U.S. GEOLOGICAL SURVEY CIRCULAR 890

Borehole Gravimetry Reviews

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By STEPHEN L. ROBBINS

A. What is Borehole Gravimetry?—A Summary

B. Borehole Gravity Measurements, Data Reduction, and Precision—A Review and Update of U.S. Geological Survey Methods

C. Bibliography with Abridged Abstracts of Borehole (Subsurface) Gravimetry and Corresponding In-place Rock Density Determinations

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BOREHOLE GRAVIMETRY REVIEWS

By Stephen L. Robbins

Chapter A. What is Borehole Gravimetry?—A Summary

CONTENTS

FIGURE

INTRODUCTION

Borehole gravimetry is the measurement, in a borehole, and the interpretation of gravity or gravitational acceleration. To accomplish this measurement, a gravity meter adapted to the borehole environment is required (a borehole gravity meter, BHGM, described in chapter B) with an operating and recording system for leveling and nulling the meter's sensing element while it is hanging stationary at selected depths within the borehole. After the measurement readings have been reduced (meter values converted to milligals), and various corrections (tide, meter drift, terrane effects, for example) have been added (described in chapter B), gravity value differences between stations in the borehole (ΔG) are divided by the vertical separations between these stations (ΔZ). The resultant values are the vertical gravity gradients for the measured interval within the well.

These gradients are directly affected by all horizontal differences in in situ (in place) bulk-rock density. If a borehole is located in an area where there is no complicating subsurface structure (simple area) and all density variations are in the vertical sense (all beds are nearly horizontal), then the calculated in situ bulk densities are assumed to be real. However, in a structurally or stratigraphically complex area (for example, faults, dipping beds, facies changes and caverns), then an "apparent" bulk density is determined (LaFehr, 1983). These apparent values, when plotted against density values from conventional logs and (or) cores (assumed real values), yield curves that can elucidate the subsurface structure.

A very large horizontal radius of investigation and direct dependence of measurements on bulk-rock density are the two unique characteristics of BHGM surveys. Responses of conventional logging tools (such as a gamma-gamma density tool) is from rock from only the first few inches out from the borehole wall (Sherman and Locke, 1975). Therefore, if a well is cased, most measurements from conventional logs are not very meaningful. BHGM measurements are not significantly influenced by casing, borehole rugosity, or formation damage caused by drilling, and although expensive, can be very useful.

The BHGM has been in use for over 20 years. Its potential for some purposes was recognized more than 35 years ago (Smith, 1950). In 1966, as the first BHGM was being made for the USGS, McCulloh (1966) reviewed the principles of borehole gravimetry and provided us an insight as to what a BHGM is and how this new logging tool would be of use to us.

This report is a brief introduction to the principles of borehole gravimetry and a synopsis of the uses the BHGM has been put to in the 20+ years of its existence; it is written primarily for the earth scientist, engineer, or student who has little or no knowledge of gravimetry. The capabilities of the BHGM are examined, successful and unsuccessful uses are enumerated, and other areas of possible use are suggested.

Discussions of the equipment used in conducting a BHGM survey, reduction of field data, and the precision that can be expected are contained in chapter B. A complete listing (with abstracts) of references on borehole gravimetry occupies chapter C. A good detailed introduction to the fundamentals of conducting a borehole gravity survey is in Beyer (1983).

ADVANTAGES OF BOREHOLE GRAVIMETRY

The BHGM permits direct measurement of the average gravity gradient $\Delta G/\Delta Z$ between two vertically separated points in a borehole. From this gradient, a density value can be determined (formula 1, chapter B, p. 15). In a structurally simple area, the density contrasts so derived between beds will be true, and the absolute in situ bulk-density values should be nearly accurate depending on the error in the free-air gravity gradient (F). (See Robbins, 1981.) At many borehole sites where F is not known, the BHGM logs can be normalized (adjusted) against core-sample density determinations and (or) conventional logs. The apparent bulk-density values (Beyer, 1983; LaFehr, 1983) that are determined in structurally complex areas must be compared with density values determined by other means in order to obtain useful information. Uses for the BHGM in these types of areas will be discussed in the section, "Applications for Borehole Gravimetry."

The in situ bulk-density value determined from BHGM data is an average value representative of a relatively large volume because of the BHGM's large horizontal radius of investigation. One common question is, "What is this large radius?" A value that is about five times the vertical spacing between the gravity stations (ΔZ) is cited as an approximate radius of investigation by several authors (McCulloh and others, 1968; Farley, 1971; and Bradley, 1976). This value is simply the radial distance that produces 90 percent of the total gravimetric effect for that interval (ΔZ) (fig. 1). The actual radius of investigation is variable and is dependent on the density contrasts encountered horizontally from the borehole and on the precision

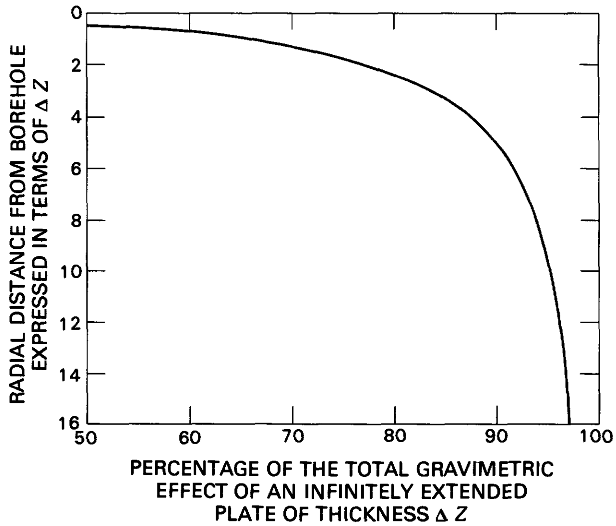

Figure 1. Graph of gravimetric effects at the axis of cylindrical plates (from McCulloh, 1966, p. 4).

of the gravity data (chapter B; Beyer, 1983; LaFehr, 1983). Since the gravitational attraction (f) between two masses (m_1 and m_2) is directly proportional to the product of the masses and inversely proportional to the square of the distance (r) between them as shown in the relationship

$$f = k\,\frac{m_1 m_2}{r^2} \qquad (1)$$

(where k is the Newtonian gravitational constant (Robbins, 1981)), the greater the horizontal distance a contrasting mass is from a borehole, the larger the density contrast must be in order to be detectable. Thus, a large high-density-contrast body at a large distance from a borehole will be detectable, but the same sized body with a small-density-contrast at a smaller distance from the borehole may not be detectable.

One method used to determine the porosity (ϕ) of a unit is from the relationship:

$$\phi = \frac{(\rho_b - \rho_g)}{(S_f\,\rho_f - \rho_g)} \qquad (2)$$

(where ρ_b is the bulk-density, ρ_g is the grain density, ρ_f the fluid density, and S_f is the fluid saturation). Since the bulk-density values determined from BHGM data represent a very large volume of rock when compared to the very small-volumed values on conventional logs, the porosity values calculated from fully corrected BHGM data using formula 2 more closely represent the true porosity values for a formation.

McCulloh (1967) presented a comprehensive discussion of density and porosity relationships in terms of hydrocarbon reservoirs and their recognition. For example, beds containing gas or gas-saturated oil in their pores are lower in density than when the same beds are water saturated or infiltrated, which occurs when the beds are adjacent to a borehole, due to the drilling process. Gamma-gamma (or most other conventional) logging tools "see" only this altered portion of the beds, therefore, anomalous porosity values will be calculated if the wrong ρ_f is used.

The BHGM has several other advantages over conventional logs in addition to its large radius of investigation. Following is a summary list of BHGM advantages:

1. Large radius of investigation makes the density values more representative of the measured formation.
2. In cased holes, casing does not significantly influence BHGM measurements, but most conventional logging tools are either useless or marginally useful.
3. In boreholes where the sidewall has been altered during drilling (including caving (rugosity) and mud filtrate invasion), again BHGM readings are not significantly influenced.
4. Allows studying off-hole structures (such as remote sensing of faults, salt diapir overhangs, and edges of thrust sheets) which no other density logging tool is capable of.
5. The BHGM enables the determination of in situ bulk-density directly (for areas of horizontal structure) instead of indirectly as an effect of some other property, such as electron density in gamma-gamma logs where a (Z/A) ratio is assumed (Z is the number of electrons per atom and A is the atomic weight); see Robbins (1979) for an example in which the wrong assumed Z/A caused a 0.1 g/cm³ error in the gamma-gamma density log for lignite.

Disadvantages of the BHGM include the following:

1. It is a costly tool in terms of initial investment ($300,000–$500,000), delivery delay (2 to 3 years), and maintenance.
2. Logging time is longer (usually about 5 minutes per station reading) compared to most other tools, which record continuously at relatively high logging speeds.
3. Instrument limitations include that the "slimhole" BHGM is $4\frac{1}{8}$ inches in diameter, thus usually

requiring a minimum 5-inch-diameter borehole; maximum temperature that can be logged is about 120 °C (250 °F); and maximum tolerable borehole deviation is about 12°–14°.

4. Thin beds are difficult and more costly to measure because the field data have to be of the highest precision possible, which requires several repeated occupations of each station and takes extra time (chapter B, fig. 6).

APPLICATIONS FOR BOREHOLE GRAVIMETRY

The first consideration as to whether a BHGM survey is useful is the characteristics of the borehole itself. If the hole is uncased and to gauge and the formation is undamaged or unaltered from drilling, then a gamma-gamma log may provide adequate density values. However, if the hole has been washed out, damaged, or otherwise altered, then a BHGM survey is likely to offer the only reliable density information (Pritchett, 1980). If the hole is cased, then a BHGM is essentially the only way of obtaining a meaningful density log. The BHGM is necessary in most unconsolidated sediments because (1) the well has to be cased as it is being drilled, and (2) greater mud invasion occurs than in more consolidated rocks, because of the greater porosity and permeability. The BHGM has proven to be very successful in older oil fields where the wells were drilled and cased before logging tools as sophisticated as those available today were run routinely (Bradley, 1976; Gournay and Maute, 1982). Exploration Data Consultants Inc. (EDCON) (LaFehr and others, 1979) of Lakewood, Colo., has reported that about 20 percent of their commercial BHGM business is in searching for natural gas behind casing.

The second consideration is the geologic structure and petrophysics of the survey area. In simple areas, if the beds are competent and homogeneous, and hydrocarbon detection is not a goal, then a conventional density log would suffice. In heterogeneous beds, the BHGM is the only means of obtaining density values that can be used to calculate meaningful porosities. In studies where porosities are determined, saturation percentages can sometimes be calculated (Robbins, 1979, p. JJ15). Also, if BHGM surveys are repeated in a well over a period of time, saturation changes and (or) water/oil/gas percentage changes may be observable. For hydrocarbon detection, McCulloh (1967) has illustrated what the bulk densities should be for various geologic environmental and fluid conditions and how BHGM surveys may be of use.

In structurally complex areas, most BHGM studies are designed to search for off-hole structures. LaFehr and others (1979) stated that 20 percent of EDCON's BHGM business is for this purpose. However, few case histories in sedimentary rocks of these types of surveys have been published (Bradley, 1976; Clark and Hearst, 1983; Hearst and McKague, 1976; LaFehr and Dean, 1983; Schmoker, 1977; and Schmoker, 1980). There are several underground gravity applications in mining districts that contain anomalous lateral mass distributions; see for example Sumner and Schnepfe (1966). True in situ bulk densities can be determined for some strata in complex areas if the densities of nearby beds are independently known, the BHGM data are normalized to those density values, and no complex structure exists in the immediate vicinity of the beds of interest.

Carbonate reservoirs occur in both simple and complex areas. LaFehr and others (1979) reported that about 60 percent of EDCON's BHGM business is in "evaluation of carbonate reservoirs (finding oil and gas missed by other techniques)." Consequently, many surveys utilize the simple-area approach and some utilize Bradley's (1976) complex-area methods.

Data from BHGM surveys can also be useful in improving structural interpretations that are determined from surface gravity and (or) seismic data (Smith, 1950; LaFehr and Dean, 1983; LaFehr and others, 1983).

Most BHGM studies have been related to petroleum exploration and production (Bradley, 1976; Farley, 1971; and McCulloh and others, 1968), and some surveys have been related to mining studies (Robbins, 1979; Schmoker, 1979). Other topic applications are (a) ground-water studies (Head and Kososki, 1979; Robbins, 1986; and Tucci and others, 1983), (b) radioactive waste-disposal site studies (LaFehr and Dean, 1983; Robbins, 1986; Robbins and others, in press; and Schmoker, 1980), and (c) other research studies relating to structurally complex areas (Hearst and McKague, 1976; Schmoker, 1977). Chapter C contains references to all BHGM studies and case histories presently in the literature (1986).

FUTURE STUDY POSSIBILITIES

There are many areas in which borehole gravimetry has yet to be better tested before its full potential can be realized. After a review of the literature and discussions with several colleagues, a number of potential study areas are proposed in the following discussion:

1. Only one report has been published pertaining to the BHGM's use in engineering geology (Nichols and Collins, 1986). The BHGM should be useful in compaction studies, comparisons with conventional logs in rock types where little is known about the log responses, remote sensing of caverns, measurement of water saturation, and subsidence measurements.
2. Very little has been published on use in ground-water problems compared to the potential that the instrument offers in this field. Future study possibilities include better measurements for the calculation of maximum water yields, compaction rates due to water withdrawal, physical properties of aquifers and surrounding sediments, silting-in of aquifers, and calculations of basin depth and shape.
3. Only 3 of the 39 articles on the use of gravimetry in mining environments are related to borehole gravimetry. The remaining articles describe studies using surface gravity meters in shafts and adits. Many more studies are needed in this field, including rock-type comparision studies with conventional logs (intrusives, volcanics, metamorphics, and so forth) and remote sensing of old tunnels, caverns, anomalous masses, and structure.
4. Two reports are available on the construction of high-temperature sondes with heat sinks for the BHGM that would allow its use in very hot wells including geothermal wells for short periods of time (as long as 30 hours) (Baker, 1977; Black and Herring, 1983). The reports conclude that such sondes can be and are being made. One type of sonde is now in operation by EDCON. When further improved, it will increase the BHGM's useful capabilities, including the ability to monitor changes in steam-reservoir density through time where geothermal energy or thermal recovery techniques are being utilized (LaFehr and Nur, 1983).
5. Only one paper (LaFehr and Dean, 1983) has been published illustrating the usefulness of borehole gravimetry in the interpretation of surface gravity surveys. Robbins and others (in press) is a radioactive-waste disposal study where eight shallow wells (less than 1,000 feet deep) have been logged with the BHGM (Robbins and others, 1983) in order to determine the lateral changes in the near-surface sediments so that the top of the basalts' configuration beneath these sediments can be determined from the surface gravity. (The density contrasts, both vertically and laterally, and acoustic impedances within and at the base of the sediments are so large that reflection seismic surveys have proven difficult to run and interpret.) Possible areas of study include (a) determining lateral density changes within various alluvial basins and glacial deposits, (b) interpreting large surface-gravity anomalies when insufficient data are available to understand the anomalies, and (c) constructing density-with-depth profiles in selected young oil-producing basins as starting points to aid in gravity stripping for interpretation of the lower oil-producing rocks.
6. Several areas remain within the oil and gas industry where there apparently has been little testing of the BHGM's. In the area of reservoir engineering, fluid modeling and changes (Gournay and Maute, 1982), coning (Al-Khafaji and Schultz, 1983), pumping-down, compaction, and enhanced oil-recovery problems could be more completely understood if BHGM surveys were repeated over a period of time. As previously indicated, more studies are needed in complex areas. Studies at sites within high fluid-pressure areas, both in and outside the Gulf Coast, would help to better understand these environments (Pritchett, 1980). BHGM surveys could also help in studies of diagenetic changes, and secondary porosities. Some oil production occurs in atypical rock reservoirs (such as volcanics and intrusives); BHGM surveys, when compared with conventional logs, would aid in gaining a better understanding of the conventional log responses in unusual environments.

Comparisons between BHGM density profiles and borehole acoustic logs (sonic logs) and (or) vertical seismic profiles (VSP) can lead to better understanding of the elastic response of sedimentary-rock sections in terms of porosity and lithology. Such comparison can also promote understanding of the strengths and limitations of the acoustic impedance and reflection coefficient determinations of each of the different seismic measurements.

Borehole gravimetry's usage in scientific research has only begun. Its potential remains large and includes earthquake risk, hazard, and prediction studies, crustal studies, regional studies, and heat-flow studies. In heat-flow studies, for example, few temperature measurements are made in deep-sedimentary-basin wells because of the uncertainty of the porosity of the rocks penetrated and the subsequent effect of incorrect values on the thermal conductivities used in the heat-flow calculations. The BHGM should be able to provide the needed porosity values used in these calculations. This would also allow us to better understand the thermal conditions prevailing in these deep-sedimentary basins. As borehole gravimetry becomes better understood, more refined, and is used more, other areas of use not listed here will become evident.

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BOREHOLE GRAVIMETRY REVIEWS

By Stephen L. Robbins

Chapter B. Borehole Gravity Measurements, Data Reduction, and Precision—A Review and Update of U.S. Geological Survey Methods

CONTENTS

FIGURES

INTRODUCTION

The U.S. Geological Survey (USGS) has been conducting borehole gravity meter (BHGM) surveys since 1966 (McCulloh, LaCoste, and others, 1967) using the first La Coste and Romberg, Inc. borehole gravity meter built (BH–1). Equipment (including a new smaller-diameter meter), methods of data acquisition and reduction, and data precision have steadily improved. The purpose of this report is to describe the equipment used, procedures developed, and the precision that the USGS was obtaining at the end of 1982. Some background information and recent industry improvements are also included.

BHGM EQUIPMENT

Two types of gravity meter systems have been used successfully in making high-precision BHGM surveys. The first utilizes a sensing element designed around the vibrating-string principle. Operational meters were built by Shell Development (Goodell and Fay, 1964) and by Esso Production Research Co. (Howell and others, 1966). These meters, although successful, have been used very little, apparently because of instrumental maintenance problems and slow operation, and this type of meter is not considered further here.

The second type employs a zero-length-spring suspension, and LaCoste and Romberg, Inc. is the only manufacturer, to 1986, that has built a successful borehole meter of this type. Their first three BHGM's utilized sensors from their land geodetic meters (McCulloh, LaCoste, and others, 1967). Two of these BHGM's are still in operation (the USGS prototype BH–1 with sensor G–95 (fig. 1), and BH–2 operated by Amoco Production Co.). They are between $5\frac{1}{2}$ and 6 in. in diameter, are thermostated (maintained) at a temperature of about 100 °C, and can be operated in a borehole with up to a 6° deviation from vertical. In 1975, LaCoste and Romberg started development of a new "slimhole" BHGM that is $4\frac{1}{8}$ in. in diameter (fig. 1) and utilizes a redesigned sensor two-thirds the previous size. Their thermostated temperature is between 120 and 125 °C, and they can be operated in a borehole deviated up to $14\frac{1}{2}$°. Nine of these second-generation instruments are currently in operation (including USGS's BH–6). Black and Herring (1983, p. 21) are now (1986) operating these meters in boreholes at temperatures as high as 200 °C with the use of a new high-temperature (larger diameter) sonde.

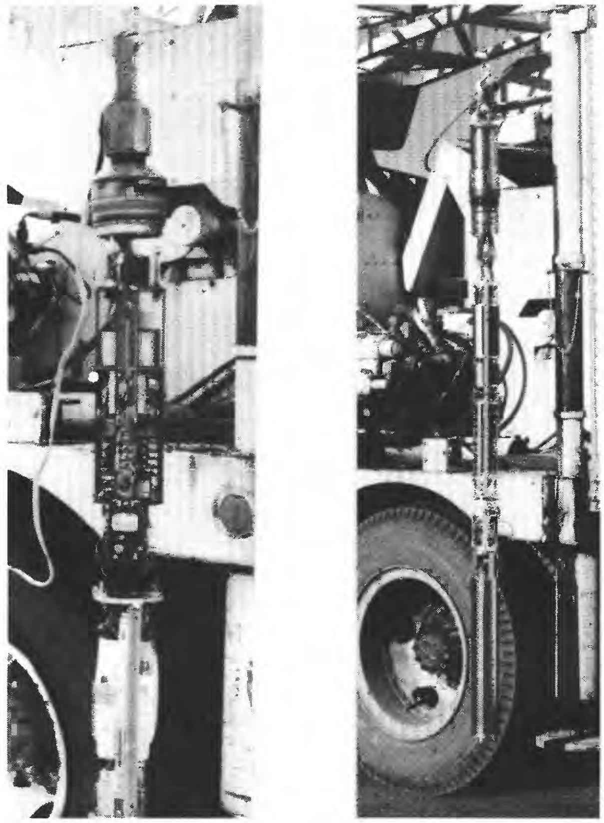


Figure 1. U.S. Geological Survey Borehole Gravity Meters BH–1 (left) and BH–6 (right) built by LaCoste and Romberg, Inc.

The electronic control and power systems used on LaCoste and Romberg meters are not supplied by the manufacturer, although LaCoste and Romberg did supply electronic packages for the original three BHGM's. The first package, however, required a special 13–conductor wireline and could not be operated from a standard 7–conductor cable. As a result, several different electronic systems have been designed and built by owners of these meters. The USGS meter BH–1 employs an FM system developed by F.G. Clutsom (1984a). A quasi-digital system, also developed by F.G. Clutsom (1984b), has been installed on BH–6 because of the increased number of control functions on the "slimhole" meters. Amoco Production Co. developed its own independent control system. EDCON of Lakewood, Colo., has purchased the Amoco design and has made extensive modifications to it (J.E. Seibert, oral commun., 1980). Amoco and EDCON meters contain microprocessors for speedier leveling of the meters. Amoco has developed a new automated beam nulling system for operation of their meters (Lautzenhiser, 1983).

Maintenance on BHGM's is expensive because mechanical and electronic components associated with the sensor are susceptible to high-temperature fatigue, corrosion from well fluids that can occasionally damage components, and electrical arcing in cable or tool connectors. Fluid leaks into the tool sondes have occurred several times and were the cause of the destruction of Amoco's BH-3. Periodic high-temperature lab tests, and cleaning and lubricating of the sensor components are also necessary.

BHGM surveys can be run from most of the logging trucks that the commercial logging service companies own. Many of the BHGM surveys run by EDCON were from other commercial logging service company trucks, although now EDCON uses their own truck whenever possible. The USGS has its own logging truck (Robbins, 1979), which has allowed acquisition of better quality data at less expense than when commercial companies were used prior to the completion of the truck in 1977. Problems encountered while employing the services of some commercial wireline units included the following: (1) generator fluctuations and failure, (2) poor gamma-ray equipment, (3) difficulty in finding seven good conductors within the cable, (4) resistances or capacitances too high for the BHGM in some cables, (5) trouble providing or finding adaptors to match the cablehead to our tool, (6) time and effort required in instructing the truck operator in the unusual techniques needed for logging with our tool, (7) the logistics of locating an available truck when and where needed, (8) inadequate care in the handling of electronic consoles by the airline companies during shipment to and from a wellsite location, and (9) in one instance, the parting of a logging cable which almost destroyed BHGM BH-1. Cities Service Co. put into operation a research logging truck that is completely computerized including winch operations for gravity and vertical seismic profiling surveys (Caton and others, 1983).

A new downhole clamping device, built by SIE of Fort Worth, Texas, is now allowing EDCON to log from floating drilling platforms (Black and Herring, 1983, p. 21).

DATA ACQUISITION PROCEDURES

Gravity data collected by the USGS utilized LaCoste and Romberg BHGM's BH-1 and BH-6 (fig. 1). All boreholes logged by the USGS since early 1977 were run from the USGS logging truck, and its operation is discussed in Robbins (1979). For the acquisition of the gravity data, the BHGM has to be stationary. Therefore, the procedures for the acquisition of data are divided into three subsections: (a) selection of station (meter reading) locations, (b) mechanical operation of the meter before and at a station location, and (c) data recorded and system of station occupations and reoccupations.

Station Locations

The objective in choosing station locations is to end up with intervals between the stations that are lithologically homogeneous. To this end, the locations of tops and bottoms of formations and lithologic units were used.

In identifying these locations:

1. All available logs were first studied and preliminary locations chosen.
2. A natural gamma-ray (G-R) log was then obtained using the same truck and cable that was to be used for the BHGM survey.
3. This G-R log was then used to adjust for any datum and (or) cable differences that might have existed between the earlier logs and this one.
4. If any new lithologic information was evident on this G-R log, station locations were added, subtracted, or moved, and the final location depths chosen.

It cannot be stressed enough that picking the proper locations (intervals of homogeneous densities) for the gravity stations is essential and will determine the usefulness of the BHGM survey. Surveys with poorly picked station locations may be almost useless. LaFehr (1983) has suggested that, for surveys where anomalous masses are present (geologically complex areas), the station locations be both "just outside as well as just within the zone of interest" from which a calculation of the real density change at the boundary (the "Poisson jump") can be made.

Meter Operation

Standard meter operation procedures are contained in the manufacturer's operation manual. In addition, USGS surveys in the field included:

1. Setting the meter into sonde and into borehole at least 12 hours before start of survey (to allow for temperature stabilization).
2. Exercising of screw and springs and tune-up (check of beam sensitivity and levels) at least 1 hour before beginning each survey.

3. A maximum of 50 feet per minute for movement of instrument inside the borehole (to keep tares and temperature effects to a minimum).
4. Logging going into the well (to minimize temperature effects).
5. Screw position was preset to the approximate (guessed at) next station reading before or during travel to that location (to minimize the effect of the mechanical hysteresis of the flat springs in the beam lever system).
6. At all base and other station locations to be reoccupied, placing tape and paint on the cable at the well head.
7. When reoccupying a station, moving the cable and sonde the final 10 to 20 ft always from the same direction (usually down).
8. For leveling BH-6, keeping rotation of meter within sonde to a minimum (to minimize temperature effects).

Data Collection

This section, an extension of the Meter Operation section, describes how the BHGM electronic signals at the meter console are converted into meaningful gravity values and are recorded, what other data are recorded, the procedures for occupying the gravity stations and for repeating bases, and what preliminary calculations were done during a survey.

The electronic signals to and from the BHGM's are controlled from the BHGM consoles (fig. 2). Through the use of switches on the console which control electric motors in the meter, one can level the meter sensor, rotate the meter (BH-6), change the screw position, unclamp and clamp the beam, and position the beam anywhere between its stops. Signals that come to a console from the BHGM are displayed on the console face by use of analog meters showing the position of the meter sensor relative to level, the rotation orientation of BH-6, the sonde temperature, and the position of the sensor beam. The screw position is shown through a combination of a numerical counter and an analog meter (the large one, fig. 2). The BHGM beam output voltage signal at the console is a function of the beam's position relative to null (that position where the suspension spring is zero-length). Zero voltage means the beam is in the null position; a negative voltage is outputted when the beam is on the low side (low gravity) of null; and a positive voltage is outputted when the beam is on the high side. By inputting this

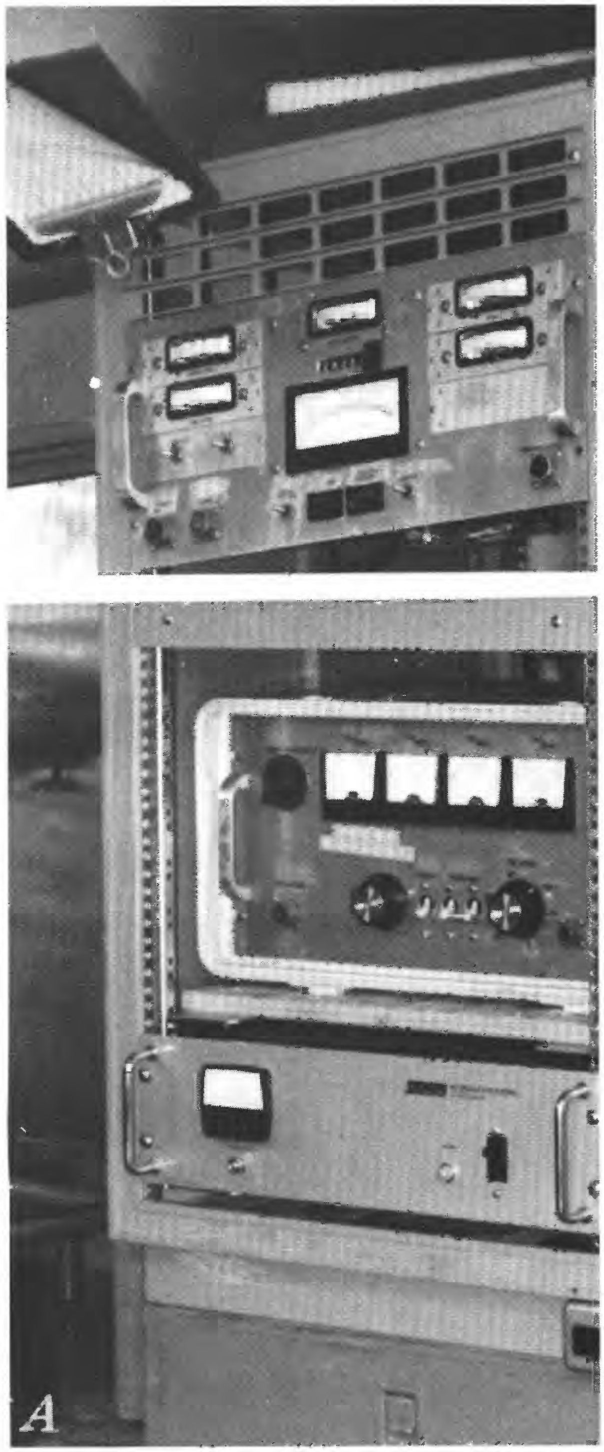
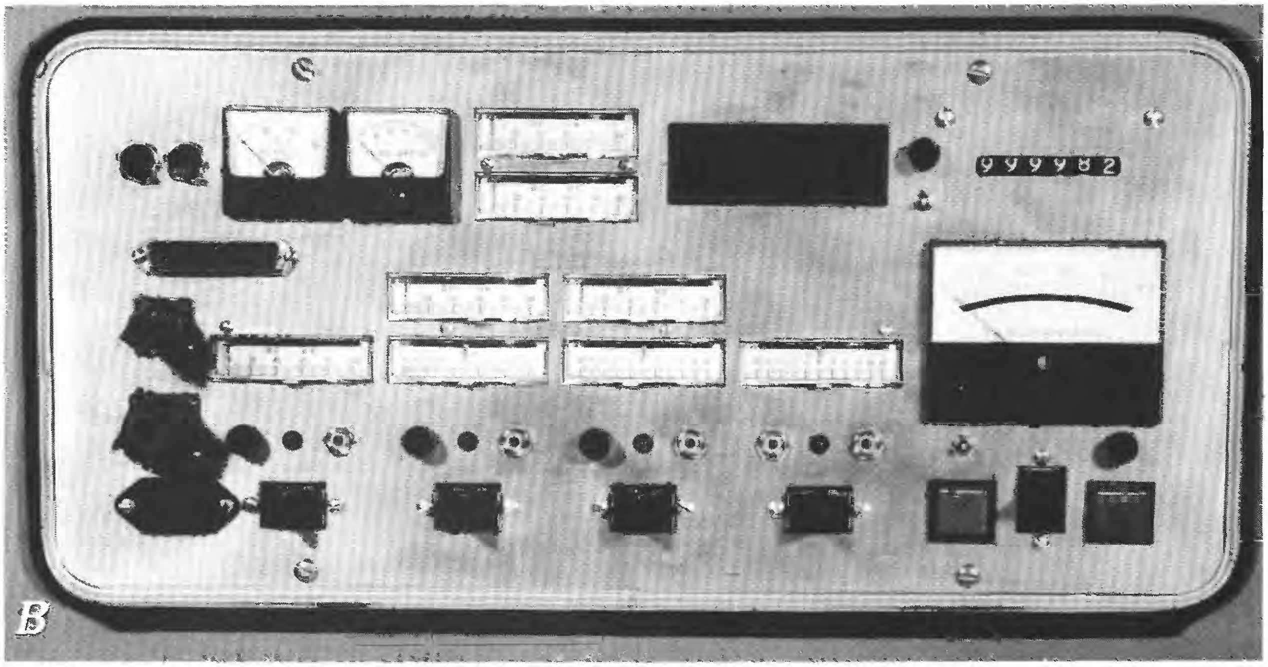


Figure 2 (above and facing page). Control consoles used to operate USGS BHGM's: *A*, BHGM BH-1; *B*, BHGM BH-6.

beam signal into a constant-speed strip-chart recorder, an analog record of the BHGM beam position relative to time can be made. The angles of the recorded line



segments (slopes) relative to the horizontal axis of the strip chart (fig. 3) represent excursion velocities of the beam away from the null position (the beam is placed at the null position by a control switch on the console) when the counter-screw is not at the null setting (null is 0° slope). Because the beam is damped, the excursion rate (slope) varies as a linear function of the screw setting relative to null when the screw setting is within 40 or 50 μgal (microgals) of null.

The procedures which follow were developed so that the data collected would contain as few errors as possible and the data precision would be at a maximum:

1. Three or more slopes and counter readings were obtained which reveal the null position even if null was not occupied directly. Most of EDCON's surveys (J.E. Seibert, oral commun., 1980) were run using only the null readings that apparently took almost as much time as when we took three or more non-null readings. I believe that the multiple reading method produces better quality data because the beams on these meters occasionally stick, usually around the null position. Amoco has a new automated system (Lautzenhiser, 1983) which does away with the above procedure: in Amoco's system, the measuring screw is brought to within 100 μgal of null, an electrostatic force and feedback system is used to null the beam, and the resultant voltage output is converted into an electrostatic correction, which is added to the measuring screw reading.
2. Station location depths were recorded to the nearest 0.1 ft or to hundredths when station intervals were small (less than 20 ft).
3. A separate record was kept containing only occupied station depths. Adjustments to the chosen location depths were made during the survey based on reoccupation depth differences caused by cable stretch and (or) shrinkage.
4. Starting at a primary base station (usually deep enough to be a quiet station), 5 to 7 stations were read with the last station being a new base station. The meter was then returned to the primary base station thus creating a loop. If the meter reading closure was good (±30 μgals or less after tidal corrections), then a new loop was started at the new base station. This procedure was continued to the bottom of the well. If a loop closure was not good, then the stations were repeated and a possible tare located.
5. Loops were not used in some early surveys (surveys in 1975–1976). Instead, stations were read from the top directly to the bottom of the borehole and about every fifth-to-seventh station was reoccupied coming back out.
6. Stations directly above and below the water table were occupied at least twice. The change in the

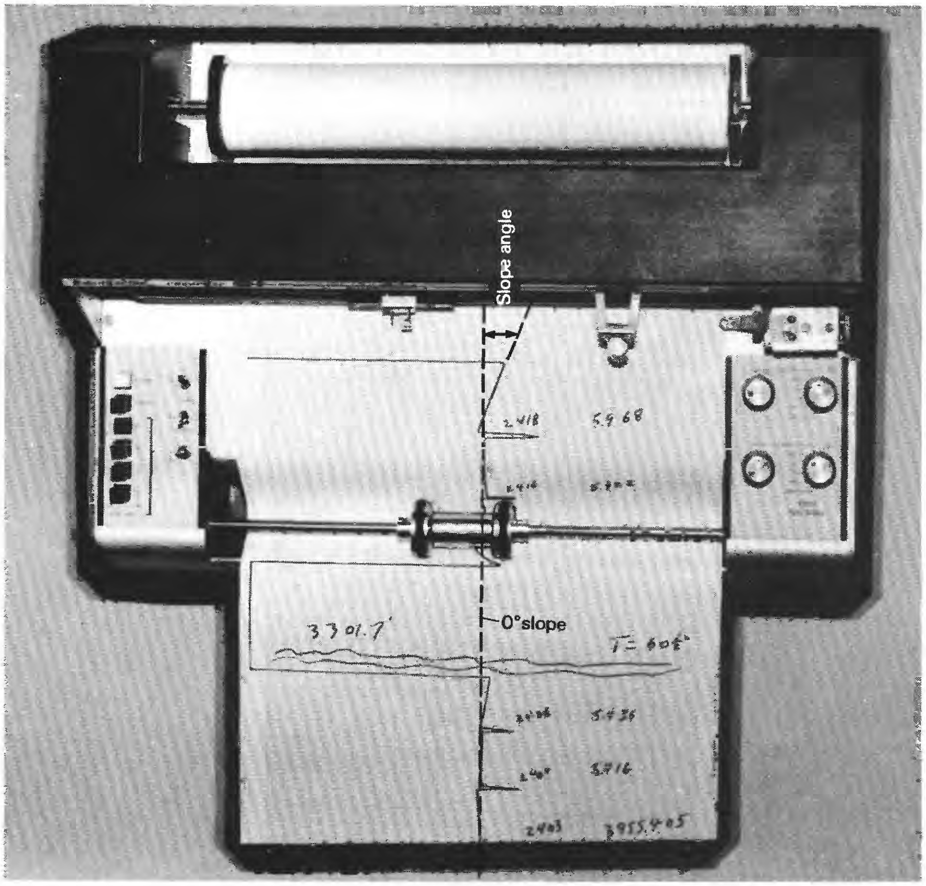


Figure 3. Strip-chart recorder with record segments.

temperature gradient on and within the sonde can be fairly abrupt when it transits the air to water boundary and can sometimes cause some temperature effects, especially if the meter temperature setting has shifted a little (the optimum temperature at which any LaCoste and Romberg gravity meter should be set is dependent on the metallographic makeup of the sensor materials and the only accurate way of checking for this shift is in a temperature chamber in the laboratory).

7. At shallow depths or when it was windy, a clamp was attached to the cable at the well head and tension was released between the clamp and the truck, thus reducing oscillations at the meter.
8. Two separate records of the data were made during the survey:
   a. The first set was recorded on the analog strip-chart paper and included the date, the tune-up information, the station depth, the slopes and their corresponding meter counter readings and times of observation, the sonde temperature, and any other information pertaining to the quality of the data.
   b. The second listing on a separate sheet includes the date, the station depth, a visual estimate (eyeballing the slopes on the strip-chart record) of the meter counter reading at 0° slope (null) (these estimates were usually good to better than ± 5 μgal), the time, and the gravity tide corrections (taken from tide tables that had been prepared before leaving for the field). From these data, a preliminary density value was calculated. If this value appeared unusual (when compared to gamma-gamma logs and (or) knowledge of the lithology), then the interval stations were reocccupied and checked for possible reading errors or tares.

DATA REDUCTIONS

Data reductions consist of determining the meter null counter reading, converting this number into milligal values, adding in tide corrections, determining instrument drift and tare corrections, making terrain corrections, calculating the measured gravity gradients between adjacent stations, and calculating density values. These reductions were normally done in the office except for the preliminary calculations discussed in 8b, p. 14. The procedure used in the reduction of the borehole gravity field data is as follows:

1. The slope angles of the beam excursions on the strip-chart record were measured using a protractor.
2. The angles for a given station were then plotted against the counter-screw readings (fig. 4) for that station which then revealed the null counter reading at the 0° slope position.
3. The null position meter counter readings were converted into arbitrary milligal values using the BHGM's calibration tables (it was found that the small differences between the factory-determined calibration values and subsequently determined calibration values, although significant in large surface gravity surveys, do not measurably change the density calculations of borehole data).
4. Tidal gravity corrections were added in.
5. The resultant values for the base stations and any other repeated stations were plotted against time in order to determine the drift and tare behavior of the meters during the surveys and these corrections were added in.
6. Terrain corrections were calculated, in accordance with the methods and principles described by Hammer (1939), or Swick (1942), and Hearst and others (1980). When the terrain within the first 100 ft or so of the borehole had slopes greater than 5°, the terrain was sketched so that the correction could be later calculated in the office. Many of the surveyed boreholes had surface terrain corrections calculated out at least to a distance of 72,000 ft (22.9 km), corresponding to zone M of Hammer's (1939) terrain correction chart; others had corrections computed out through Hayford-Bowie zone O (167 km). These terrain correction values were then entered into a computer program by Beyer and Corbato (1972) for the calculation of the terrain corrections at the different station depths within the borehole.

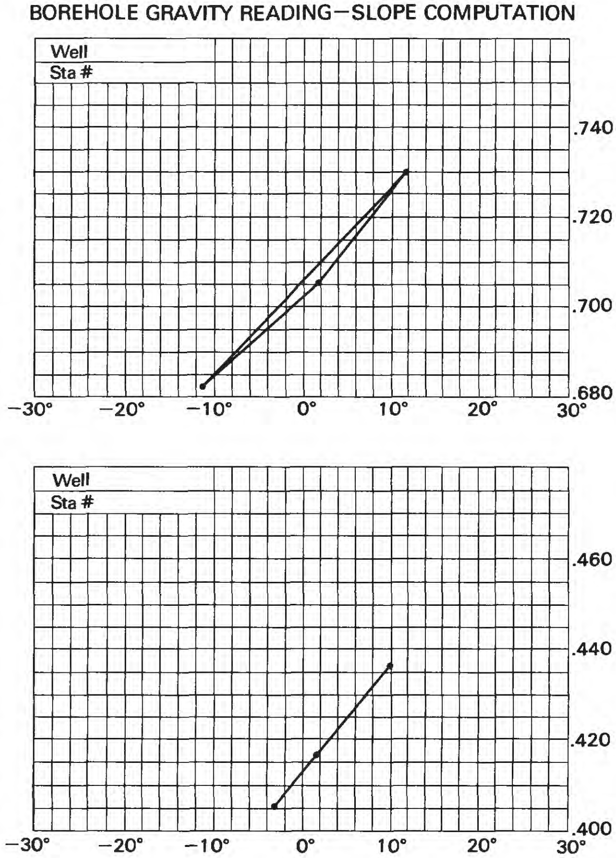


Figure 4. Null-position determination chart with example.

7. The terrain corrections were added in, thus creating corrected observed gravity values.
8. These observed gravity values were then subtracted from the adjacent stations' observed values (ΔG) and the result divided by the vertical intervals (ΔZ), thus giving the measured gravity gradients between each station ($\Delta G/\Delta Z$).
9. Bulk density values (ρ_B) were calculated using the formula:

$$\rho_B = \frac{F - \dfrac{\Delta G}{\Delta Z}}{4\pi k} \qquad (1)$$

where F is the free-air gradient, and k is the Newtonian gravitational constant (Robbins, 1981; Smith, 1950); F is discussed further in the Data Interpretation section.

DATA PRECISION

Questions commonly asked about BHGM surveys pertain to data precision. Typical questions are, "How accurate is the survey?" and "How thin a bed can be measured?"

McCulloh and others (1967b) suggested from early tests with meter BH–1 that a reading precision of ±8 μgal is obtainable because they obtained an average precision of ±16 μgal for each pair of stations $\Delta(\Delta G)$, based on 20 gravity readings (including both meter readings and depth measurements). Their depth measurement accuracy ranged between 0.05 and 0.2 ft. Brown and others (1975) obtained a standard deviation error of ±18 μgal from 150 repeated $\Delta(\Delta G)$ readings with BH–2, and Schmoker (1978), using 132 interval measurements from BH–1, obtained a standard deviation of ±19 μgal and a standard error of 13.4 μgal. This suggests a reading precision of ±7 μgal. Schmoker (1978, p. 541) also found that, by restricting the intervals to less than 70 ft and the time between readings to less than 0.6 hours, a reading precision of ±5 μgal could be obtained.

For slimhole meters, LaFehr and others (1979) reported that EDCON under most operating conditions achieved average $\Delta(\Delta G)$ repeats of ±10–20 μgal from BH–4. Caton (1981), in analyzing seven BHGM surveys run using BH–10, did not calculate any $\Delta(\Delta G)$ errors. However, he did conclude that he was able to achieve a ±5 μgal reading precision at the 90–percent confidence level if three or more independent readings per station were made. Black and Herring (1983), after making some heat-compensation adjustments to the EDCON BHGM's thermostating circuitry, obtained, in a test survey of over 200 gravity readings at 20 stations, a standard deviation error of ±2.6 μgal per reading.

Interpretation of the above reports and of data that I have personally worked with leads me to believe:

1. Most BHGM surveys, with only one reading per station and repeats of every few stations, will achieve standard deviation errors for $\Delta(\Delta G)$ of ±14 to 20 μgal, or better.
2. If maximum care is taken (that is, allowing a longer time for temperature stabilization before and during the survey, keeping the internal meter rotation to a minimum, making repeats at least every 1 to 2 hours, and so forth), then $\Delta(\Delta G)$ errors will be ±10 to 14 μgal.
3. If multi-readings are made, an optimum error of ±6 μgal per $\Delta(\Delta G)$ can be achieved. Beyer (1983) believed that this error optimally should approach ±2 to 4 μgal.

Interval depth errors are believed by McCulloh, Schoellhamer, and others (1967), Beyer (1971), Schmoker (1978), Caton (1981), and myself to be minimal (usually less than ±0.1 ft). In checking for errors in our cable system, I have found that we were within 2 ft over a 10,000–ft interval of cased hole. This is an error of 0.1 ft in 500 ft. Moreover, most depth errors are reflected in the $\Delta(\Delta G)$ error. That is, if a station location is lower by 0.1 ft than is believed, then the measured $\Delta(\Delta G)$ for the interval above the station will be higher by 3 to 5 μgal depending on the density of the rocks and too low by the same amount for the interval below the station.

Although depth errors are usually minimal and are usually part of the $\Delta(\Delta G)$ error, figures 5 and 6 show that it is necessary to keep these depth measurements as accurate as possible (especially when logging thin beds). It should also be noted that the density error for a given depth error is also a function of the density of the surrounding rocks. The USGS truck has two cable measuring systems (Robbins, 1979), and one displays the cable depth to the nearest hundredth of a foot, values that were used in surveys where the intervals logged were less than 15 ft thick.

The minimum bed thickness (ΔZ) that one can measure with a BHGM is dependent on the accuracy of the density data needed and on the accuracy of the BHGM data obtained. Figure 6 can be used to determine this minimum bed thickness and shows that optimally, for a required density precision of ±0.02 g/cm^3, a 15–ft bed can be surveyed. If less density precision is acceptable, then thinner beds can be surveyed.

For a more complete discussion on gravimetry repeatability and errors, see Beyer (1983).

DATA INTERPRETATION

Density values (ρ_B) that are determined from BHGM surveys using formula 1 (p. 15) are known as interval densities. These values in areas of complex geology become apparent bulk densities (Beyer, 1983; LaFehr, 1983). In order to understand and utilize these values, the question, "Do the lithologic beds dip more than about seven degrees and (or) is there structural complexity in the area (for example, faults, salt domes, facies changes, reefs, or caverns)?" needs to be answered.

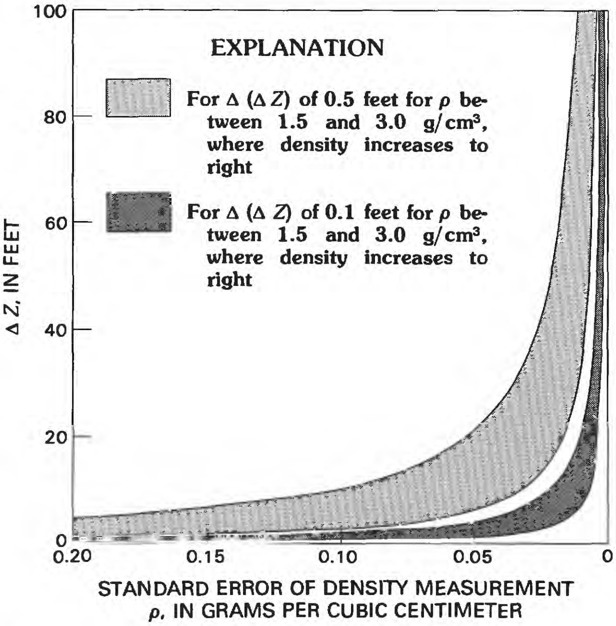


Figure 5. Standard errors of borehole gravimetric determinations of density as a function of ΔZ, assuming no error in measurement of Δ(ΔG).

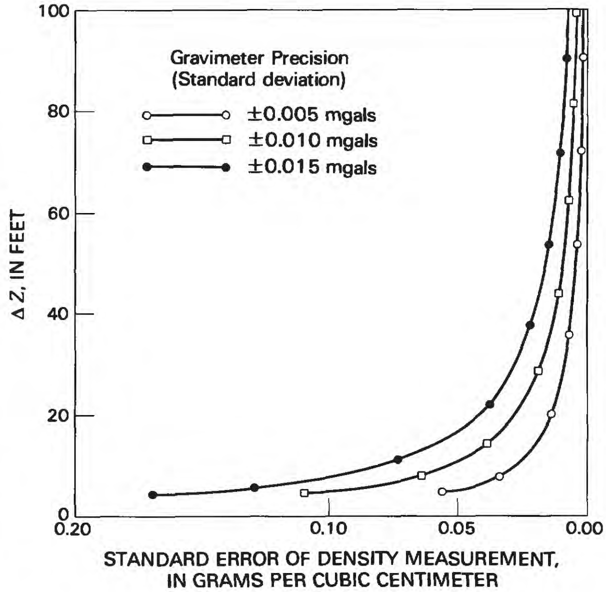


Figure 6. Standard errors of borehole gravimetric determinations of density as a function of ΔZ, assuming no errors in measurement of Δ(ΔZ) (from McCulloh and others, 1968, p. 8).

When the answer to both parts of the question is "no" (simple area; that is, horizontally homogeneous density values with all density variations in the vertical sense), the ρ_B values, if not exact, are very close to being true bulk densities and F is not likely to vary much from the normal value of 0.09406 mgal/ft (0.3086 mgal/m), unless the borehole is located within a large graben or horst-like structure. A wrong value of F changes the computed absolute densities, causing a dc shift, but does not affect density differences between intervals. Also, in many cases, the surveys were normalized against accurate core analyses or gamma-gamma density logs.

In structurally complex areas, not only are the ρ_B values different for the interval horizontally opposite an anomalous structure, but the structure also affects ρ_B values for some distance above and below the structure (example, fig. 7; LaFehr, 1983). Also, local surface geologic effects can cause F to vary more than 10 percent from the normal value (McCulloh, 1966, p. 2-3). These effects will also cause F to vary over the length of a borehole. Therefore, in order to understand and interpret the differences between BHGM ρ_B values and true values, good core analyses and (or) gamma-gamma density logs are necessary.

One way of interpreting apparent BHGM ρ_B values in complex areas is to compare these values with the density values that have been determined by other methods and have been averaged over the BHGM survey intervals. The BHGM ρ_B values are then normalized against the above averaged values, and differences are taken. The measured differences can now be compared and matched with calculated difference curves for simple-body models. Figure 7 is an example for a vertical fault (displaced horizontal bed) with 100 ft of displacement. By making assumptions based on knowledge of the local geology such as having a 100-ft displacement fault as in figure 7, curves can be calculated and matched to the measured differences for subsurface structural models that are reasonable to the area of the survey. The paper by Clark and Hearst (1983) is an excellent example of a study in a complex area.

SUMMARY

This chapter has provided a brief introduction to the equipment and procedures, used by the USGS, in conducting borehole gravity surveys over a 16-year period. For a detailed discussion of the fundamentals of borehole gravimetry, including theory of operation, basic well-measurement procedures, data reductions and corrections, measurement errors, and repeatability of measurements, see Beyer (1983).

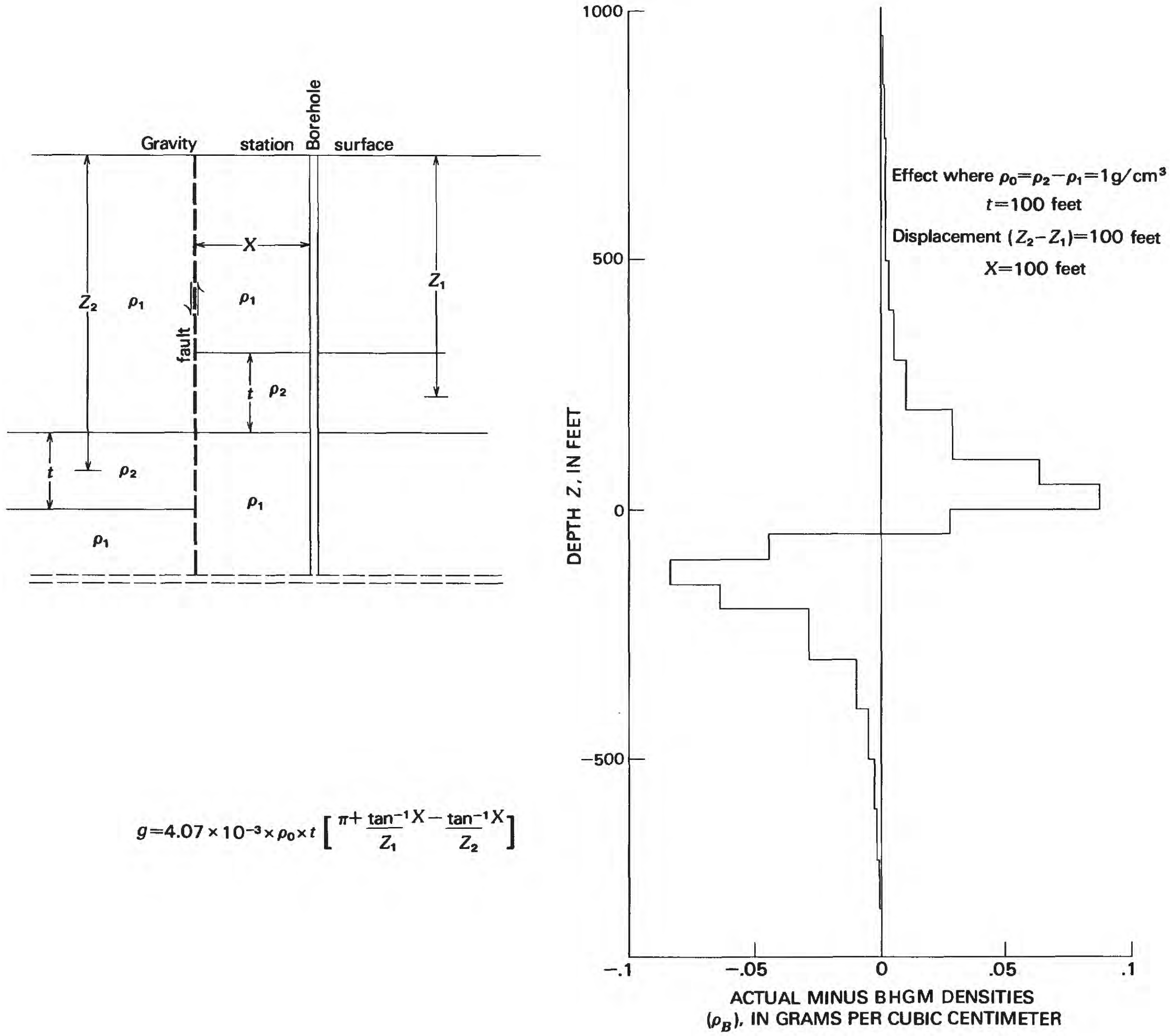


Figure 7. Example of effect of a displaced horizontal bed (vertical fault) on borehole gravity determined densities.

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By Stephen L. Robbins

Chapter C. Bibliography with Abridged Abstracts of Borehole (Subsurface) Gravimetry and Corresponding In-place Rock Density Determinations

CONTENTS

FIGURES

INTRODUCTION

This compilation lists 246 reports that contain information pertaining to subsurface gravity and the corresponding in situ rock density determinations. Most of the reports are on borehole gravimetry. However, 55 reports listed discuss gravity measurements in mine shafts and underground diggings, such as coal, copper, and salt mines.

A little more than half the reports were published with abstracts that are reproduced here; many abstracts are abridged because of their length. Asterisks represent ellipses in original abstracts. For other reports, short abstracts have been added. Several in foreign languages have only a translation of the title.

The reports are divided into four categories: theory, instrumentation, case histories, and basic data. Author and title indexes are provided at the end. A report pertaining to more than one category is referenced in each section, and its abstract appears only in the first section in which it is referenced.

I compiled this list by searching the reference lists in the borehole gravimetry reports already known to me and then by checking the references in these reports, and so forth. Cumulative indexes for Geophysics and the Society of Professional Well Log Analysts (SPWLA) publications were searched. Colleagues were asked if they knew of any reports. This list is quite comprehensive, although a few papers may have been overlooked.

I wish to acknowledge L.A. Beyer's (of the U.S. Geological Survey) assistance in locating many of these references.

Reports on subsurface gravimetry started appearing with regularity about 30 years ago. Only four reports (1, 5, 89, and 191) predate 1947. Figure 1, a graph showing the number of reports published each year, shows three progressively larger periods of activity. The first peak was in the late 1940's to mid-1950's, and a number of good theoretical papers were published, including report 105, which is considered by some to be the classic in the fundamentals of borehole gravimetry. The second period was in the mid-1960's when several good reports that can be used as basic references were written. These include reports 80 and 82. The third period started in the mid-1970's and continues to the present. This group contains some good case history studies.

Over half of the reports were published in U.S. Geological Survey (USGS) publications and in publications of SEG (Society of Exploration Geophysicists). Figure 2 shows the distribution of the bibliography by publisher.

The first category contains reports that pertain to theory, methods, data reduction, and applications. Several reports in this section are noteworthy; namely 6, 80, 82, and 105. Reports 10 and 11 are good beginning references. A good set of literature now exists on terrain corrections; this includes reports 9, 10, 12, 45, 59, and 103. The following reports contain discussions on deducing structure away from the borehole (remote sensing): reports 26, 46, 49, 50, 53, 56, and 106.

The second section contains 30 reports that pertain to instrumentation. Within borehole gravimetry, two types of instruments have been developed: (1) vibrating filament, and (2) astatized spring. Instruments of the first type have been built by Esso Production Co., Exxon, and Shell Development and are discussed in reports 132, 133, 135, 137, and 146. LaCoste and Romberg, Inc. makes the only borehole gravity meters (BHGM) of the second type. Reports 6, 11, 121, 122, 123, 124, 126, 138, 139, 142, 143, and 149 describe these meters.

The third section lists 74 reports that contain only case histories. Thirty-seven reports listed in the first two sections are also listed in this section. Case histories are given for surveys run in boreholes and in underground mines in the following States and countries: Arizona, California, Colorado, Florida, Michigan, Missouri, Nevada, New Mexico, Ohio, South Dakota, Texas, Washington, West Virginia, Wyoming, Australia, Austria, Canada, Czechoslovakia, Denmark, England, Germany, Hungary, India, Libya, New Zealand, Poland, Russia, and Scotland.

The last section lists reports that contain only basic gravity data with reductions and corrections. Additionally, reports 225 through 232, 235, 236, 238, 239, 243, 244, and 246 contain preliminary density and (or) porosity determinations,and gamma-ray logs are included in reports 233, 234, 236, 237, 238, 241, 242, 243, and 245. Data are from the following States: California, Colorado, Florida, Michigan, Montana, Nevada, New Mexico, Texas, Washington, West Virginia, and Wyoming.

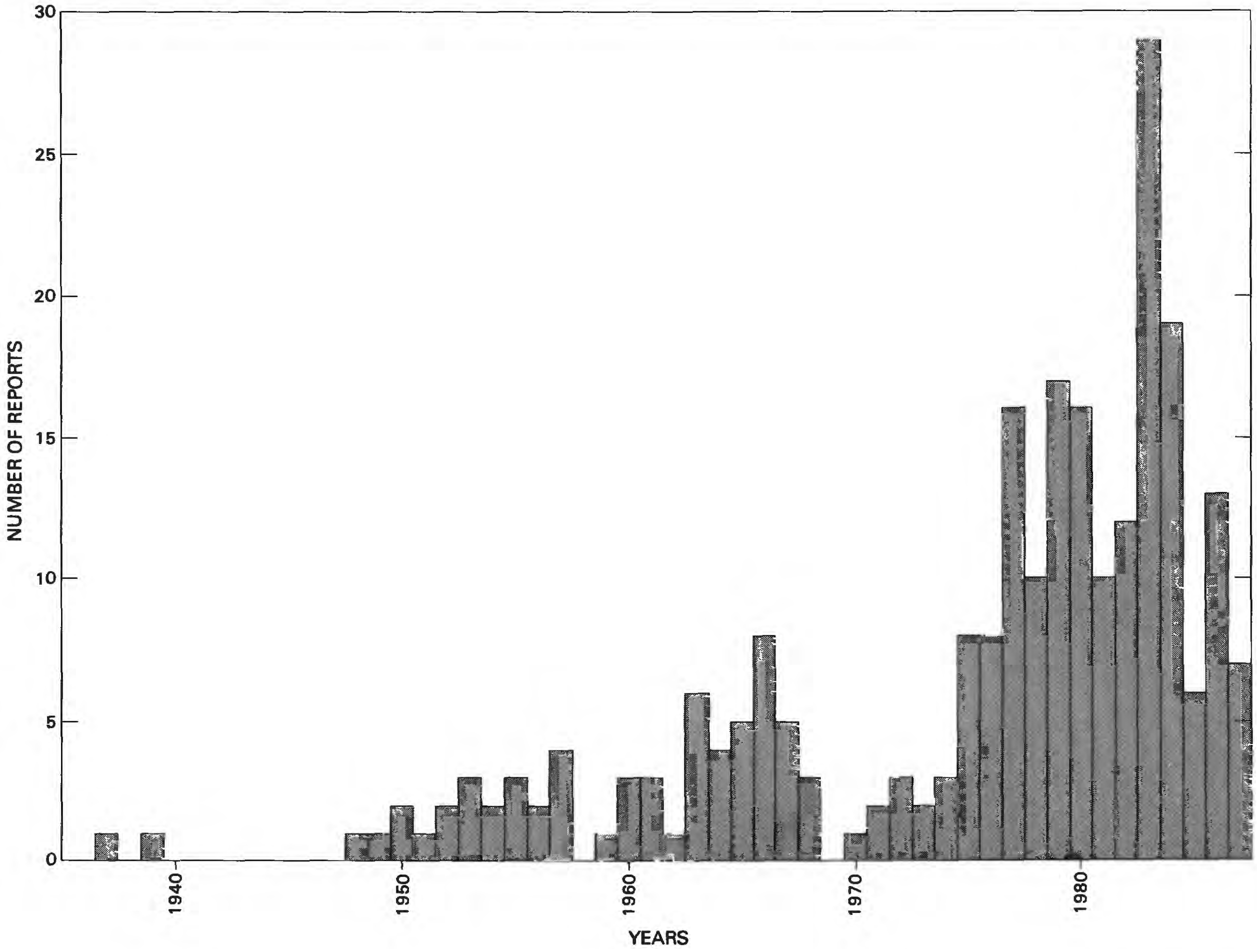

Figure 1. Number of reports and abstracts on subsurface gravimetry published per year between 1937 and 1987.

BIBLIOGRAPHIC LIST WITH ABRIDGED ABSTRACTS

Theory, Methods, Data Reduction, and Applications

1. Airy, G. B., 1856, Account of pendulum experiments undertaken in the Harton Colliery for the purpose of determining the mean density of the Earth: London, Royal Society Philosophical Transactions, v. 146, nos. 14, 15, p. 297–355.

This report is a very detailed step-by-step account of the events that occurred in the author's attempts to determine the mean density of the Earth by measuring the different periods of a pendulum swing at the top and bottom of a vertical mine shaft.

This report is also referenced in Case Histories.

2. Khafaji, S.A. and Schultz, A.K., 1983, Application of the borehole gravity meter (BHGM) to hydrocarbon exploration: Society of Exploration Geophysicists 53rd Annual Meeting, Las Vegas, Nevada, Expanded Abstracts with Biographies, September 11–15, p. 26–28.

The capability of the BHGM in determining accurate bulk densities for a large radius of investigation makes it a powerful tool to locate porosity zones around a borehole and analyze reservoir properties. The remote sensing capabilities of the BHGM need to be considered before converting the gravity values to density, and hence porosity, and integrating it with other open-hole logs. In general, the BHGM faithfully maps and confirms porous zones indicated by other tools in a given borehole. In more than one case, it also pointed out other areas of interest in a given reservoir which were missed by the other tools either because of their limitations or the conditions of the wellbore. The case history examples which are presented demonstrate the application of the BHGM to a carbonate reservoir where matrix porosity is enhanced by fractures. There were sufficient density contrasts for the high

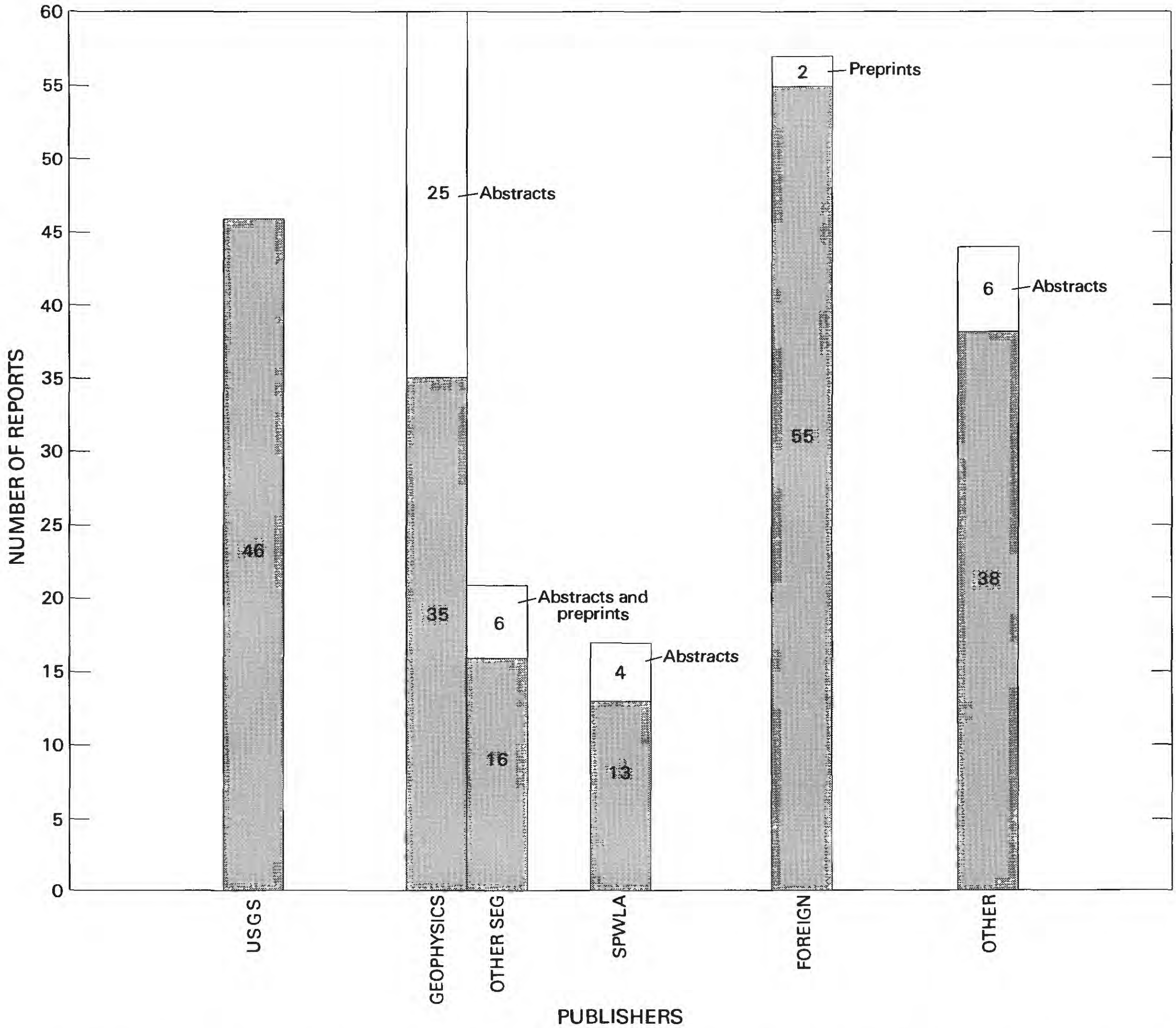

Figure 2. Number of reports on subsurface gravimetry, published between 1937 and 1987, by publisher. SEG, Society of Exploration Geophysicists; SPWLA, Society of Professional Well Log Analysts.

sensitivity of the BHGM to detect. An opening of a zone based BHGM in one well increased the rate of flow to make the well commercial, and perforation of zones in other wells resulted in large quantities of hydrocarbons which otherwise might have been completely missed.

Use of the BHGM as a density logging tool suggests that a reservoir might be monitored for redistribution of fluids as a result of pressure gradients induced by pumping. This fluid movement is sometimes referred to as "coning." A gas zone may intrude downward toward a perforation and a water zone may intrude upward toward a perforation resulting in production problems. The difference between densities of gas, oil, and water should be reflected in altered gravity data due to their redistribution from the prepump to the postpump stage. A theoretical study was done of a real world reservoir using prepump and postpump models. Measurable density differences occurred between the two configurations. However, the density differences are of such a subtle nature that it is imperative to collect data initially in the prepump configuration as well as in the postpump stages.

3. ______1984, Application of the borehole gravity meter (BHGM) to hydrocarbon exploration [abs.]: Geophysics, v. 49, no. 5, p. 596.

Same abstract as report 2.

4. Allen, W.A., Jr., 1956, The gravity meter in underground prospecting: American Institute of Mining Engineering Transactions, v. 205, p. 293–295.

Gravity meter surveys have been used for underground prospecting in the copper mines at Bisbee, Ariz. Evaluation of results indicates definite potentialities under proper conditions. Equipment, procedures, and methods of handling data are described.

5. Benfield, A.E., 1937, Note on the variation of gravity with depth: Zeitschrift fur Geophysik, v. 13, p. 157-158.

A table and curve showing the value of "g" at different distances from the centre of the earth have been computed from the latest density distribution data. Gravity is shown to be remarkably uniform over a large distance.

6. 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.

A detailed presentation of the theory of borehole gravimetry and how to reduce and interpret borehole data is given, including appendices of all pertinent formulae.

*** observed vertical gradients from high-precision detailed gravity surveys made in seven shallow oil wells that penetrate a late Cenozoic sequence of marine and nonmarine rocks in the Midway-Sunset oil field, California, are interpreted to obtain vertical density profiles. ***.

The unadjusted density profiles of six wells are on the average systematically greater than core densities by .05 g/cm^3. Adjusted profiles for the same wells agree with core densities to within .01 g/cm^3 on the average. Densities of an adjusted profile of a seventh well are .15 g/cm^3 less than those of the unadjusted profile and are in better agreement with core densities by that amount. However, residual systematic discrepancies between core and gravimetric densities for this seventh well indicate a measurable variation of the anomalous vertical gradient with depth and (or) lack of representative core density data.

Topographic effects and anomalous vertical gradients in boreholes are usually small and change slowly with depth but, in some instances, may be comparatively large and change rapidly with depth. In the former case, gravimetric density profiles unadjusted for these effects can be in error by as much as about .05 g/cm^3 and, in the latter case, by as much as several tenths of a g/cm^3. In both cases, relative errors between neighboring parts of the density profiles are much smaller.

In cases where the anomalous vertical gradient changes appreciably with depth, it cannot be reliably estimated in the borehole from surface gravity measurements or from tower gradient measurements, which are especially sensitive to very shallow local density irregularities. At any borehole depth the anomalous gradient can be estimated from the difference between core and gravimetric densities of the same borehole interval. The core densities must be highly accurate and representative of the interval and the gravimetric density must be adjusted for topographic effects.

Measured borehole vertical gradients have precisions of .00025 to .00050 mgal/ft (8 to 16 Eötvös units) for vertical intervals as small as 10 ft (3 m); ***.

This report is also referenced under Instrumentation and Case Histories.

7. ______1977, The interpretation of borehole gravity surveys [abs.]: Geophysics, v. 42, no. 1, p. 141.

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 (mass anomalies) of detectable magnitudes that may occur in the region surrounding the surveyed well.

In many cases, a uniform and horizontally layered earth can be assumed 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 vertical density profiles. Principal interpretation efforts involve the application of the vertical density profiles to formation evaluation, reservoir engineering, well-log and core analysis evaluation, surface gravity and seismic studies, or engineering and rock property investigations.

Lateral density variations may be significant where 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 isopycnic (equal density) surfaces generally are not known and may be complex in shape. Separation of borehole gravity effects due to vertical and to lateral density variations is possible if independent and reliable vertical rock density information can be obtained from well logs, core analyses, or other sources. Interpretation of borehole gravity effects due to remote lateral density variations is influenced heavily by independent geologic and geophysical data from which the structural and stratigraphic setting of the well can be inferred. Interpretations are not unique and by necessity usually are simple.

Interpretations are presented of borehole gravity surveys made (1) in a steeply dipping section, (2) in axial and flank locations on a narrow anticline, (3) through an overthrust, (4) through a prominent unconformity, (5) through a carbonate reservoir with irregularly distributed porosity, and (6) at equivalent subsurface elevations in neighboring wells. Analysis techniques and practical limitations are discussed.

8. ______1979a, Terrain corrections for borehole and tower gravity measurements: U.S. Geological Survey Open-File Report 79-721, 17 p.

Terrain corrections were calculated for borehole gravity and tower gravity surveys made in a variety of topographic settings. The effect of terrain corrections on vertical density profiles calculated from borehole measurements also is shown.

9. ______1979b, Terrain corrections for borehole gravity measurements: Geophysics, v. 44, no. 9, p. 1584-1587.

This note discusses terrain corrections only for borehole gravity measurements and is a condensed version of report 8.

10. ______1982, The interpretation and application of borehole gravity surveys: Society of Exploration Geophysicists Course Notes, 226 p.

This course [see entry 108] is designed to provide an introductory yet up-to-date description of borehole gravity logging and how it can be used to enhance formation/reservoir evaluation and subsurface exploration.

This report accompanies the course described in entry 108 and contains discussions of the: 1) mechanics of borehole gravity surveys, 2) nature of BHGM measurements, 3) density and porosity of sedimentary rocks, 4) conventional methods for estimating formation density and porosity, 5) formation and reservoir evaluation with BHGM surveys, 6) systematic and analysis of borehole gravity anomalies, 7) studies of borehole gravity anomalies, 8) other uses of BHGM surveys, 9) planning and management of BHGM surveys, 10) applications and future directions, 11) exercises, and 12) reprints of several reports on borehole gravimetry including reports 20, 53, 60, 80, 105, 209, 211, and 216.

Successful use of borehole gravity surveys more often than not requires knowledge of the strengths and weaknesses of conventional open-hole logs and the factors that control density and porosity fluctuations in sedimentary rocks. The joint effort of the area or well geologist, a geophysicist, a well log analyst, and possibly a reservoir engineer or petrophysicist may be necessary to derive the maximum information from the survey.

11. ______1983, Borehole gravity surveys; theory, mechanics, and nature of measurements: U.S. Geological Survey Open-File Report 83-76, 87 p.

The theory, historical development, mechanics and nature of borehole gravity survey are presented here for the reader who is unfamiliar with these surveys or the gravity method of exploration geophysics.

This report contains much of the same material that is presented in entry 10.

12. 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, VA 22161.

The program calculates terrain corrections at equally or unequally spaced gravity stations in a vertical borehole (or on a tower above ground) and also calculates vertical gradients and density corrections over intervals between stations for analysis of borehole gravity measurements. Terrain must be described by a standard scheme (e.g., Hayford-Bowie, Hammer) or a special zone and compartment scheme. Terrain density may be specified as constant for all zones or as variable by compartment. An approximate correction for the earth's curvature is included.

This program presents an improved algorithm to the one offered in entry 45.

13. Beyer, L.A., Brune, R.H., and Schmoker, J.W., 1975, Application of borehole gravity to exploration for petroleum [abs.]: Program 50th Annual Pacific Section Meeting, American Association of Petroleum Geologists–Society of Economic Paleontologists and Mineralogists–Society of Exploration Geophysicists, Long Beach, California, April 23-25, p. 29.

Gravity measurements in boreholes provide direct bulk-density estimates of the formations penetrated by the well. These density estimates are highly accurate (.005 to .03 g/cm^3) and are based on the integrated effect of large volumes of rock. The technique is especially well suited to evaluation of fracture or vugular porosity, to detection of oil or gas sands behind casing, and to any situation where hole conditions make conventional open-hole porosity and density logs unreliable. In special circumstances downhole gravity measurements extend mapping of the anomalous gravity field into the subsurfaces for purposes of remote sensing of anomalous masses.

A reliable smaller diameter borehole gravimeter (tool O.D. of 4.25 inches versus existing 5.5 inches and larger tools) is under development for the USGS and research is underway to study the feasibility of developing a continuous reading borehole gravity gradiometer.

14. Black, A.J., 1985, Application of well log density data from borehole gravity and gamma-gamma measurement to geophysical exploration: Society of Exploration Geophysicists, 55th Annual Meeting, Washington, D.C., Expanded Abstracts with Biographies, October 6-10, p. 280-281.

Density measurements obtained from well logging tools are used in the interpretation of gravity surveys recorded both on the surface and downhole. Density information is also used to calculate reflection coefficients for use in seismic modeling. The greatest demands for well log density accuracies are made when they are used for downhole gravity structural interpretations.

The vast majority of well log density information is provided by the gamma ray back-scattering technique which is often referred to as the gamma-gamma density method.***.

15. ______1986, Application of well log density data for borehole gravity and gamma-gamma measurements to geophysical exploration [abs.]: Geophysics, v. 51, no. 2, p. 468.

Same abstract as report 14.

16. Black, A.J., and Herring, A.T., 1983, Offset of borehole gravity densities due to geologic structures: Preprint, Canadian Society of Exploration Geophysicists, Annual Meeting, Calgary, Alberta, April, 20 p.

This report was written to enlarge on two discussions on the usefulness of borehole gravity density logging that were published in the July, 1981, issue of Geophysics.

[This report] start[s] by briefly describing the current state of the art of instrumentation, surveying methods, and derivation of densities from the gravity measurements. [Then,] computer modelled density logs from some typical petroleum exploration environments [are presented, which] serve to illustrate the anomalous density patterns which must be accounted for in order to arrive at good formation densities.

17. Bližkovsky, M., 1979, Processing and applications in microgravity surveys: Geophysical Prospecting, v. 27, no. 4, p. 848-861.

An economic and precise processing system for microgravity surveys is presented. Three computer processing modes covering areal ground and underground measurements, measurements in vertical shafts, and measurements of vertical gravity gradients with a 3 m high tower are dealt with.

Diagrams for manual calculation of gravity effects of prismatic walls, vertical shafts, and horizontal galleries, as well as programs for calculation of accurate terrain corrections and corrections for gravity effects of bodies with complicated ground-plan are proposed.

The method of processing microgravity data is two to three times quicker than any traditional way, with maximum accuracy preserved in resulting gravity micro-anomalies. Applications from the field of mining geophysics and archaeology are included.

18. Bodemüller, H., 1954, Der schwereunterschied in korrespondierenden punkten über und unter tage: Stuttgart, Zeitschrift fur Vermessungswesen v. 79, no. 8, p. 263–268. [The gravity difference between corresponding points above and below ground.]

19. Bradley, J.W., 1974, The commercial application and interpretation of the borehole gravimeter, *in* Contemporary geophysical interpretation, a symposium: Geophysical Society of Houston, December 4–5, 14 p., 11 figs.

Basic theory and the data and experience, from several of the approximately 50 wells that Amoco Production Company has surveyed with the borehole gravimeter using the results for reservoir analysis, are presented here. Case history areas are (1) Miocene fresh-water dry gas sands in the Gulf Coast, and (2) carbonate rocks in Grand Traverse and Kalkaska Counties, Mich.

This report is also referenced in Case Histories.

20. ______1976, The commercial application and interpretation of the borehole gravimeter, *in* Jantzen, R.E., ed., Tomorrow's oil from today's provinces: American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 24, p. 98–109.

See report 19 for abstract. This report also referenced in Case Histories.

21. Brown, A.R., and Lautzenhiser, T.V., 1982, The effect of dipping beds on a borehole gravimeter survey: Geophysics, v. 47, no. 1, p. 25–30.

We study the effects of dipping beds on a borehole gravimeter (BHGM) survey. A dipping bed solution is presented which uses an anomalous bed density in a regional framework. A method of application is shown which provides an estimate of the regional framework density and dip angle of the beds. The method of application requires measuring local formation density independently.

22. Brown, A.R., Rasmussen, N.F., Garner, C.O., and Clement, W.G., 1975, Borehole gravimeter logging fundamentals: Preprint, Society of Exploration Geophysicists 45th Annual Meeting, Denver, Colorado, 9 p., 20 fig.

See report 23 for abstract.

23. ______1976, Borehole gravimeter logging fundamentals [abs.]: Geophysics, v. 41, no. 2, p. 345.

The borehole gravimeter (BHGM) gives us the capability of determining accurate bulk densities from measurements of the earth's gravity field in cased or open holes. Effective use of the BHGM as a practical logging tool in the petroleum industry requires feasibility studies, careful survey planning, and strict attention to survey procedures, as well as theoretically sound interpretation techniques. The interpretation of gravity data, based on the assumption of a parallel layered earth model, is augmented by incorporating measurements from other logging tools and direct gravity modeling. This integrated approach requires the combined skills of both a geophysicist experienced in gravity interpretation and a log analyst.

24. Casten, Uwe, 1984, Subsurface gravity measurements to demonstrate mining-induced changes in rock density: Geofizikai Kozlemények, Geophysical Transactions of the Eötvös Lorand Geophysical Institute of Hungary, Budapest, v. 30, no. 3, p. 227–236.

Because of the underlying workings, subsurface mining results in deformation of the top layers. Within certain zones around working faces and accompanying roads changes in density and stress distribution are of interest because rock bursts may occur there. Gravity measurements were performed in the base roads and the main road of longwall retreat coal faces in a deep mine of the Ruhr coal district. Time dependent differences with amplitudes up to 0.1 mgal were observed by repeated observations at fixed points. The induced anomalies could be correlated with the advance of working faces and with de-stressing activities carried out by miners. Negative anomalies were interpreted by positive changes in density within the top layers, in good accordance with a zone of clastic deformation in front of the faces.

This report is also referenced in Case Histories.

25. Caton, P.W., 1981, Improved methods for reducing borehole-gravity data—Applications and analyses of reduced gravity plots: Society of Professional Well Log Analysts 22nd Annual Logging Symposium Transactions, v. 2, p. RR1–RR44.

*** Precise BHGM density estimates can be obtained from numerous repeated measurements, but due to time considerations, the data are necessarily sparse. Existing analysis procedures identify data precisions and errors from density and instrument drift plots; however, these approaches are cumbersome, and several factors affecting the measurements are not always obvious. A new presentation, the "reduced gravity plot," has been developed which illustrates data precisions and errors, instrument drift and tares, and the nonlinear effects due to temperature stabilization. The plot can be constructed on site, during data collection, to evaluate survey and instrument performance before coming out of the hole.

*** Results [from two 1980 BHGM surveys and older data] indicate significant temperature influence on slim tool BHGM measurements, and the effects due to magnetized sondes and operator reading errors are obvious. Additionally, two to three instrument tares seem common during BHGM surveys. ***. Fortunately, from reduced plot analyses of repeated measurements, [these] anomalous [effects] can be identified and subsequently removed.

Improved analyses of BHGM data require three independent readings per station. The total BHGM survey time needed for three measurements per station is increased 15–20 percent when compared to two per station; however, density resolution of 0.02 g/cm^3 can be achieved at the 90 percent confidence level after compensating for anomalous instrument responses. ***.

26. Coyle, L.A., 1976, The application of borehole gravimetry to remote sensing of anomalous masses: Lafayette, Ind., Purdue University M.S. thesis, 89 p.

The potential of the borehole gravimeter as a remote sensing tool is investigated by analyzing the gravity distribution in a vertical cross section caused by five ideal masses approximating specific geologic features. The gravitational attraction of these bodies will cause perturbations in the normal free-air–Bouguer anomaly curves through the geologic section if they are near enough for detection. This distance is a function of the physical size and shape of the anomalous mass and the density contrast involved.

The gravity-depth profile, after corrections are made for nonstandard conditions, the free-air effect, and the Bouguer component, will indicate the presence or absence of a remote mass. If a local positive or negative perturbation exists in the profile, the cause is a layer of density unaccounted for in the reduction of the Bouguer effect. If a local positive and negative perturbation exists in the profile, the cause may be due to a remote body. The separation distance of the maximum and minimum values is the maximum thickness of the remote mass; and the zero gravity value depth is the depth of the center of mass of the remote body. The geometrical shape of the body cannot be deduced uniquely from the gravity-depth profile.

The distance to the remote body can be determined within certain limits from the analysis of the $\Delta\sigma_a$ curve, the difference between the densities recorded by the BHGM log and FDC log or from the direct modeling of the gravity-depth profile. The actual position of a remote body cannot be determined from the measurements in a single drill hole. However, by superimposing the circular rings defined by the maximum and minimum distance limits as determined from the observations from more than one drill hole, it is possible to decrease the potential area in which the anomalies mass is located.

27. Domzalski, W., 1954, Gravity measurements in a vertical shaft: London, Bulletin of Institute of Mining and Metallurgy Transactions 571, v. 63, p. 429–445.

After a short introduction on the application of gravity measurements in a shaft and the description of such a survey carried out in the shaft at Snowdown Colliery, Kent, [England,] the factors affecting the vertical distribution of gravity are discussed. The results *** are analyzed and the effects of errors in the measurements of gravity and distance are discussed.

This report is also referenced in Case Histories.

28. ______1955, Relative determination of the density of surface rocks and the mean density of the earth from vertical gravity measurements: Geophysical Prospecting, v. 3, no. 3, p. 212–227.

The gravity difference between two stations, one at the surface and the other underground vertically below the former and at a given distance from it, depends on the mean density of the earth, σ_m, as well as on the density of the layer of rock contained between the two stations. When one of these densities is known, the other can be computed from this gravity difference. The reliability of this determination depends on the relative accuracies with which σ_m and σ can be obtained.

These accuracies are discussed***. The mean density of the earth has been determined with an accuracy of approximately 0.01 gm/cm^3. The determination of the density of a layer of rock depends on density determinations of rock samples which are not representative of the layer as a whole. Thus the accuracy of the value of σ based on a number of sample determinations will depend on many factors, including the method of averaging the density values obtained from the samples and the degree of uniformity in the geology.

To investigate the problem discussed above, three sets of gravity measurements were made under differing conditions [at Godstone Quarries and at Cumberland, England]. *** ***.

This report is also referenced in Case Histories.

29. EDCON, 1977, Borehole gravity meter manual: Lakewood, Colorado, Exploration Data Consultants Inc., 44 p.

This manual was put together for the benefit of EDCON's customers and contains a complete introduction to the principles of borehole gravimetry including theory, data acquisition, data reduction, and interpretation.

30. Egyed, Lázlo, 1960, Zur frage der Schweremessungen in Bohrlöchern: Freiburger Forschungshefte C81, Geophysik, p. 167–170 (in German). [On the question of gravity measurements in boreholes.]

With the determination of various physical parameters in boreholes, the ability to determine the background density is made possible. We can make a density profile, provided we have a method for the determining the average vertical gradient

$$\text{where} \quad \bar{U}_{zz} = \frac{g_2 - g_1}{h};$$

$$\text{then} \quad g_2 - g_1 = 4\pi f h X \, \sigma = C\sigma.$$

σ is the average density between the points 1 and 2, X is dependent on the ratio d/h (d = borehole diameter, h = measurement interval). The determination of the average gradient seems to be feasible with the presently available technology. The author has designed some fundamental and practical aspects of the construction of such instruments.

This report is also referenced in Instrumentation.

31. Fajklewicz, Zbigniew, 1966, Effect of roof fall zones on the accuracy of underground microgravity measurements: Bulletin de l'Académie Polonaise des Sciences, Série des Sciences Géologiques et Géographiques, v. 14, no. 1, p. 13–15.

[This report examines the effect of roof fall zones near where subsurface gravity stations are located and concludes] that minor roof fall zones in the hanging layer of mine workings cannot exert any essential influence on the results of underground microgravity measurements.

32. ______1973, Grawimetria Poszukiwawcza: Skrypty Uczelniane nr. 335, Warszawa, Wydawnictwa Geologiczne, 416 p. [Gravimetric explorations.]

This report contains a complete discussion on land gravimetry. This includes instrumentation, data reduction, and qualitative and quantitative interpretation including examples. Also included are discussions on borehole and subsurface gravity, deep crustal interpretations, and rock density.

33. ______1980, Mikrograwimetria górnicza: Katowice, Poland, Slask Publishing Co., 264 p. (in Polish). [Mining microgravimetry.]

In this book are described the basic theory and methods of surveying and interpretation of microgravimetric research performed for the needs of mining and engineering geology.

Special attention has been given to problems of discovering cavities after exploitation, research of discontinuous tectonics, karst and erosion landforms, investigations of ground conditions disturbed by underground exploitation, and detecting useful mineral deposits.
***.

Discussions on both borehole and subsurface gravity are included.

34. Fajklewicz, Zbigniew, and Duda, Wladyslaw, 1964, Próba zastosowania pomiarów mikrograwimetrycznych dla potrzeb górnictwa weglowego: Technika Poszukiwan, rok 3, zeszyt 9, p. 1-7. [Test of the application of microgravimetric measurements for coal mining requirements.]

The article deals with the experimental works concerning application of microgravimetric measurements in coal mining industry. Technique and results of microgravimetric measurements carried out to detect the Carboniferous faults and mine workings, and to trace erosional forms occurring at the top of the Carboniferous strata are discussed, as well.

35. Fajklewicz, Zbigniew, Gliński, A.L.R., and Sliz, Janusz, 1982, Some applications of the underground tower gravity vertical gradient: Geophysics, v. 47, no. 12, p. 1688-1692.

Underground tower gravity vertical gradient (UTGVG) measurements made in mine workings have been applied to the detection of caverns, old mine workings, dislocations, and erosive or karstic forms. Since UTGVG measurements are subject to large errors, Kotelnikov's criterion can be used to determine the probability of isolation of the useful anomalies.

The properties of the UTGVG reduce the ambiguity of interpretation of underground gravity surveys.

Simultaneous Δg and UTGVG measurements carried out in the same underground profile frequently replace a three-dimensional or multilevel gravity survey.

The paper presents some applications of the UTGVG [in three mines in Poland].

This report is also referenced in Case Histories.

36. Garland, G.D., 1981, Discussion on "Densities determined from surface and subsurface gravity measurements" by B.A. Sissons with reply by author: Geophysics, v. 47, no. 10, p. 1460.

This paper contains a brief discussion on B.A. Sissons' report (no. 99) and a brief reply by B.A. Sissons.

37. Gliński, A.L.R., 1974, Sposób uwzgledniania grawitacyjnego wplywu wyrobisk górniczych w podziemnych pomiarach mikrograwimetrycznych: Technika Poszukiwán rok 13, zeszyt 1/49, p. 1-7.

Method of allowance of the gravitational effect of mining diggings in underground microgravimetric measurements.

38. ______1978, Podziemne wielopoziomowe zdjecia mikrograwimetryczne i ich zastosowanie w badaniu budowy geologicznej górotworu: Polska Akademia Nauk, Oddziol w Krakowie, Komisja Nauk Geologicznych, Prace Geologiczne 109, 60 p. (in Polish).

Underground multi-level microgravity surveys and their application to the study of the geologic structure of the rock mass.

39. Gournay, L.S., 1983, Detection of bypassed gas using borehole gravimeter and pulsed neutron capture logs [abs.]: The Log Analyst, v. 24, no. 3, p. 27.

Same abstract as report 42. This report also referenced in Case Histories.

40. Gournay, L.S., and Lyle, W.D., 1984, Determination of hydrocarbon saturation and porosity using a combination borehole gravimeter (BHGM) and deep investigating electric log [abs.]: The Log Analyst, v. 25, no. 2, p. 59-60.

The BHGM measures the change in gravity with depth at discrete points or stations along a borehole. Formation bulk density between stations is then calculated from the change in gravity with depth. As a first approximation the volume sensed by the BHGM and for which the bulk density is calculated is a cylinder centered on the borehole of height equal to the station separation and radius equal to five times the station separation. The bulk density equation for this volume contains terms corresponding to porosity, fluid densities, matrix density, and fluid saturations. Since the fluid saturations must sum to one the equation can be reduced to an equation containing these density and porosity parameters, and with water saturation the only saturation term present. Assuming the component densities in the equation are known, the bulk density equation can then be viewed as an equation containing two unknown parameters—porosity and water saturation.

Archie's equation relates water saturation, formation resistivity, water resistivity, and porosity. An equivalent resistivity obtained as a properly weighted average of the resistivities measured by a deep investigating resistivity log such as the induction or older electric log can be calculated such that the equivalent resistivity closely approximates the resistivity of the cylinder described above. Using this equivalent resistivity Archie's equation becomes a bulk equation applying to the same volume as that sensed by the BHGM. Assuming that the cementation factor, saturation exponent, and water resistivity are known the bulk Archie equation contains the unknown quantities porosity and water saturation. Solving the Archie equation and bulk density equations simultaneously results in estimates of bulk porosity and bulk water saturation. Hydrocarbon saturation is then known since the sum of water saturation and hydrocarbon saturation equals one.

The advantage of this approach is that the porosity and saturation estimates obtained are not severely affected by wellbore damage and drilling filtrate invasion, and are therefore estimates of the formation undisturbed by the drilling operation. Actual field test results for five wells are presented to illustrate the technique. Conditions under which the technique can be applied to the problem of detection of by-passed oil and gas in old wells are also presented.

This report is also referenced in Case Histories.

41. ______1984, Determination of hydrocarbon saturation and porosity using a combination borehole gravimeter (BHGM) and deep investigating electric log: Society of Professional Well Log Analysts, 25th Annual Logging Symposium Transactions, v. 2, p. WW1-WW14.

Formation bulk density over a radius of at least 50 feet from the wellbore is routinely obtained using the BHGM. The bulk density equation for this volume of rock contains terms for porosity, fluid densities, matrix density, and fluid saturations. Assuming the component densities are known, the bulk density equation can be reduced to one containing only two unknown parameters—porosity and water saturation.

Archie's equation relates water saturation, formation resistivity, water resistivity, and porosity. By properly weighting the formation resistivities measured by a deep investigating resistivity log, one can obtain an equivalent resistivity for a bulk Archie's equation that applies to the same volume that is sampled by the BHGM. If the cementation factor, saturation exponent, and water resistivity are independently known, Archie's equation reduces to one containing two unknowns—porosity and water saturation.

A simultaneous solution of the bulk density and Archie equations is possible, and this solution provides values of porosity and water saturation within the volume sampled by the BHGM and resistivity log. Hydrocarbon saturation is then easily obtained, since it plus water saturation must equal one.

It is important to note that porosity values are obtained from this approach alone and are not required from any other external source such as logs or cores.

One advantage of this technique is that the computed porosities and saturations are very insensitive to wellbore conditions, filtrate invasion, and other drilling disturbances. Another advantageous result is the investigation of a large, representative volume of reservoir rock that is not normally accessible by conventional logging methods.

Actual field results for several wells are presented. Applications include the detection of bypassed hydrocarbons and the determination of residual oil saturation.

This report is also referenced in Case Histories.

42. Gournay, L.S., and Maute, R.E., 1982, Detection of bypassed gas using borehole gravimeter and pulsed capture logs: The Log Analyst, v. 23, no. 3, p. 27-32.

A method is described where the Borehole Gravimeter (BHGM) and Pulsed Neutron Capture (PNC) logs are used together to identify bypassed gas. The technique was tested in a 40 year-old oil field. Five wells were logged; four potential sands were identified and tested. Two of these produced 933 MCFD and 940 MCFD each with no oil or water. Fluid redistribution due to production was revealed by the BHGM in a third well.

A case is examined where the BHGM alone could unambiguously detect gas. A field example is also given where BHGM data would negate useless testing of a tight zone that showed gas potential on neutron and resistivity logs.

This report is also referenced in Case Histories.

43. Hammer, Sigmund, 1950, Density determinations by underground gravity measurements: Geophysics, v. 15, no. 4, p. 637-652.

Gravimeter observations, in a vertical shaft 2,247 feet deep of the Pittsburgh Plate Glass Company's limestone mine at Barberton, Ohio, for the purpose of determining the densities of the subsurface rock strata, are reported. The survey was made with a standard-type gravimeter to simulate the data which would be obtained by a borehole gravimeter to aid in the anticipation and formulation of problems in the development and application of a borehole gravimeter for gravity prospecting.

Density measurements on many selected core drill rock samples are compared with the densities determined from the gravimeter data. The individual sample measurements show large scatter and systematically low values. Attempts to restore the samples to initial conditions underground were unsuccessful. It appears that density determinations of finite intervals of underground rock strata can be done better with the gravimeter than by laboratory measurements of rock samples.

See references 134 and 196 for discussion of instrument calibration error in this study. This error negates some of the above conclusions.

This report is also referenced in Case Histories.

44. ______1963, Rock densities and vertical gradient of gravity in the earth's crust: Journal of Geophysical Research, v. 68, no. 2, p. 603-604.

This is a discussion of the feasibility of obtaining gravity measurements in the Mohole project.

45. Hearst, J.R, 1968, Terrain corrections for borehole gravimetry: Geophysics, v. 33, no. 2, p. 361-362.

This report describes the method and formulas used in a computer program written for the application of terrain corrections to borehole gravimetry measurements. See report 12 for an improved procedure.

46. ______1977a, On the range of investigation of a borehole gravimeter: Society of Professional Well Log Analysts 18th Annual Logging Symposium Transactions, p. E1-E12.

Concepts of the range of investigation of a borehole gravimeter are reviewed. It is shown that the maximum sensitivity to a mass point at a horizontal distance R from a borehole occurs at a vertical distance $Z = R/\sqrt{2}$. Thus, the angle of maximum sensitivity is about 55° from the vertical. It is also shown that the absolute value of the gravitational effect decreases with increasing R. There are two maxima of the vertical gradient of gravity (at $Z=0$ and at $Z=\sqrt{3/2}\,R$). The minimum distance required between gravimeter stations to obtain a usable measurement can be determined. The slab radius R for which the gravitational effect of a horizontal slab is equal to 45%, 90%, and etc., of that of an infinite horizontal slab is a function of the measurement spacing. The closer the measurement spacing, the more information obtained.

47. ______1977b, Estimation of dip and lateral extent of beds with borehole gravimetry: Geophysics, v. 42, no. 5, p. 990-994.

Simple expressions for the estimation of dip or lateral extent of a bed whose extent is large compared to its thickness have been developed. ***. Numerical solutions are obtained and graphed.

48. ______1978, BIFUR II, a program for calculating borehole gravity caused by two-dimensional structure: Lawrence Livermore Laboratory Interdepartmental Letter 17852, AG78-54, 22 p.; available from National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161.

A revised computer program, BIFUR II has been written to compute the gravitational effect of structures describable in two dimensions by straight line segments. The primary application is to borehole gravimetry, but surface gravity problems can also be investigated. Input is *** not limited to structures bounded by vertical sides.

This program has been superseded by BIFUR III. See report 49 for reference.

49. ______1981, BIFUR III, a program for calculating borehole and surface gravity caused by two-dimensional structure in Cartesian or cylindrical coordinates: Lawrence Livermore Laboratory Report UCID–19030, 100 p.; available from National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161.

[BIFUR III is] an interactive computer program***. It computes the gravitational effect of two-dimensional structures bounded by planes (Program BIFUR3) or co-axial cylindrical surfaces (Program BIFURC). The calculated gravimetric density can be compared to density calculated from measurements of gravity in a borehole and from a density log. The user can change the structure online and compare the results of different change. The primary application is to borehole gravimetry, but surface gravity problems can also be investigated.

50. ______1983, Revealing subsurface structure with borehole gravimetry: Energy and Technology Review, UCRL–52000–83–9, September, p. 18–29; available from National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161.

In recent years, computational methods comparing hypothetical models of subsurface structure at NTS with data obtained from borehole gravimetry and other geophysical logs have greatly reduced the need for exploratory drilling.

51. Hearst, J.R, and Carlson, R.C., 1977, The gravimetric density formula for a spherical shell: Geophysics, v. 42, no. 7, p. 1469.

This short note derives the formula for the change in gravity through a spherical shell.

52. ______1982, Measurement and analysis of gravity in boreholes, *in* Fitch, A.A., ed., Developments in geophysical exploration methods—3: Essex, England, Applied Science Publishers LTD., p. 269–303.

This paper discusses the history of the development of borehole gravimetry and the borehole gravimeter. Important aspects of field operations are described and the corrections necessary for data reduction are explained. The several methods of analysing the data to attempt to infer subsurface structure from borehole gravity and density log data are outlined. Finally, a number of applications of the method are listed.

53. Hearst, J.R, and McKague, H.L., 1976, Structure elucidation with borehole gravimetry: Geophysics, v. 41, no. 3, p. 491–505.

The observed densities, assuming infinite homogeneous-horizontal beds, computed from borehole gravimetry were as much as 15 percent greater than those derived from gamma-gamma density logs in the lower portion of several clustered boreholes at the U.S. Energy Research & Development Administration (USERDA) Nevada Test Site. A model having a single high- density buried scarp to the west of the holes was constructed, the gravimetric density calculated, and the model varied in an attempt to improve agreement between measurement and calculation. Only slight improvement was obtained. Newly acquired geologic information made it possible to construct a more complex multiscarp model, providing much better agreement between measurement and calculation. In turn, this more complete model was refined with the help of the calculations.

This method permits one to choose between qualitatively different models and, given a qualitatively correct model, to improve it quantitatively.

This report is also referenced in Case Histories.

54. Hearst, J.R, and Nelson, P.H., 1985, Well logging for physical properties: New York, McGraw-Hill Book Co., 571 p.

[This book's] aim is to teach basic understanding of the [well log] methods [and the] large number of pitfalls in obtaining data from the [well] logs. [Also discussed are] the physical principles behind the logging methods and the assumptions used in the conversion of the signals obtained from the logging equipment into values of the properties of the formation being logged.

Included in this book are two sections of borehole gravimetry. The first is a general introduction to the methods, and the second is an application of the method used in inferring geologic structure at the Nevada Test Site.

This report is also referenced in Case Histories.

55. Hearst, J.R, Carlson, R.E., and Clark, S.R., 1986a, Calculation of gravimetric density caused by three-dimensional structure [abs.]: The Log Analyst, v. 27, no. 1, p. 78–79.

For many years we have been comparing measured and calculated gravimetric density to density from a gamma-gamma density log to infer subsurface structure. We have used two-dimensional models, usually geologists' cross sections, to provide input for calculation of corrected gravimetric density for comparison with measured gamma-gamma density. Often the real structures could be better described in three dimensions.

The difficulty with calculating the gravitational effect of three-dimensional structure is not in the calculation itself, but in the description of the structure such that it fills all space and does not contain voids. We have solved this problem by using contour maps of subsurface boundaries between media of different density. The contour lines are digitized, and the digitized data are used to construct a function that is then evaluated over a fine grid surrounding the borehole. The algorithm used to construct the approximating function is a modification of Hardy's multiquadric method for interpolating scattered data. ***.

The gravity calculation uses an algorithm by Banerjee and Gupta for the calculation of the gravitational effect of a right rectangular prism. For each rectangle of the grid, the depth of the corners is averaged and used for the depth of one end of the prism. At each grid rectangle there are two prisms: one with the top at the top surface and the bottom at the contact surface, the other with the top at the contact surface and the bottom at the bottom surface. Two contact surfaces (describing three layers) can be used, in which case a third prism, with its ends on the two contact surfaces, is calculated. Gravimetric density is then calculated from the vertical gradient of gravity.

The method has been checked against structures [at the Nevada Test Site] for which analytical solutions are available and agrees within the error of digitization. When applied to real structures, the input is simple and the results plausible. Consequently, three-dimensional geologic models are now practical.

This report is also referenced in Case Histories.

56. ______1986b, Calculation of gravimetric density caused by three- dimensional structure: Society of Professional Well Log Analysts, 27th Annual Logging Symposium Transactions, v. 1, p. F1–F22.

Same abstract as report 55. This report also referenced in Case Histories.

57. Hearst, J.R, Kasameyer, P.W., and Owen, L.B., 1978, Potential uses for a high-temperature borehole gravimeter: Lawrence Livermore Laboratory, California, CRL-52421, 8 p.; available from National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161.

It is possible to design a canister to cool a borehole gravimeter for use in geothermal and high-temperature (up to 350 °C) gas wells. Repeat surveys with such a gravimeter could (1) help estimate the extent of reservoir plugging in geothermal injection well after one year of operation and (2) detect compaction of a geothermal aquifer if the change in thickness of the aquifer exceeds 1 m. The instrument could be used together with conventional logging tools to evaluate radial dependence of density around a well, or to estimate gas-filled porosity around wells drilled with mud. A high-temperature borehole gravimeter could also be used to evaluate structure and stratigraphy around geothermal and high-temperature gas wells.

58. Hearst, J.R, Schmoker, J.W., and Carlson, R.C., 1979, Effects of terrain on borehole gravity data [abs.]: Geophysics, v. 44, no. 3, p. 370–371.

The effect of terrain on gravity measurements in a borehole and on formation density derived from borehole gravity data is studied as a function of depth in the well, terrain elevation, terrain inclination, and radial distance to the terrain feature. ***.

59. ______1980, Effects of terrain on borehole gravity data: Geophysics, v. 45, no. 2, p. 234–243.

Same abstract as report 58.

60. 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.

A brief review of lateral and vertical response characteristics of various logging devices indicates that correction of logging responses for borehole and near-borehole effects is inadequate when rock heterogeneity and (or) filtrate invasion characteristics approach or exceed the bulk resolution of conventional logging devices.

The lateral response of borehole gravimeters is shown to be a function of the geometry of density contrasts along a lateral plate of infinite extent resulting in bulk volume porosity measurements compatible with deep investigating resistivity devices.

The development of special logging techniques and the evaluation of tool characteristics of the borehole gravimeter have resulted in successful applications of borehole gravimetry to reservoir analysis.

***.

61. ______1980, New well logging tools improve formation evaluation: World Oil, March, p. 89–103.

Downhole equipment that provides better information about reservoir rock and fluid characteristics is being developed by Amoco. Thus far, an improved density device [(BHGM)] has reached commercial acceptance. Other tools that show promise include a borehole televiewer, hard rock sidewall coring systems, and a new wireline formation tester.

62. ______1983, New techniques in well logging [abs.]: The Log Analyst, v. 24, no. 3, p. 27.

Well logging, one of the oldest measuring techniques in petroleum geology, is being enhanced by recently developed methods and equipment. The presentation will detail the new tools in well logging along with their applications and limitations. Of special interest will be the down-hole gravity meter.

This report is also referenced under Instrumentation.

63. Jones, B.R., 1972, The use of downhole gravity data in formation evaluation: The Log Analyst, v. 13, no. 6, p. 15–21. ***.

The high precision and large rock-volume measurement capabilities of the borehole gravity meter [are discussed. These capabilities] make it especially useful in measuring low porosities, as for example, that of a fractured quartzite in Libya; and fluid density behind casing, for example, gas in Texas.

64. Karl, J.H., 1983, The normal vertical gradient of gravity: Geophysics, v. 48, no. 7, p. 1011–1013.

This paper proposes a new value for the normal vertical gradient of gravity which is about 14 percent lower than the value which has been assumed for the past several decades.

See reports 72 and 112 for disagreements with this article.

65. Kazinskii, V.A., 1963, The means of development and methods of solving problems of underground gravimetry: Bulletin (Izvestiya) Academy of Sciences, U.S.S.R., Geophysics Series; translated and published by American Geophysical Union, Washington, D.C., no. 5, p. 463–472.

The article presents the results of the development of underground gravimetry, which was for a long time considered a little-studied area of geophysics.

66. Labo, J.A., 1987, Borehole gravimeter principles, *in* A practical introduction to borehole geophysics: Society of Exploration Geophysicists Geophysical References no. 2, chapter 9, p. 179–195.

This paper discusses: (1) gravity formation-density relationships and measurement, (2) EDCON borehole gravimeter tool, (3) depth of investigation, (4) measurement technique, (5) manual corrections, (6) formation evaluation, and (7) remote sensing.

67. LaFehr, Ed, and Nur, Amos, 1983, Application of the borehole gravity meter to thermal recovery: Society of Exploration Geophysicists, 53rd Annual Meeting, Las Vegas, Nevada, Expanded Abstracts with Biographies, September 11-15, p. 31–33.

Thermal techniques have become increasingly important in enhanced oil recovery and in extracting heavy crude from reservoirs. Of interest to the petroleum engineer and development geophysicist is a better understanding of the shape, rate, and direction of propagation of a thermal front as these parameters bear directly on production. Many logging and seismic methods have been used in studying thermal flooding and have met with varying success. For example, the extremely shallow depth of penetration of standard logging devices prohibits a study of thermal processes at great distances from the borehole.

This paper will evaluate the possibility for monitoring thermally produced low-density zones by the borehole gravity meter (BHGM). The BHGM is a nonstandard logging device with a theoretically infinite lateral depth of penetration. For this reason, detecting density contrasts away from the well bore can be accomplished by the BHGM. A thermal recovery process produces a low density body which is precisely the situation to employ the BHGM.

From BHGM measurements one can calculate an apparent density contrast produced by the actual density contrast at the leading edge of the low-density zone. It is this measurement-calculation of apparent density contrast that determines distance to the front. We analyzed a hypothetical tar-sand formation flooded by fire and steam, first examining the case for the BHGM and thermal process in the same hole. Secondly, we studied the BHGM response in a peripheral well to the thermal process.

68. ______1984, Application of the borehole gravity meter to thermal recovery [abs.]: Geophysics, v. 49, no. 5, p. 595.

Same abstract as report 67.

69. LaFehr, T.R., 1980, Gravity method: Geophysics, v. 45, no. 11, p. 1634–1639.

Developments in the field of gravity exploration have been significant from Galileo to the recent adaptation of inertial navigation systems. ***.

Gravity meters have been made to operate remotely on the water bottom, on the sea surface, in the air, and in boreholes. The final accuracies are generally limited by errors in positioning data rather than the precision of gravity instruments. The achievement of microgal precision (a few parts per billion) is one of the most remarkable engineering developments.

Interpretation has nearly kept pace with instrument development, but reports on methods and successes seriously lag (by at least 10 years) in the literature. The problem of ambiguity with respect to mass distributions has been clearly reported. This problem, however, is not adequately treated with respect to anomaly separation. Nonetheless, many excellent papers dealing with anomaly resolution are scattered throughout the literature, from ring operators to fast Fourier transforms. Much discussion also exists on forward and inverse calculations, but little attention has been given in the literature to practical interpretation, especially in the integration of gravity with seismic, magnetic, and borehole geophysical data.

70. ______1982, Apparent density from borehole gravity survey [abs.]: Geophysics, v. 47, no. 4, p. 447-448.

The formula widely used for determination of rock density between two gravity stations in a well bore yields apparent density, not bulk density or average density as so often stated. Apparent density equals bulk density only if the earth is composed of horizontal, infinitely wide, uniformly thick, constant density beds. Although departures from these assumptions are sometimes too insufficient to cause concern, borehole gravity meter (BHGM) surveys can be better planned and more effectively interpreted by a deeper understanding of the apparent density measurement.

When the borehole intersects an anomalous mass, the controlling mathematical relationship changes from LaPlace's to Poisson's equation. Because the horizontal derivatives are continuous across the density boundary and the vertical derivative is discontinuous, an abrupt change ("the Poisson jump") in apparent density which approximates the actual density contrast of the anomalous mass with respect to the host rocks is measured by the BHGM. Within the anomalous mass, the apparent density anomaly is some fraction of the actual density contrast and for some conditions is independent of the size of the anomalous mass and the station depth in the hole.

Significant distortions in BHGM densities can occur outside the zone containing anomalous masses, and appreciable departures from formation bulk density can occur within the zones of interest because of the influence of the vertical gravity gradient. A simple understanding of the phenomenon significantly improves the interpretability of BHGM data, but even more useful exploration results can be obtained by quantitatively integrating the BHGM data with other geophysical or geological data.

At least two gravity stations should be occupied just above as well as just within the geologic formation or zone of interest to enhance the determination of the Poisson jump. Much thinner beds can be studied with the BHGM than generally believed, perhaps as thin as 3 ft, even with much wider station spacing. In many cases, formation bulk density can be derived, not by computing the difference between the $\gamma\gamma$ log and BHGM densities, but by applying corrections based on the available data.

A geologic case history is presented from two wells surveyed in a salt dome in Denmark. These surveys, together with extensive other information, yield interesting and informative results about salt, salt dome behavior, and BHGM apparent density anomalies.

This report is also referenced in Case Histories.

71. ______1983, Rock density from borehole gravity surveys: Geophysics, v. 48, no. 3, p. 341-356.

The borehole gravity meter (BHGM) is recognized as an important logging tool for obtaining formation bulk density. In general, however, the difference between two gravity observations vertically separated in a well leads to an apparent and not the actual bulk density. BHGM-derived apparent densities are equal to the formation bulk densities when the instrument passes through beds which are horizontal, infinitely extended laterally, uniformly thick, and constant in density. For many applications, departures from these assumed conditions are so slight that their effects can be ignored, and the BHGM essentially yields bulk density with a large radius of investigation.

In the presence of anomalous masses, significant distortion in formation bulk density is possible. The apparent density anomaly produced in the well by an elongated, offset density contrast is proportional to the angle subtended by the density-change interface. For a density-change boundary having circular symmetry with respect to the well, the apparent density anomaly at the center of the bed is proportional to the sine of the subtended angle.

Because the distortion in bulk density is the same above a horizontal boundary as it is just below (in the limit, at the boundary, for a normally incident well), an abrupt change in apparent density is equal to the real density change at the boundary. This change in density, termed "the Poisson jump," is independent of geometry; our ability to measure it, however, is a function of station location with respect to the geologic bodies.

Two methods are suggested for obtaining bulk densities from BHGM apparent densities: (1) by obtaining two stations just outside as well as just within the zone of interest, the Poisson jump can be approximated and added to an independent density source (e.g., the gamma-gamma log), and (2) the apparent density anomaly within the formation of interest can be derived by modeling (perhaps based on seismic or well data) and added to the BHGM-determined densities.

Thinner beds can be studied with the BHGM than generally believed, even with much greater station spacing.

72. LaFehr, T.R., and Chan, K.C., 1986, On "The normal vertical gradient of gravity," by J.H. Karl (Geophysics, 48, 1011-1013, July, 1983): Geophysics, v. 51, no. 7, p. 1505-1508.

In this paper, the authors dispute the conclusions of J.H. Karl in his paper on the normal vertical gradient of gravity. In disputing Karl's discussion, LaFehr and Chan refer to the extensive data from borehole gravity surveys for support of their disagreement.

Report 64 is the paper disputed in this article. Also see report no. 112 for a disagreement to report 64.

73. Laurin, P.J., Black, A.J., LaFehr, T.R., and Bichara, M., 1981, Borehole gravimetry; an application example to engineering: Société pour L'Avancement de L'Interpretation des Diagraphies, 7th European Logging Symposium Transactions, no. 27, 10 p. (in French).

The aim of this paper is, after a review of some theoretical aspects of BHGM, to present an example in engineering where its use was found very useful.

The case concerned a well drilled in a salt dome [in the Texas gulf coast]. There were two objectives for this logging.

(1) determining the proximity of edge of salt from the well
(2) determination of the extension of high density formations (probably anhydrite blocks) within the salt which were encountered in drilling.

This well was planned to be used in leaching the salt in order to create a natural reservoir for petroleum.

Whereas, due to a low density contrast between the salt and sedimentary formation, the first point was inconclusive, it was possible to assert that there was no extension to the high density formations. This permitted the well to be planned for a leaching operation.

This report is also referenced in Case Histories.

74. Lindner, Harold, Hanemann, K.-D., and Schubert Heinz, 1981, Methodik zur Bestimmung der Streckenreduktion in der Untertagegravimetrie: Neue Bergbautechnik, seiten 257, bis 312, Heft 5, p. 271-276. [Method of determination of the space reduction in underground gravimetry.]

75. Lukavchenko, P.I., 1948, K voprosu ob izmereniyakh sily tyazhesti v burovykh skvazhinakh: Applied Geophysics, v. 4, Gostoptekhizd, p. 159-167. [The problem of gravity measurements in wells.]

76. ______1955, Gravity measurements in boreholes: Prikladnaya Geopizika, no. 12, p. 157-176; Translated August 1959, Liaison Office, Technical Information Center, MCLTD, Wright-Patterson Air Force Base, Ohio, MCL-20/V, 24 p.

In this paper, the fundamental theoretical questions of gravitational logging are discussed.

77. McCalpin, G.A., 1985, Operational and technical results from a multi-well borehole gravity survey [abs.]: Unconventional Methods in Exploration for Petroleum and Natural Gas, Symposium IV, Institute for the Study of Earth and Man, Dallas, Texas, May 1-2, p. 32.

[Unpublished manual for symposium participants.]

Restated in report 78. This report is also referenced in Case Histories.

78. ______1986, Operational and technical results of a multiwell borehole gravity survey, *in* Davidson, M.J., ed., Unconventional methods in exploration for petroleum and natural gas IV: Dallas, Texas, Institute for the Study of Earth and Man, Southern Methodist University Press, p. 313-320.

A twelve-well borehole gravity meter survey was conducted for Sun Exploration and Production Company in August, 1983, in South Texas in temporarily abandoned wells ***. The twelve wells were logged in a period of nineteen days, including moving days and off-days. Average "hole time" for the surveys was slightly over eight hours, with rig-up and rig-down time adding an additional two to three hours. The time between station readings averaged about ten minutes for the 429 stations and repeats in the surveys.

One hundred eighty zones were examined, ranging in depth from 890 ft. to 4,950 ft. A porosity, assuming 100% water saturation, was computed for each of these zones from the gravity-derived density and compared with the porosity determined from a compensated neutron log. On the basis of this comparison approximately 61% of the zones were interpreted as water sands, 28% as hard streaks, and 11% as prospective for either oil or gas.

This report is also referenced in Case Histories.

79. McCulloh, T.H., 1966a, Gravimetric effects of petroleum accumulations—A preliminary summary: U.S. Geological Survey Circular 530, 4 p.

Negative gravity anomalies of very local extent and with amplitudes of 1.2 milligals or less have been observed over some known petroleum and natural gas fields in southern California and South Dagestan, U.S.S.R. Field evidence, laboratory measurements, and theory indicate that these anomalies are mainly the result of hydrocarbon pore fluids of densities significantly lower than that of water. Gravity meters already available have the precision necessary to detect some of these anomalies from surface measurements. In addition, a high-precision borehole gravity meter has been developed, by the industrial firm of LaCoste and Romberg, Inc., that can be used ***. ***These observations and the new gravimeter should aid in the search for new petroleum fields and for new reservoirs in known fields that are incompletely explored.

80. ______1966b, The promise of precise borehole gravimetry in petroleum exploration and exploitation: U.S. Geological Survey Circular 531, 12 p.

The underground vertical gravity gradient is related to rock density in situ, gravimetric effects of nonlevel surfaces of equal rock density beneath and around the borehole (including topographic effects), and the free-air vertical gravity gradient.

Accurate determinations of average rock density in situ underground could be calculated from properly interpreted precise borehole gravimeter measurements. Such determinations would be relatively free from the effects of rock damage due to drilling or invasion by mud filtrate. The measurements could be made in cased wells, and they would be based on much larger volumes of rock than are sampled by any other method. Such measurements would be independent of core-analysis data and would therefore provide a standard against which to judge the core-analysis data as well as to evaluate conclusions drawn from gamma-gamma or other logs.

Conversely, independent knowledge of rock density at a borehole would permit separation of the gravitational effects of rocks beneath and around the surveyed borehole from other effects naturally integrated in the borehole gravimeter measurements and thereby offer unique opportunities for geological exploration.

*** Instrumental and operational characteristics of an experimental prototype borehole gravimeter are considered.

81. ______1967a, Borehole gravimetry—New developments and applications, *in* Origin of oil, geology and geophysics: London, Elsevier, 7th World Petroleum Congress, Mexico City, April 2-8, Proceedings, v. 2, p. 735–744.

Announcements in late 1965 and early 1966 of successful independent developments of two dissimilar borehole gravimeters having precisions close to 0.01 milligals began a new era of subsurface geophysical research. ***

Full use of such high precisions requires various corrections. ***.

Heavy dependence of underground vertical gravity gradients upon rock density encourages the use of borehole gravimetry for studies of density, porosity, and fluid character. However, the partial dependence of gravity and gradients on nonlevel isopycnic surfaces below the borehole forces caution on the interpreter while also providing a tool of value in geological exploration.

A borehole gravimetric density and porosity profile of a marine clastic Pleistocene-Pliocene section is in excellent agreement with laboratory measurements of conventional cores. Underground and surface gravity and geologic data for the residual gravity minimum of Santa Fe Springs oil field illustrate the potential exploration value of borehole gravimetry.

This report is also referenced in Case Histories.

82. ______1967b, Mass properties of sedimentary rocks and gravimetric effects of petroleum and natural-gas reservoirs: U.S. Geological Survey Professional Paper 528–A, 50 p.

Relatively negative gravity anomalies of very local extent and with amplitudes of 1.2 milligals or less have been observed over some known petroleum and natural-gas fields in southern California and in South Dagestan, Azerbaijan, U.S.S.R. These anomalies indicate that such productive hydrocarbon reservoirs are lower in density than surrounding strata. The hypothesis that the low densities result importantly from hydrocarbon pore fluids that have densities significantly lower than the density of water suggests that most petroleum and natural-gas reservoirs should produce negative gravimetric effects, although such effects may be small enough in many instances to be obscured or hidden by other anomalies. This hypothesis and its practical prospecting consequences and limitations are examined and analyzed in detail.

***.

Hypothetical gravimetric effects computed from density models based on selected well-drilled California oil fields of small to moderate size illustrate the kinds and magnitudes of effects expectable. ***.

The hypothetical gravimetric effects computed from the density models were utilized also for an examination of the subsurface gravimetric effects that would be obtainable through use of a borehole gravimeter ***. Underground (borehole) gravity measurements should be of particular value in exploration for deep and small hydrocarbon accumulations in extensively explored basins, where much is already known about the rocks and structures and their densities, by extending to depth the technique of detection of the relatively negative gravimetric effects of petroleum and natural-gas reservoirs. Bore-hole gravimeter measurements should also prove of great value in exploration for deeper pools and lateral extensions of known pools in partly developed oil fields, thereby lowering development risks and costs. Because of the prounounced gravimetric effects of variations in porosity and pore fluid composition, borehole gravity measurements could be utilized also with advantage in evaluating reservoir properties and monitoring reservoir performance in a developing and producing field.

This report is also referenced in Case Histories.

83. 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.

***.

Novel borehole gravity meters suitable for logging formation density consist of single high-sensitivity gravity sensors operated on conventional multiconductor well logging wireline. Discontinuous logs of gravity versus depth result. Average interval formation densities are calculated from vertical gradients of gravity by simple inverse proportionality. Gravity sensors now available are sufficiently precise to measure the differences in formation density caused by the presence in the pores of most crude oils rather than water. Intervals should be about 30 feet thick or more for such measurements. Complicating effects of surface topography or nonlevel underground surfaces of equal rock density can be evaluated. Borehole irregularities, or variable mudcake, filtrate invasion, casing, and cement produce practically negligible effects.

***.

A deep well in Santa Fe Springs oil field, California, was surveyed during tests of the U.S. Geological Survey-LaCoste and Romberg borehole gravimeter. Unsuccessful and successful recompletion attempts in a nearby well confirmed that the technique has the professed capability of detecting anomalously low density undepleted oil- and gas-bearing zones. Careful interpretation permits distinguishing between these, more dense water-saturated zones, and less dense depleted secondary gas caps. Net oil production of 14,000+ barrels in 10 months attests to the method's potential value.

Entry 83 is also referenced in Case Histories.

84. Miller, A.H., and Innes, M.J.S., 1953, Application of gravimeter observations to the determination of the mean density of the Earth and of rock densities in mines: Canada Dominion Observatory, Ottawa Pubs., v. 16, no. 4, p. 3-17.

Subterranean observations of gravity can be employed to determine the densities of rock layers beneath the surface. This paper demonstrates this application in connection with the results at Lake Shore Mine, Kirkland Lake, Ontario, and Horne Mine, Noranda, Quebec.

This report is also referenced in Case Histories.

85. Mudrecova, E.A., 1960, Underground gravity surveys in copper sulphide deposits in the Central Ural Mountains: Geofizicheskaia Razvedka, no. 2, p. 31-59 (in Russian).

This report also referenced in Case Histories.

86. Murty, B.V.S., and Chandra Reddy, P., 1983, The problem of hollow space correction in subsurface gravity surveys: Geophysics, v. 48, no. 10, p. 1406-1408.

When correcting for the effect of hollow spaces in subsurface gravity surveys, a three-dimensional assumption is advantageous because the entire hollow space can be fully accounted for and also knowledge of the density of the material removed can be properly utilized.

The approach suggested here is equally applicable for manual or computer estimation.

Very accurate reading of distances is essential or else the estimated hollow space effect can be erroneous.

87. Oelsner, Christian, 1960, Schweremessungen unter Tage: Zeitschrift für Angewandte Geologie, v. 4, p. 172-177. [Underground gravity measurements.]

Measurements were made at the Otto-Brosowski mine, Germany.

This report is also referenced in Case Histories.

88. Overton, A., 1975, Borehole gravimetry, *in* Dyck, A. V., ed., Borehole geophysics applied to metallic mineral prospecting—a review: Canadian Geological Survey Paper 75-31, p. 31-33.

This report is a brief description of the uses to which borehole gravimetry can be put and of available meters and their limitations.

89. Poynting, J. H., 1894, The mean density of the Earth: London, Charles Griffin and Co., 156 p., 9 diagrams.

This Essay, ***, gives an account of the various experiments, including one by the author, which have been made to determine the mean density of the earth.

The First Part consists of an introductory discussion of the problem and an account of the experiments hitherto made on the subject. ***.

The Second Part contains an account of my own experiments,***.

I have prefixed a bibliography of works and papers containing important or noteworthy contributions to the subject. ***.

A few of these works and papers contain accounts of subsurface gravity measurements.

90. Pritchett, W.C., 1982, Physical properties of shales and possible origin of high pressures: Society of Exploration Geophysicists, 52nd Annual Meeting, Dallas, Texas, Expanded Abstracts with Bibliographies, October 17-21, p. 504-505.

It is commonly thought that all high-pressure shales in the U.S. Gulf Coast have low density and have never undergone normal compaction. But these shales are easily altered and much of the density data for these shales may not be accurate. The scatter gamma ray density log has an extremely shallow depth of investigation and would not see through a zone of altered shale surrounding the borehole. The borehole gravimeter tools would be ideal for measuring the in-situ density of these shales, but we do not have such data. Neutron lifetime logs have a moderate depth of investigation. Studies of these logs in three wells indicate that the high-pressure shales encountered had undergone normal compaction and have normal densities or possibly higher than normal densities.

***.

It might be important to oil and gas exploration to determine to what extent each of the two theories for generating high pressures (dewatering or continuous undercompaction) accounts for the high-pressure shales in a given basin. The best and most reliable method for making such determinations is by bulk density measurements with the borehole gravimeter. Alternatively, or in addition, neutron lifetime logs should be run to measure total water content (pore water plus interlayer water). Data should be acquired for shales with both high and normal pressures and from shallow to great depths.

This report is also referenced in Case Histories.

91. ______1983, Physical properties of shales and possible origin of high pressures [abs.]: Geophysics, v. 48, no. 4, p. 483.

Similar abstract as in report 90. This report is also referenced in Case Histories.

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

The borehole gravity meter survey provides a unique advantage to the log analyst. This is the capability of determining accurate bulk densities for a large radius of investigation in cased or open boreholes. The accuracy requirements for formation evaluation are exacting, and established survey procedures must be strictly observed to obtain accurate results. A comparison of survey results using the LaCoste Romberg borehole gravity meter shows that 75% of the interval gravity measurements repeat to 10 microgals or better. These results are taken from a number of surveys conducted under ideal conditions. Prior to the survey, the feasibility of attaining the survey objectives and the economics of success can be reasonably assured. A number of corrections are needed and should be considered during the planning phase. If proper data are obtained, most corrections can be combined into a single vertical gradient correction.

93. ______1975, Borehole gravimeter finds bypassed oil, gas: Oil and Gas Journal, v. 73, no. 39, p. 100-104.

A new logging tool is being successfully applied in original completions and old wells to find production bypassed with conventional formation-evaluation equipment and techniques. ***. [Basic principles and interpretation techniques

are presented along with] successes [which range] from shallow gas plays in South Texas to the reef play in northern Michigan.

94. ______1977, Gravity logs promise new applications: Petroleum Engineer International, July, p. 21-24.

Borehole gravimetry promises two theoretical uses for enhanced recovery applications. One is determination of gas saturation and the other is determination of sweep efficiency.

95. ______1984, Borehole gravity used together with surface gravity, *in* Davidson, M.J., and Gottlieb, B.M., eds., Unconventional methods in exploration for petroleum and natural gas III: Dallas,Texas, Institute for the Study of Earth and Man, Southern Methodist University Press, p. 90-103.

Structural interpretation is one of the uses of borehole gravity surveys. The effectiveness of structural interpretation is enhanced by including high resolution gravity and airborne magnetic surveys. All types of data that can be used to improve the interpretation should be included. While the use of subsurface and seismic data is obvious, the use of surface gravity and airborne magnetic surveys is not.

Prior to conducting and interpreting the borehole gravity survey, geological and geophysical data are used to create a detailed computer model. This model is used to calculate the predicted structural effects curve for the borehole gravity survey. This curve can be used as part of a feasibility study to determine whether or not a borehole gravity survey can resolve the detail needed for interpretation.

Once the feasibility is demonstrated and the survey is conducted, the predicted structural effects curve is compared with the actual structural effects curve. Significant differences between the two indicate the existence of structural configurations not previously interpreted. The resulting changes in the interpretation are incorporated as changes in the computer model used. The theoretical effects calculated from the model must agree with both the surface and the borehole gravity data.

The theoretical applications include the interpretation of structures and reservoirs below the total depth of the borehole. Distances to basement, the presence of deep faults, and the presence of potential reservoirs are some of the significant factors that can be determined by this method.

96. Rische, Hans, 1957, Dichtebestimmungen im Gesteinsverband durch Gravimeter- und Drehwaagemessungen unter Tage: Freiberger Forschungshefte, C35, 84 p.

Density determinations in the rock assemblage through gravity-meter and torsion-balance measurements made underground.

Case histories are in central Germany.
This report is also referenced in Case Histories.

97. Robbins, S.L., 1980, Bibliography with abstracts of subsurface gravimetry (especially borehole) and corresponding in situ rock density determinations: U.S. Geological Survey Open-File Report 80-710, 47 p.

This Open-File is superseded by the present report.

98. ______1981, Reexamination of the values used as constants in calculating rock density from borehole gravity data: Geophysics, v. 46, no. 2, p. 208-210.

This report examines the accuracy and values of the constants F (free-air gradient) and k (Newtonian gravitational constant) used in the formula for determining in situ bulk density from borehole gravity data.

99. ______1986a, The use of borehole gravimetry in water well and waste disposal site evaluations [abs.], *in* Surface and borehole geophysical methods and ground water instrumentation—A conference and exposition: National Water Well Association Program, Denver, Colorado, October 15-17.

For the past 20 years the U.S. Geological Survey has been a pioneer in the development and application of borehole gravimetry. During this time, borehole gravity surveys for water well and waste disposal site evaluation have been conducted in more than 40 wells in Arizona, Colorado, Florida, Montana, Nevada, New Mexico, South Dakota, Washington and Wyoming.

Borehole gravity measurements are converted directly to the in situ bulk density value of the rocks that surround the borehole. The resulting densities are averages for rocks which extend a large distance from the borehole (the actual rock volume is dependent on the vertical spacing between stations within the borehole). In areas where there is no complicating subsurface structure and where lithologic beds are nearly horizontal, the measured densities are assumed to be true values. In structurally or stratigraphically complex areas, an "apparent" bulk density is determined. When this is compared with density values determined by other methods, elucidation of the subsurface structures is possible.

All the water-well studies and some of the waste-disposal evaluations were conducted in areas of near horizontal beds with no complicating structure. Many of the density values were used to calculate porosities for use in water yield and potential storage calculations. In the waste disposal evaluations where complex structure existed, the borehole gravity density data were used for structural analyses.

The advantages of borehole gravimetry in water well evaluations are: (1) the density values represent the formation for some distance from the borehole; whereas, a more conventional method such as a gamma-gamma density log only "sees" the first few inches, and (2) many water wells are in alluvial sediments that need to be cased quickly, and a more conventional log run in a cased hole is not meaningful; whereas, casing does not affect a borehole gravity measurement.

This report is also referenced in Case Histories.

100. ______1986b, The use of borehole gravimetry in water well and waste disposal site evaluations, *in* Proceedings of the surface and borehole geophysical methods and ground water instrumentation conference and exposition: Dublin, Ohio, National Water Well Association, p. 474-486.

Same abstract as report 99. This report is also referenced in Case Histories.

101. ______1989a, What is borehole gravimetry?—A summary: This report, chapter A.

This paper defines borehole gravimetry, examines the capabilities of the BHGM, relates already successful or nonsuccessful uses of the meter and suggests other areas of possible use for the BHGM.

102. ———1989b, Borehole gravity measurements, data reduction, and precision—A review and update of U.S. Geological Survey methods: This report, chapter B.

This paper discusses the equipment used in making a BHGM survey, field and office procedures developed and used in the reduction of the gravity data, and the precision that the U.S. Geological Survey obtained before 1983.

103. Schmoker, J.W., 1980, Terrain effects of cultural features upon shallow borehole gravity data: Geophysics, v. 45, no. 12, p. 1869–1871.

This report presents four figures that can be used to simplify making terrain corrections due to cultural features (like water tanks) when obtaining borehole gravity data at shallow depth.

104. Sissons, B.A., 1981, Densities determined from surface and subsurface gravity measurements: Geophysics, v. 46, no. 11, p. 1568–1571.

A least-squares method for the direct inversion of surface and subsurface gravity measurements to obtain in situ density estimates is presented. The method is applied to a set of measurements made in a tunnel through the flank of [Tihia] andesitic volcano [in central North Island, New Zealand]. Densities obtained are 2.14 g/cm^3 for material in the top 100 m increasing to 2.32 g/cm^3 at about 200 m depth. The average density for rocks penetrated by the tunnel is, from laboratory measurements, 2.42 g/cm^3, i.e., about 4 percent higher. The difference is ascribed to joints and voids present in situ and not sampled in the laboratory specimens.

A brief discussion on this report by G.D. Garland and a reply by B.A. Sissons are listed as report 36.

This report is also referenced in Case Histories.

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

The immediate urge for gravity meter surveys in boreholes is the desire to improve the gravity method itself but there are other potential uses for data so obtained. Borehole gravity surveys, through the influence of density, would be related to numerous important rock properties such as the velocity of seismic waves, the coefficient of reflection, the electrical resistivity, lithology, porosity, and the kinds and states of fluids in the rock. Therefore, in addition to improvement in gravity prospecting, the data would bear upon seismic techniques and, depending on accuracy and detail, upon the interpretation of lithologic and electric logs. The more obvious of the possible uses are indicated and some of the problems and inherent limitations holding up development are discussed.

106. Snyder, D.D., 1976, The borehole Bouguer gravity anomaly—Application to interpreting borehole gravity surveys: Society of Professional Well Log Analysts, 17th Annual Logging Symposium Transactions, p. AA1–AA20.

When employing the borehole gravity meter for remote sensing applications, it is useful to reduce the borehole gravity data to the Bouguer anomaly before interpretation. This paper deals with the calculation and subsequent quantitative interpretation of the borehole Bouguer anomaly. Numerical modeling of lateral density contrasts such as reefs and salt domes are shown to illustrate the effect that these mass distributions have on the bulk density calculated from borehole gravity measurements. The borehole Bouguer anomaly data for several borehole gravity surveys dramatically indicate the presence of inhomogeneities which do not intersect the borehole.

107. Snyder, D.D., and Merkel, R.H., 1977, Generalized correction for dipping beds for the borehole gravity meter: The Log Analyst, v. 18, no. 2, p. 41–43.

Formulas expressing the relationship between dipping beds of differing densities and borehole vertical gravity gradients are presented for both two-dimensional and three-dimensional problems.

108. Society of Exploration Geophysicists, 1986, Focusing on SEG continuing education; borehole gravity surveys: The Leading Edge of Exploration, v. 5, no. 4, p. 62–63.

This article contains a brief description of SEG's continuing education course ''Borehole gravity surveys.'' This course is usually offered one or more times a year and is taught (to 1988) by Larry A. Beyer.

109. Stacey, F.D., and Tuck, G.J., 1981, Geophysical evidence for non-Newtonian gravity: Nature, v. 292, no. 5820, p. 230–232.

Measurements of the variation of gravity with depth in mines and boreholes permit the densities of intervening rock strata to be inferred. In the few cases in which reliable absolute values of density have been independently determined, the calculations can be used to check the value of the Newtonian gravitational constant, G. Such large-scale measurements of G are important because the validity of the inverse square law of gravity at short range is being questioned. We have made such a series of measurements and have found four other data sets in the literature that suffice for the estimation of G. We also report here a statistical analysis of 1,100 km^2 of overlapping sea floor and sea surface gravity data from the Gulf of Mexico (made available by Exxon). All these estimates of G give values that are higher then the conventional, laboratory-determined one. While the possibilities of systematic errors in these data sets preclude a definite conclusion that Newton's law of gravity fails at short range, the strong circumstantial evidence suggests that well controlled large-scale experiments on the inverse square law are urgently required.

110. Stacey, F.D., Tuck, G.J., Holding, S.C., Maher, A.R., and Morris, D., 1981, Constraint on the planetary scale value of the Newtonian gravitational constant from the gravity profile within a mine: Physical Review D, v. 23, no. 8, p. 1683–1692.

Measurements of gravity down a 950-m vertical line within the mine at Mount Isa, Queensland, [Australia,] are used to estimate the value of the Newtonian gravitational constant G on a geophysical scale. The value obtained is $(6.71 \pm 0.13) \times 10^{-11}$ m^{3}kg^{-1}sec^{-2}. The assigned uncertainty is the possible (but not probable) systematic error arising from density inhomogeneity and indicated by local variations in gravity

gradient, and is several times as large as the formal error of a least-squares fit to the gravity-depth data. A dramatic improvement in accuracy can be anticipated if measurements can be made in a flat-lying sedimentary basin, or even better within the sea in a gravitationally featureless area.

111. Stewart, R. M., 1949, Gravity in the interior of the Earth: Royal Astronomical Society of Canada Journal, v. 43, no. 4, Whole 379, p. 129-137.

General formulae are developed which show the manner in which the existence of maxima and minima of gravity in the interior of the earth is dependent on the variation of density with distance from the earth's center.

Several special cases are discussed among which is the assumed approximation of a succession of layers, each of uniform density, separated by definite surfaces.

In an added note, an article by Benfield [report 5], listing values of density and gravity at various depths, is compared with the conclusions of this paper.

112. Swain, C.J., 1984, On "The normal vertical gradient of gravity," by J.H. Karl (Geophysics, 48, 1011-1013): Geophysics, v. 49, no. 9, p. 1563.

This paper disputes the conclusions of J.H. Karl in his paper on the normal vertical gradient of gravity. Report 64 is the paper disputed in this article.

Also see report 72 for a disagreement to report 64.

113. Thyssen-Bornemisza, Stephen, 1963, The vertical gravity gradient in borehole exploration: Geophysics, v. 28, no. 6, p. 1072-1073.

This short note discusses theoretically what information could be derived from a borehole gravity survey.

114. ______1963, Determination of Bouguer density in shallow holes: Geophysics, v. 29, no. 3, p. 445-446.

This short note suggests that a borehole gravity meter could be used in shallow holes for obtaining density data for surface gravity studies.

115. ______1965a, Determination of the vertical density gradient in a borehole: Geophysics, v. 30, no. 3, p. 439-440.

This short note presents formulas for the determination of the vertical density gradient for borehole gravity data.

116. ______1965b, The anomalous free-air vertical gradient in borehole exploration: Geophysics, v. 30, no. 3, p. 441-443.

The average vertical gradient of gravity generated by a buried vertical cylinder is noted.

117. ______1966, Possible application of the anomalous free-air vertical gradient to marine exploration: Geophysics, v. 31, no. 1, p. 260-263.

This short note presents the concept that a borehole gravity meter could be used in measuring anomalous free-air vertical gravity gradients above a marine well site.

118. Vaschilov, U.N., 1964, Ōochye vliyäniyä ryelyefa myestnosti pri gravimyetrichyeskikh nablûyeniyakh v podeyemnĕkh gornĕkh vĕrabotkakh i skvazhnakh: Razvedochnaya i Promyslovaya Geofizika, v. 51, p. 71-75 (in Russian). [Allowance for the effects of the relief of the locality in gravimeter observations in underground workings and boreholes.]

119. Zagonov, A.V., and Lukavchenko, P. I., 1974, Opryedyelyeniye izbĕtochnōe plotnosti vozmōōshchaūshchikh obyektov po dannĕm nazemnoë i skvazhinnoë gravirazvedki s pomoshchū lineĕnogo programmirovaniyä: Prikladnaia Geofizka, v. 75, p. 158-165 (in Russian). [The excess density estimation of disturbing bodies from surface and borehole gravimetry observations with the use of linear programming.]

Instrumentation, Data Accuracy, and Precision

120. Baker, G.E., 1977, Gravity instrument canister feasibility study: San Ramon, Calif., EG&G Report GEB77-57, 63 p.

A feasibility study was made for a canister to contain a gravity instrument used for well logging. The canister will protect the gravity instrument for a typical 30-hour logging cycle in an environment of 350 °C and 17,000 psi. The internal canister temperature will be maintained at a nominal 100 °C. The canister has a diameter of 5 in. and a length of 18 ft. The housing for the gravity instrument has a diameter of $5\frac{9}{16}$ in. and a length of 6 ft.

This report describes: (1) preliminary specifications for the canister, (2) methods of absorbing heat, and (3) a survey of suppliers for a super- insulated dewar. It also presents the preliminary calculations justifying a detailed study for the building and testing of the canister.

121. Beyer, L.A., 1968, Recent tests of the U.S. Geological Survey-La Coste and Romberg borehole gravimeter system [abs.]: Geophysics, v. 33, no. 6, p. 1030.

Repeatability tests using the La Coste and Romberg borehole gravimeter No. 1 and established depth measuring techniques suggest that interval gravity gradients in boreholes can be reproduced to about 0.00025 mgal/ft, depending on the magnitude of the vertical interval between measurements and the number of repeated gravity observations at each station. The conversion of interval gravity gradients in boreholes to absolute values of in situ rock densities may require careful reduction of the borehole gravity measurements in conjunction with surface gravity observations, subsurface geologic data, and well history information. These factors are considered in the analysis of borehole gravity measurements in the Lakeview area of the Midway-Sunset Oil field, California.

6. ______1971, The vertical gradient of gravity in vertical and near-vertical boreholes: U.S. Geological Survey Open-File Report 71-42, 229 p.

This report is referenced under Theory and Case Histories. The abstract is located under Theory.

122. Black, A.J., 1983, Performance characteristics of the LaCoste and Romberg borehole gravity meter [abs.]: Program, 36th Annual Midwest Meeting, Society of Exploration Geophysicists, Denver, Colorado, March 6-9, p. 50.

Recent application of Borehole Gravity surveys to determination of reservoir fluid saturations have emphasized a need for higher than usual gravity reading accuracies. To ensure these accuracies could be realized in the well environment a close study of the Borehole Gravity Meter's (BHGM) reading accuracy as a function of environmental and temporal changes was made. Temperature change emerged as the largest cause of reading disturbance. Implementation of electronic controls suggested by Dr. L. LaCoste and the development of a down-hole Dewar flash have both decreased temperature disturbances and allowed surveys at temperatures at 400 °F. A survey strategy involving multiple repeat station occupations minimizes drift error and provides improved statistical accuracies. An example data set shows that apparent density calculations accurate to ±.01 g/cc over 10 foot station intervals are routinely available with these improvements.

123. ______1986, Improved accuracy of a computer controlled borehole gravity system and applications to reservoir flood monitoring: Preprint, Center for Potential Field Studies Symposium, Colorado School of Mines, Golden, September 17, 9 p.

A new computer controlled system for LaCoste and Romberg Borehole Gravity meters has been used for field surveys since January 1986. The system uses an amplitude modulated electrostatic force feedback system in combination with the measuring screw. Repeatable, operator independent gravity readings with accuracies on the order of ±1 to 2 microgals are obtainable under field conditions. Under laboratory conditions, reading noise levels are less than 0.3 microgals. The system can be operated in environments with noise levels of about 1.5 milligals.

An application of this instrument is to monitor reservoir floods. A flood front approaching an observation well may be detected by observing differences between repeated gravity measurements in an observation well at appropriate intervals as a flood front approaches. After the flood has passed the well, density changes corresponding to changes in the reservoir fluid composition may be measured and estimate of fluid saturation changes may be made. The largest of these effects will be seen in steam and CO_2 floods.

This report is also referenced in Case Histories.

124. Black, A.J., and Herring, A.T., 1983, Borehole gravity; expanded operating limits and performance: Society of Exploration Geophysicists, 53rd Annual Meeting, Las Vegas, Nevada, Expanded Abstracts with Biographies, September 11-15, p. 21-23.

Borehole gravity meter (BHGM) surveys have been applied to numerous petroleum exploration and engineering projects in North America, Europe, and the Middle East. The highest percentage of surveys were for petroleum exploration within the United States, where the majority of applications used the BHGM's ability to provide a density log over a wide radius investigation.

High temperature boreholes and wells drilled from floating platforms were inaccessible to the BHGM until recently. (Thermoshield^{TM}, PDA Engineering) suggests that the design criteria of an operating temperature of 200 °C (400 °F) at 25,000 psi have been met. A downhole clamping device that couples to the BHGM sonde was tested and will enable routine logging from floating drilling platforms. Application of the BHGM to a wide radius of investigation density-porosity measurements requires higher accuracy than required by most structural modeling problems. To achieve such high accuracy, optimum survey planning, meter operation, and meter preparation are essential. Change in the gravity meter's thermal environment is now recognized as generally the most important source of BHGM error. Progress in controlling the BHGM's thermal environment resulted in improved accuracy. Further stabilization of the BHGM's thermal environment will result from the use of the Thermoshield.

125. ______1984, Borehole gravity: expanded operating limits and performance [abs.]: Geophysics, v. 49, no. 5, p. 594.

Same abstract as report 24.

126. Byerley, K.A., 1977, A field test for borehole gravity meter precision in shallow wells: Boulder, Colo., University of Colorado M.S. thesis, 78 p.

Three water wells located in Douglas County, Colorado, were logged using a LaCoste and Romberg gravity meter ***. The purpose of the survey was to study the field precision of the instrument in shallow wells. Data [were] collected and reduced using standard techniques.

A total bulk density error relationship was developed as well as a nomogram that graphically interprets some of the error levels involved. Lithologic interpretation of the relative density variation is attempted although it involves numerous uncertainties.

127. Caton, P.W., Clement, W.G., and Witterholt, E.J., 1983, Borehole gravity logging developments; a status report: Society of Exploration Geophysicists, 53rd Annual Meeting, Las Vegas, Nevada, Expanded Abstracts with Biographies, September 11-15, p. 23-26.

During the 1960s, LaCoste and Romberg developed the first successful borehole gravity meter (BHGM) in cooperation with the USGS (Beyer, 1968). ***. In the late 1970s, Edcon and Amoco added microprocessors in order to speed leveling of the LaCoste and Romberg meters, but since that time, there have been few hardware improvements or new approaches to speed data collection.

***. This paper reviews recent developments for improving BHGM survey performance by discussing a new special purpose logging truck designed for "slow" tool operations and a digital telemetry system which has the flexibility to add other tools to the BHGM sonde. Also discussed are new borehole gravity sensors, of standard and unconventional designs, that are anticipated to have increased latitude and temperature ranges, with improved accuracy, and those with fewer mechanical parts, which should improve instrument ruggedness.

The quality of a BHGM density survey depends on two factors: first is instrument performance, which determines gravity measurement precisions and accuracies, and the second is depth control. Thus, the ability to locate the tool accurately and to reoccupy instrument depth positions becomes an integral part of quality control during a survey. ***

128. ______1984, Borehole gravity logging developments; a status report [abs.]: Geophysics, v. 49, no. 5, p. 594.

Same abstract as report 127.

129. Clutsom, F.G., 1984a, U.S. Geological Survey borehole gravimeter no. 1 electronic system schematics: U.S. Geological Survey Open-File Report 84-337.

This report contains the schematics for the electronic circuitry used on BHGM no. 1.

130. ______1984b, U.S. Geological Survey borehole gravimeter electronic system borehole gravimeter no. 6 mechanical drawings: U.S. Geological Survey Open-File Report 84-338.

This report contains the schematics for the electronic circuitry used on BHGM no. 6 (a slimline meter). This system, much newer than the one in report 129, is also better.

131. Dolbear, D.W.N., 1959, Design considerations of a borehole gravimeter: Geophysical Prospecting, v. 7, no. 2, p. 196-201.

Due weight must be given to three factors (1) its purpose, (2) the limitations imposed by nature, industry and environment, (3) the effect of errors in auxiliary measurements. Together the last two factors give an estimate of the accuracy which can be achieved. If this is sufficient for the instrument to fulfil its purpose, design and construction can proceed. If it is not, a detailed survey of the last two factors is necessary in order to estimate the research effort that will be required when directed into the most effective channels. If the project is considered worth the effort it can proceed. These factors are discussed in relation to a borehole gravimeter. ***

30. Egyed, Lázlo, 1960, Zur Frage der Schweremessungen in Bohrlöchern: Freiburger Forschungshefte C81, Geophysik, p. 167-170.

This report is referenced under Theory, where the abstract is also located.

132. Gilbert, R.L.G., 1952, Gravity observations in a borehole: Nature, v. 170, no. 4523, p. 424-425.

This report describes a vibrating filament borehole gravity meter along with some preliminary tests.

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

The Shell Development borehole gravimeter is an instrument which utilizes as a measure of gravity the frequency of a chosen mode of vibration of a string supporting a freely suspended mass. The instrument, which is capable of determining differences in gravity between stations to one milligal or better, has been in semiroutine use by Shell for over two years. The most common application of such a meter, the determination of average densities for intervals of the order of one thousand feet, is illustrated by data from several wells.

Errata for article appears in Geophysics, v. 30, no. 2, p. 337.

134. Hammer, Sigmund, 1965, Density determinations by underground measurements—Sequel: Geophysics, v. 30, no. 6, p. 1133-1134.

This report confirms report 196 finding that the gravity meter used in Hammer's earlier report 39 had a calibration error of about 12 percent.

135. Heintz, K.O., and Alexander, M., 1979, Sulfur exploration with core hole and surface gravity [abs.]: Geophysics, v. 44, no. 3, p. 370.

In 1968 a major sulfur exploration play was touched off in the Texas Permian basin. Both the geologic setting and operational logistics were particularly favorable for gravity method use, and it was adopted as the optimum geophysical technique for West Texas sulfur exploration. The typical sulfur prospect was relatively shallow and areally compact, with light-density ore filling fractures and vugs in a dense carbonate or sulfate host rock. Since the ore body could be irregularly shaped, with sulfur concentrations varying widely within the zone of deposition, prospect analysis required high-resolution gravity data and good density control. The usual stages of prospecting included: definition of the surface gravity anomaly, preliminary core hole program planning, density measurement, gravity modeling, and finally, revision of the core hole program.

Exxon added downhole remote sensing capabilities through development of a miniaturized version of its EPR vibrating string borehole gravity meter. This new core hole meter operated successfully in 4-inch holes to a depth of almost 3000 ft. Comparisons between densities derived from meter measurements, gamma-gamma logs, and core samples indicate the meter provided the most consistently useful data.***. A plunge in sulfur prices abruptly ended the West Texas play before several indicated anomalies were fully evaluated.

This report is also referenced in Case Histories.

136. Howell, L.G., Heintz, K.O., and Barry, A., 1965, The development and use of a high-precision downhole gravity meter [abs.]: Geophysics, v. 30, no. 6, p. 1237.

The vibrating-string downhole gravity meter is described which has a precision of about 0.01 mgal in gravity measurement. With measurements of this precision, density of a 30-ft section in the subsurface can be determined with an accuracy of .02 gm/cm^3. These density measurements are useful in gravity interpretation, in computing acoustic impedance for use in seismology, and in estimating porosities of formations. Examples of density profiles measured in boreholes are given.

137. ______1966, The development and use of a high-precision downhole gravity meter: Geophysics, v. 31, no. 4, p. 764-772.

Same abstract as report 136.

62. Jageler, A.H., 1983, New techniques in well logging [abs.]: The Log Analyst, v. 24, no. 3, p. 27.

This report is referenced under Theory, where the abstract is also located.

138. LaFehr, T.R., Merkel, R.H., and Herring, A.T., 1979, Evaluation and applications of new LaCoste and Romberg borehole gravity meter [abs.]: Geophysics, v. 44, no. 3, p. 369-370.

The new ($4\frac{1}{8}$ inch) LaCoste and Romberg BHGM has been operational for about one year. Its limitations are minimum cased hole inside diameters of $4\frac{3}{4}$ inches, maximum hole deviations where readings are made of $14\frac{1}{2}$ degrees, and maximum pressure of 12,000 psi. BHGM no. 4 has a nominal drift rate of about 0.5 μgal per minute.

Laboratory measurement repeatability of 3 μgal is routinely achieved. Well bore repeatability depends upon differential sticking in the hole (with resultant errors in depth determination), seismic noise (both natural and man-made), fluid movement in the well, and wind noise in the surface rigging. Average interval difference repeats of 6 μgal have been achieved under optimal conditions. Average repeatability of

10–20 µgal is normally achievable under most operating conditions. Although adverse well environments can degrade repeatability to 20–60 µgal, poorer repeatability is very rare. Statistical methods can identify poor stations and improve accuracy.

The tools are now being used approximately as follows: (1) finding natural gas behind casing; about 20 percent; (2) remote sensing (salt overhang, missed reefs and edges of thrust sheets, etc.); about 20 percent; and (3) evaluation of carbonate reservoirs (finding oil and gas missed by other techniques); about 60 percent.

139. Lautzenhiser, T.V., 1983, Amoco/LaCoste and Romberg automated borehole gravity meter: Society of Exploration Geophysicists, 53rd Annual Meeting, Las Vegas, Nevada, Expanded Abstracts with Biographies, September 11–15, p. 20–21.

The LaCoste and Romberg borehole gravity meter (BHGM) with Amoco electronics proved to be a highly reliable and precise instrument. However, use of the BHGM required a high level of training for the operators as well as extended concentration for long periods from the operators. Even good operators become less effective as time passes in real field situations. Consequently, there was a need to automate the reading process of the BHGMs. In Block and Moore (1966), the use of linearized electrostatic forcing and feedback to control the beam position of a LaCoste and Romberg gravity meter is described. Their use of the system was for long period measurements for use in tide measurements and related work. Electrostatic feedback is utilized in the control and in the calculation of the resultant data for the automated borehole gravity meter.

140. ______1984, Amoco/LaCoste and Romberg automated borehole gravity meter [abs.]: Geophysics, v. 49, no. 5, p. 594.

Same abstract as report 139.

141. Lukavchenko, P.I., 1962, Nabliûdeniiâ s gravimetrami v burov'ykh skvazhina i shakhtakh: Razvedochnaiâ i Promyslovaiâ Geofizika, no. 43, p. 52–64 (in Russian).

Observations with gravity meters in wells and mine shafts.

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

A special modification of the LaCoste and Romberg astatized spring-type geodetic meter is the gravity sensor of the precise borehole gravimeter system. The sensor and certain support components are insulated and operate normally at a thermostatically controlled 101 °C. ***. Heavy damping of the gravimeter beam and the generally quiet conditions in the borehole permit the gravimeter to be leveled and read remotely, [at a stationary point in the hole,] in the unanchored sonde. When gravity and depth measurements are carefully made and reduced, the usual overall precision of gravity determinations is better than 0.016 mgal for all depths. A single gravity reading requires less than 10 and generally 3–5 minutes.

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

The U.S. Geological Survey and LaCoste and Romberg, Inc., have developed a borehole gravimeter system and components characterized by precision of (1) depth measurements in the range of 0.05 to 0.2 ft between the surface and 9,500-ft depth, and (2) downhole gravity measurements ranging from a high of 0.008 mgal to a low of 0.02 mgal. An average precision of 0.016-mgal is attainable at all depths and includes both precision of gravimeter readings and of depth measurements. Time tests suggest that, during normal routine operation, detailed (one station every 100 ft) and precise (±0.01 mgal) gravimeter surveys of wells less than 10,000 ft deep may be made at 300 to 500 ft per hour (including base checks for drift control) by a skilled three-man crew. In the laboratory, an increase or decrease in environment temperature of 60 °C on the gravity sensor produces a maximum change in apparent gravity reading of 0.1 mgal. ***.

144. Mobil Oil Corp., 1986, Continuous gravity gradient logging: U.S. Patent 4,602,508, August 29.

A continuous gravimetry survey is carried out with a gravity logging tool having a column of fluid * within the tool. First and second pressure sensors *,* are located at spaced-apart axial positions within an upper portion of the fluid column. Third and fourth pressure sensors *,* are located at spaced-apart axial positions within a lower portion of the fluid column. The outputs from the first and second pressure sensors are differenced to produce a first pressure difference signal. The outputs of the third and fourth pressure sensors are also differenced to produce a second pressure difference signal. The difference between these first and second pressure difference signals is related to the gravity gradient along the earth formation adjacent the fluid column. Such a gravity gradient is a continuously moving gradient that is insensitive to acceleration effects from unsteady motions of the logging tool as it traverses the earth formation during the gravimetry survey.

145. Nieto, M.N., Goldman, T., and Gutschick, V.P., 1983, An electronic gravimeter to measure g(r): Geophysics, v. 48, no. 1, p. 39–41.

We point out that a battery may be designed so that in a gravitational field it will have a gravitationally induced emf in addition to an electrochemical one. The gravitationally induced emf of a battery with a small "effective" electrochemical potential and a long "effective" length can readily be measured to very high precision by means of any precise voltmeter, and in particular by a Josephson junction. Such a device may be employed to measure any component of the gravitational acceleration vector. It can be constructed compactly enough to be placed down a borehole. Thus, in principle it is an extremely precise and adaptable tool for geophysical exploration.

146. Oil and Gas Journal, 1966, Esso licenses downhole gravity meter: Oil and Gas Journal, v. 64, no. 26, p. 101–102.

This report describes a vibrating-wire gravity meter which Esso Production Research Co. was testing.

147. Robbins, S.L., 1979, 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.

The U.S. Geological Survey has developed a logging truck designed specifically for the operation of borehole gravity meters. The truck is self-contained for most logging operations and can accommodate most conventional wireline tools. ***.

***.

148. ______1980, Display of features on the U.S. Geological Survey's logging truck built especially for borehole gravity surveys [abs.]: Geophysics, v. 45, no. 4, p. 552.

Same abstract as report 147.

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

Repeated subsurface gravity measurements, obtained with the U.S. Geological Survey–LaCoste and Romberg borehole gravity meter, were studied to determine the accuracy of the borehole gravity data, the dependence of accuracy upon elapsed time and vertical separation, and the precision of bulk densities calculated from borehole gravity measurements. The likelihood of poor interval gravity measurements increases sharply for vertical intervals greater than 150 ft, and increases approximately linearly with increasing time between readings. After a brief warmup period, data quality does not improve with the passage of time from the beginning of the survey. If the stations of a borehole gravity survey are separated by less than 70 ft, and the time between readings is less than 18 minutes, the gravity difference between two points in a borehole can be measured to ± 10 μgals. For intervals greater than 20 ft, this is equivalent to a density error of $\pm .02$ g/cm^3 or less.

Case Histories

1. Airy, G.B., 1856, Account of pendulum experiments undertaken in the Harton Colliery for the purpose of determining the mean density of the Earth: London, Royal Society Philosophical Transactions, v. 146, nos. 14, 15, p. 297–355.

This report is referenced under Theory, where the abstract is also located.

150. Algermissen, S.T., 1961, Underground and surface gravity survey, Leadwood, Missouri: Geophysics, v. 26, no. 2, p. 158–168.

A surface gravity survey consisting of 214 stations covering approximately four square miles was conducted over and adjacent to the North Leadwood Mines at Leadwood, Missouri. A corresponding survey of 278 stations was carried out in the mine workings. A method of reducing underground gravity observations is outlined. The principal factors limiting the accuracy of the underground observations are given. Methods for determining rock densities are described. A comparison of the surface and underground gravity maps shows that major Precambrian knobs were revealed by both surveys. Smaller structures not shown on the surface map were revealed by the underground survey. Anomalous density areas between the level of the two surveys were easily located.

6. 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.

This report is referenced under Theory and under Instrumentation. The abstract is located under Theory.

151. ______1977, Interpretation of borehole gravity in the southern San Joaquin Basin [abs.]: Geophysics, v. 42, no. 5, p. 1100.

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 (mass anomalies) of detectable magnitudes that may occur in the region surrounding the surveyed well.

***.

Variations in lateral density may be significant where 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 difficult because isopycnic (equal density) surfaces generally are not known and may be complex in shape. Separation of borehole gravity effect due to vertical and to lateral density variations is possible if independent and reliable information about vertical rock densities can be obtained from well logs, core analysis, or other sources.

In a well that penetrates the steeply dipping section at the Santiago area of the Midway–Sunset oil field, borehole gravity effects due to lateral density variations are calculated, with the aid of core analysis and known subsurface structure, to be as great as 25 percent of the gravity effects due to the vertical density variations. In other areas of the Midway–Sunset oil field and in the Kern River oil field where lateral density variations are believed to be small, density and porosity profiles calculated from borehole gravity surveys are compared to core analyses and conventional open-hole logs in order to maximize formation evaluation. Borehole gravity measurements made at equivalent subsurface elevations in a series of wells across the Thirty-Five Anticline in the Midway–Sunset oil field illustrates the change in form of a gravity anomaly with increasing depth.

152. ______1979, Borehole gravity study of the density and porosity of selected Frontier, Tensleep, and Madison reservoirs in the Bighorn Basin, Wyoming [abs.]: American Association of Petroleum Geologists Bulletin, v. 63, no. 5, p. 822.

Borehole gravity surveys in the Gebo, Garland, and Big Polecat oil fields of Wyoming uniquely assess the density and porosity of the reservoir and associated rocks. ***.

Interval density and porosity profiles determined from the Bighorn basin surveys were compared with gamma-gamma density logs, neutron porosity logs, and density and porosity measurements of core samples. Discrepancies between the density and porosity methods arise because borehole gravity, owing to its large radius of investigation, measures an average porosity that includes the irregularly distributed component (e.g., vugular porosity of reservoir rocks in the Madison Limestone at Garland) which is less effectively evaluated by conventional shallow-penetration logs or core samples. Other discrepancies are usually due to the inherent limitations of one or several of the methods and are mostly dependent on the composition and coherence of the rocks.

Variations in the contribution of fracture porosity to total porosity in the Tensleep Sandstone reservoir at Gebo are masked by much larger fluctuations in intergranular porosity caused by differences in the cementation and abundance of dolomite. Whatever the cause, the magnitude of fracture porosity is probably below the threshold of detection with borehole gravity. High-porosity (>15 percent) and (or) gas-filled sandstone units, principally in the Frontier Formation, were easily detected behind casing in the three oil fields. An abrupt and possibly widespread downward increase in porosity in the upper part of the Frontier Formation may (1) reflect lithologic and mineralogic variations owing to changes in the depositional environment, (2) be related to a previously proposed unconformity, and (3) have exploration significance.

153. ______1980, Benefits of borehole gravity studies in the San Joaquin Basin, and suggested future work [abs.]: Geophysics, v. 45, no. 8, p. 1330.

Seventeen borehole gravity surveys and related studies made by the Geological Survey in five oil fields in the southern San Joaquin basin have yielded the following results. Confirmation of high precision borehole gravity measurements and detection of dry gas and oil sands behind casing were first demonstrated in 1968. Borehole gravity measurements were analyzed in structurally complex sections, where anomalous vertical gravity gradients are significant, in three separate studies in the Twenty-five Anticline and Santiago areas of the Midway-Sunset oil field and the Lost Hills oil field between 1969 and 1975. Comparisons of density and porosity profiles, calculated from borehole gravity surveys, with conventional core analyses and open-hole logs in shallow, poorly consolidated rocks were completed in 1976. Results not previously shown of a borehole gravity survey in a northeast flank well at Elk Hills reveal shallow gas sands and generally low porosity in the uppermost Miocene section at this location.

Future uses of borehole gravity in the San Joaquin Basin may profitably focus on (1) confirmation of subtle porosity changes associated with diagenesis and facies changes, (2) evaluation and calibration of conventional open-hole porosity logs in cases where they are insufficiently precise or unreliable, (3) monitoring of fluid conditions in high porosity reservoirs, and (4) in special cases, detection of laterally adjacent reservoirs missed by the drill. ***.

154. ______1983a, Density and porosity changes with depth, Sisquoc and Monterey Formations, Santa Maria-Point Conception region, California [abs.]: Program, 58th Annual Pacific Section Meeting, American Association of Petroleum Geologists–Society of Economic Paleontologists and Mineralogists–Society of Exploration Geophysicists, Sacramento, California, May 18–21.

Borehole gravity, well log, and core data from selected locations of the onshore Santa Maria Basin and adjacent offshore area show that bulk density of Tertiary siliceous rocks increases sharply with increasing depth. Borehole gravity surveys indicate that saturated bulk density increases in the Sisquoc and Monterey Formations from about 1.8 to 2.4 g/cm^3 *** at Casmalia, from about 1.65 to 2.4 g/cm^3 *** at Orcutt, and from about 2.2 to 2.55 g/cm^3 *** at West Cat Canyon. ***. [At] offshore Point Conception ***, log interpretations suggest that bulk density increases from about 1.95 to 2.5 g/cm^3 ***. The rates of increase of bulk density with depth are atypically high, exceeding all rates observed in studies of comparably aged California marine sandstones and clay shales.

Large-scale, sharp increases of bulk density and concomitant decreases of porosity of siliceous rocks in the Santa Maria region are caused primarily by burial diagenesis (as reported in papers by Isaacs, Pisciotto, and others) aided by higher than average subsurface temperature gradients. Transitions between silica phases, ***, are evident in the interval density profiles from the borehole gravity surveys at Casmalia, Orcutt, and West Cat Canyon. More locally, interval density fluctuations within the Monterey are related partly to various recognized zones or facies and, on a smaller scale, partly to variations of the abundance of such rock constituents as silica, calcite, dolomite clay, or organic matter.

Interval density profiles from the borehole gravity surveys are converted to porosity profiles by assignment of grain densities based on silica phase or phases present and estimated abundances of rock constituents. Generalized density and porosity variations of the Sisquoc and Monterey Formations are presented for the range of depths investigated.

155. ______1983b, Estimation of reservoir porosities from borehole gravity surveys, Long Beach Unit, Wilmington Oil Field, California [abs.]: Program, 58th Annual Pacific Section Meeting, American Association of Petroleum Geologists–Society of Economic Paleontologists and Mineralogists–Society of Exploration Geophysicists, Sacramento, California, May 18–21.

Borehole gravity measurements made from the uppermost Tar zone through the lowermost 237 zone of the Long Beach unit are interpreted as vertical profiles of interval (total) porosity. Calculated porosities range from as much as 35 percent in upper zones to about 20 percent in deep zones and have uncertainties, due to gravity measurement errors, that range from less than 1 to about 2 porosity percent. Additional uncertainties in porosity depend on the reliability of independent estimates of grain and pore-fluid densities and may be as large as 1 to 2 porosity percent. Where reservoirs consist of thinly interbedded sand, silt, and clay, porosity analysis of sands is improved by knowledge of the relative compaction behavior of these sediments which can be inferred from the borehole gravity measurements. Discrepancies between porosities determined from core measurements, gamma-gamma density logs, and borehole gravity measurements are largest for shallow producing zones that consist of unconsolidated to poorly consolidated sands. Apparently open-hole density and porosity logs are strongly affected by drilling-induced formation damage in these shallow zones and samples recovered by coring are so physically altered that laboratory measurements, indicative of reservoir porosity, are difficult or impossible to make. Porosity estimates from borehole gravity measurements are also preferable in the deep fractured shale (237) zone because these measurements examine volumes of reservoir rocks that are about four to seven orders of magnitude greater than volumes examined by conventional well logs or coring processes.

156. ______1987, Porosity of unconsolidated sand, diatomite and fractured shale reservoirs, South Belridge and West Cat Canyon oil fields, California, *in* Meyer, R.F., ed., Exploration for heavy crude oil and natural bitumen: American Association of Petroleum Geologists Studies in Geology, no. 25, p. 395–413.

157. Beyer, L.A., and Clutsom, F.G., 1978a, Borehole gravity survey in the Dry Piney Oil and Gas Field, Big Piney-LaBarge area, Sublette County, Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart OC–84, 2 sheets, 12 p.

This report analyzes rock density and porosity changes through 3,000 ft of Paleozoic rocks and 2,000 ft of underlying Cretaceous rocks, separated by the Hogback thrust in western Wyoming in terms of lithology, age, and possible structural effects.

Comparisons with open-hole logs are made, and a comprehensive explanation for the reduction and precision of the borehole gravity measurements is given.

158. ______1978b, 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 sheets, 16 p.

This report interprets rock density and porosity changes through 5,083 ft of Pennsylvanian to Upper Cretaceous rocks in the Big Horn Basin in terms of lithology, age, depth of burial, facies changes and probable pore-fluid content.

Comparisons with open-hole logs are made, and a comprehensive explanation for the reduction and precision of the borehole gravity measurements is given.

159. ______1980, Density and porosity of Upper Cretaceous through Permian formations from borehole gravity measurements, Big Polecat oil and gas field, Park County, Wyoming: U.S. Geological Survey Oil and Gas Investigations Chart OC-103, 3 sheets.

This report analyzes rock density and porosity changes through 5,359 ft of Permian to Upper Cretaceous rocks in the northern Big Horn Basin in terms of lithology, age, depth of burial, facies changes, presence of coal, and probable pore-fluid content. Comparisons with open-hole logs are made and a comprehensive explanation for the reduction and precision of the borehole gravity measurements is given.

160. Bhattacharji, J.C., 1963, Investigation of the vertical gradients of gravity measured inside the Earth, *in* Geophysical exploration, a symposium, Baroda, India, 1959: Proceedings Council of Scientific and Industrial Research, New Delhi, India, p. 39–46.

Vertical gradients of gravity have been reduced from observations carried out with the Frost gravimeter at various depths inside the Nundydroog mine in the Kolar Gold Field in Mysore, in 1948. These results have been found to be in general agreement with those derived on theoretical consideration.

Densities of finite intervals of underground rock strata have been determined from the measured vertical gradients. Though the results have shown slight discordance with the measured densities, yet these are likely to be more representative and as such may prove more adequate for the purpose of gravity prospecting than what are ordinarily obtained from measurements of rock samples.

123. Black, A.J., 1986, Improved accuracy of a computer controlled borehole gravity system and applications to reservoir flood monitoring: Preprint, Center for Potential Field Studies Symposium, Colorado School of Mines, Golden, September 17, 9 p.

This report is referenced under Instrumentation, where the abstract is also located.

19. Bradley, J.W., 1974, The commercial application and interpretation of the borehole gravimeter, *in* Contemporary geophysical interpretation, a symposium: Geophysical Society of Houston, December 4–5, 14 p., 11 figs.

This report is referenced under Theory, where the abstract is also located.

161. ______1975, The application of the borehole gravimeter to the evaluation and exploration of oil and gas reservoirs: Preprint, Society of Exploration Geophysicists, 45th Annual Meeting, Denver, Colorado, 8 p., 7 fig.

In recent years, Amoco Production Co. has evaluated approximately 80 wells with the LaCoste–Romberg borehole gravimeter. A large number of these surveys have been in the search for and evaluation of commercial hydrocarbon reservoirs. Additional surveys have provided background density information for geophysical and geological evaluations, including surface gravity interpretation and seismic modeling.

There are two primary applications in which the BHGM has been run routinely with economic success. The first takes advantage of the BHGM's capability to operate in the presence of casing, distinguishing between shallow dry gas and fresh water sands in the Gulf Coast. The second application involves reservoir definition in lime reef environments. Fracture porosity, as well as porosity in proximity to the well bore, has successfully been isolated where normal logging procedures have failed. This application has been especially successful economically.

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162. ______1976a, The application of the borehole gravimeter to the evaluation and exploration of oil and gas reservoirs [abs.]: Geophysics, v. 41, no. 2, p. 344.

Same abstract as report 161.

20. ______1976b, The commercial application and interpretation of the borehole gravimeter, *in* Jantzgen, R.E., ed., Tomorrow's oil from today's provinces: American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 24, p. 98–109.

This report is referenced under Theory. The abstract is also located under Theory, in entry 19.

24. Casten, Uwe, 1984, Subsurface gravity measurements to demonstrate mining-induced changes in rock density: Geofizikai Közlemenyer, Geophysical Transactions of the Eötvös Lorand Geophysical Institute, Budapest, Hungary, v. 30, no. 3, p. 227–236.

This report is referenced under Theory, where the abstract is also located.

163. Clark, S.R., and Hearst, J.R, 1983a, Determination of subsurface geological structure with borehole gravimetry [abs.]: Abstracts, 2nd Symposium on Containment of Underground Nuclear Explosions, Albuquerque, New Mexico, August 2–4, p. 15.

Conventional gamma-gamma and gravimetric density measurements are routinely gathered for most holes used for underground nuclear tests. The logs serve to determine the subsurface structural geology near the borehole. The gamma-gamma density log measures density of the rock within about 15 cm of the borehole wall. The difference in gravity measured at two depths in a borehole can be interpreted in terms of the density of an infinite, homogeneous, horizontal bed between those depths. When the gravimetric density matches the gamma-gamma density over a given interval it is assumed that the bed actually exists, and that rocks far from the hole must be the same as those encountered adjacent to the borehole. Conversely, when the gravimetric density differs from the gamma-gamma density, it is apparent that the gravimeter is being influenced by a rock mass of different density than that at the hole wall. This mismatch can be a powerful tool to deduce the local structural geology. The geology deduced from gravity measurements in emplacement hole, U4al, and the associated exploratory hole UE4al, is an excellent example of the power of the method.

164. ______1983b, Determination of subsurface geological structure with borehole gravimetry: Proceedings of the 2nd Symposium on Containment of Underground Nuclear Explosions, Albuquerque, New Mexico, August 2–4, v. 1, p. 205–211.

Same abstract as report 163.

165. ______1983c, Determination of subsurface geologic structure with borehole gravimetry; case history: Society of Exploration Geophysicists, 53rd Annual Meeting, Las Vegas, Nevada, Expanded Abstracts with Biographies, September 11–15, p. 35–37.

Same abstract as report 163.

166. ______1984, Determination of subsurface geologic structure with borehole gravimetry; case history [abs.]: Geophysics, v. 49, no. 5, p. 596.

Same abstract as report 163.

167. Cook, A.H., and Thirlaway, H.I.S., 1951, A gravimeter survey in the Bristol and Somerset Coalfields: Geological Society of London Quarterly Journal, v. 107, pt. 3, p. 255–286.

Gravity measurements in the Bristol and Somerset coalfields are described and discussed. Accounts are given of the methods of measuring gravity, of calculating the gravity anomalies and estimating the densities of rocks. It is shown that the variations of gravity correspond in a general way to the geological structure of the coalfields but that discrepancies in detail indicate that the anomalies are partly due to structures lying below the coalfields which may have controlled the development of sedimentation and deformation in the region. Detailed studies were made in the neighborhoods of Bitton, Chew Stoke, Ston Easton and Avonmouth with a view to assisting the planning of a boring programme for the development of the coalfields in these areas.

27. Domzalski, W., 1954, Gravity measurements in a vertical shaft: Bulletin of the Institute of Mining and Metallurgy Transaction 571, v. 63, p. 429–445.

This report is referenced under Theory, where the abstract is also located.

168. ______1955a, Three dimensional gravity survey: Geophysical Prospecting, v. 3, no. 1, p. 15–55.

The paper describes and discusses the results of an experimental gravity survey which was carried out underground on different levels of a mine, in the mine shafts, and on the surface above the mine workings [in Cumberland, England].

***. *** gravity measurements in the shaft give attention to the particular problem of the terrain corrections underground ***. The interval densities from gravity measurements in the shafts are computed and adjusted in accordance with known geology and compared with the stratigraphical columns of the shafts. The effect of the ore body on the stations in the shaft is derived theoretically and compared with the observed one.

The gravity contours are constructed on different levels in the mine workings [and on the surface] and are discussed in relation to the known extent of the ore body [and known geology including faulting]. ***.

The densities computed from the gravity measurements are compared with the laboratory determinations of the densities, carried out on samples from different parts of the mine.

The contours on the top of the base formation are constructed from the information obtained from the boreholes, and are compared with the gravity contours on the surface above.

A simple method of computation of the effects of slabs and blocks is presented as applied to the calculation of the corrections for underground drifts and faults. ***.

28. ______1955b, Relative determination of the density of surface rocks and the mean density of the Earth from vertical gravity measurements: Geophysical Prospecting, v. 3, no. 3, p. 212–227.

This report is referenced under Theory, where the abstract is also located.

169. Drake, R.E., 1967, A surface-subsurface measurement of an anomaly in the vertical gradient of gravity near Loveland Pass, Colorado: University of California at Riverside M.S. thesis, 41 p.

The validity of using the theoretical normal value of the vertical gradient of gravity in the free-air correction of gravity data is questionable due to the magnitude of local variations in this value.

Surface-subsurface measurements of the actual vertical gradient along an 8,300–foot tunnel line at an approximate elevation of 12,000 feet near Loveland Pass, Colorado, were made using a gravimetrically determined density of 2.76 gm/cm^3 for the intervening mass of rock. The results show an anomaly in the normal vertical gradient of gravity ranging from +0.4 to +3.7 percent.

It is concluded that the magnitude of observed anomalies in the vertical gradient in the area are too great to be ignored. This is particularly true at high elevations, and errors introduced by these anomalies in the vertical gradient may be minimized by reducing gravity data to a local datum rather than sea-level, and by making individual vertical gradient measurements at each gravity station.

170. Facsinay, László, and Haaz, R.H., 1953, Közetsürüségmeghatározós a fetszin alatt kulonbozo mélységekben végzett graviméter-mérések alapján: Magyan Állami Eötvös Loránd Geofizikai Intézet, Geofizikai Közlemények, v. 2, no. 4, p. 41–49 (in Hungarian).

Density determinations of rocks, based on subsurface gravimeter measurements at different depths.

Gravimeter measurements were made by the authors on different levels of a mine in Hungary. The density variations resulting from these measurements, are in good agreement with the geological log. The computed values for the densities are higher than the densities determined in laboratory. It is suggested that calculations of gravitational effects should be based on density values resulting from gravimeter measurements made in mine-shafts or in boreholes. For this purpose a gravimeter with 0.1 mgal precision is sufficient.

171. Fajklewicz, Zbigniew, 1956, O podzienmych Pomiarach grawimetrycznych w zastosowaniu do górnictwa weglowego. Wyniki prac w kopalni Miechowice: Archiwum Górnichwa, tom I, zeszyt 4, p. 345-355 (in Polish with English abstract). [Underground gravity measurements applied to coal mining results at the Miechowice Mine.]

Underground gravity measurements were carried out at the Miechowice mine in order to determine the actual density of the rocks. ***.

The influence of shafts and excavations was taken into account in the treatment of experimental data ***.

The mean density obtained *** is 2.589 g/cm^3. This value is greater by 4.00% than the value used, $\rho = 2.50$ g/cm^3. As the error is 0.111 mgl, the densities are determined with the following error:

1. The complex strata from surface to 370 m level $d\rho = 0.4\%$
   The complex strata from 370 m level to 520 m level $d\rho = 0.9\%$
   The complex strata from 520 m level to 620 m level $d\rho = 1.34\%$
   The complex strata from 620 m to 720 m level $d\rho = 1.32\%$

Laboratory measurements provide an error of the order of 10-15%. The actual density ρ being known and the velocities the seismic waves V_p and V_s, the Young modulus, the Poisson constant, the Lamé constants and derived values may be determined. The gravity measurements of the densities enable maps of isodenses to be drawn and these may serve for the analysis of the gravimetric image of Silesia in order to investigate the tectonics. The gravimetric method may help to discover faults and hollow spaces in mines.

172. ______1957, Podziemne pomiary grawimetryczne w kopalniach Górnego Ślaska: Geodezja i Kartografia, tom 6, zeszyt 3, p. 161-173. [Subsurface gravimetry measurements in the mines of the Upper Silesia.]

173. ______1957, Underground gravity measurements in the mines of Upper Silesia: Académie Polonaise des Sciences, Comité de Géodésie, Vasovie, Toronto, Canada, September 3-14, 16 p.

174. ______1963, Detection of fault in the BD Coal Mine by means of microgravity measurements: Bulletin de l'Académie Polonaise des Sciences, Série des Sciences Géologiques et Géographiques, v. 11, no. 4, p. 197-200.

This report describes the use of a gravimeter along mine workings at 5 m intervals in a coal mine in Upper Silesia, Austria. The purpose of the study was to detect from gravity anomalies, faults that cross the carboniferous layer. Maximum detectable change in the gravity anomalies caused by the faults was about 0.20 mgal. The study was able to detect and follow some of the faults.

175. ______1972, Pustki poeksploatacyjne i odkształcenia objetościowe górotworu w świetle pomiarów gradientu pionowego sily ciezkości i jej mikroanomalii: Przeglad Górniczy, v. 10, p. 425-431 (in Polish). [Post-exploitation cavities and volumetric deformation of the rock mass in the light of measurement of the gravity vertical gradient and gravity anomalies.]

176. ______1975, Pionowe przekroje pola sily ciezkośu i ich zwiazek z odksytalceniami górotworu: Kraków, Akademia Górniczo-Hutniczej, Zeszyty Naukowe, Górnictwo z. 76, nr. 522, p. 185-195 (in Polish with English summary). [Vertical sections of gravity field and their relation with orogen strains.]

In the work there are presented results of periodical microgravimetric investigations carried on in two sections located under coal stratum deposited on depths 120-160 meters. These sections each 1,100 meters long were situated perpendicularly to extent of the wall, mining of which was planned for the nearest future. Measuring points in each of them were situated in intervals of 10 to 20 meters. On so prepared traverse before mining starting there were made measurements of gravity microanomalies and were determined with great accuracy heights of each measuring point. These measurements set was repeated after 3, 9, 19 and 25 months from the moment of mining end. As time passed there was observed decrease of measured values of gravity microanomalies corresponding with terrain surface lowering. Values of changes of measured values of gravity microanomalies in comparison with vertical movements of terrain surface show quicker manifestation, in measured values of gravity microanomalies, after-mining changes in orogen mass distribution in relation to formation time of settlement basin.

To determine sources of changes of gravity microanomalies field in time, there was made analytical prolongation of measured distribution of gravity force microanomalies to depth exceeding the mining depth. Analytical prolongations were also made for intermediary levels, what enables drawing of vertical sections of gravity anomalies field. These sections allow to determine singular points of gravity potential and its derivatives and to determine their shifts as time passes. We ought to add, that the mentioned singular points are treated as sources generating the measured fields of gravity microanomalies.

The investigations results show origining of local disturbances of gravity anomalies field occurring on different depths, specially in place of old mining headings, lying over the mined stratum, or along fault planes. The above investigations show places of occurrence of the strongest volumetric strains of orogen and may be useful in investigation of orogen strain mechanism in its mining effect.

177. ______1982, Neue Perspektiven der Mikrogravimetrie—Teil der Gebirgsschlagprognose: Neue Bergbautechnik, seiten 121, bis 176, heft 3, p. 140-143. [New perspectives in microgravimetry—part of the rock burst problem.]

178. ______1983, Rock-burst forecasting and genetic research in coal mines by microgravity method: Geophysical Prospecting, v. 31, no. 5, p. 748-765.

Microgravity can be used for predicting rock bursts. For the first time gravity anomalies related to rock bursts have

been recorded. The methodology developed has led to the first successful predictions. The depth of the rock-burst focus might be determined on the basis of analytical downward continuation of related gravity anomalies: the focus is treated as a singular point of the gravity potential and its derivatives.

The rock-burst gravity anomalies might be explained on the basis of the assumed dilatancy process that causes the rock burst. The mean density change of the rock mass threatened with rock bursts can be estimated from the corresponding rock-burst gravity anomalies.

34. Fajklewicz, Zbigniew, and Duda, Wladyslaw, 1964, Próba zastosowania pomiarów mikrograwimetrycznych dla potrzeb górnictwa weglowego: Technika Poszukiwan, rok 3, zeszyt 9, p. 1-7. [Test of the application of microgravimetric measurements for coal mining requirements.]

This report is referenced under Theory, where the abstract is also located.

179. Fajklewicz, Zbigniew, Duda, Wladyslaw, and Rejman, T., 1966, Geophysical measurements of density in closely neighboring mine shafts: Bulletin de l'Académie Polonaise des Sciences, Séries des Sciences Géologiques et Géographiques, v. 14, no. 1, p. 7-11.

This report presents and discusses density calculations from gravity measurements in three mine shafts in the Upper Silesian Coal Mines.

35. Fajklewicz, Zbigniew, Gliński, A.L.R., and Sliz, Janusz, 1982, Some applications of the underground tower gravity vertical gradient: Geophysics, v. 47, no. 12, p. 1688-1692.

This report is referenced under Theory, where the abstract is also located.

180. Farlay, D.G., 1971, Application of the downhole gravity meter for porosity determination: Preprint, Libyan Association of Petroleum Technologist 7th Annual Meeting, p. 1-20.

A high precision downhole gravity meter developed by Esso Production Research Co. has been run in a number of Esso Libya wells in an attempt to improve the reliability and accuracy of porosity determinations in vuggy limestone and fractured quartzite reservoirs. In general, porosities determined from the gravity meter were higher than those determined previously from sonic logs using conventional interpretation relationships. When a relationship between porosity values and sonic log readings—established with density data—was used in calculating the sonic logs, porosities for specific intervals sometimes gave poor agreement with those from the downhole gravity meter, but the average thickness-weighted values gave good agreement.
***.

181. Fausset, N.E., and Butler, David, 1979, Computer modeling of the theoretical borehole gravity response in the vicinity of the Aneth Field, Paradox Basin [abs.]: Geophysics, v. 44, no. 3, p. 370.

Borehole gravimetry has proven useful as a petroleum reservoir evaluation tool in that calculations from precise gravimeter measurements yield accurate determinations of average rock density in situ. However, independent knowledge of rock densities throughout a penetrated section may permit separation of gravitational effects due to rocks intersecting the borehole and rocks remote from the borehole. In this manner, the borehole gravimeter may be used as a remote sensing tool and provide unique opportunities in geophysical exploration.

By adapting Talwani's algorithm for computer use, the gravitational effects of various shaped 3-D bodies may be easily calculated.

The Aneth field of the Paradox basin was chosen as a model because of the sharp lateral density contrast between the reservoir and the surrounding country rock. ***.

Due to the small relief and the large areal extent of the reservoir, it was modeled as two abutting semi-infinite sheets. The vertical component of attraction was then calculated in hypothetical boreholes at various distances from the reservoir edge. Results from this idealized model indicate the Aneth field may be detected by borehole gravimetry up to 450 ft from its boundary. ***.

Although these results show that the borehole gravimeter is not significantly affected by bodies at large distances from the wellbore, they also show that the remote sensing of anomalous masses is possible for concise bodies marked by large density contrasts. ***.

182. Gibb, R.A., and Thomas, M.D., 1980, Density determinations of basic volcanic rocks of the Yellowknife supergroup by gravity measurements in mine shafts—Yellowknife, Northwest Territories: Geophysics, v. 45, no. 1, p. 18-31.

Gravity measurements were made in two gold mine shafts sunk in the Archean Yellowknife greenstone belt to determine the in situ densities of basic volcanic rocks of the Kam formation, Yellowknife supergroup. ***. Densities were computed using the terminology of borehole gravimetry with appropriate corrections for surface terrain and underground voids such as shafts, drifts, and stopes. [These values are compared to values from rock samples.]
***.

39. Gournay, L.S., 1983, Detection of bypassed gas using borehole gravimeter and pulsed neutron capture logs [abs.]: The Log Analyst, v. 24, no. 3, p. 27.

This report is referenced under Theory, where the abstract is also located.

40. Gournay, L.S. and Lyle, W.D., 1984a, Determination of hydrocarbon saturation and porosity using a combination borehole gravimeter (BHGM) and deep investigating electric log [abs.]: The Log Analyst, v. 25, no. 2, p. 59-60.

This report is referenced under Theory, where the abstract is also located.

41. ______1984b, Determination of hydrocarbon saturation and porosity using a combination borehole gravimeter (BHGM) and deep investigating electric log: Society of Professional Well Log Analysts, 25th Annual Logging Symposium Transactions, v. 2, p. WW1-WW14.

This report is also referenced under Theory. The abstract is under Theory in entry 40.

183. Halley, R.B., and Schmoker, J.W., 1983, High-porosity Cenozoic carbonate rocks of south Florida; progressive loss of porosity with depth: American Association of Petroleum Geologists Bulletin, v. 67, no. 2, p. 191-200.

Porosity measurements by borehole gravity meter in subsurface Cenozoic carbonates of south Florida reveal an extremely porous mass of limestone and dolomite which is transitional in total pore volume between typical porosity values for modern carbonate sediments and ancient carbonate rocks. A persistent decrease of porosity with depth, similar to that of chalks of the Gulf Coast, occurs in these rocks. [No attempt is made] to differentiate depositional or diagenetic facies which produce scatter in the porosity/depth relationship; the dominant data trends thus are functions of carbonate rocks in general rather than of particular carbonate facies. Carbonate strata with less than 20% porosity are absent from the rocks studied here.

Aquifers and aquicludes cannot be distinguished on the basis of porosity. ***.

Dolomites [are equally] porous or slightly less porous than [the] limestones [they replace] *** [suggesting] dolomitization does not take place by a simple ion-for-ion replacement of magnesium for calcium. ***.

The great volume of pore space in these rocks serves to highlight the inefficiency of early diagenesis in reducing carbonate porosity and to emphasize the importance of later porosity reduction which occurs during the burial or late near-surface history of limestones and dolomites.

43. Hammer, Sigmund, 1950, Density determinations by underground gravity measurements: Geophysics, v. 15, no. 4, p. 637-652.

This report is referenced under Theory, where the abstract is also located.

184. Head, W.J., and Kososki, B.A., 1979, Borehole gravity—a new tool for the ground water hydrologist [abs.]: Transactions American Geophysical Union, v. 60, no. 18, p. 248.

The basic principles that have made the BHGM useful to the energy industry can also be applied to ground water investigations. ***.

The results of borehole-gravity surveys in the Madison Limestone of northeast Wyoming and in an alluvial aquifer at the Nevada Test Site provide two examples that illustrate the value of BHGM logging techniques. In the Madison Limestone, the neutron log recorded zones of relatively high porosity, which borehole televiewer logging indicated were the result of secondary porosity development. In some instances, on the basis of borehole gravity data, the authors concluded that this secondary porosity was only of local extent and did not represent zones of high water production. This conclusion was subsequently supported by flow tests.

In the alluvial aquifer, the invasion of drilling fluids and hole rugosity seriously degrade the quality and hence the interpretation of conventional wire-line logs. In this case, the BHGM with its relatively large radius of investigation, which minimizes the effects of near-borehole conditions, proved to be a superior logging tool.

185. Healey, D.L., 1970, Calculated in situ bulk densities from subsurface gravity observations and density logs, Nevada Test Site and Hot Creek Valley, Nye County, Nevada, *in* Geological Survey research 1970: U.S. Geological Survey Professional Paper 700-B, p. B52-B62.

At the Nevada Test Site and Hot Creek Valley a borehole gravity meter was used to log four holes, and standard gravity meters were used to log five 48-inch-diameter holes and a vertical shaft. Three holes (Ue2y, test well B, and UCe-18) and the U5i shaft penetrated alluvium, and six holes penetrated Tertiary volcanic rocks on Pahute Mesa. The weighted average densities determined in the holes and shaft in alluvium are 1.94, 1.69, 2.22, and 2.05 g/cc, respectively; the density determined in five of the six holes in Tertiary volcanic rocks ranged from 1.98 to 2.06 g/cc. One hole (UE19n) penetrated a thick ash-flow tuff that averaged 1.51 g/cc. Density logs were taken in 10 additional holes. In Yucca Flat the mean density of more than 7,000 feet of alluvium is 2.01 g/cc, and in Hot Creek Valley the mean of more than 18,000 feet is 2.18 g/cc.

53. Hearst, J.R, and McKague, H.L., 1976, Structure elucidation with borehole gravimetry: Geophysics, v. 41, no. 3, p. 491-505.

This report is referenced under Theory, where the abstract is also located.

54. Hearst, J.R, and Nelson, P.H., 1985, Well logging for physical properties: New York, McGraw-Hill Book Co., 571 p.

This report is referenced under Theory, where the abstract is also located.

55. Hearst, J.R, Carlson, R.E. and Clark, S.R., 1986a, Calculation of gravimetric density caused by three-dimensional structure [abs.]: The Log Analyst, v. 27, no. 1, p. 78-79.

This report is referenced under Theory, where the abstract is also located.

56. ______1986b, Calculation of gravimetric density caused by three-dimensional structure: Society of Professional Well Log Analysts, 27th Annual Logging Symposium Transactions, v. 1, p. F1-F22.

This report is also referenced under Theory. The abstract is under Theory in entry 55.

135. Heintz, K.O., and Alexander, M., 1979, Sulfur exploration with core hole and surface gravity [abs.]: Geophysics, v. 44, no. 3, p. 370.

This report is referenced under Instrumentation, where the abstract is also located.

186. Hinze, W.J., Bradley, J.W., and Brown, A.R., 1978, Gravimeter survey in the Michigan Basin deep borehole: Journal of Geophysical Research, v. 83, no. B12, p. 5864-5868.

Borehole gravimetric measurements were made at major Phanerozoic formation contacts and within the Precambrian sedimentary rocks to a depth of 4 km in the McClure-Sparks No. 1-8 drill hole. The inplace densities of these units were calculated from the corrected observations. The densities of the Phanerozoic rocks vary considerably owing to the presence of evaporites contrasting with the clastic and carbonate rocks, and the mean density of the Phanerozoic rock column is 2.61 g/cm^3. The borehole gravimeter density of the Precambrian clastic rocks is 2.77 g/cm^3, 0.05 g/cm^3 greater than the density obtained from sample cuttings. The source of this discrepancy is unknown, but one possible explanation is the gravimetric effect of mafic igneous rocks, which may be more common within the Precambrian sedimentary rocks than is indicated by intersection of these rocks in the drill hole.

187. Hussain, A., 1979, Untertagegravimetrie in alpinen Gebieten mit besonderer Berucksichtegung des Blei-Zink-Bergbaus Bleiberg-Kreuth (Kärnten): Leobon, Mining and Metallurgy University, Ph. D. thesis, 176 p.

[Underground gravimetry in alpine regions with specific consideration of the lead-zinc mine Bleiberg, Carinthia.]

188. ______1983, Underground gravity surveys, *in* Fitch, A.A., ed., Developments in geophysical exploration methods—5: Essex, England, Applied Science Publishers LTD, p. 35–63.

The gravimeter used in underground mines is a three-dimensional exploration device which provides very valuable information about the density distribution around the measurement level. In this article we will examine its application for density determination in situ and for 'anomalous zone' definition in the mines. Practical examples of subsurface gravity surveys carried out in the shafts of a coal mine and in different levels of a lead-zinc mine will be presented. Gravity anomaly maps and profiles were constructed from different levels and compared with the known geology. The results demonstrate that gravity studies are the best first phase of study for defining drilling targets.

189. Hussain, A., and Walach, G., 1980, Subsurface gravity measurements in a deep intra-Alpine Tertiary basin: Geoexploration, v. 18, p. 165–175.

This paper is concerned with an underground gravity survey carried out in the Fohnsdorf-Knittelfeld basin, Styria, Austria. The measurements were made in three vertical shafts, reaching to a depth of 833 m, within the Fohnsdorf coal mines. The in situ densities, calculated from the corrected gravity values, furnished information about the three-dimensional density distribution within the basin which was helpful in interpreting other geophysical data from this area. The density profiles from each shaft were compared with one another and with the surrounding geology. About 50 m thick coal formation (6 m thick coal seam and remaining light marl) provided a significant density contrast with the upper lying marl and the lower lying sandstone. The accuracy achieved in the in situ density determinations was better than 0.01 g/cm^3. The gravimetric densities agree well with the hand sample densities collected from outcrops and the shaft surroundings.

190. Hussain, A., Walach, G., and Weber, F., 1981, Underground gravity survey in Alpine regions: Geophysical Prospecting, v. 29, no. 3, p. 407–425.

An underground gravity study was carried out under extreme conditions of the Alpine regions. The lead-zinc mine Bleiberg, Carinthia, [Austria,] was selected as an example to show the possibilities and limitations of the subsurface gravity method. For in situ density determinations, gravity measurements were made in two vertical mine shafts passing through Triassic sedimentary rocks of the Bleiberg Unit. The main problem in gravity data reduction in extremely rugged topography is the accurate calculation of the terrain effect on underground stations. A general discussion of the various corrections required for the gravity measurements in the mine is presented. The mean interval densities in the two shafts, in limestone, dolomite, and schists formations, were determined as 2.76 and 2.77 g/cm^3, respectively, with an accuracy of better than 0.01 g/cm^3 for depth interval of 50 m. The interval densities provide valuable information about the lithological and structural changes in the shaft surroundings and also agree well with the representative hand sample densities.

In the second part, the applications of subsurface horizontal gravity surveys in exploration are discussed. Since the influence of topography is less underground because of the greater distance to the surface, subsurface surveys have definite advantages over surface surveys and can be very helpful in locating anomalous density zones in the mines. An example of gravity survey with a station spacing of 10 m at a depth of about 540 m is presented.

191. Jung, Heinrich, 1939, Dichtebestimmung in anstehenden Gestein durch Messung der Schwerebeschleunigung in verschiedenen Tiefen unter Tage: Zeitschrift fur Geophysik, v. 15, p. 56–65.

Density determinations in the solid rock from measurement of the gravity acceleration at differing depths beneath the surface.

Measurements were made in the Wilhelms Shaft near Clausthal, Germany.

70. LaFehr, T.R., 1982, Apparent density from borehole gravity surveys [abs.]: Geophysics, v. 47, no. 4, p. 447–448.

This report is referenced under Theory, where the abstract is also located.

192. LaFehr, T.R., and Dean, V.C., 1983, Borehole gravity case history of the Mors Salt Dome, Denmark: Society of Exploration Geophysicists, 53rd Annual Meeting, Las Vegas, Nevada, Expanded Abstracts with Biographies, September 11–15, p. 33–35.

Two wells (Erslev 1 and 2) were drilled and logged (conventional and BHGM) in the Mors salt dome, Denmark. A third well was drilled and conventionally logged (no BHGM) about 10 km north-northeast of the dome. Surface seismic and gravity data were acquired, modeled (LaFehr et al, 1983, [report 194]), and used as a geologic constraint for this borehole gravity study. We expect, and see, in the Erslev 1 and 2 BHGM logs three responses within the MORS salt dome: (1) the structural effect of the salt dome, (2) the primary effect of pure halite, and (3) the effects of impurities in the salt and its internal structure. The mean density of the salt dome is about 2.2 g/cm^3, or close to that of pure halite.

Observed BHGM structural effects of the Mors salt dome are compared with the calculated density from seismic models. The two models produce significantly different BHGM density curves; a deeper base of salt beneath the overhang, together with the seismic interpretation with less overhang is supported by the BHGM data. The cap rock and deeper anhydrite zones produce very strong BHGM anomalies. Modeling of the deeper zones suggests their off-well connection and through-the-well dip. However, a more quantitative interpretation must await a better modeling capability. Smaller high frequency variations in the BHGM data suggest variations in the anhydrite concentrations in the rock salt, fluctuating between 0–5 percent.

193. ______1984, Borehole gravity case history of the Mors Salt Dome, Denmark [abs.]: Geophysics, v. 49, no. 5, p. 595–596.

Same abstract as report 192.

194. LaFehr, T.R., Dean, V.C., Davis, T.L., and Hilterman, F.J., 1983, Seismic and gravity modeling of the Mors Salt Dome, Denmark: Society of Exploration Geophysicists, 53rd Annual meeting, Las Vegas, Nevada, Expanded Abstracts with Biographies, September 11–15, p. 301–303.

Seismic and gravity modeling are used to investigate salt domes located in Denmark. ***. An extremely diverse and impressive array of geologic, geochemical, geophysical, and engineering disciplines has been engaged ***.

Each individual discipline, certainly the seismic and gravity methods, requires high specialization to understand their application and limitations fully, but it is equally important to have the general view of contributions from the disciplines to fully utilize the information at hand. Viewed from the perspective of integrated geophysics and geology, the surface and borehole seismic and gravity data have important roles. They respond to changes in rock density, which is one of the most important of rock properties. In addition to its effect on gravity anomalies, density influences seismic wave speeds, (whether compressional or shear), acoustic impedance (whose changes are required for the occurrence of seismic reflections) and is influenced by porosity development, fluid density, mineralogy, and compaction.

Different combinations of geologic structures and rock densities can give rise to the same gravity observations, so the incorporation of independent seismic and geologic information is critical in the evaluation of gravity data. ***.

195. ______1984, Seismic and gravity modeling of the Mors Salt Dome, Denmark [abs.]: Geophysics, v. 49, no. 5, p. 629–630.

Same abstract as report 194.

73. Laurin, P.J., Black, A.J., LaFehr, T.R.,and Bichara, M., 1981, Borehole gravimetry; an application example to engineering: Société pour l'Avancement de l'Interprétation des Diagraphies, 7th European Logging Symposium Transactions, no. 27, 10 p. (in French).

This report is referenced under Theory, where the abstract is also located.

77. McCalpin, G.A., 1983, Operational and technical results from a multi-well borehole gravity survey [abs.]: Unconventional Methods in Exploration for Petroleum and Natural Gas, Symposium IV, Institute for the Study of Earth and Man, Dallas, Texas, May 1–2, p. 32.

This report is also referenced under Theory. The abstract is under Theory in entry 78.

78. ______1986, Operational and technical results of a multiwell borehole gravity survey, *in* Davidson, M.J., ed., Unconventional methods in exploration for petroleum and natural gas IV: Dallas, Texas, Institute for the Study of Earth and Man, Southern Methodist University Press, May 1–2, 1985, p. 313–320.

This report is referenced under Theory, where the abstract is also located.

196. McCulloh, T.H., 1965, A confirmation by gravity measurements of an underground density profile based on core densities: Geophysics, v. 30, no. 6, p. 1108–1132.

Accurate laboratory measurements of dry bulk densities of 79 samples of Paleozoic sedimentary rocks from a 2,851-ft deep core hole near Barberton, Ohio, are the basis of a vertical profile of "natural" density which differs on the average 0.013 gm/cm^3 or less from a profile of in situ density calculated from gravity variations observed using a LaCoste and Romberg gravimeter in an adjacent 2,247-ft-deep vertical mine shaft. Both profiles agree well with the most meaningful Barberton core sample densities reported by Hammer (1950, Fig. 3 [report 39]), but are significantly lower than in situ interval densities calculated by Hammer from gravity variations observed in the shaft using a Gulf gravimeter. The 0.13 gm/cm^3 average discrepancy between the old and new in situ density profiles is probably attributable to a 12-percent error in calibration of the Gulf gravimeter.

The close agreement between the new profiles of "natural" and in situ density suggests that changes in bulk volume of compact sedimentary rocks that occur during or following the coring process are probably ordinarily so small that properly constructed core sample density profiles are reproducible and reliable even when small numbers of samples of aged cores are used. ***.

81. ______1967a, Borehole gravimetry—New developments and applications, *in* Origin of oil, geology and geophysics: London, Elsevier, 7th World Petroleum Congress, Mexico City, April 2–8, Proceedings, v. 2, p. 735–744.

This report is referenced under Theory, where the abstract is also located.

82. ______1967b, Mass properties of sedimentary rocks and gravimetric effects of petroleum and natural gas reservoirs: U.S. Geological Survey Professional Paper 528-A, 50 p.

This report is referenced under Theory, where the abstract is also located.

83. 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.

This report is referenced under Theory, where the abstract is also located.

197. McLean, A.C., 1961, Density measurements of rocks in southwest Scotland: Royal Society of Edinburgh Proceedings, sec. B, v. 68, pt. 2, p. 103–111.

A large number of density measurements of the more important rock-types exposed at the surface in Ayrshire and certain neighboring areas provide information for the interpretation of gravity measurements. The three methods employed of determining density are (1) laboratory measurements of rock samples, (2) gravimeter measurements in mineshafts, and (3) gravimeter measurements over topographic features.

The first method, the most widely used is the only one applicable to many of the geological formations. A total of 600 specimens measured cover all the common rock types of the Lower and Upper Palaeozoic systems and their associated igneous rocks. Use of the second method is restricted to Carboniferous rocks, in which records from four mineshafts—Littlemill 5, Mauchline 1, Auchincruive 1, and Houldsworth—cover much of the Carboniferous succession in south Ayrshire. The third method was seldom applied as there are few suitable topographic features, independent of geological structure, in Ayrshire.

The results of the measurements are summarized, and their reliability discussed. Two contrasts of rock density of regional importance occur in the sedimentary succession of south Ayrshire—the first at the plane of unconformity between Upper and Lower Old Red Sandstone, and the second between Lower Old Red Sandstone and the Lower Palaeozoic greywackes. A marked contrast of local importance occurs between the Permian sandstones of the Mauchline Basin and the underlying lavas and Carboniferous rocks. In north Ayrshire the most important density contrast lies between the Upper Palaeozoic sediments and the associated dense igneous rocks—the Clyde Plateau Lavas, the Millstone Grit lavas, and the thick dolerite intrusions.

198. Miles, D.R., 1977, A gravity survey in the haulage tunnel of the Henderson Mine near Berthoud Pass, Colorado: Golden, Colo., Colorado School of Mines M.S. thesis, 37 p., 2 plates.

A gravity survey was conducted in the haulage tunnel of the Henderson Mine, followed by the reduction and interpretation of the data and analysis of errors. The gravity survey consisted of 64 stations in the tunnel and five stations on the surface ***. ***. The computed bulk densities show a slightly higher than average density implying that the country rock is a mixture of granite and metasediment.

The uncertainties in the complete Bouguer-corrected data are as large ($\pm$1.30 mgals) as most of the anomalies. The large relief ($\simeq$2,500 feet to 3,300 feet or $\simeq$0.75 km to 1.0 km) caused usually trivial errors in the terrain correction to account for most of the uncertainty in the data. Thus, a criterion utilizing the surface gravity survey and the deviation from the regional gradient was developed.

Four anomalies based on the criteria appear to be caused by granite or metasediment pods in the mixed granite–metasediment country rock, rather than uncertainties in the data. Models of the source of the anomalies range in size from between 500 ft. (152 m) and 3,000 ft. (914 m.) from the tunnel.

***.

84. Miller, A.H., and Innes, M.J.S., 1953, Application of gravimeter observations to the determination of the mean density of the Earth and of rock densities in mines: Canada Dominion Observatory, Ottawa Publications, v. 16, no. 4, p. 3-17.

This report is referenced under Theory, where the abstract is also located.

85. Mudrecova, E.A., 1960, Underground gravity surveys in copper sulphide deposits in the Central Ural Mountains: Geofizicheskaia Razvedka, no. 2, p. 31-59 (in Russian).

This report is referenced under Theory, where the abstract is also located.

199. Murty, B.V.S., Chandra Reddy, P., Venkat Reddy, P., and Ghyasuddin, Mohd., 1984, Subsurface gravity survey in aid of mine planning and development; a case study from Mailaram Copper Mines, Andhra Pradesh, India: Society of Exploration Geophysicists, 54th Annual Meeting, Atlanta, Georgia, Expanded Abstracts with Biographies, December 2-6, p. 226-228.

Toward demonstrating the usefulness of the subsurface gravity technique in mine planning and development, a gravity survey was conducted in the different levels, shafts, and crosscuts in the Mailaram copper mines of Andhra Pradesh, India. The authors report the results of the investigation which helped decipher the geometry of the chalcopyrite ore, the zones of its probable extension, structural features like faults, and the extent of the ore available in the mine. It is suggested that accurate gravity measurements, attention toward necessary corrections to obtain the subsurface Bouguer anomalies, and due weightage to surface and subsurface geologic information could help using the successful subsurface gravity technique toward solving mining geophysical problems.

200. ______1985, Subsurface gravity survey in aid of mine planning and development; a case study from Mailaram Copper Mines, Andhra Pradesh, India: Geophysics, v. 50 , no. 2, p. 293.

Same abstract as report 199.

201. Murty, B.V.S., Ghyasuddin, Mohd., and Venkat Reddy, P., 1982, Subsurface gravity measurements and density mapping in the Mailaram Copper Mines, Andhra Pradesh, India: Geophysical Prospecting, v. 30, no. 4, p. 444-453.

Gravity measurements were made in the Mailaram copper mines, Andhra Pradesh. The observations were distributed between the two shafts situated about 220 m apart and in the three levels up to a maximum depth of 100 m. Assuming a normal free-air gradient, average densities for the three layers were determined as 2.631, 2.604, and 2.823 g cm^{-3}, respectively. Upon incorporating the weighted mean density values from measurements on samples, the free-air gradients were found to be 0.315 mGal m^{-1} for the second layer (i.e. between the first and second levels) and 0.2978 mGal m^{-1} for the third layer (i.e. between the second and third levels). The density variation map obtained from the gravity data, the deduced anomalies, the weighted mean density values from measurements on rock samples, and the varying free-air coefficients all suggest correspondence with the concentration of ore lodes.

202. Nichols, T.C., Jr., and Collins, D.S., 1986, In situ and laboratory geotechnical tests in the Pierre Shale near Hayes, South Dakota: U.S. Geological Survey Open-File Report 86-152, 24 p.

A geotechnical investigation of the Pierre Shale near Hayes, S. Dak., was conducted by the U.S. Geological Survey. The physical and mechanical properties of the shale were determined through use of four core holes and several supplementary holes, drilled to a maximum depth of 184 m. In situ borehole determinations included a gravimeter survey, pressuremeter testing, thermal profile measurements, and borehole velocity measurements of shear and primary waves. Onsite laboratory measurements included geologic logging of cores, bulk density determinations, moisture content determinations, and rebound measurements. Offsite laboratory measurements included sonic velocity measurements of shear and primary waves, X-ray mineralogy and major element determinations, size analyses, fracture analyses, fabric analyses, and determination of thermal properties.

203. Nichols, T.C., Jr., Collins, D.S., and Davidson, R.R., 1986, In situ and laboratory geotechnical tests of the Pierre Shale near Hayes, South Dakota—A characterization of engineering behavior: Canadian Geotechnical Journal, v. 23, no. 2, p. 181-194.

The abstract for this report is similar to report 202. The report itself is an expanded version of report 202.

87. Oelsner, Christian, 1960, Schweremessungen unter Tage: Zeitschrift fur Angewandte Geologie, v. 4, p. 172-177.

This report is referenced under Theory, where the abstract is also located.

204. Picha, Jan, 1953, Tíhove' zrychlení pod povrchem zemským v dole "Anna" na Březových Horách: Geofysikální Sborník, no. 9, p. 119-129 (in Czechoslovakian).

[Underground gravity surveys in the "Anna" shaft in Brezowe Góry.]

205. Plouff, Donald, 1961, Gravity profile along Roberts Tunnel, Colorado: U.S. Geological Survey Professional Paper 424-C, p. C263-C265.

This report discusses density determinations from gravity data collected in and above the Harold D. Roberts Tunnel east of Dillon, Colo. This study is part of a regional gravity survey of the Colorado Rocky Mountains.

206. Pritchett, W.C., 1980, Physical properties of shales and possible origin of high pressures: Society of Petroleum Engineers Journal, v. 20, no. 5, p. 341-348.

Laboratory and borehole measurements of shale properties may be unreliable because of modification during or after drilling or coring. The borehole gravimeter is an ideal tool for measuring the bulk density of thick shale units because of its great depth of investigation and negligible sensitivity to shale in the vicinity of the borehole, which may have been modified in drilling. By contrast, the scatter gamma ray density log has an extremely shallow depth of investigation and its response may be dominated by modified shale surrounding a borehole. A comparison of bulk densities measured by these two methods in both sands and shales was made in three U.S. Gulf Coast wells. In all three wells, the two methods yielded comparable densities for the sands. But in two wells, which were drilled with fresh muds, the density log yielded shale bulk densities significantly less than those shown by the borehole gravimeter. These data indicate that shale adjacent to the borehole in these two wells had been modified by drilling and the modified shale densities had been reduced significantly. ***.

High-pressure shales are particularly susceptible to modification during drilling since they are relatively permeable and soft. ***. Density log data in high-pressure shales are unreliable due to probable shale modification. ***.

90. ______1982, Physical properties of shale and possible origin of high pressures: Society of Exploration Geophysicists, 52nd Annual Meeting, Dallas, Texas, Expanded Abstract with Biographies, October 17-21, p. 504-505.

This report is referenced under Theory, where the abstract is also located.

91. ______1983, Physical properties of shales and possible origin of high pressures [abs.]: Geophysics, v. 48, no. 4, p. 483.

This report is also referenced under Theory. The abstract is under Theory in entry 90.

207. Prudic, D.E. and Herman, M.C., in press, Ground water hydrology and simulated effects of pumping patterns in Paradise Valley, a stream dominated basin in Humboldt County, Nevada: U.S. Geological Survey Professional Paper 1409-F.

Reference is made in this paper to BHGM surveys in two shallow wells within the basin. See report 238 for the principal facts to these surveys.

208. Rasmussen, N.F., 1975a, The successful use of the borehole gravity meter in northern Michigan: Transactions, Canadian Well Logging Society, Fifth Formation Evaluation Symposium, paper X.

See report 209 for abstract.

209. ______1975b, The successful use of the borehole gravity meter in northern Michigan: The Log Analyst, v. 16, no. 5, p. 3-10.

Borehole gravity surveys have been used in Northern Michigan to make producers out of otherwise dry holes. Wells which are drilled in thick, tight, salt-plugged reefs may have encountered a very restricted, tight facies. The borehole gravity survey can be used to detect nearby porosity. Such porosity zones can be entry beds to the main reservoir. The basis for qualitative interpretation is to determine the sidewall lithology and then evaluate which rock parameters could vary laterally to change bulk density. Porosity changes produce distinct low density deflections on gravity log plots. The bases for quantitative evaluations are the results of computer models or of simple cylindrical models. The maximum distance to a porous zone can be calculated using a cylindrical or ring-shaped model.

96. Rische, Hans, 1957, Dichtebestimmungen im Gesteinsverband durch Gravimeter und Drehwaagemessungen unter Tage: Freiberger Forschungshefte, C35, 84 p.

This report is referenced under Theory, where the abstract is also located.

210. Robbins, S.L., 1979, 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.

Two 50- to 55-meter-deep test holes near Watkins, Colorado, penetrate through an 8-meter-thick lignite zone within the Upper Cretaceous and Paleocene Denver Formation. These test holes were surveyed using a borehole gravity meter and the principal facts along with a summary of data-interpretation relationships and data accuracies are presented. Conclusions derived from the BHGM data and comparisons of these data with gamma-ray and gamma-gamma logs are as follows: (1) The lignite densities are in the 1.3- to 1.4-g/cm^3 range, with differences between the BHGM density values and gamma-gamma density values for these zones ranging from 0.2 to 0.3 g/cm^3 higher for the gamma-gamma values. (2) These differences are probably caused by both mud invasion into parts of the lignite seams and a (Z/A) ratio in the gamma-gamma log reduction that is too low. (3) Porosities for the clastic sediments are between 27 and 42 percent. (4) Water saturation of these sediments above the water table at the time of the survey was about 70 percent. (5) Since the gamma-ray logs proved to be a poor method in this area for ash content determination and the density values from the gamma-gamma logs were too high, care must be used when interpreting logs from radiation sensitive tools in wells containing organic material.

99. ______1986a, The use of borehole gravimetry in water well and waste disposal site evaluations [abs.], *in* Surface and borehole geophysical methods and ground water instrumentation—A conference and exposition: National Water Well Association Program, Denver, Colorado, October 15-17.

This report is referenced under Theory, where the abstract is also located.

100. ______1986b, The use of borehole gravimetry in water well

and waste disposal site evaluations, *in* Proceedings of the surface and borehole geophysical methods and ground water instrumentation conference and exposition: Dublin, Ohio, National Water Well Association, p. 474–486.

This report is also referenced under Theory. The abstract is under Theory, entry 99.

211. Robbins, S.L., Kunk, J.R. and Bjornstad, B.M., in press, Three-dimensional density modeling from borehole gravity surveys in late Cenozoic sediments at the Hanford Site, Washington: Journal of Geophysical Research.

Nine boreholes that penetrate the suprabasalt sediments at the Hanford Site, Washington, were surveyed by borehole gravity meters so that accurate densities could be obtained. The boreholes are in an area designated as the Reference Repository Location which lies within the Cold Creek syncline in the western Pasco Basin in the western Columbia Plateau.

The density layers in the four two-dimensional profiles presented here were determined by a technique that has not been previously described.

Observations about the geologic character of the sediments based on interpretation of the profiles [are] include[d] ***.

212. Rogers, G.R., 1952, Subsurface gravity measurements: Geophysics, v. 17, no. 2, p. 365–377.

Gravity data were obtained at approximately 100-foot intervals in a vertical mine shaft 2,916 feet deep [in Arizona]. The shaft passed through a region of high positive density contrast, and a local anomaly was observed of plus 14.0 gravity units to minus 17.9 gravity units. Calculations for Bouguer densities were carried out with the gravity measurements. A theoretical sphere that closely approximates the observed data and known conditions is derived from the gravity data.

213. Schaefer, D.S., in press, Geophysical techniques to determine hydrologic parameters and specific basin studies in the Great Basin, Nevada and Utah: U.S. Geological Survey Professional Paper.

Reference is made in this paper to BHGM surveys in three shallow wells within Nevada. See report 238 for the principal facts to these surveys.

214. Schmoker, J.W., 1977a, Density variations in a quartz diorite determined from borehole gravity measurements, San Benito County, California: The Log Analyst, v. 18, no. 2, p. 32–38.

In situ bulk densities were determined in the Stone Canyon Experimental No. 1 well, San Benito County, California, using the U.S. Geological Survey–LaCoste and Romberg borehole gravity meter. The well penetrates granitic rocks of the Gabilan Range which are highly fractured, presumably from the tectonic effects of the nearby San Andreas fault. Densities measured in the well varied by .30 g/cm^3. A particularly disturbed zone between 497 and 673 ft (151–205 m) was found. The borehole gravity method for determining in situ density variations appears particularly useful in highly fractured rocks such as these found in the Stone Canyon well.

215. ______1977b, A borehole gravity survey to determine density variations in the Devonian shale sequence of Lincoln County, West Virginia: U.S. Department of Energy, Energy Research Center, MERC/CR-77/7, 15 p.

In situ bulk densities of the Devonian shale section penetrated by the Columbia Gas Transmission Corp. 20402 well, Lincoln County, West Virginia, were determined using the U.S. Geological Survey–LaCoste and Romberg borehole gravity meter. Densities from two gamma-gamma logs, run by different companies, were also available. A cumulative difference of .034 g/cm^3/1,000 ft (.112 g/cm^3/km) exists between the two gamma-gamma logs. The two intervals of lowest density derived from the borehole gravity data show higher densities on both gamma-gamma logs, possibly indicative of the deeper investigation radius of the borehole gravity meter. In most intervals, higher gamma-ray intensity correlates with lower density, indicating that organic content is the primary variable affecting both bulk density and uranium concentration.

216. ______1979, Interpretation of borehole gravity surveys in a native-sulfur deposit, Culberson County, Texas: Economic Geology, v. 74, p. 1462–1470.

Borehole gravity surveys to determine formation densities were conducted by the U.S. Geological Survey in four exploratory wells penetrating the native-sulfur deposit at the Duval Culberson property, Culberson County, Texas. The borehole gravity meter has a depth of penetration comparable to the recovery radius of the Frasch process for mining sulfur, which is an advantage for evaluating the sulfur content of heterogeneous deposits. Mineralized zones are treated as three-component systems—bioepigenetic limestone, interstitial sulfur, and water-filled pores. A ternary diagram relating combinations of these components to borehole gravity densities, together with empirical data relating sulfur content and water-filled porosity, are used to estimate sulfur volumes from the borehole gravity data. Estimated sulfur contents range from 0 to 33 percent. Comparisons with the amount of sulfur observed in core and cuttings from the four study wells and from surrounding wells show both the positive benefits of a greater range of investigation and the negative effects of relying solely on formation density as a measure of sulfur volume. Estimates of sulfur content based on borehole gravity data can supplement conventional analyses of core, as well as standard geophysical surveys of boreholes.

217. ______1980, Effect upon borehole gravity data of salt structures typical of the WIPP Site (northern Delaware Basin), Eddy County, New Mexico: U.S. Geological Survey Oil and Gas Investigations Chart OC-109.

This report presents the feasibility of detecting and defining salt structures at the WIPP site with borehole gravimetry. Since the gravity signal due to salt structures is small and falls off rapidly with distance, the meter is not very effective here.

218. Schmoker, J.W., and Halley, R.B., 1982, Carbonate porosity versus depth—A predictable relation for South Florida: American Association of Petroleum Geologists Bulletin, v. 66, no. 12, p. 2561–2570.

This study examines the porosity of limestones and dolomites in the South Florida basin. Porosity data are derived from borehole-gravity measurements and from suites of acoustic, neutron, and density logs. ***. Investigation depths range from the surface to about 18,000 ft (5,500 m) and span the transition from high-porosity near-surface carbonate sediments of Pleistocene age to much denser Mesozoic carbonate rocks with porosities of only a few percent.

Carbonate porosity in the South Florida basin was affected by a variety of diagenetic processes. *** The basin contains little clastic material; present depths of burial are about equal to maximum depths of burial; the influences of tectonism, geopressures, and hydrocarbon accumulations are minimal.

Curves of porosity versus depth, reflecting large-scale porosity-loss processes in the subsurface, are derived for a composite carbonate section and for carbonate strata of different ages and compositions. The decrease of porosity with depth for a composite carbonate section representing a wide range of depositional environments and subsequent diagenetic histories can be characterized by the exponential function $\phi = 41.73e^{-z/8197}$ (ft) [$\phi = 41.73e^{-z/2498}$ (m)], where ϕ is the porosity (%) and z is the depth below ground level (feet or meters). Average porosity is reduced by a factor of two in a depth interval of about 5,700 ft (1,740 m).

Carbonate strata of different ages that are buried to equal depths show no systematic porosity differences. This implies that the effect of time on porosity in these rocks is probably subordinate to that of burial depth. The data also show a faster than expected rate of porosity decrease with depth for rocks of Eocene age and younger. If it is assumed that the decrease in the volume of evaporites in these rocks indicates less saline pore fluids, porosity loss in shallow-water carbonates may be inversely related to the magnesium content of pore waters.

Dolomite porosity is lower than limestone porosity in the near surface, but does not decrease as rapidly with depth. Below about 5,600 ft (1,700 m), dolomite is more porous than limestone. It is hypothesized that most dolomitization occurred relatively early and either reduced original porosity or selectively favored lower-porosity limestones. With continued burial, dolomite was more resistant than limestone to associated porosity-reducing effects.

104. Sissons, B.A., 1981, Densities determined from surface and subsurface gravity measurements: Geophysics, v. 46, no. 11, p. 1568-1571.

This report is referenced under Theory, where the abstract is also located.

110. Stacey, F.D., Tuck, G.J., Holding, S.C., Maher, A.R., and Morris, D., 1981, Constraint on the planetary scale value of the Newtonian gravitational constant from the gravity profile within a mine: Physical review D, v. 23, no. 8, p. 1683-1692.

This report is referenced under Theory, where the abstract is also located.

219. Sumner, J.S., and Schnepfe, R.N., 1966, Underground gravity surveying at Bisbee, Arizona, *in* Mining Geophysics, v. 1, Case histories: Society of Exploration Geophysicists, Tulsa, Oklahoma, p. 243-251.

During the past fifteen years, Phelps Dodge Corporation has actively used underground gravity surveying at Bisbee, Arizona. The method has proven to be quite useful for purposes of locating and assisting in the development of massive sulfide bodies within the district. Host rocks for replacement sulfides are fairly uniform in density, being in the range 2.65 to 2.70 gm/cm^3. Average densities of sulfide bodies reach as high as 4.00 gm/cm^3, providing a strong density contrast.

In development of the gravity station network it was necessary to make extensive topographic corrections in order to compensate for nearby and overlying mountainous terrain.

Because of the complex nature of the mine workings, results are interpreted quantitatively without regard to corrections for underground openings. ***

Raw gravity readings are corrected and reduced by applying the free air correction, the Bouguer correction, a combined correction, and a "sigma" correction. ***

Residual gravity values are plotted on level plan maps and these values are contoured. ***

Vertical sections of gravity data are prepared from level maps. These sections are contoured and then interpreted to give a measure of "apparent density" by relating vertical gravity gradient to density, using the departure from the assumed Bouguer density value. ***

***.

220. Tucci, Patrick, 1981, Density of basin-fill deposits calculated from borehole gravity data in four basins in central and southern Arizona [abs.]: Eos, v. 62, no. 45, p. 863.

In situ density values for basin-fill deposits in four basins in Arizona were calculated from borehole gravity measurements in six wells—the first such measurements for hydrologic investigations in the State. Density values ranging from 1.73 to 2.46 grams per cubic centimeter were calculated from the 300 to 600 meters of basin fill that were logged. Density values are similar to those obtained from gamma-gamma logs and samples of basin fill in Arizona and from borehole gravity data from Nevada. The values obtained from borehole-compensated gamma-gamma logs below the water table are slightly less than and those above the water table slightly more than the borehole gravity values.

From two to four distinct density layers, defined by the density plots, are present in the basins. Shape of the plot and density range of the layers differ from basin to basin and may differ within a basin. A general depth-density curve, based on the borehole gravity data, may be used to approximate the depth-density relation in basins where subsurface data are sparse.

Porosity calculated from the borehole gravity data depends to a large extent on the gain density of the basin fill. Porosity of the saturated density layers ranges from 17 to 33 percent, assuming a grain density of 2.65 grams per cubic centimeter. A comparison between basin-fill density and hydraulic conductivity generally indicates that lithologically similar high-density deposits have a low hydraulic conductivity.

221. Tucci, Patrick, Schmoker, J.W., and Robbins, S.L., 1982, Borehole-gravity surveys in basin-fill deposits of central and southern Arizona: U.S. Geological Survey Open-File Report 82-473, 23 p.

Principal facts and density estimates are provided from borehole gravity surveys in six wells in Avra, Butler, and Vekol Valleys and the Tucson basin, Arizona. A brief discussion of density comparisons in basin-fill deposits is provided along with some porosity averages and ranges below the water table.

222. ______1983, Density of basin-fill deposits calculated from borehole gravity data in four basins in central and southern Arizona: Society of Exploration Geophysicists 53d Annual Meeting, Las Vegas, Nevada, Expanded Abstracts with Biographies, September 11-15, p. 28-31.

In situ density value for basin-fill deposits in four Arizona basins were computed from borehole-gravity measurements. The measurements were made in the upper 300 to 600 meters of six wells, the first such measurements for hydrologic investigations in the State. Calculated density values range from

1.73 to 2.46 g/cm^3. These densities are similar to reported values derived from conventional gamma-gamma logs and samples of basin fill in Arizona, and from borehole gravity data in Nevada. Densities obtained from gamma-gamma logs in the wells logged here tend to be lower than borehole gravity values below the water table, and higher than borehole gravity values above the water table.

***. The thicknesses, depths, and densities of the layers vary from basin to basin and within basins. In general, densities of the basin fill increase with depth from the surface to about 240 m, and then remain approximately constant or even decrease with additional depth. A composite plot of density versus depth presented here can be used to estimate density in basins where subsurface data are lacking.

Porosity values calculated from the borehole gravity data range from 17 to 33 percent, assuming a grain density of 2.65 g/cm^3. In some instances when other geologic factors remain approximately constant, porosity shows a positive correlation with hydraulic conductivity and so is related to potential aquifer production.

223. ______1984, Density of basin-fill deposits calculated from borehole gravity data in four basins in central and southern Arizona [abs.]: Geophysics, v. 49, no. 5, p. 595.

Same abstract as report 222.

224. Whetton, J.T., Myers, J.O., and Smith, R., 1957, Correlation of rock density determinations for gravity survey interpretation: Geophysical Prospecting, v. 5, no. 1, p. 20–43.

The results of field and laboratory methods of density determination on a series of Coal Measure, Permian and Triassic rocks are presented and the different methods compared. It is concluded that the most satisfactory method is that of measuring the vertical change of gravity in a mine shaft. Nettleton's method is unsatisfactory to us, due to weathering of the rocks (particularly Magnesian Limestone) and possible effects from drift. Laboratory measurements are of variable value depending on the lithology and source of the samples.

A method adopted to solve the problem of finding the true densities for use in a local gravity survey in N.E. England is given.

Reports Containing Only Basic Gravity Data and Reductions with some Preliminary Density and Porosity Determination

225. Beyer, L.A., 1980, Narrative and basic data of the U.S. Geological Survey borehole gravity program (1963–1975): U.S. Geological Survey Open-File Report 80-903, 76 p.

This report describes the development of the first reliable and durable high-precision borehole gravity meter. Also included are basic borehole gravity data for 21 surveys made in California and Wyoming between 1968 and 1975.

226. Beyer, L.A., Robbins, S.L., and Clutsom, F.G., 1985, Basic data and preliminary density and porosity profiles for twelve borehole gravity surveys made in the Los Angeles, San Joaquin, Santa Maria and Ventura Basins, California: U.S. Geological Survey Open-File Report 84–42, 66 p.

This report presents a brief summary of the borehole gravity method, a description of the data reduction and error estimate procedures, and preliminary density and porosity profiles for twelve borehole gravity surveys made in California by the U.S. Geological Survey. A brief description of the geologic setting and petroleum field characteristics for each surveyed well is also included.

227. Byerley, K.A., and Schmoker, J.W., 1977, Density and porosity estimates from borehole gravity data in the Castle Pines #1, 2, and 3 water wells, Douglas County, Colorado: U.S. Geological Survey Open-File Report 77-875, 17 p.

This report presents the basic gravity data plus reduction corrections and includes density and porosity determinations. SP and resistivity curves are also presented for the lower sections of wells 3, and 2.

228. Healey, D.L., Clutsom, F.G. and Glover, D.A., 1984, Borehole gravity meter surveys in drill holes USW G–3, UE–25p#1 and UE–25c#1, Yucca Mountain area, Nevada: U.S. Geological Survey Open-File Report 84-672, 16 p.

[This report presents the basic BHGM data plus reduction corrections and includes the interval densities.] Free-air gradient (FAG) measurements were made at UE–25p#1 and UE–25c#1. The BHGM data in these two holes were reduced using the measured FAG values. *** The measured FAG values are 0.8 and 0.97 percent higher and the calculated densities are 0.07 and 0.04 mg/m^3 higher than values calculated using the "normal" value. These calculated differences in density are not insignificant and indicate the need to measure the FAG at each logged hole.

229. ______1986, Borehole gravity meter survey in drill hole USW G–4, Yucca Mountain area, Nye County, Nevada: U.S. Geological Survey Open-File Report 86-205, 18 p.

Drill hole USW G–4 was logged with the U.S. Geological Survey borehole gravity meter (BHGM) BH–6 as part of a detailed study of the lithostratigraphic units penetrated by this hole. *** USW G–4 is an especially important hole because of its proximity to the proposed exploratory shaft at Yucca Mountain.

The BHGM data were reduced to interval densities using a free-air gradient (F) of 0.3083 mGal/m (0.09397 mGal/ft) measured at the drill site. The interval densities were further improved by employing an instrument correction factor of 1.00226. This factor was determined from measurements obtained by taking gravity meter BH–6 over the Charleston Peak calibration loop.

The interval density data reported herein should be helpful for planning the construction of the proposed shaft.

230. Kososki, B.A., and Robbins, S.L., 1979, In situ bulk density and porosity estimates from borehole gravity data in the Madison Limestone test well no. 1, Crook County, Wyoming: U.S. Geological Survey Open-File Report 79-1514, 14 p.

This report presents the basic gravity data plus reduction corrections for the well and includes density and porosity determinations. A generalized stratigraphic section is also included.

231. ______1980a, In situ bulk-density estimates from borehole gravity data in the Madison Group test well no. 3, Yellowstone County, Montana: U.S. Geological Survey Open-File Report 80-784, 11 p.

This report presents the basic gravity data plus reduction corrections for the well and includes density determinations. A generalized stratigraphic section is also presented.

232. ______1980b, In situ bulk-density estimates from borehole gravity data from the Madison Group test well no. 2, Custer County, Montana: U.S. Geological Survey Open-File Report 80-982, 11 p.

This report presents the basic gravity data plus reduction corrections for the well and includes density determinations. A generalized stratigraphic section is also included.

233. Kososki, B.A., Robbins, S.L., and Schmoker, J.W., 1978a, Principal facts for borehole gravity stations in stratigraphic test well ERDA no. 9, Eddy County, New Mexico: U.S. Geological Survey Open-File Report 78-696, 11 p.

This report presents the basic gravity data plus reduction corrections for the well. A gamma-ray log and a generalized stratigraphic section also are reproduced.

234. ______1978b, Principal facts for borehole gravity stations in test well Ue19z, exploratory drill hole PM-1, and water well 5a, Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Open-File Report 78-983, 16 p.

This report presents the basic gravity data plus reduction corrections. Gamma-ray curves and generalized stratigraphic sections are also presented.

235. Robbins, S.L., and Clutsom, F.G., 1983, Principal facts and density estimates for borehole gravity stations in exploratory wells Ue7h, Ue4al, and Ue1la at the Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Open-File Report 83-244, 20 p.

This report presents the basic gravity data plus reduction corrections (including instrument drift correction curves). Density determinations and generalized stratigraphic sections are also presented.

236. Robbins, S.L., Kunk, J.R., and Clutsom, F.G., 1983, Principal facts and density estimates for borehole gravity stations in boreholes RRL-3, -4, -5, -6B, -7, -8, and -9 at the Hanford Site, Benton County, Washington: U.S. Geological Survey Open-File Report 83-386, 39 p.

This report presents the basic gravity data plus reduction corrections (including instrument drift correction curves). Density determinations, gamma-ray curves, and generalized stratigraphic sections are also included.

237. Robbins, S.L., Martinez, R.J., and Smith, D.L., 1979, Principal facts for borehole gravity stations in wells DC-3, DC-5, and DC-7 at the Hanford Works, Washington, and in well RSH #1 on Rattlesnake Hills Ridge, Washington: U.S. Geological Survey Open-File Report 79-849, 27 p.

This report presents the basic gravity data plus reduction corrections (including instrument drift correction curves). Gamma-ray and CCL logs are also included.

238. Robbins, S.L., Prudic, D.E., Schaefer, D.H., and Clutsom, F.G., 1983, Principal facts and density estimates for borehole gravity stations in three water wells located in Dixie and Paradise Valleys, Nevada: U.S. Geological Survey Open-File Report 83-426, 20 p.

This report presents the basic gravity data plus reduction corrections (including instrument drifts correction curves). Density determinations, gamma-ray curves, and generalized lithologic sections are also presented.

239. Robbins, S.L., Schmoker, J.W., and Hester, T.C., 1982, Principal facts and density estimates for borehole gravity stations in exploratory wells Ue4ah, Ue7j, Ue1h, Ue1q, Ue2co, and USW-H1 at the Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Open-File Report 82-277, 33 p.

This report presents the basic gravity data plus reduction corrections (including instrument drift correction curves). Density determinations and generalized stratigraphic sections are also presented.

240. Schmoker, J.W., 1976, Principal facts for borehole gravity stations in the Columbia Gas #20402 well, Lincoln County, West Virginia: U.S. Geological Survey Open-File Report 76-593, 5 p.

This report presents the basic gravity data plus reduction corrections for the well.

241. Schmoker, J.W., and Kososki, B.A., 1977, Principal facts for borehole gravity stations in the Columbia Gas Transmission Corp. 4771 well, Kanawha County, West Virginia: U.S. Geological Survey Open-File Report 77-267, 6 p.

This report presents the basic gravity data plus reduction corrections. A gamma-ray log is also presented.

242. ______1978, Principal facts for borehole gravity stations in test wells Ue10j, Ue7ns, and Ue5n, Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Open-File Report 78-212, 11 p.

This report presents the basic gravity data plus reduction corrections. Gamma-ray curves are shown for wells Ue10j, and Ue7ns.

243. Schmoker, J.W., and Robbins, S.L., 1979, Borehole gravity surveys in native sulfur deposits, Culberson and Pecos Counties, Texas: U.S. Geological Survey Open-File Report 79-361, 22 p.

This report presents the basic gravity data plus reduction corrections. Density determinations and gamma-ray curves are also included. Temperatures for well C-211 are also listed.

244. Schmoker, J.W., Halley, R.B., Meyer, F.W., and Robbins, S.L., 1979, Preliminary porosity estimates of south Florida

Cenozoic carbonate rocks based on borehole gravity measurements: U.S. Geological Survey Open-File Report 79-1652, 17 p.

This report presents density and porosity determinations from five wells situated along a more or less north-south profile in southern Florida. Lithologic information is also summarized.

245. Schmoker, J.W., Robbins, S.L., Clutsom, F.G., and Martinez, R.J., 1977, Principal facts for borehole gravity stations in the Columbia Gas Transmission Corp. 4982, 5016, and 6871 wells, Jackson and Kanawha Counties, West Virginia: U.S. Geological Survey Open-File Report 77-852, 10 p.

This report presents the basic gravity data plus reduction corrections. It also includes gamma-ray logs for the wells.

246. Secor, G.B., Jr., Meyer, H.J., and Hinze, W.J., 1963, A density determination by underground gravity measurements in Michigan: Geophysics, v. 28, no. 4, p. 663–664.

This report presents density determinations for three locations in and adjacent to the Detroit Salt Mine, Michigan.

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