UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

BIBLIOGRAPHY WITH ABRIDGED ABSTRACTS OF SUBSURFACE GRAVIMETRY (ESPECIALLY BOREHOLE) AND CORRESPONDING IN-SITU ROCK DENSITY DETERMINATIONS

by

Stephen L. Robbins

Open-File Report 80-710

1980

This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards.

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I. Introduction

This compilation lists 118 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 there are 23 reports listed that discuss gravity measurements in mine shafts and underground diggings, such as coal, copper and salt mines.

A little over half of the reports were published with abstracts that are reproduced here. However, many have been abridged because of their length. For the rest of the reports, short abstracts have been added, except for those in foreign languages which 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. Reports listed in more than one category have the letter or letters of the other categories listed after the report number.

This list was compiled by searching the reference lists in the borehole gravimetry reports known to me and then by obtaining these references and checking their references, etc. Cumulative indexes for Geophysics and the Society of Professional Well Log Analysts (SPWLA) publications were checked. Colleagues were asked if they knew of any reports. This list is believed to be comprehensive although a few papers may have been overlooked.

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

II. Discussion

Reports on subsurface gravimetry started appearing with regularity about 30 years ago. Only four reports (nos. 1, 3, 4, and 95) predate 1949. Figure 1, a graph showing the number of reports published each year, shows that there were three periods of activity. The first was in the early to mid 1950's and a number of good theoretical papers were published including report no. 43 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 included report nos. 38 and 40. The third period started in the mid 1970's and continues to the present. This group contains some good case history studies.

Almost half of the reports were published in U.S. Geological Survey (USGS) publications and in Geophysics. Figure 2 shows the distribution of the bibliography by publisher.

The first category (section A) contains reports that pertain to theory, methods, data reduction and applications. Several reports in this section are noteworthy; namely nos. 50, 38, 40, and 5. Report no. 19 is a good beginning reference. There is now a good set of literature on terrain corrections and this includes report nos. 7, 8, 9, 23, 31, and 49. The following reports contain discussions on deducing structure away from the borehole: nos. 16, 24, 26, 28, and 51.

Section B contains 20 reports that pertain to instrumentation. Within borehole gravimetry, there are two types of instruments that have been developed: (1) vibrating filament, and (2) astatized spring. Esso Production Co., Exxon, and Shell Development have built instruments of the first type which are discussed in report nos. 63, 64, 66, 68, and 73. LaCoste and Romberg makes the only borehole gravity meters (BHGM) of the second type. Report nos. 5, 60, 61, 69, 71, 72, and 76 describe these meters.

Section C lists 40 reports that contain case histories. Eleven of these reports are also listed in sections A and B. Case histories are given for surveys run in boreholes and in underground mines in the following states and countries: Arizona, California, Colorado, Michigan, Missouri, Nevada, New Mexico, Ohio, Texas, West Virginia, Wyoming, Canada, England, Germany, India, and Libya.

Section D lists reports that contain only basic gravity data with reductions and corrections. Additionally, report nos. 106, 107, 110, 116, 117, and 118 contain preliminary density and (or) porosity determinations, and Gamma-ray logs are included in report nos. 108, 109, 111, 113, 114, 115, and 116. Data are from the following states: California, Colorado, Florida, Michigan, Nevada, New Mexico, Texas, Washington, West Virginia, and Wyoming.

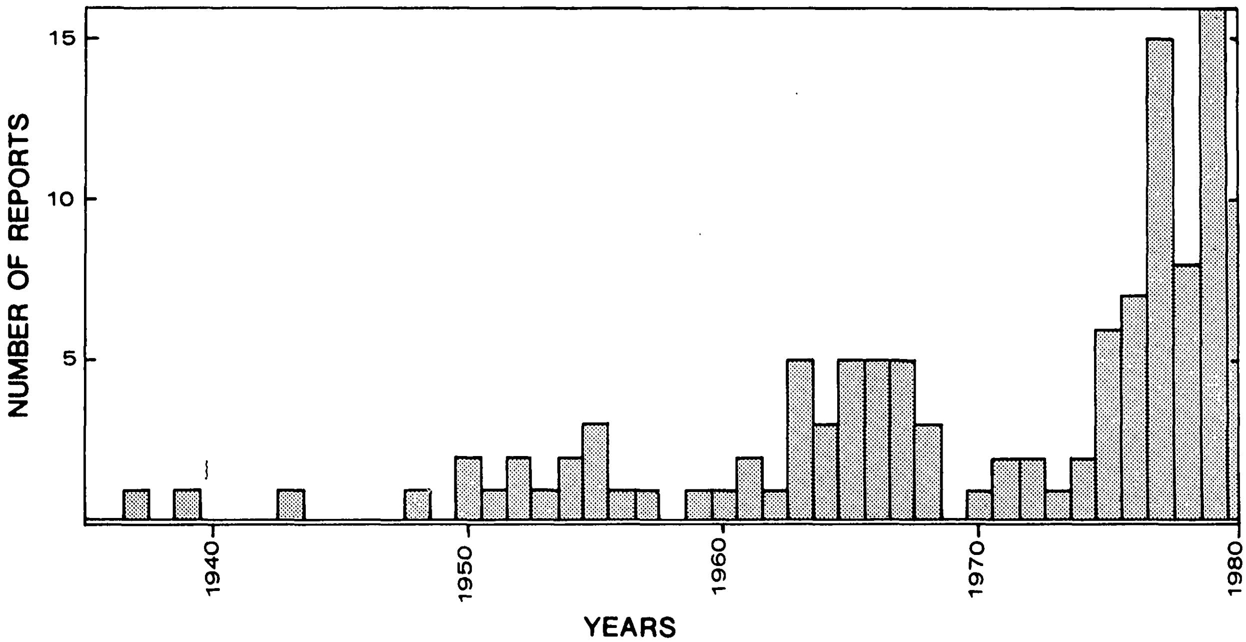

FIGURE 1. Number of reports and abstracts on subsurface gravimetry published per year between 1937 and 1980.

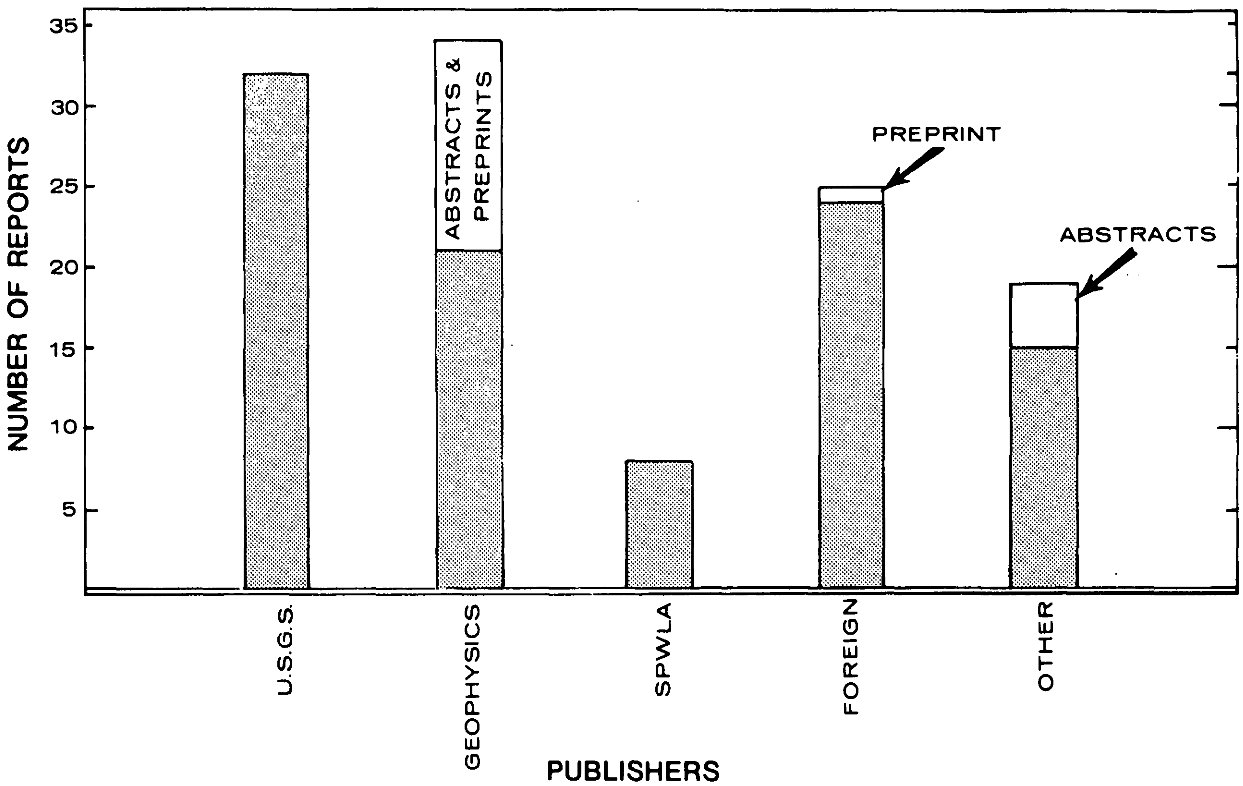

FIGURE 2. Number of subsurface gravity reports by publisher.

III. Bibliographic list with abridged abstracts.

A. Theory, methods, data reduction, and applications.

1-C. 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 Philos. Trans., 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.

2. Allen, W. A., Jr., 1956, The gravity meter in underground prospecting: A.I.M.E. Trans., v. 205, p. 293-295.

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

3. Barnitzke, J. E., 1943, Bestimmung der Bodendichte aus gravimetermessungen: Beitr. zur Angew. Geophys., v. 10, p. 85-95.

Determination of the Earth's density from gravimeter measurements.

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

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

5-B,C. 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 0.05 g/cm^3. Adjusted profiles for the same wells agree with core densities to within 0.01 g/cm^3 on the average. Densities of an adjusted profile of a seventh well are 0.15 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 0.05 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 0.00025 to 0.00050 mgal/ft (8 to 16 Eötvös units) for vertical intervals as small as 10 feet (3 meters).

6. ______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 foled 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.

7. ______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.

8. ______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 no. 7.

9. 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 Nat'l Tech. Inform. Service, Springfield, Virginia.

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 report no. 23.

10. Beyer, L. A., Brune, R. H., and Schmoker, J. W., 1975, Application of borehole gravity to exploration for petroleum [abs.]: Program 50th Ann. Pacific Section Meeting, AAPG-SEPM-SEG, 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 (0.005 to 0.03 gm/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 inch 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.

11. 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 towers 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 geophysis and archaeology are included.

12. Bodemüller, H., 1954, Der schwereunterschied in korrespondierenden punkten über und unter tage: Stuttgart, Zeitschr. fur Verm. Wesen., v. 79, no. 8, p. 263-268.

The gravity difference between corresponding points above and below ground.

13-C. Bradley, J. W., 1976, The commercial application and interpretation of the borehole gravimeter, <u>in</u> Jantzen, R. E., ed., Tommorow's oil from today's provinces: American Assoc. Petro. Geologists, Pacific Section, Miscellaneous Pub. 24, p. 98-109.

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, Michigan.

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

See report no. 15 for abstract.

15. ______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.

16. Coyle, L. A., 1976, The application of borehole gravimetry to remote sensing of anomalous masses: Purdue Univ., unpub. MS 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.

17-C. Domzalski, W., 1954, Gravity measurements in a vertical shaft: London, Bull. Inst. Mining and Metallurgy Trans. 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.

18-C. ______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.

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.

19. EDCON, 1977, Borehole gravity meter manual: Lakewood, Colorado, EDCON, 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.

20-b. Egyed, Lazlo, 1960, Zur frage der Schweremessungen in Bohrlöchern: Freiburger Forschungshefte C81, Geophysik, p. 167-170.

To the question of gravity measurements in boreholes.

In the case of the determination of the various physical parameters in boreholes, the ability to determine the background density has come. We will be able to undertake a density profile, provided we have a method for the determination of the average vertical gradient

$$\bar{U}_{zz} = \frac{g_2 - g_1}{h}$$

where, then $g_2 - g_1 = 4\pi fh\chi\ \sigma = C\ \sigma$.

σ is the average density between the points 1 and 2, χ 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 present technical ability. The author has designed also some fundamental and practical aspects of the construction of such instruments.

21-C. 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 report nos. 65 and 96 for reference to instrument

calibration error in this report. This error negates some of the above conclusions.

22. _________1963, Rock densities and vertical gradient of gravity in the earth's crust: Jour. Geophysical Research, v. 68, no. 2, p. 603-604.

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

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

This report describes the method and formulae used in a computer program written for the application of terrain corrections to borehole gravimetry measurements. See report no. 9 for an improved procedure.

24. ______1977a, On the range of investigation of a borehole gravimeter: SPWLA 18th Annual Logging Symposium Trans., 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^{o} 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%, etc., of that of an infinite horizontal slab is a function of the measurement spacing. The closer the measurement spacing, the more information obtained.

25. ______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.

26. ______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 Nat'l. Tech. Inform. Ser., Springfield, Virginia.

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.

27. 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.

28-C. 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.

29. 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 Nat'l Tech. Inform. Ser., Springfield, Virginia.

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.

30. 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.

31. _______1980, Effects of terrain on borehole gravity data: Geophysics, v. 45, no. 2, p. 234-243.

See report no. 30 for the abstract.

32. Jageler, A. H., 1976, Improved hydrocarbon reservoir evaluation through use of borehole gravimeter data: Jour. 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 heterogenity 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.

Future applications of borehole gravity data indicates a need for developing new logging devices to complement the deep investigation ability of the borehole gravimeter.

33. 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.

34. Kazinskii, V. A., 1963, The means of development and methods of solving problems of underground gravimetry: Bulletin (Izvestiya) Academy of Sciences, USSR, 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.

35. Lukavchenko, P. I., 1948, K voprosu ob izmereniyakh sily tyazhesti v burovykh skvazhinakh: Applied Geophysics, v. 4, Gostoptekhizd.

The problem of gravity measurements in wells.

36. ______1955, Gravity measurements in boreholes; Prikladnaya Geopizika, no. 12, p. 157-176; Translated August 1959, Liaison Office, Tech. Inform. 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.

37. 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.

38. ________1966b, The promise of precise borehole gravimetry in petroleum exloration 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.

39. ________1967a, Borehole gravimetry--new developments and applications <u>in</u> Origin of oil, geology and geophysics: London, Elsevier Publishing Co, 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 milligal began a new era of subsurface geophysical research.

Full use of such high precisions require 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.

40. ______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.

41-C. McCulloh, T. H., Kandle, J. R., and Schoellhamer, J. E., 1968, Application of gravity measurements in wells to problems of reservoir evaluation: SPWLA 9th Annual Logging Symposium Trans., p. 01-029.

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.

42-C. 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.

43. 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 the meters and their limitations that are available.

44. Rasmussen, N. F., 1973, Borehole gravity survey planning and operations: SPWLA 14th Annual Logging Symposium Trans., 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 percent 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.

45. ________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.

46. ________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.

47-C. 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 underground. Case histories in central Germany.

48. Robbins, S. L., in press, Reexamination of the values used as constants in calculating rock density from borehole gravity data: Geophysics.

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.

49. Schmoker, J. W., in press, Terrain effects of cultural features upon shallow borehole gravity data: Geophysics.

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.

50. 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.

51. Snyder, D. D., 1976, The borehole Bouguer gravity anomaly--application to interpreting borehole gravity surveys: SPWLA 17th Annual Logging Symposium Trans., 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.

52. 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.

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

53. 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.

54. __________1964, 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.

55. __________1965a, Determination of the vertical density gradient in a borehole: Geophysics, v. 30, no. 3, p. 439-440.

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

56. __________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.

57. Vaschilov, U. N., 1964, Ōochye vliyäniyä ryelyefa myestnosti pri gravimyetrichyeskikh nablûdyeniyakh v podeyemnëkh gornëkh vërabotkakh i skvazhnakh: Razvedochnaya i Promyslovaya Geofizika, v. 51, p. 71-75.

Allowance for the effects of the relief of the locality in gravimeter observations in underground workings and boreholes.

58. Zagonov, A. V., and Lukavchenko, P. I., 1974, Opryedyelyeniye izbëtochnoē plotnosti vozmōōshchaūshchikh obyektov po dannëm nazemnoë i skvazhinnoë gravirazvedki s pomoshchǖ lineënogo programmirovaniyä: Prikladnaia Geofizka, v. 75, p. 158-165.

The excess density estimation of disturbing bodies from surface and borehole gravimetry observations with the use of linear programming.

B. Instrumentation and data accuracy and precision.

59. Baker, G. E., 1977, Gravity instrument cannister feasibility study: San Ramon, California, EG&G, Report no. GEB77-57, 63 p.

A feasibility study was made for a cannister to contain a gravity instrument used for well logging. The cannister will protect the gravity instrument for a typical 30-hour logging cycle in an environment of 350°C and 17,000 psi. The internal cannister temperature will be maintained at a nominal 100°C. The cannister has a diameter of 5 in. and a length of 18 ft. The housing for the gravity instrument has a diameter of 3-9/16 in. and a length of 6 ft.

This report describes: (1) preliminary specifications for the cannister, (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 cannister.

60. 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 the 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.

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

See report no. 5-a for abstract.

61. Byerly, K. A., 1977, A field test for borehole gravity meter precision in shallow wells: Colorado Univ., unpub. MS 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.

62. 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.

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

See report no. 20-a for abstract.

63. 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.

64. 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.

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

This report confirms report no. 96's finding that the gravity meter used in Hammer's earlier report (no. 21-a) had a calibration error of about 12 percent.

66-c. 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.

67. 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 described 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 0.02 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.

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

See report no. 67 for abstract.

69. 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. 369-700.

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

70. Lukavchenko, P. I., 1962, Nabliûdeniiâ s gravimetrami v burov′ykh skvazhina i shakhtakh: Razvedochnaiâ i Promyslovaiâ Geofizika, no. 43, p. 52-64.

Observations with gravimeters in boreholes and mine shafts.

71. McCulloh, T. H., LaCoste, L. J. B., Schoellhamer, J. E., and Pampeyan, E. H., 1967a, The U.S. Geological Survey-LaCoste and Romberg precise borehole gravimeter system--instrumentation and suppport 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 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.

72. McCulloh, T. H., Schoellhamer, J. E., Pampeyan, E. H., and Parks, H. B., 1967b, 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.

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

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

74. 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 accomodate most conventional wireline tools.

75. _______ 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.

See report no. 74 for abstract.

76. 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 ±0.02 g/cm^3 or less.

C. Case histories.

1-a. Airy, G. B., 1856, Account of pendulum experiments undertaken in the Harton Colliery for the purpose of determining the mean density of the earth: Royal Soc. [London] Philos. Trans., v. 146, nos. 14, 15, p. 297-355.

See report no. 1-a for abstract.

77. 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 survey were easily located.

5-a,b. 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.

See report #5-a for abstract.

78. ______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 post depositional processes) intersect or occur within dectable 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.

79. _______1979, Borehole gravity study of the density and porosity of selected Frontier, Tensleep, and Madison reservoirs in the Bighorn Basin, Wyoming [abs.]: American Assoc. 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.

80. _______1980, Benefits of borehole gravity studies in the San Joaquin Basin, and suggested future work [abs.]: Program 54th Ann. Meeting, Pacific Sections, AAPG-SEPM-SEG, Bakersfield, California, April 9-11, p. 61.

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. The maximum temperature limit of the borehole gravity meter (about 115°C) will continue to limit the depth to which surveys can be made, until a sonde is developed that will shield the gravity meter against higher downhole temperatures.

81. 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 pl., 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.

82. ______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 pl., 16 p.

This report interprets rock density and porosity changes through 5,083 ft of Pennsylvanian to Late 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.

83. ______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 pl.

This report analyzes rock density and porosity changes through 5,359 ft of Permian to Late 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.

84. 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.

85. Bradley, J. W., 1975, The application of the borehole gravimeter to the evaluation and exploration of oil and gas reservoirs: Preprint, SEG 45th Annual Meeting, Denver, Colorado, 8 p., 7 fig.

In recent years, Amoco Production Co. has evaluated approximately 80 wells with the La Coste-Romberg borehole gravimeter. A large number of these surveys have been in the search for and evaluation of commerical 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 succesfully been isolated where normal logging procedures have failed. This application has been especially successful economically.

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

See report no. 85 for abstract.

13-a. ______1976b, The commercial application and interpretation of the borehole gravimeter, in Jantzgen, R. E., ed., Tomorrow's oil from today's provinces: American Assoc. Petro. Geologists, Pacific Section, Miscellaneous Pub. 24, p. 98-109.

See report 13-a for abstract.

87. Cook, A. H., and Thirlaway, H.I.S., 1951, A gravimeter survey in the Bristol and Somerset Coalfields: Geol. Soc. London Quart. Jour., 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.

17-a. Domzalski, W., 1954, Gravity measurements in a vertical shaft: Bull. Inst. Mining and Metallurgy Trans. 571, v. 63, p. 429-445.

See report no. 17-a for abstract.

88. _______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.

18-A. ______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.

See report no. 18-a for abstract.

89. Drake, R. E., 1967, A surface-subsurface measurement of an anomaly in the vertical gradient of gravity near Loveland Pass, Colorado: Univ. of California at Riverside, unpub. MS 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/cc for the intervening mass of rock. The results show an anomaly in the normal vertical gradient of gravity ranging from +0.04 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.

90. Farlay, D. G., 1971, Application of the downhole gravity meter for porosity determination: Preprint, Libyan Assoc. 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.

91. 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.

92. 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.

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

See report no. 21-a for abstract.

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

The basic principles that have made the borehole gravity meter 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.

94. 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.

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

See report no. 28-a for abstract.

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

See report no. 66-b for abstract.

95. Jung, Heinrich, 1939, Dichtebestimmung in anstehenden Gestein durch Messung der Schwerebeschleunigung in verschiedenen Tiefen unter Tage: Zietschr. Geophysik, v. 15, p. 56-65.

Density determinations in the solid rock through measurement of the gravity acceleration at differing depths beneath the surface. Measurements were made in the Wilhelms Shaft near Clausthal, Germany.

96. 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 no. 21-a), 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.

41-a. McCulloh, T. H., Kandle, J. R., and Schoellhamer, J. E., 1968, Application of gravity measurements in wells to problems of reservoir evaluation: SPWLA 9th Annual Logging Symposium Trans., p. 01-029.

See report no. 41-a for abstract.

42-a. 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.

See Report no. 42-a for abstract.

97. 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, Colorado. This study is part of a regional gravity survey of the Colorado Rocky Mountains.

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

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.

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

See report no. 47-a for abstract.

99. Robbins, S. L., 1979, Density determinations from borehole gravity data from a shallow lignite zone within the Denver Formation near Watkins, Colorado: SPWLA, 20th Annual Logging Symposium Trans., 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.

100. 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.

101. 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 0.30 g/cc. 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.

102. ________1977b, A borehole gravity survey to determine density variations in the Devonian shale sequence of Lincoln County, West Virginia: U.S. Dept. 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 0.034 g/cm^3/1000 ft (0.112 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.

103. ________1979, Interpretation of borehole gravity surveys in a native-sulfur deposit, Culberson County, Texas: Economic Geol., 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.

104. ______in press, 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-.

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.

105. Sumner, J. S., and Schnepfe, R. N., 1966, Underground gravity surveying at Bisbee, Arizona _in_ Mining Geophysics, v. 1, case histories: SEG, 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.

D. Reports containing only basic gravity data and reductions with some preliminary density and porosity determinations.

106. Beyer, L. A., in press, Narrative and basic data of the U.S. Geological Survey borehole gravity program (1963-1975): U.S. Geological Survey Open-file Report 80- .

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.

107. Byerly, 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 nos. 3, and 2.

108. 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 is also reproduced.

109. _______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 are also presented for wells PM-1 and 5a.

110. 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.

111. 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 (including instrument drift corrections curves) plus reduction corrections. Gamma-ray and CCL logs are also included.

112. 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.

113. 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.

114. _______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.

115. 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.

116. 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.

117. 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.

118. Secor, G. B., 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.

IV. Author Index

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