of the well records and all of the unwashed ditch samples and conventional cores.

BOREHOLE GRAVITY SURVEY IN THE 341-11P WELL

Sixty valid downhole gravity stations were occupied between ground level and a depth of 6,825 ft using equipment described by Robbins (1979b).[1] All depths are measured well depths. Fifty repeat downhole gravity measurements were made to monitor gravity meter drift and improve the precision of gravity gradients measured between successive downhole stations. Depths of gravity stations below 1,600 ft were selected from openhole well logs and other downhole information to bracket intervals of confirmed or suspected distinct lithologic and(or) physical properties. In the absence of open-hole well logs or a ditch sample log above 1,600 ft, gravity stations from ground surface to 1,600 ft were evenly spaced at 200-foot intervals.

The BHGM survey in the 341-11P well, when fully interpreted, will provide accurate large-volume measurements of in situ bulk density of the rocks surrounding the well. With the addition of grain density information derived from cores and drill cuttings, in situ bulk density can be interpreted in terms of total porosity and pore-fluid density. These unique data can be used in several ways to improve our understanding of the Kettleman structure and rocks.

Bulk density and porosity data from the upper part of the well, when examined with comparable data from the adjacent synclines will indicate how much overburden has been removed from the Kettleman anticline by erosion. Knowledge of prior maximum overburden is crucial to understanding the temperature, compaction, and diagenetic history of the rocks. Present-day vertical stress, improved thermal conductivity, and more accurate acoustic impedance can also be calculated from the BHGM bulk density data. Lastly, a number of individual zones, including a sloughing shale zone (long hated by drillers), partially depleted gas- and oil-bearing beds, and known oil-bearing fractured rocks can be examined in terms of their total porosity and pore-fluid density. To aid the interpretation of the BHGM survey, drill cuttings and conventional cores from the 341-11P and other wells, have been gathered to independently describe mineralogy, diagenesis, grain density, and small-scale bulk density and porosity of the reservoirs. Study of this data set is expected to improve understanding of the mechanisms responsible for the distribution and characteristics of the oil and gas reservoirs in this giant field.

[1] Gravity measurements were planned to a depth of 9,150 ft but fiscal constraints and partial malfunction of the cable hoist system prevented these deeper measurements. A BHGM survey of the interval from 6,825 to near the top of the 4 1/2-inch casing at 9,163 ft is being considered.

BASIC DATA AND PRELIMINARY DENSITY PROFILE

Preliminary results of the BHGM survey in the 341-11P well consist of a BHGM apparent density profile (Fig. 5) and a tabulation of the basic borehole gravity data (Table 1). Densities were calculated by assuming 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 shown as error bars on the plotted profile. These error estimates do not include uncertainties due to anomalous gravity (ΔG_g) which may be significant in the 341-11P well and will be evaluated in a future paper.

BHGM densities and porosities given in Figure 5 and Table 1 are *apparent* values because no effort was made to separate out anomalous gravity effects in this preliminary report. The true rock densities surrounding the 341-11P well are greater than the *apparent* densities calculated from the BHGM survey due to the positive gravity anomaly (Boyd, 1948) over the Kettleman Hills anticline. Differences between the *apparent* BHGM densities and true densities of the rocks surrounding the well decrease with increasing depth and probably do not exceed 5 to 7% for the uppermost intervals.

An explanation of columns 1 through 15 in Table 1 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 (ft). Values are not corrected for borehole deviation from the vertical.

Column 3

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

Column 4

Terrain corrections calculated out through Hayford-Bowie zone O using variable terrain density (Beyer and Corbato, 1972) (mGals).

Column 5

Relative gravity with uppermost station set equal to zero (mGals). 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 gravity reading(s) at station, gravity meter repeatability, and drift behavior of gravity meter (mGals).

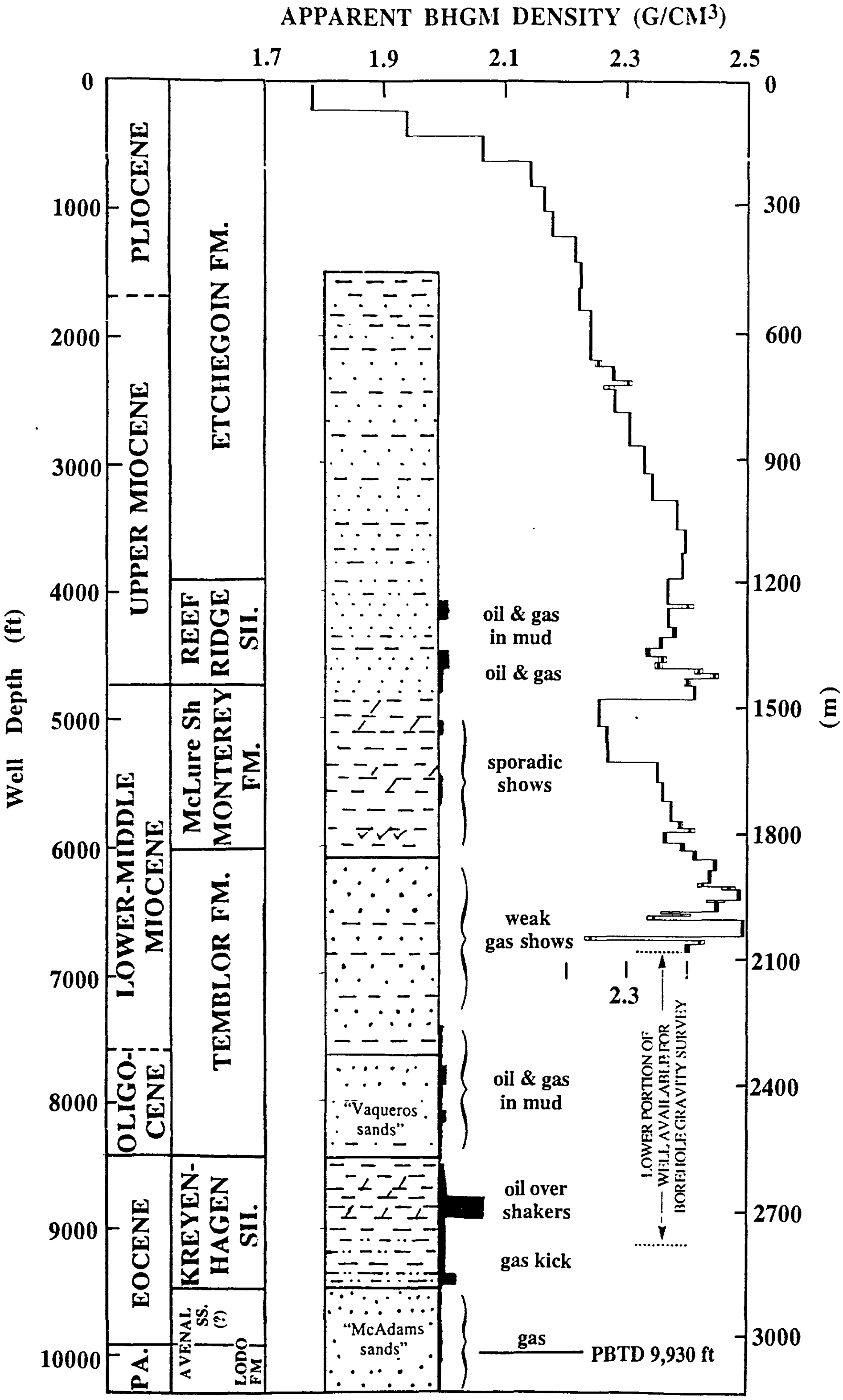

Figure 5. Apparent BHGM density profile calculated from borehole gravity survey in the 341-11P well with stratigraphic column, generalized lithologic column, and oil and gas shows. Density values do not have high absolute accuracy at shallow depths where unevaluated anomalous gravity effects may be significant. Deeper portion of well available for a borehole gravity survey is indicated.

Table 1. Basic data for BHGM survey in the 341-11P well, Kettleman North Dome oil field, California. See pages 9, 14, and 15 for explanation.

USGS BOREHOLE GRAVITY SURVEY: Chevron USA Inc 341-11P
LOCATION: 11-22S-17E Kettleman North Dome Oil Field Kings County California

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	922.0	29.5	1.424	0.000	.002															
						9.712	.005	200.01	0.05	.04856	.094053	1.780	.001	2.67	.02	0.00	.00	33.3	0.6	1
2	722.0	229.5	1.765	9.712	.002															
						8.904	.006	199.99	0.05	.04452	.094056	1.938	.002	2.67	.02	0.40	.20	32.2	3.5	2
3	522.0	429.5	1.756	18.616	.003															
						8.264	.006	200.00	0.05	.04132	.094059	2.064	.002	2.67	.02	0.70	.20	30.8	3.9	3
4	322.0	629.5	1.631	26.880	.002															
						7.861	.005	200.01	0.05	.03930	.094061	2.143	.001	2.68	.02	1.00	.00	32.0	0.9	4
5	122.0	829.5	1.477	34.741	.002															
						7.748	.006	199.99	0.05	.03874	.094064	2.165	.002	2.67	.02	1.00	.00	30.3	0.9	5
6	-78.0	1029.5	1.314	42.489	.003															
						7.681	.006	200.02	0.05	.03840	.094067	2.178	.002	2.67	.02	1.00	.00	29.5	0.9	6
7	-278.0	1229.5	1.148	50.170	.002															
						7.490	.005	199.99	0.05	.03745	.094069	2.215	.001	2.67	.02	1.00	.00	27.2	1.0	7
8	-478.0	1429.5	0.980	57.660	.002															
						7.445	.006	199.99	0.05	.03723	.094072	2.224	.002	2.67	.02	1.00	.00	26.7	1.0	8
9	-678.0	1629.5	0.809	65.105	.003															
						6.492	.006	174.01	0.05	.03731	.094075	2.221	.002	2.67	.02	1.00	.00	26.9	1.0	9
10	-852.0	1803.5	0.660	71.597	.002															
						7.215	.006	195.99	0.05	.03681	.094077	2.241	.002	2.67	.02	1.00	.00	25.7	1.0	10
11	-1048.0	1999.5	0.491	78.812	.003															
						6.996	.006	190.04	0.05	.03681	.094080	2.241	.002	2.67	.02	1.00	.00	25.7	1.0	11
12	-1238.0	2189.5	0.327	85.808	.002															
						1.823	.005	49.96	0.05	.03649	.094082	2.253	.005	2.66	.02	1.00	.00	24.5	1.2	12
13	-1288.0	2239.5	0.284	87.631	.002															
						3.946	.005	110.01	0.05	.03587	.094083	2.278	.002	2.66	.02	1.00	.00	23.0	1.1	13
14	-1398.0	2349.5	0.189	91.577	.002															
						1.376	.005	39.02	0.05	.03526	.094084	2.301	.007	2.67	.02	1.00	.00	22.1	1.3	14
15	-1437.0	2388.5	0.155	92.953	.002															
						1.117	.005	30.97	0.05	.03607	.094085	2.270	.009	2.68	.02	1.00	.00	24.4	1.4	15
16	-1468.0	2419.5	0.128	94.070	.002															
						6.410	.005	179.01	0.05	.03581	.094085	2.280	.001	2.67	.02	1.00	.00	23.3	1.0	16
17	-1647.0	2598.5	-0.027	100.480	.002															
						9.181	.005	260.99	0.05	.03518	.094088	2.305	.001	2.67	.02	1.00	.00	21.9	1.0	17
18	-1908.0	2859.5	-0.252	109.661	.002															
						7.533	.005	218.03	0.05	.03455	.094091	2.330	.001	2.67	.02	1.00	.00	20.4	1.0	18
19	-2126.0	3077.5	-0.439	117.194	.002															
						7.272	.005	212.48	0.05	.03422	.094094	2.343	.001	2.67	.02	1.00	.00	19.6	1.0	19

Table 1. Continued. Basic data for BHGM survey in the 341-11P well, Kettleman North Dome oil field, California. See pages 9, 14, and 15 for explanation.

USGS BOREHOLE GRAVITY SURVEY: Chevron USA Inc 341-11P
LOCATION: 11-22S-17E Kettleman North Dome Oil Field Kings County California

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
20	-2338.5	3290.0	-0.620	124.466	.002															
						7.629	.005	229.99	0.05	.03317	.094097	2.384	.001	2.67	.02	1.00	.00	17.1	1.1	20
21	-2568.5	3520.0	-0.815	132.095	.002															
						5.908	.005	180.01	0.05	.03282	.094100	2.398	.001	2.66	.02	1.00	.00	15.8	1.1	21
22	-2748.5	3700.0	-0.966	138.003	.002															
						6.590	.005	200.01	0.05	.03295	.094102	2.393	.001	2.67	.02	1.00	.00	16.6	1.1	22
23	-2948.5	3900.0	-1.132	144.593	.002															
						6.714	.005	199.99	0.05	.03357	.094105	2.368	.001	2.68	.02	1.00	.00	18.5	1.0	23
24	-3148.5	4100.0	-1.296	151.307	.002															
						0.982	.006	30.01	0.05	.03272	.094108	2.402	.010	2.66	.02	1.00	.00	15.6	1.6	24
25	-3178.5	4130.0	-1.320	152.289	.003															
						5.037	.007	150.16	0.05	.03354	.094108	2.370	.002	2.67	.02	1.00	.00	18.0	1.1	25
26	-3328.7	4280.2	-1.442	157.326	.003															
						2.658	.006	79.84	0.05	.03329	.094110	2.380	.004	2.66	.02	1.00	.00	16.9	1.2	26
27	-3408.5	4360.0	-1.506	159.984	.002															
						2.878	.005	85.00	0.05	.03386	.094111	2.357	.003	2.68	.02	1.00	.00	19.2	1.1	27
28	-3493.5	4445.0	-1.575	162.862	.002															
						2.236	.005	64.99	0.05	.03441	.094112	2.336	.004	2.66	.02	1.00	.00	19.5	1.2	28
29	-3558.5	4510.0	-1.626	165.098	.002															
						1.521	.006	45.00	0.05	.03380	.094113	2.360	.007	2.66	.02	1.00	.00	18.1	1.4	29
30	-3603.5	4555.0	-1.662	166.619	.003															
						1.698	.006	50.00	0.05	.03396	.094114	2.354	.006	2.66	.02	1.00	.00	18.5	1.3	30
31	-3653.5	4605.0	-1.702	168.317	.002															
						1.226	.005	38.00	0.05	.03226	.094115	2.420	.007	2.66	.02	1.00	.00	14.5	1.4	31
32	-3691.5	4643.0	-1.732	169.543	.002															
						1.233	.005	39.01	0.05	.03161	.094115	2.446	.007	2.66	.02	1.00	.00	12.9	1.4	32
33	-3730.5	4682.0	-1.763	170.776	.002															
						1.833	.005	55.99	0.05	.03274	.094116	2.402	.005	2.66	.02	1.00	.00	15.6	1.3	33
34	-3786.5	4738.0	-1.807	172.609	.002															
						3.505	.005	108.05	0.05	.03244	.094116	2.413	.002	2.67	.02	1.00	.00	15.4	1.2	34
35	-3894.6	4846.1	-1.891	176.114	.002															
						7.803	.005	213.94	0.05	.03647	.094118	2.255	.001	2.66	.02	1.00	.00	24.4	1.0	35
36	-4108.5	5060.0	-2.056	183.917	.002															
						4.520	.005	125.01	0.05	.03616	.094121	2.268	.002	2.66	.02	1.00	.00	23.6	1.0	36
37	-4233.5	5185.0	-2.152	188.437	.002															
						5.781	.005	160.07	0.05	.03612	.094122	2.270	.002	2.66	.02	1.00	.00	23.5	1.0	37
38	-4393.6	5345.1	-2.273	194.218	.002															
						5.407	.005	158.93	0.05	.03402	.094125	2.352	.002	2.69	.02	1.00	.00	20.0	1.0	38
39	-4552.5	5504.0	-2.391	199.625	.002															
						4.933	.005	146.00	0.05	.03379	.094127	2.361	.002	2.69	.02	1.00	.00	19.5	1.1	39

Table 1. Continued. Basic data for BHGM survey in the 341-11P well, Kettleman North Dome oil field, California. See pages 9, 14, and 15 for explanation.

USGS BOREHOLE GRAVITY SURVEY: Chevron USA Inc 341-11P
LOCATION: 11-22S-17E Kettleman North Dome Oil Field Kings County California

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
40	-4698.5	5650.0	-2.499	204.558	.002															
						5.182	.005	154.99	0.05	.03343	.094129	2.375	.002	2.68	.02	1.00	.00	18.2	1.1	40
41	-4853.5	5805.0	-2.612	209.740	.002															
						1.818	.005	55.01	0.05	.03305	.094131	2.390	.005	2.69	.02	1.00	.00	17.8	1.3	41
42	-4908.5	5860.0	-2.652	211.558	.002															
						0.979	.005	30.00	0.05	.03263	.094131	2.406	.009	2.67	.02	1.00	.00	15.8	1.5	42
43	-4938.5	5890.0	-2.674	212.537	.002															
						2.763	.005	81.99	0.05	.03370	.094132	2.365	.003	2.69	.02	1.00	.00	19.3	1.1	43
44	-5020.5	5972.0	-2.733	215.300	.002															
						1.979	.005	60.04	0.05	.03296	.094133	2.393	.004	2.68	.02	1.00	.00	17.1	1.2	44
45	-5080.5	6032.0	-2.776	217.279	.002															
						2.269	.005	69.96	0.05	.03243	.094134	2.414	.004	2.67	.02	1.00	.00	15.3	1.2	45
46	-5150.5	6102.0	-2.826	219.548	.002															
						2.686	.005	85.05	0.05	.03158	.094135	2.448	.003	2.67	.02	1.00	.00	13.3	1.2	46
47	-5235.5	6187.0	-2.886	222.234	.002															
						3.052	.005	95.95	0.05	.03181	.094136	2.439	.003	2.66	.02	1.00	.00	13.3	1.2	47
48	-5331.5	6283.0	-2.953	225.286	.002															
						0.931	.005	29.01	0.05	.03209	.094137	2.428	.009	2.66	.02	1.00	.00	14.0	1.6	48
49	-5360.5	6312.0	-2.974	226.217	.002															
						0.713	.005	23.00	0.05	.03100	.094137	2.470	.011	2.66	.02	1.00	.00	11.4	1.7	49
50	-5383.5	6335.0	-2.990	226.930	.002															
						2.507	.005	82.00	0.05	.03057	.094138	2.487	.003	2.66	.02	1.00	.00	10.4	1.3	50
51	-5465.5	6417.0	-3.047	229.437	.002															
						0.536	.005	16.99	0.05	.03155	.094139	2.449	.015	2.66	.02	1.00	.00	12.7	2.0	51
52	-5482.5	6434.0	-3.058	229.973	.002															
						2.301	.005	73.01	0.05	.03152	.094139	2.450	.004	2.66	.02	1.00	.00	12.6	1.3	52
53	-5555.5	6507.0	-3.109	232.274	.002															
						0.535	.005	15.99	0.05	.03346	.094140	2.374	.016	2.67	.02	1.00	.00	17.7	2.0	53
54	-5571.5	6523.0	-3.120	232.809	.002															
						0.562	.005	17.04	0.05	.03298	.094140	2.393	.015	2.67	.02	1.00	.00	16.6	1.9	54
55	-5588.5	6540.0	-3.132	233.371	.002															
						1.092	.007	31.96	0.05	.03417	.094141	2.347	.011	2.66	.02	1.00	.00	18.9	1.6	55
56	-5620.5	6572.0	-3.153	234.463	.004															
						3.953	.007	129.99	0.05	.03041	.094141	2.494	.003	2.67	.02	1.00	.00	10.6	1.2	56
57	-5750.5	6702.0	-3.242	238.416	.002															
						1.033	.005	28.03	0.05	.03685	.094143	2.242	.010	2.66	.02	1.00	.00	25.2	1.5	57
58	-5778.5	6730.0	-3.261	239.449	.002															
						0.967	.005	29.99	0.05	.03224	.094143	2.422	.009	2.68	.02	1.00	.00	15.4	1.5	58
59	-5808.5	6760.0	-3.281	240.416	.002															
						2.130	.005	65.04	0.05	.03275	.094143	2.402	.004	2.66	.02	1.00	.00	15.5	1.3	59
60	-5873.5	6825.0	-3.325	242.546	0.002															

Column 7

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

Column 8

Uncertainty in gravity difference (Δg_{error}) that is the sum of gravity reading uncertainties (column 6) (mGals).

Column 9

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

Column 10

Estimated uncertainty (Δz_{error}) in depth difference is .05 ft.

Column 11

Interval vertical gradient ($\Delta g/\Delta z$) (mGals/ft).

Column 12

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

$$F = .094114 - .000135 \sin^2\phi - .134 \times 10^{-7} h$$

where $\phi = 36.0342°$ is latitude of well and h is elevation of gravity station in feet. Equation is from Heiskanen and Moritz (1967) with constants of the 1980 Geodetic Reference System.

Column 13

BHGM 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 BHGM density (ρ_{error}) due to Δg_{error} and Δz_{error} (g/cm^3). See equation 2, Appendix.

Column 15

Assumed grain (or matrix) density (ρ_g) (g/cm^3). Based on previous studies of California Tertiary clastic rocks (McCulloh, 1967; Beyer, 1971), grain density values of 2.66 to 2.69 are assigned to sandstone to claystone or shale, respectively, with siltstone, mudstone and interbedded sequences of sand- and clay-sized units given intermediate values.

Column 16

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

Column 17

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

Column 18

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

Column 19

BHGM apparent porosity (φ) calculated from equation 3, Appendix (percent).

Column 20

Maximum likely error in BHGM apparent porosity ($\phi_{\ error}$) due to uncertainties ρ_{error}, $\rho_{g\ error}$, and $\rho_{f\ error}$ (porosity percent). See equation 4, Appendix.

Column 21

Sequential numbers for borehole intervals between successive gravity stations from shallow to deep.

PRELIMINARY DISCUSSION

Several observations of the results of the borehole gravity survey in the upper portion of the 341-11P well are possible even though the density and porosity data are in preliminary form:

1. The apparent BHGM densities of the uppermost three intervals are affected by varying water saturation in addition to uncorrected anomalous gravity. Circulation of drill mud was repeatedly lost within the uppermost 600 to 700 ft when the well was drilled and the top of the zone of saturation is somewhere below a well depth of 200 feet. Apparent BHGM porosity of the top interval is about 33%, assuming no water saturation and is about 32% for the fourth interval assuming 100% water saturation (Table 1). Partial water saturations of 0.4 and 0.7 for the second and third intervals lead to calculated apparent porosities of 32% and 31%, respectively (Table 1). If the apparent BHGM porosities derived from this working hypothesis for the uppermost three intervals are approximately correct, along with the apparent porosities from 800 to about 4,000 ft, the section is clearly overcompacted when compared to Neogene sections of California basins where no uplift and unloading by erosion has occurred (McCulloh, 1967). The presence of upper Pliocene to Quaternary units on the flanks of the Kettleman North Dome anticline, and their

absence on the anticline, clearly indicates removal of overburden. A quantitative estimate of overburden removed by erosion should be possible and will be part of a future paper.

2. The comparatively less dense three intervals from 4,846 to 5,345 ft correspond to the most siliceous facies of the upper part of the McLure Shale Member of the Monterey Formation and indicate a compaction behavior that is distinctly different from that of the overlying terrigenous deposits (Figure 5). At shallow burial depths, these biogenic siliceous rocks are diatomite, or diatomaceous mudstone or shale when detritus is present as a subordinate constituent. The biogenic silica is opal-A and these rocks have conspicuously low bulk densities and high porosities. The bulk density and porosity of these rocks change comparatively abruptly with increasing burial depth when burial temperatures reach values that initiate silica phase transformations (opal-A to opal-CT at 44° to 48° C and opal-CT to quartz at 65° to 82° C, depending on the abundance of subordinate detritus in the rock) (Isaacs, 1982; Keller and Isaacs, 1985). The present day temperature of the upper interval from 4,846 to 5,060 ft is 72° to 76° C, based on a high precision temperature log run four years after cessation of activity in the 341-11P well (T. H. Moses, personal communication, 1994). It is not known if the biogenic silica is opal-CT or quartz in the strata corresponding to these lower density intervals. Determination of the silica phase from available drill cuttings will help explain the observed density and porosity of these rocks and provide an additional estimate of prior maximum burial temperature. Abundant solid organic matter, which would lower the mean grain density from the assumed value of 2.65 g/cm^3, and a pore-fluid density less than the assumed value of 1.00 g/cm^3 also would help to explain the comparatively low densities of these intervals and lead to lower calculated porosities.

3. The third interval of apparent BHGM density from the bottom of the density profile (interval #57 in Table 1) is an interval in the gas zone of the Temblor Formation (Figure 5). By virtue of its comparatively low BHGM density, this interval must contain fluids whose mean density is less than 1.00 g/cm^3, the assumed value for water saturation used in Table 1. For example, if the porosity of interval #57 is 16%, similar to the porosities of nearby intervals assuming water saturation, then the apparent BHGM density of 2.242 g/cm^3 of interval #57 means that the pore fluid density of this interval is 0.05 g/cm^3. This is consistent with an interval that is largely or wholly saturated with low pressure gas. This hypothesis depends of course on the validity of the assumption of water saturation of nearby intervals from which the estimate of 16% porosity was obtained. Other determinations with different porosity values are easily computed using eq. 3 in the Appendix. It is expected that a borehole gravity survey of the deeper portion of the well will delineate more zones saturated with fluids significantly less dense than formation water, and possibly more highly fractured intervals of the Kreyenhagen Shale.

ACKNOWLEDGEMENTS

The authors are deeply indebted to Dana B. Wagner, former Chevron USA, Inc., development geologist for the Kettleman North Dome oil field, who enthusiastically obtained necessary permission for release of data and suggested that the U.S. Geological Survey assume ownership of the 341-11P well to avoid its abandonment in late 1991. The BHG survey reported here would not have been possible without Ms. Wagner's encouragement and active help. The prior Chevron development geologist, Donald W. Clark, obtained early release of well data and helped obtain permission for Geological Survey temperature surveys in the 341-111P well or the borehole gravity survey. Lastly, Chevron's willingness to transfer ownership is gratefully acknowledged.

REFERENCES

Antkiw, S., 1976, Depth of investigation of the dual-spacing thermal neutron decay time logging tool: Society of Professional Well Log Analysts, 17th Annual Logging Symposium Transactions, p. CC1-CC10.

Baker, L. J., 1984, The effect of the invaded zone in full waveform acoustic logging: Geophysics, v. 49, p. 796-809.

Bateman, R. M., 1985, Log quality control: Boston, International Human Resources Development Corporation, 398 p.

Bent, J. V., 1985, Provenance of Upper Oligocene-Middle Miocene sandstones fo the San Joaquin basin, California, in Graham, S. A., ed., Geology of the Temblor Formation, western San Joaquin basin, California: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 44, p. 97-120.

Berry, F. A. F., 1973, High fluid potentials in California Coast Ranges and their tectonic significance: American Association of Petroleum Geologists Bulletin, v. 57, no. 7, p. 1219-1249.

Beyer, L. A., 1971, The vertical gradient of gravity in vertical and near-vertical boreholes: U.S. Geological Survey Open-File Report 71-42, 229 p.

Beyer, L. A., 1979, Terrain corrections for borehole gravity measurements: Geophysics, v. 44, no. 9, p. 1584-1587.

Beyer, L. A., 1983, Borehole gravity surveys: Theory, mechanics, and nature of measurements: U.S. Geological Survey Open-File Report 82-76, 91 p., 43 figs.

Beyer, L. A., 1987a, Porosity of unconsolidated sand, diatomite and fractured shale reservoirs, South Belridge and West Cat Canyon oil fields, California, in R. F. Meyer, ed., Exploration for Heavy Crude Oil and Natural Bitumen, American Association of Petroleum Geologists, Studies in Geology No. 25, p. 395-413.

Beyer, L. A., 1987b, Analysis of borehole gravity surveys at Oak crater, Chapter 2, in Henry, T. W., and Wardlaw, B. R., eds., Pacific Enewetak Atoll Crater Exploration (PEACE) Program, Enewetak Atoll, Republic of the Marshall Islands, Part 4: Analysis of borehole gravity surveys asnd other geologic and bathymetric studies in the vicinity of Oak and Koa craters: U.S. Geological Survey Open-File Report 87-665, 46 p., 20 figs., 9 tbls.

Beyer, L. A., and Clutsom, F. G., 1978, Density and porosity of oil reservoirs and overlying formations from borehole gravity measurements, Gebo Oil Field, Hot Springs County, Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart OC-88, 3 pls., 16 p.

Beyer, L. A., and Corbato, C. E., 1972, A Fortran IV computer program for calculating borehole gravity terrain corrections: U.S. Geological Survey Open-File Report, 30 p.; available as report PB-208-679 from National Technical. Information. Service, Springfield, Virginia.

Boyd, L. H., 1948, Gravity-meter survey of the Kettleman Hills-Lost Hills trend, California: Geophysical Case Histories, v. 1, Society of Exploration Geophysicists, Tulsa, p. 523-528.

Bradley, J. W., 1976, The commercial application and interpretation of the borehole gravimeter, in Jantzen, R. W., ed., Tomorrow's Oil from Today's Provinces: American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication. 24, p. 98-109.

California Division of Oil and Gas, 1973, California Oil and Gas Fields, Volume 1, North and East Central California: California Division of Oil and Gas, Department of Conservation, Sacramento, unpaginated.

California Division of Oil and Gas, 1991, 76th Annual Report of the State Oil and Gas Supervisor: California Department of Conservation, Division of Oil and Gas, Publication No. PRO6, 165 p.

Dodd, J. R., and Stanton, R. J., Jr., 1975, Paleosalinities within a Pliocene bay, Kettleman Hills, California: a study of the resolving power of isotopic and faunal techniques: Geological Society of America Bulletin, v. 86, p. 51-64.

Ekström, Goran, Stein R. S., Easton, J. P., and Eberhart-Phillips, D., 1992, Seismicity and geometry of a 110-km-long blind thrust fault 1. The 1985 Kettleman Hills, California, earthquake: Journal of Geophysical Research, v. 97, n. B4, p. 4843-4864.

Fielding, E., Barazangi, M., Brown, L., Oliver, J., and Kaufman, S., 1984, COCORP seismic profiles near Coalinga, California: Subsurface structure of the western Great Valley: Geology, v. 12, p. 268-273.

Gester, G. C., and Galloway, J., 1933, Geology of Kettleman Hills oil field, California: American Association of Petroleum Geologists Bulletin, v. 17, p. 1161-1193.

Goudkoff, P. P., 1934, Subsurface stratigraphy of Kettleman Hills oil field, California: American Association of Petroleum Geologists Bulletin, v. 18, p. 435-475.

Hammer, S., 1970, The anomalous vertical gradient of gravity: Geophysics, v. 35, no. 1, p. 153-157.

Heiskanen, W. A., and Mortitz, H., 1967, Physical geodesy: W. H. Freeman & Co., San Francisco, 364 p.

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.

Isaacs, C. M., 1982, Influence of rock compositions on kinetics of silica phase changes in the Monterey Formation, Santa Barbara area, California: Geology, v. 10, p. 304-308.

Jageler, A. H., 1976, Improved hydrocarbon reservoir evaluation through use of borehole gravimeter data: Journal of Petroleum Technology, v. 28, no. 6, p. 709-718.

Keller, M. A., and Isaacs, C. M., 1985, An evaluation of temperature scales for silica diagenesis in diatomaceous sequences including a new approach based on the Miocene Monterey Formation, California: Geo-Marine Letters, v. 5, p. 31-35.

Kharaka, Y. K., Berry, F. A. F., and Friedman, Irving, 1973, Isotopic composition of oil field brines from Kettleman North Dome, California: Geochimica et Cosmochimica Acta, v. 37, p. 1899-1908.

Kharaka, Y. K., and Berry, F. A. F., 1974, The influence of geological membranes on the geochemistry of subsurface waters from Miocene sediments at Kettleman North Dome in California: Water Resources Research, v. 10, p. 313-327.

Kuespert, J., 1985, Depositional environments and sedimentary history of the Miocene Temblor Formation and associated Oligo-Miocene units in the vicinity of Kettleman North Dome, San Joaquin Valley, California, in Graham, S. A., ed., Geology of the Temblor Formation, western San Joaquin basin, California: Pacific Section Society of Economic Paleontologists and Mineralogists, v. 44, p. 53-67.

Loomis, K. B., 1992a, New K-Ar ages from tuffs in the Etchegoin Formation, San Joaquin basin, California: Isochron West, n. 58, p. 3-7.

Loomis, K. B., 1992b, New $^{87}Sr/^{86}Sr$ data from invertebrate macrofossils in the neogene Etchegoin Formation, San Joaquin basin, California: Isochron West, n. 58, p. 17-21.

Luther, G. G., and Towler, W. R., 1982, Redetermination of the Newtonian gravitational constant "G": Physical Review Letters, v. 48, p. 121-123.

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., 1967, Mass properties of sedimentary rocks and gravimetric effects of petroleum and natural-gas reservoirs: U. S. Geological Survey Professional Paper 528-A, 50 p.

McCulloh, T. H., Kandle, J. R., and Schoellhamer, J. E., 1968, Application of gravity measurements in wells to problems of reservoir evaluation: Society of Professional Well Log Analysts, 9th Annual Logging Symposium Transactions., p. O1-O29.

McCulloh, T. H., La Coste, L. J. B., Schoellhamer, J. E., and Pampeyan, E. H., 1967a, The U.S. Geological Survey-La Coste 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 Geological Survey-La Coste and Romberg precise borehole gravimeter system--Test results, in Geological Survey Research 1967: U.S. Geological Survey Professional Paper 575-D, p. D101-D112.

Merino, E., 1975a, Diagenesis in Tertiary sandstones from Kettleman North Dome, California. I. Diagenetic mineralogy: Journal of Sedimentary Petrology, v. 45, p. 320-336.

Merino, E., 1975b, Diagenesis of Tertiary sandstones from Kettleman North Dome, California. II. Interstitial solutions: distribution of aqueous species at 100° C and chemical relation to the diagenetic mineralogy: Geochimica et Cosmochimica Acta, v. 39, n. 12, p. 1629-1645.

Namson, J. S., and Davis, T. L., 1988, Seismically active fold and thrust belt in the San Joaquin valley, central California: Geological Society of America Bulletin, v. 100, p. 257-273.

Rasmussen, N. F., 1973, Borehole gravity survey planning and operations: Society of Professional Well Log Analysts, 14th Annual Logging Symposium Transactions, Q1-Q28.

Rasmussen, N. F., 1975, The successful use of the borehole gravity meter in northern Michigan: The Log Analyst, v. 16, no. 5, p. 3-10.

Robbins, S. L., 1979a, Density determinations from borehole gravity data from a shallow lignite zone within the Denver Formation near Watkins, Colorado: Society of Professional Well Log Analysts, 20th Annual Logging Symposium Transactions, p. JJ1-JJ20.

Robbins, S. L., 1979b, Description of a special logging truck built for the U.S. Geological Survey for borehole gravity surveys: U.S. Geological Survey Open-File Report 79-1511, 67 p.

Robbins, S. L., 1981, Reexamination of the values used as constants in calculating rock density from borehole gravity data: Geophysics, v. 46, no. 2, p. 208-210.

Schmoker, J. W., 1979, Interpretation of borehole gravity surveys in a native-sulfur deposit, Culberson County, Texas: Economic Geology, v. 74, p. 1462-1470.

Sherman, H., and Locke, S., 1975, Depth of investigation of neutron and density sondes for 35-percent-porosity sand: Society of Professional Well Log Analysts, 16th Annual Logging Symposium Transactions, p. Q1-Q14.

Smith, N. J., 1950, The case for gravity data from boreholes: Geophysics, v. 15, no. 4, p. 605-636.

Stanton, R. J., Jr., and Dodd, J. R., 1970, Paleoecologic techniques--comparison of faunal and geochemical analyses of Pliocene paleoenvironments, Kettleman Hills, California: Journal of Paleontology, v. 44, p. 1092-1121.

Stein, R. S., and Ekström, G., 1992, Seismicity and geometry of a 110-km-long blind thrust fault, 2, Synthesis of the 1982-1985 earthquake sequence: Journal of Geophysical Research, v. 97, n. B4, p. 4865-4883.

Sullivan, J.C., 1966, Kettleman North Dome oil field: Summary of Operations, California Oil Fields, California Division of Oil and Gas, v. 52, no. 1, p. 5-21, 3 pls.

Tucci, P., Schmoker, J. W., and Robbins, S. L., 1983, Density of basin-fill deposits calculated from borehole gravity data in four basins in central and southern Arizona: Expanded Abstracts with Biographies, 1983 Technical Program, Society of Exploration Geophysicists, 53rd Annual International Meeting, September 11-15, 1983, Las Vegas, Nevada, p. 28-31.

Wentworth, C. M., Blake, M. C., Jones, D. L., Walter, A. W., and Zoback, M. D., 1984, The tectonic wedging associated with emplacement of the Franciscan assemblage, California Coast Ranges, in Blake, M. C., Jr., ed., Franciscan geology of northern California: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 43, p. 163-173.

Woodring, W. P., Stewart, Ralph, and Richards, R. W., 1940, Geology of the Kettleman Hills oil field, California: stratigraphy, paleontology, and structure: U. S. Geological Survey Professional Paper 195, 170 p.

Yerkes, R. F., Levine, Paia, and Wentworth, C. M., 1990, Abnormally high fluid pressures in the region of the Coalinga earthquake sequence and their significance, in Rymer, M. J., and Ellsworth, W. L., eds., The Coalinga, California, earthquake of May 2, 1983: U. S. Geological Survey Professional Paper 1487, p. 235-257.

APPENDIX: 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. 6).

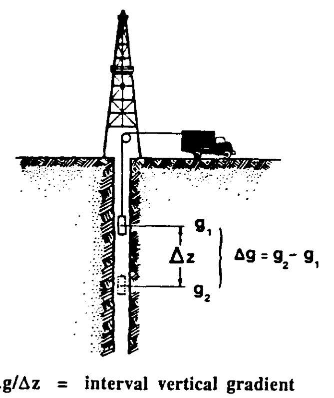

Figure 6. Schematic diagram showing measurement of gravity (Δg) and depth differences (Δz) in the borehole.

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

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

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).

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 BHGM (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 BHGM (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 BHGM density profiles. The word "apparent" is omitted from BHGM density in this case because the BHGM 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, BHGM (apparent) density is used.

BHGM 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:

$$\rho_{error} = \frac{1}{4\pi k}\left(\frac{\Delta g}{\Delta z}\right)\left[\frac{\Delta g_{error}}{\Delta g} + \frac{\Delta z_{error}}{\Delta z}\right] \quad (g/cm^3) \qquad (2)$$

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 BHGM survey and development of density models from independent geological and geophysical data to fit the "anomalous" part of the BHGM 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. BHGM porosities are calculated from BHGM densities using the familiar equation for porosity:

$$\phi = 100\left[\frac{\rho_g - \rho}{\rho_g - \rho_f}\right] \tag{3}$$

where ϕ = total porosity (percent), ρ = BHGM 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 BHGM porosity ϕ.

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

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

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 BHGM density, respectively, expressed in g/cm^3. ϕ is expressed as a fraction. ϕ_{error} is the resultant error or uncertainty in calculated BHGM 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 BHGM 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 2. 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.

Table 2. 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). 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).

Logging method	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	(0.04)
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)

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 (1979a), Tucci and others (1983), and Beyer (1987a, b).