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BOREHOLE GRAVITY SURVEYS: THEORY, MECHANICS, AND NATURE OF MEASUREMENTS

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ABBREVIATIONS, SYMBOLS, AND DEFINITIONS

BHGM	Borehole gravity meter
Anomalous density structure or lateral density variations	Any stratigraphic, structural or diagenetic effect that causes surfaces of equal density in the earth to depart from the horizontal
$\Delta g/\Delta z$	Interval vertical gradient of gravity measured in borehole
g_{error}	Error in borehole gravity reading
z_{error}	Depth mislocation of a reoccupied borehole gravity station or relative to a rock layer
Δg	Gravity difference measured between two locations in the borehole
Δg_{error}	Error in gravity difference due to either instrumental factors or depth mislocation, or both
Δz	Measured depth difference between two borehole gravity stations
Δz_{error}	Error in measured depth difference
ΔG_t, ΔG_b, ΔG_g	Fractional parts of measured $\Delta g/\Delta z$ that are due to topographic, borehole, and anomalous density structure
$\bar{\phi}$, $\bar{\rho}$, $\bar{\rho}_g$, $\bar{\rho}_f$,	Average interval total porosity, density, grain or matrix density, and pore fluid density that are calculated from $\Delta g/\Delta z$ or otherwise determined for the Δz interval

ϕ, ρ, ρ_g, ρ_f	Same as above except for a point location or core sample
"Natural" density	Water-saturated bulk density calculated from measurements of conventional core samples
γ-γ log	Gamma-gamma density log (formation density log)
F	Average value of theoretical free-air vertical gradient of gravity based on the 1967 Geodetic Reference System (.09406 mgal/ft)
k	Universal Gravitational Constant
LC&R	LaCoste and Romberg Company--manufacturer of presently-used BHGM

(see page 3 for definition of gravity units)

(see page 34 for constants and conversions used in BHGM surveys)

BOREHOLE GRAVITY SURVEYS: THEORY, MECHANICS AND NATURE OF MEASUREMENTS

1.0 INTRODUCTION

1.1 Introductory Remarks

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

Borehole gravity measurements are responsive primarily to the vertical density variations in the rocks traversed by the survey and secondarily to lateral rock density variations (anomalous density structure) of detectable magnitudes that may occur in the region surrounding the surveyed well. These measurements investigate a much larger volume of rock surrounding the well than do conventional logging methods.

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 (gravimetric) interval 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.

1.2 Gravity Exploration

Gravity exploration is based on Newton's Law of Universal Gravitation

$$\text{Force} = k\,\frac{M_1 M_2}{R^2} \qquad (1\text{-}1)$$

This law states that, between any two massive objects, there is a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. Thus, the force of attraction is larger for larger masses but decreases rather rapidly for increasing distance between the masses. The constant of proportionality (k) is the universal Newtonian gravitational constant which can be determined from a common physics experiment with a Cavendish-type balance.

The most recent and reliable value for the universal Newtonian gravitational constant is given by Luther and Towler (1981):

$$k = 6.6726 \pm .0005 \times 10^{-11}\ m^3 sec^{-2} kg^{-1}$$

This new number for k represents only a slight change in value but a significant improvement in precision over the generally accepted value of

$$6.6720 \pm .0041 \times 10^{-11}\ m^3 sec^{-2} kg^{-1}.$$

See Nettleton (1976, p. 10-13) for a historical summary of the determination of k and description of the Cavendish balance.

The force acting on the sensitive element of a gravity meter is given by eq. (1-1) if M_1 is the mass of the earth and M_2 is the mass of the sensitive element. The force acting on the sensitive element M_2 may also, from Newton's Second Law of Motion, be expressed as

$$\text{Force} = M_2 a \qquad (1\text{-}2)$$

where a is the acceleration M_2 experiences under the gravitation force. Equations (1-1) and (1-2) may be combined to obtain an expression for gravity

$$g = \frac{\text{Force}}{M_2} = k \frac{M_1}{R^2} \tag{1-3}$$

Gravity is expressed in units of force per unit mass or acceleration. In geophysics the unit of acceleration has been named the "gal":

$$1 \text{ gal} = 1 \text{ cm/sec}^2 \approx 10^{-3} \text{ "g"}$$

The specific unit of measurement usually used in gravity surveys is the milligal (mgal) which is used in this report:

$$1 \text{ mgal} = 10^{-3} \text{ cm/sec}^2 \approx 10^{-6} \text{ "g"}$$

Sometimes "gravity units" (gu) are used for detailed surface gravity surveys:

$$1 \text{ gu} = 0.1 \text{ mgal} = 10^{-4} \text{ cm/sec}^2 \approx 10^{-7} \text{ "g"}$$

Units of microgals (μgals) are used occasionally in borehole, tidal, or very high precision surface gravity surveys:

$$1 \ \mu\text{gal} = 10^{-3} \text{ mgal} = 10^{-6} \text{ cm/sec}^2 \approx 10^{-9} \text{ "g"}$$

Gravity meters in use today are sensitive only to the total component of gravitational acceleration measured in the direction of the local plumbline. Consequently, the acceleration experienced by the sensitive mass of the gravity meter is

$$g_i = k \frac{m_i}{r_i^2} \cos \phi_i \tag{1-4}$$

for a mass m_i located at a distance r_i and at an angle ϕ from the local vertical line through the gravity meter (Figure 1-1).

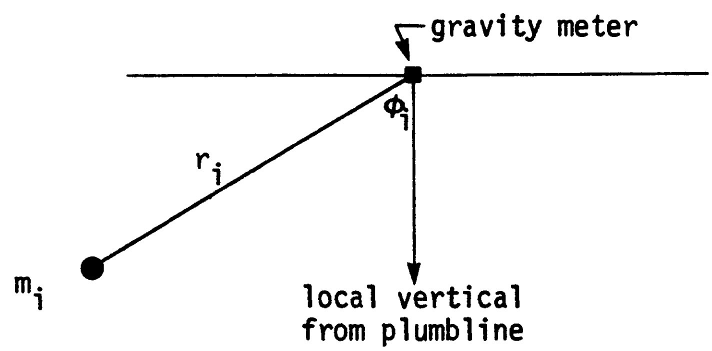


Figure 1-1. Notation for the gravitational attraction of a point mass.

If the gravity meter is moved to another location, both distance r_i and the angle ϕ_i probably change so that acceleration g_i due to the mass m_i is different. The local vertical from the plumbline may also change very slightly but this change is ignored in exploration surveys with gravity meters.

Gravity exploration of the earth usually involves questions of the spatial distribution of rocks whose masses are unknown but whose densities and volumes are partly known or can be inferred. Remembering that

$$\text{mass} = (\text{density})\ (\text{volume})$$

eq. (1-4) can be written

$$g_i = k\ \frac{\rho_i v_i}{r_i^2}\ \cos\ \phi_i \qquad (1\text{-}5)$$

where ρ_i and v_i are small density and volume elements.

In the practical case of spatially distributed mass, density-volume elements can be summed by integration. Equation (1-5) becomes, in practical form,

$$g = k \int_V \frac{\rho}{r^2}\ \cos\phi\ \ dv \qquad (1\text{-}6)$$

where dv is a volume e'ement and $\int_V$ represents a summation of the volume elements over the volume V. For example, the gravitational acceleration experienced by the sensitive mass of a gravity meter due to a spherical mass of radius R and constant density ρ located at a distance r (Figure 1-2) is

$$g = k\rho \frac{4\pi R^3}{3} \frac{1}{r^2} \cos\phi \qquad (1\text{-}7)$$

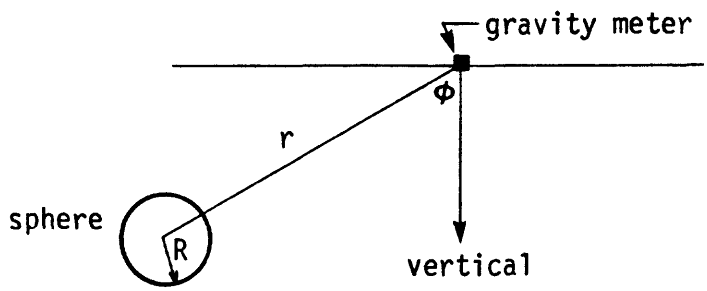


Figure 1-2. Notation for the gravitational attraction of a sphere of radius R and density ρ located at a distance r from the gravity meter.

but the mass of sphere is

$$m = \frac{4}{3}\pi\rho R^3 \qquad (1\text{-}8)$$

so that

$$g = \frac{km}{r^2} \cos\phi \qquad (1\text{-}9)$$

Thus, the gravitational acceleration due to a sphere of constant density is the same as it would be if its entire mass were concentrated at a point at its center.

Another useful example of particular importance in borehole gravity is the gravitational acceleration experienced by a gravity meter located along the vertical axis of a right circular cylinder (Figure 1-3a). In this case, the gravitational acceleration is (Nettleton, 1976, p. 199)

$$g = 2\pi k\rho[\Delta z + (R^2 + z)^{1/2} - (R^2 + (z + \Delta z)^2)^{1/2}] \qquad (1\text{-}10)$$

Fig. 1-3a

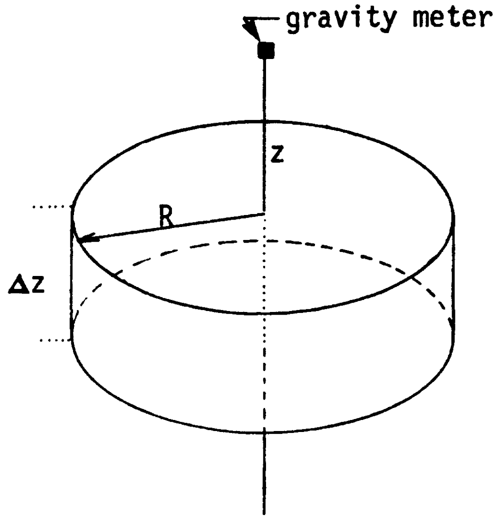


Fig. 1-3b

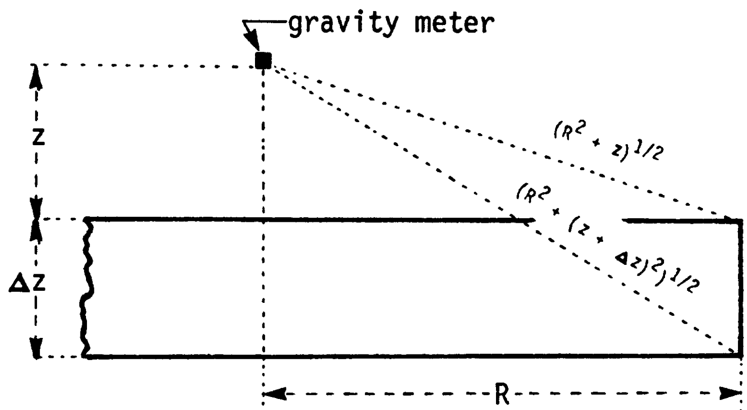


Figure 1-3. (a) Notation for the gravitational attraction at a height z along the vertical axis of a right circular cylinder of radius R and thickness Δz. (b) Section view of portion of right circular cylinder showing terms of eq. (1-10).

An extremely important formula for borehole gravity is obtained if the radius R of the cylinder is allowed to become very large. As R becomes large

$$(R^2 + z^2)^{1/2} - [R^2 + (z + \quad z)^2]^{1/2} \longrightarrow 0$$

so that eq. (1-10) becomes

$$g = 2\pi k \bar{\rho} \Delta Z \qquad (1\text{-}11)$$

According to eq. (1-11), the gravitational acceleration due to an infinitely-extended horizontal slab depends only on its density ρ and thickness Δz, not on the distance above it! The importance of this relationship will become evident later.

By following the density-volume integration given in eq. (1-6), it is possible to calculate the gravitational acceleration at any point due to any massive body that can be defined in terms of density and volume. In this way density models can be constructed to simulate proposed geologic models and the gravity accelerations they cause can be calculated and compared with measured gravity values.

When measured gravity variations over the earth's surface are adjusted for the overall average gravity field of the earth, differences in centrifugal acceleration caused by the earth's rotation, height differences between gravity stations, and effects caused by the irregular topographic surface, the remaining variations are gravity anomalies. Useful gravity anomalies occur because the distribution of mass in the earth is not radially symmetrical but varies in lateral directions, especially in the earth's crust. A gravity anomaly map of the Los Angeles Basin which shows a pronounced gravity anomaly low over the less dense sedimentary rocks of the basin is given in Figure 1-4.

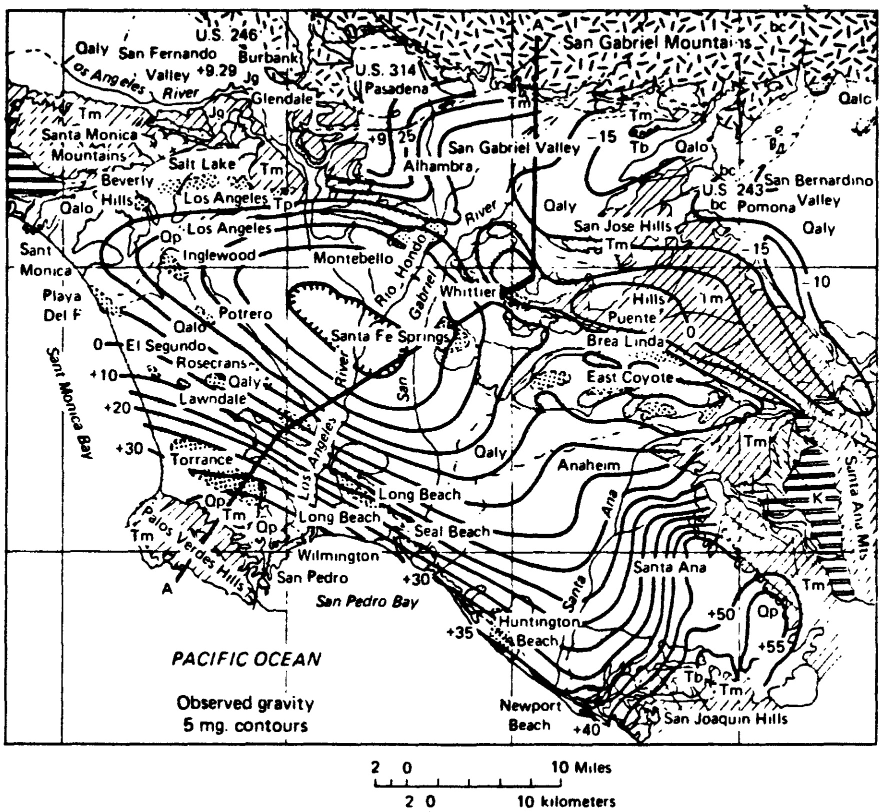


Figure 1-4 Bouguer gravity anomaly map imposed over a surface geologic map, Los Angeles Basin (modified by Nettleton, 1976, after U.S. Geol. Sur. Prof. Paper 190).

In order to understand the meaning of gravity anomaly maps, density models are generated from geologic evidence of the spatial distribution and densities of subsurface rocks. Gravity accelerations or anomalies are calculated from these models by the density-volume integration method described earlier. Information is rarely available to initially construct density models so that the anomalies calculated from them agree with anomalies mapped over the earth's surface. However, adjustments made to density models so that their associated anomalies closely approximate actual mapped anomalies can lead to new exploration information.

Two important aspects of practical gravity studies need to be mentioned. First, gravity anomalies are generated by density contrasts rather than absolute densities. For example, a gravity anomaly low usually occurs over a salt dome because the salt is less dense than the surrounding rock. Figure 1-5 illustrates the concept of density contrasts for the case in which a simple anticlinal fold has brought more dense rock strata upward into contrast with less dense surrounding strata.

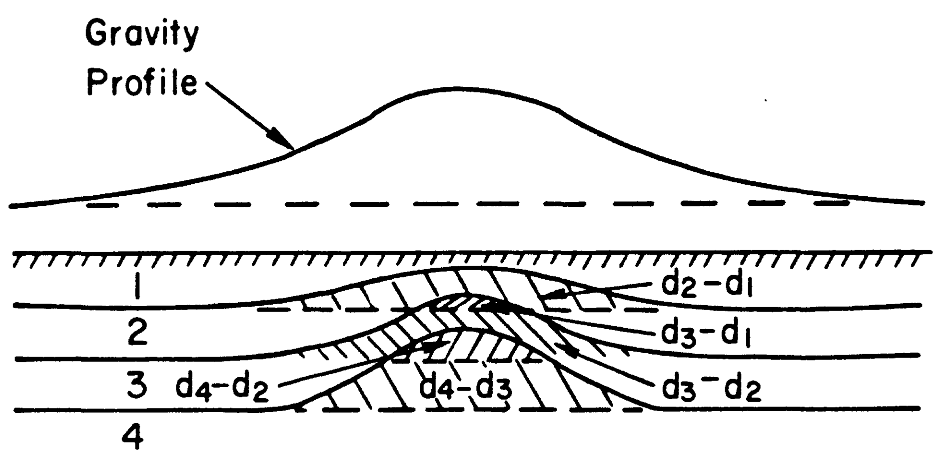


Figure 1-5. Density layers, density contrasts, and gravity anomaly(from Nettleton, 1971).

A second important practical aspect is the non-uniqueness of density models. In theory, an infinite number of density-volume configurations can be devised to generate the same gravity anomaly. Because of this "ambiguity in interpretation" geologic control and sensibility must govern all interpretations made in gravity exploration. Figure 1-6 illustrates how different density-volume configurations generate the same gravity anomaly.

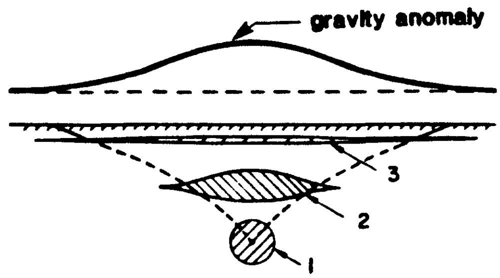


Figure 1-6. Different massive bodies that can account for the same gravity anomaly. The sphere (1) is the deepest body that can approximately account for the gravity anomaly shown. Shallower and broader bodies, such as 2 and 3, also can account for the anomaly. The density contrast of each body is different but the total mass anomaly of each, relative to the surrounding rocks, is the same (from Nettleton, 1971).

There are many more aspects of gravity exploration than are appropriate to describe here. The many excellent introductions to the gravity exploration method should be consulted for more detailed explanations (e.g., Nettleton, 1976; Grant and West, 1965; Telford and others, 1976).

1.3 Fundamental Equation of Borehole Gravity

Formulation of the distribution of gravity within a simple density model of the earth leads to the fundamental equation of borehole gravity. If the earth is assumed to be a non-rotating perfect sphere with a radially symmetrical density distribution and is isolated from the gravitational fields of other massive bodies, then gravity and the vertical gradient of gravity in free-air on the earth's surface are

$$g = k \frac{M}{R^2} \tag{1-12}$$

$$\partial g/\partial r_{r=R} = -\frac{8}{3}\pi k \bar{\rho}_R \tag{1-13}$$

where M, R, and $\bar{\rho}_R$ are the mass, radius, and mean density of the earth respectively.

At an internal point any distance r from the center of the earth, the mass of interior sphere of radius r is

$$m_r = 4\pi \int_0^r \rho(r) r^2 dr$$

where $\rho(r)$ is the internal density as a function of r. Substitution of m_r for M and r for R in eq. (1-12) gives gravity at this internal point

$$g = \frac{4\pi k}{r^2} \int_0^r \rho(r) r^2 dr \qquad \text{(Benfield, 1937)}$$

since the net attraction at r of the spherical shell between r and R is zero (Ramsey, 1940). The vertical gradient at this internal point is

$$\partial g/\partial r = \frac{4\pi k}{r^2}\frac{\partial}{\partial r}\int_0^r \rho(r)r^2 dr + \int_0^r (r)^2 dr \frac{\partial}{\partial r}\frac{4\pi k}{r^2}$$

$$\partial g/\partial r = 4\pi k\rho - \frac{8}{3}\pi k\bar{\rho}_r \qquad \text{(Miller and Innes, 1953) (1-14)}$$

where ρ is the density of the infinitesimally thin spherical shell of radius r and $\bar{\rho}_r$ is the mean density of the interior sphere of radius r. See Gutenberg (1959), Hammer (1963), and Beyer (1971) for further information and slightly different ways to derive eq. (1-14).

Because borehole gravity surveys involve measurements of finite gravity (Δg) and depth (Δz) increments, an equation in incremental instead of differential notation is needed. Although eq. (1-14) can be written in incremental notation to satisfy the requirements of borehole gravity, an intuitive derivation of the fundamental equation of borehole gravity in incremental notation follows from consideration of gravity at the outer (g_1) and inner (g_2) surfaces of a spherical shell (Figure 1-7):

$$g_1 = kM/R^2 \qquad\qquad g_2 = k(M - \Delta M)/(R - \Delta z)^2 \qquad (1\text{-}15)$$

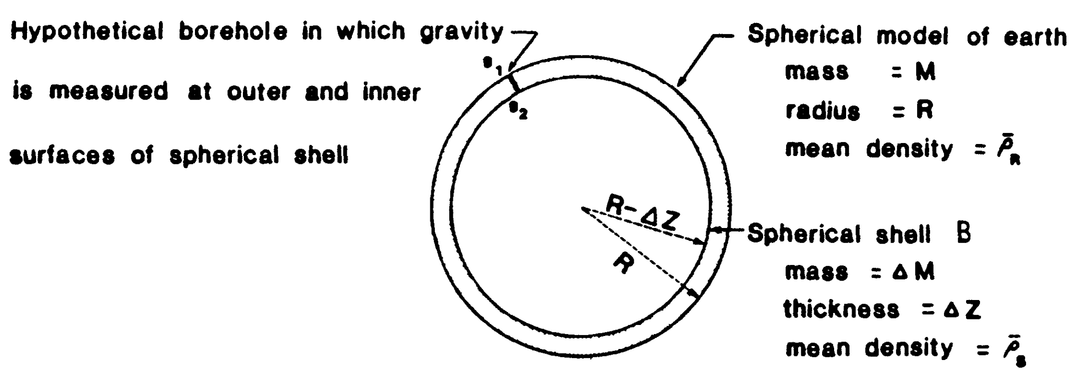


Figure 1-7. Schematic diagram of hypothetical BHGM measurements at the outer and inner surfaces of a spherical shell.

There is no gravity component in g_2 due to the spherical shell B for an earth with a radially symmetrical density distribution because the net gravitational acceleration due to a spherical shell is zero at points on its inner surface and inside of it (e. g., see Ramsey, 1940, p. 46).

The gravity difference (Δg) between the inner and outer surfaces of shell B (Figure 1-7) is

$$\Delta g = k \quad \frac{M-\Delta M}{(R-\Delta z)^2} - \frac{M}{R^2} \tag{1-16}$$

Factoring $\frac{M}{R^2}$ out of the right side of eq. (1-16) by dividing the numerator by M and the denominator by R^2 gives

$$\Delta g = k\frac{M}{R^2} \quad (1 - \frac{\Delta M}{M})(1 - \frac{\Delta z}{R})^{-2} - 1 \tag{1-17}$$

The term $(1 - \frac{\Delta z}{R})^{-2}$ can be expanded in the series

$$(1 - \frac{\Delta z}{R})^{-2} = 1 + 2\frac{\Delta z}{R} + 3(\frac{\Delta z}{R})^2 + \ldots \tag{1-18}$$

and

$$\frac{\Delta M}{M} = \frac{\bar{\rho} s}{\bar{\rho} R} \quad 1 - (1 - \frac{\Delta z}{R})^3 \tag{1-19}$$

where $(1 - \frac{\Delta z}{R})^3$ can be expanded in the series

$$(1 - \frac{\Delta z}{R})^3 = 1 - 3\frac{\Delta z}{R} + 3(\frac{\Delta z}{R})^2 - \ldots \tag{1-20}$$

Second and higher order terms in these series (eqs. 1-18 and 1-20) can be neglected because $R \gg \Delta z$. When this is done eq. (1-17) becomes

$$\Delta g = \frac{kM}{R^2}\left[2 - 3\frac{\bar{\rho}_S}{\bar{\rho}_R}\right]\left[\frac{\Delta z}{R}\right] \tag{1-21}$$

or

$$\frac{\Delta g}{\Delta z} = \frac{8}{3}\pi k\bar{\rho}_R - 4\pi k\bar{\rho}_S \qquad \text{(Airy, 1856)} \tag{1-22}$$

when the substitution $M = \frac{4}{3}\pi R^3\bar{\rho}_R$ is made in eq. (1-21).

According to eq. (1-13), the first term in eq. (1-22) is the vertical gradient of gravity in free-air for a spherical non-rotating earth. The rotation and general ellipsoidal shape of the earth can be taken into account by replacing this term with the normal free-air vertical gradient, $\partial\gamma/\partial h$. The equation for $\partial\gamma/\partial h$ is given by Heiskanen and Moritz (1967, p. 78-79) and, with the constants of the 1967 Geodetic Reference System, becomes

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

where ϕ is the latitude and h is elevation in feet. The normal free-air vertical gradient varies from the equator to either pole by less than 0.2% and with elevation by about 0.01% per 1000 feet or 0.05% per kilometer (see e.g., Hammer, 1970). These variations are negligible for borehole gravity surveys and, as in surface gravity studies, $\partial\gamma/\partial h \approx F = .09406$ mgal/ft (Figure 1-8).

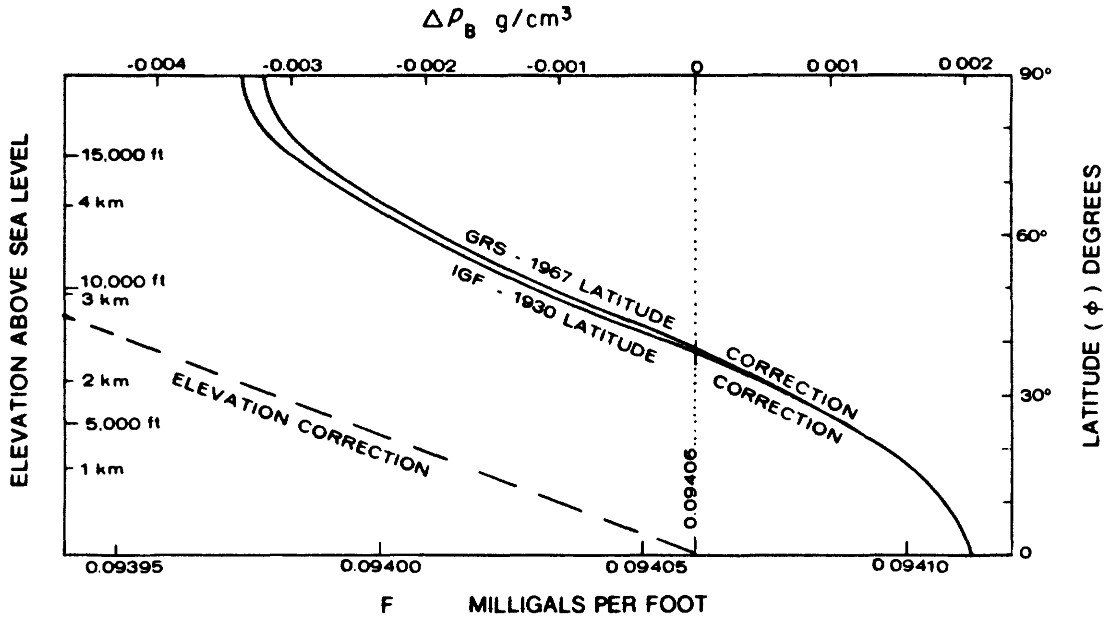


Figure 1-8. Variation of normal free-air vertical gradient, $\partial\gamma/\partial h$, with latitude and elevation. Variations with latitude are shown for both the 1930 International Ellipsoid and the 1967 Geodetic Reference System (from Robbins, 1981).

When F is substituted for this first term in eq. (1-22), the fundamental relationship between the interval vertical gradient, $\Delta g/\Delta z$, measured in a vertical borehole, and the interval density $\bar{\rho}$ of the laterally adjacent rocks for the case in which the earth possesses a radially symmetrical distribution of density is obtained.

$$\Delta g/\Delta z = F - 4\pi k\bar{\rho} \tag{1-23}$$

The subscript s has been dropped from $\bar{\rho}$ because, by neglecting the second and higher-order terms in eqs. 1-18 and 1-20, the $-4\pi k\bar{\rho}$ term applies to an infinitely extended horizontal layer of thickness Δz instead of to a spherical shell of thickness Δz. An alternative development of eq. 1-23 is presented in section 2.1

1.4 Historical Note

Underground gravity studies probably began with the pendulum measurements made during 1826, 1828, and 1854 by Airy (1856) who sought (with eq. 1-22) to determine the mean density of the earth by measuring the interval vertical gradient between the top and bottom of mine shafts. In order to determine the earth's mean density, Airy corrected the pendulum measurements for the gravitational effect of the rock section between the pendulum stations after estimating its density from laboratory measurements of bulk densities of hand samples collected from the shaft walls and after making allowances for the effect of the irregular ground surface. Experiments with similar objectives, slightly different procedures, and improved results were conducted during 1883 and 1885 by von Sterneck who swung pendulums at more than two levels in mine shafts and noted apparent non-linear changes in gravity with depth that were attributed partly to uncorrected temperature effects on the pendulums and possible to underground variation in density (Poynting, 1894, p. 29-39). Additional work with pendulums underground during the period 1871 to 1902 is tabulated by Rische (1957, p. 12).

Accurate determination of the earth's mean density from these remarkable early experiments was precluded by the relatively poor precisions of the pendulums and time-keeping procedures, the difficulty of accurately estimating the local rock density distribution from density measurements of rock samples (hence uncertainty as to the attraction of the intervening rock layer, the topography and the mine workings), and the inability (due to lack of gravity field information) to take into account possible anomalous vertical gradients. Poynting (1894, p. 39) wisely suggested the inverse problem: Determine the mean density of the earth (or the normal free-air vertical gradient) by independent means and utilize gravity measurements in vertical shafts to calculate the densities of the adjacent rocks.

An equation for the normal free-air vertical gradient that includes first-order terms for the earth's angular velocity and flattening was given by Stokes (Airy, 1856, p. 354) and later by Helmert (1884, p. 96). By the early 1900's the earth's flattening and equatorial radius were known with sufficient accuracy for Helmert (1925) to calculate a mean value for the normal free-air vertical gradient that has remained essentially unchanged during subsequent refinements of the reference ellipsoid. A second prerequisite to Poynting's suggestion--a method for determining gravity differences in mine shafts with relative ease and high accuracy--was fulfilled by the development of the portable gravimeter during the 1930's.

Gravimeter measurements have been made in mine shafts principally (1) to determine the densities of adjacent rocks (Jung, 1939; Hammer, 1950; Bodemuller, 1954; Domzalski, 1954; Whetton and others, 1957; McLean, 1961; Lukavchenko, 1962; Secor and others, 1962; Bhattacharji, 1963; McCulloh, 1965; Healy, 1970), (2) to determine the mean density of the earth (Miller and Innes, 1953; Domzalski, 1955b), or (3) to study anomalous vertical gradients caused by the large positive density contrasts connected with ore bodies (Rogers, 1952; Domzalski, 1955a). McCulloh (1965) reviewed most of this work. Other studies involved measurements underground with gravimeters (see e.g., Oelsner, 1960; Plouff, 1961; Kazinskii, 1963; Sumner and Schnepfe, 1966; Drake, 1967) and torsion balances (see e.g., Rische, 1957, p. 70-81). Development of high-precision (±.02 mgals or better) BHGMs and their early use began in the 1960's and is discussed in section 2.4. A comprehensive list of papers on borehole gravity is given by Robbins (1980).

2.0 MECHANICS OF BOREHOLE GRAVITY SURVEYS

2.1 Borehole Gravity Meters

2.1.1 Theory of operation and history of development

Gravity meters are very delicate balances that measure weight (force) changes of a sensitive mass as gravitational acceleration changes:

$$\Delta W = m \Delta g$$

A gravity meter is analogous to a bathroom scale except that a constant mass is placed on the scale and it is moved from location to location so that changes in gravity appear to the scale as changes in weight. Gravity meters were developed in the 1930's and have been used on land, aboard ships, and occasionally in aircraft (e.g., Nettleton, 1976; LaCoste, 1967).

The first successful high-precision BHGM was based on the principal of a vibrating fiber from which a mass is suspended (Howell and others, 1966). Gravity changes acting on the mass generate changes in the tension on the fiber which alters the natural frequency of vibration (Figure 2-1).

$$\frac{\Delta g}{g} = 2\frac{\Delta f}{f}$$

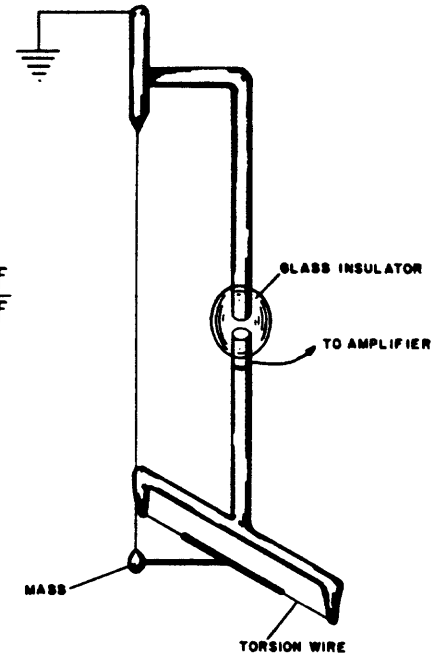


Figure 2-1. Arrangement of vibrating fiber, mass and support of Esso vibrating-string BHGM (Howell and others, 1966). Gravity differences (Δg) as a function of frequency changes (Δf) are shown in the first-order finite difference equation. Other correction factors are necessary in practice. This equation shows that a one milligal change (10^{-6} "g") corresponds to a vibration frequency change of one part in two million.

The vibrating-string technique was pursued by several petroleum companies (Gilbert, 1952; Goodell and Fay, 1964; Howell and others, 1966) prior to the development of the currently used BHGMs. Only the effort by Howell and others (1966) resulted in a relatively high-precision (about ±.01 mgal) instrument that was used intermittently during the 1960's and early 1970's. These vibrating-string BHGMs were fragile and required long reading times to determine the frequency of vibration with sufficient precision. They were, however, relatively inexpensive to build, had a relatively high temperature tolerance, and small diameter.

Presently-used BHGMs are modifications by the manufacturer of the basic LaCoste and Romberg (LC&R) geodetic gravity meter which is one of the most accurate and widely-used land gravity meters (Figure 2-2). This instrument is, in principal, a horizontal pendulum (or vertical seismometer) with a theoretically infinite period which, in practice, is usually set to about 15 seconds. An explanation of its theory of operation is given by Nettleton (1976, p. 31-34). Gravity changes are determined by a calibrated micrometer screw that applies a restoring force, through a lever-ligament-spring system, to return the beam or horizontal pendulum to a null reading position.

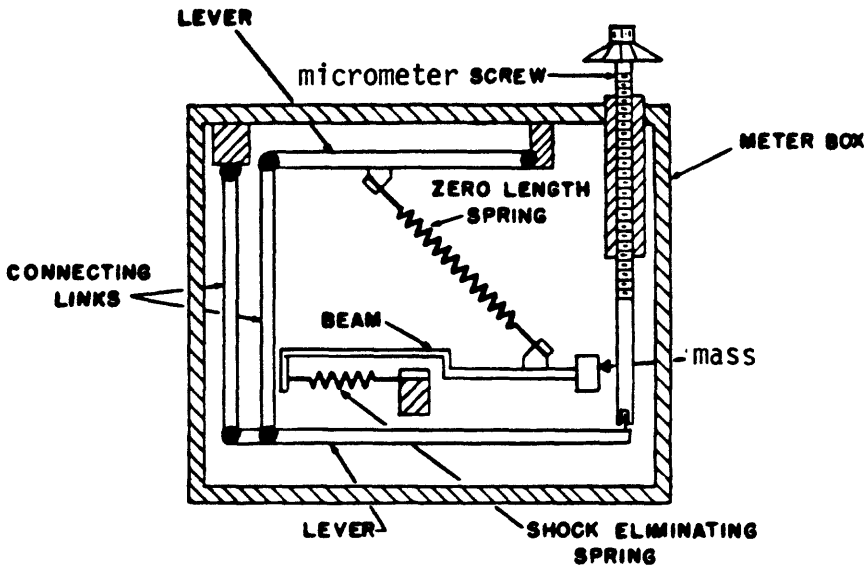


Figure 2-2. Schematic diagram of LaCoste and Romberg gravity meter (modified from Nettleton, 1976, p. 33).

Initial development of a proto-type LC&R BHGM began in 1964 under contract from the U.S. Geological Survey. LaCoste and Romberg Company demonstrated that their G-model gravity sensor could be modified to operate at a thermostated temperature of about 100°C, nearly twice the thermostated temperature of their existing gravity meters. A gimbal-type leveling system was designed and built to operate within the narrow confines of a well logging tool. Lastly, an electronic control system for remote operation of the gravity meter through 10,000 ft of multiconductor logging cable was designed and built, relying in part on existing control systems of underwater gravity meters and on experience gained from one test in 1963 of the remote operation of an underwater gravity meter through 4,000 ft of cable (Beyer and others, 1966). The first successful well test of LC&R BHGM #1 took place in April 1966 in an oil well in the Santa Fe Springs oil field, California.

During the late 1960's and early 1970's two additional LC&R BHGMs were built and operated in the petroleum industry.

It had been recognized from the outset of the development of the first LC&R BHGM that the diameter, thermostating temperature, and limited range of its leveling gimbals would restrict surveys to 7-in. and larger diameter casing, depths at which temperatures did not exceed about 95°C, and relatively undeviated boreholes (less than 7°). Development of a second-generation, more widely usable borehole gravity meter was judged to be a timely and important goal. In September 1973, T. H. McCulloh and the author prepared a proposal to develop a second-generation, smaller diameter, higher temperature borehole gravity meter.

The importance of the development of a new smaller diameter borehole gravity meter, the maximum diameter that would make such an instrument widely useful, and the intent of the U.S. Geological Survey to seek funding to develop this new instrument were conveyed to Dr. Lucien LaCoste in December 1973. In early 1974 a set of desirable instrument characteristics was sent to Dr. LaCoste. The U.S. Geological Survey contract, awarded to LaCoste and Romberg Company in June 1975, together with industry orders, have resulted in the delivery of eight smaller diameter borehole gravity meters (as of September 1981). These instruments are being used throughout North America and in many other parts of the world.

2.1.2 Instrument characteristics

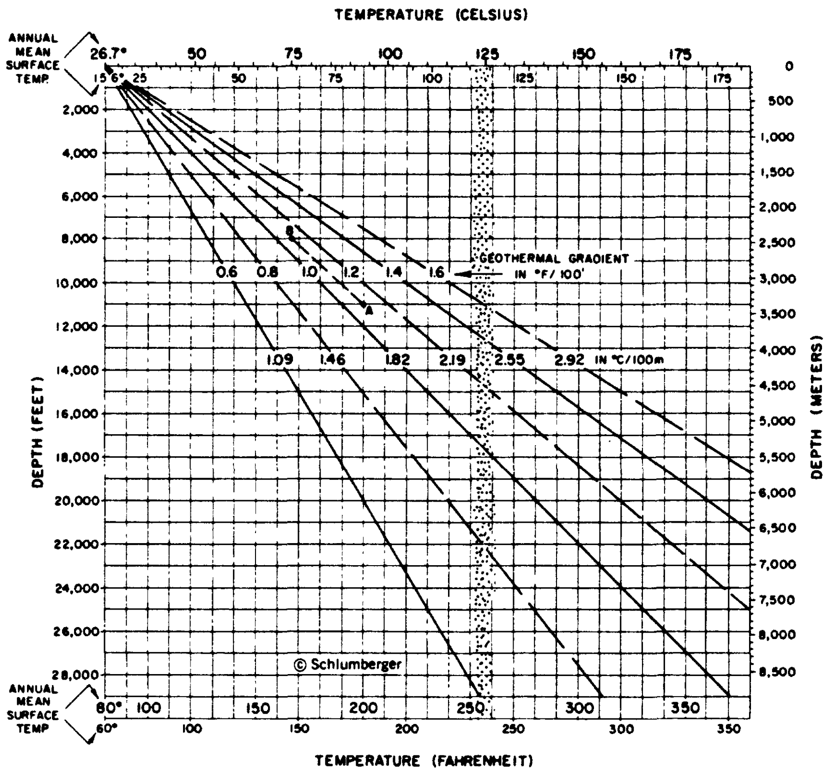
The LC&R BHGM is carefully insulated (though minimally insulated because of space limitations) and thermostated, demagnetized and shielded against magnetic fields, compensated for barometric pressure changes, and leveled with motor-driven gimbals. Two sensitive pendular levels with capacitive-type readouts are attached to each gravity meter housing and enable the gravity meter to be remotely leveled with high precision. The smaller diameter models built since 1974 have one asymmetric (horizontal) leveling gimbal and a motor-driven gimbal system for rotating the gravity sensor about the axis that is parallel to the borehole. This permits leveling of the BHGM in boreholes with larger deviations from the vertical. Table 2-1 summarizes the characteristics of the smaller diameter (or "slim hole") LC&R BHGMs.

TABLE 2-1.
CHARACTERISTICS OF SMALLER DIAMETER LC&R BHGM

Logging tool diameter	4 1/8 inches
Thermostated temperature (varies a few degrees from instrument to instrument	125°C
Maximum leveling range from vertical	12-14°

The BHGM cannot operate at well depths where temperatures approach its thermostating temperature (see Figure 2-3), in boreholes deviated by more than 12 to 14°, or in heavy-weight 5-inch or smaller diameter casing (see Table 2-2). The smaller diameter BHGMs have a gravity range of about 2500 to 2700 mgal that is set at the factory and which limits the latitude over which measurements can be made without factory "reset" (see Table 2-3). New BHGMs under development will have a "reset" screw to permit surveys at any location.

Average reading time of the BHGM at a downhole station depends on the borehole conditions (such as the presence or absence of formation vibrations or cable "yo-yoing"), the condition of the instrument, and the experience of the operator. Generally, readings take 5 to 8 minutes but may take as long as 10 to 15 minutes (Figure 2-4).



EXAMPLE: BHT is 200°F at 11,000' (Point A).
Temperature at 8,000' is 167°F (Point B).

Temperature Gradient Conversions: 1°F/100 ft = 1.823°C/100 m
1°C/100 m = 0.5486°F/100 ft

Figure 2-3. Temperature versus depth for a range of geothermal gradients and mean annual surface temperatures, assuming a linear temperature gradient (Schlumberger, 1978). Maximum likely depths to which BHGM surveys can be made is shown by patterned bar.

TABLE 2-2

DIAMETERS AND WEIGHTS OF THREADED NON-UPSET CASING

(Schlumberger, 1978)

Outside Diameter (inches)	Weight (lbs/ft)	Nominal Inside Diameter (inches)	Drift Diameter* (inches)	Clearance Between BHGM Sonde and casing** (inches)
		smaller diameter casing		
5	21.00	4.154	4.029	
			4.125 ←	outside diameter of BGHM sonde
	18.00	4.276	4.151	.013
	17.70	4.300	4.175	.025
	15.00	4.408	4.283	.079
	13.00	4.494	4.369	.122
	11.50	4.560	4.435	.155
5-1/2	23.00	4.670	4.545	.210
	20.00	4.778	4.653	.264
	17.00	4.892	4.767	.321
	15.50	4.950	4.825	.350
	15.00	4.974	4.849	.362
	14.00	5.012	4.887	.381
	13.00	5.044	4.919	.397
		larger diameter casing		

* Drift diameter is the guaranteed minimum internal diameter of any part of the casing and should be used to determine the largest diameter equipment that can be safely run inside the casing.

** Assumes no scale buildup on inside of casing.

TABLE 2-3

RANGE TABLE FOR U.S. BOREHOLE GRAVIMETERS

BHGM Number	Base Gravity Value (mgals)	High Gravity Value (mgals)	Latitude Range At Surface	Latitude Range At 5000 ft A.S.L.	Latitude Range At 5000 Ft B.S.L.	Latitude Range At 12000 Ft B.S.L.
1	worldwide range (7300 mgal)					
2	worldwide range (7000 mgal)					
3	destroyed					
*4	978034.2	980489.1	0° 43° 24'	10° 12' 45° 22'	0° 41° 22'	0° 38° 38'
5			25° 53°			
6			25° 53°			
7			25° 53°			
*8	978680.7	981451.1	20° 28' 54° 14'	23° 18' 56° 20'	17° 15' 52° 11'	11° 32' 49° 23'
*9	979555.9	982165.3	32° 41' 63° 11'	34° 48' 65° 43'	30° 29' 60° 49'	27° 14' 57° 41'
*10	980530.6	983272.5	43° 52' 90° 00'	45° 49' 90° 00'	41° 53' 81° 10'	30° 07' 74° 02'
11			25° 53°			

USGS: #1, #6

Amoco Production Company: #2, #5, #7, #11

Exploration Data Counsultants, Inc.: #4, #8, #9, #10

*These calculations were made on September 1, 1981, using current gravity readings, assuming a density of 2.3 g/cm^3, and neglecting the earth's anomalous gravity field.

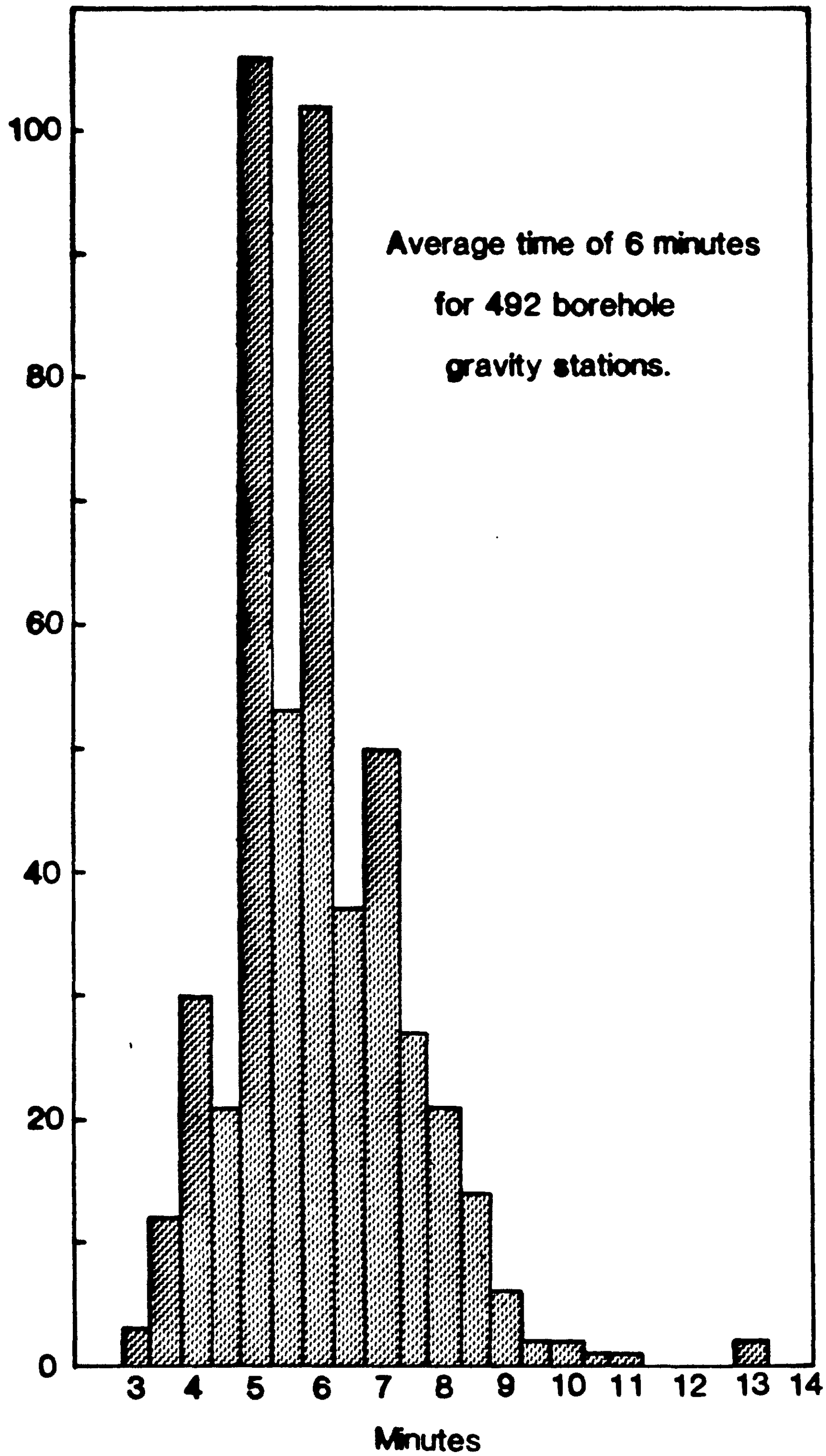


Figure 2-4. Minutes required to level and read LC&R BHGM #6 during surveys in two cased production wells, Wilmington oil field, California, in early 1981.

2.1.3 Reading resolution of the BHGM

A BHGM is an incredible instrument when one realizes that it (1) is temperature sensitive and must be precisely thermostrated against the very large range of ambient temperatures in boreholes, (2) must be remotely leveled to within a fraction of a degree, (3) must be made insensitive to magnetic and barometric pressure fluctuations, (4) must be durable enough to withstand the vibrations and shocks of well logging, and then (5) must be able to repeatedly measure displacements of a few millionths of an inch!

Reading resolution, which is analogous to the smallest readable unit of length on a rule or tape measure, is not indicative of precision or repeatability but does give an idea of the sensitivity of the LC&R BHGM. An estimate of the reading resolution of U.S. Geological Survey's LC&R BHGM #6 and its control system during early 1981 is given in Figure 2-5. Differences are shown between gravity readings determined independently by two analysts from the raw data of 187 down hole stations. Eighty-six percent of the determinations agree to within 0.002 mgals. Increasingly larger differences between the determinations of the two analysts were for increasingly poorer quality gravity readings. Noisy borehole conditions and thermal disturbances to the BHGM and its control system degraded the quality of these less reliable gravity readings. Other BHGMs may have slightly better or poorer reading resolution, depending on condition of the gravity meter and its control and telemetry systems, and how the gravity meter is operated and read.

Important point: resolution can be as good as ±.001 to ±.002 but can be much worse if borehole conditions or gravity meter performance is poor.

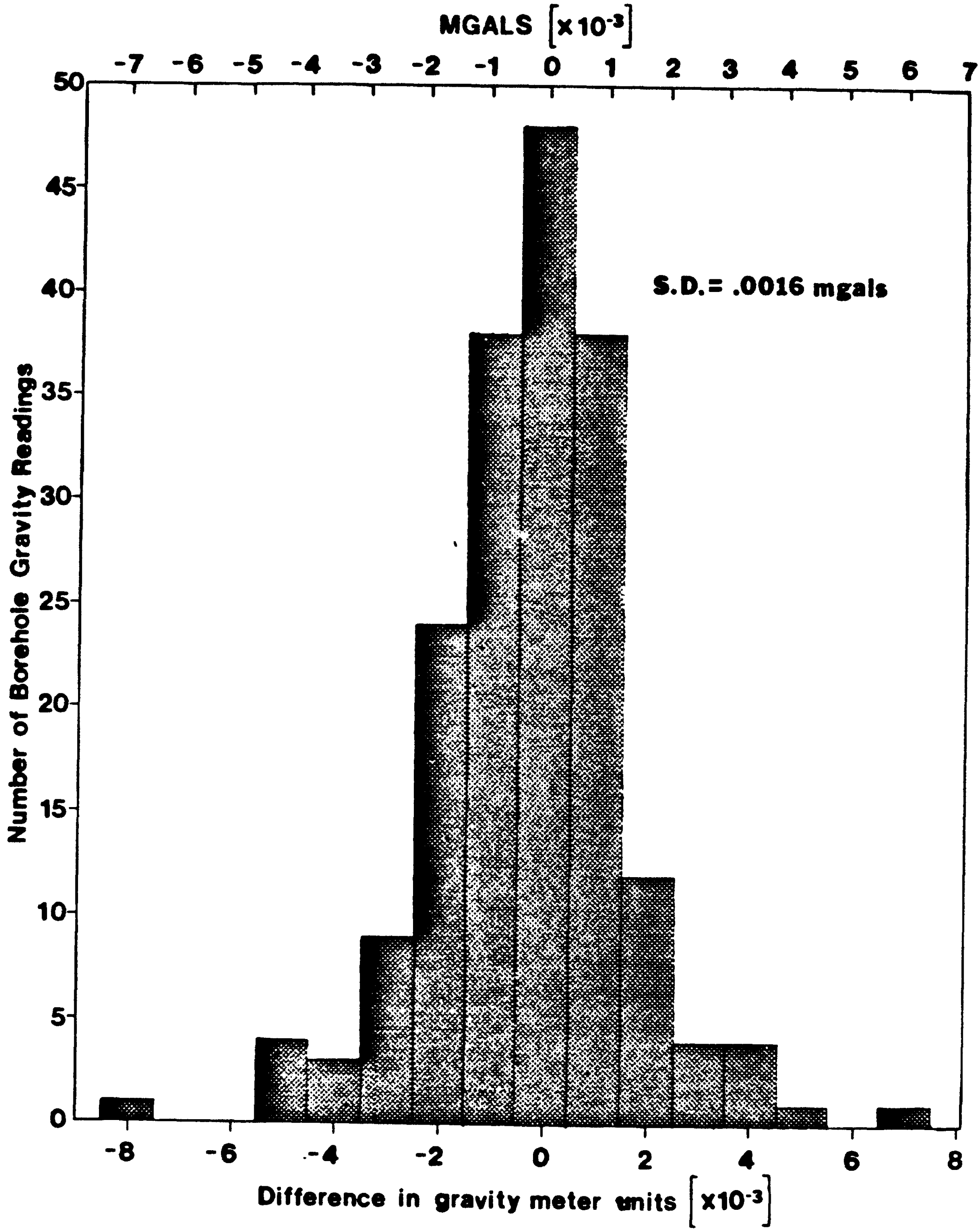


Figure 2-5. Estimated reading resolution of LaCoste & Romberg meter #6 during surveys in two cased production wells, Wilmington oil field, California, 1981.

2.2 Basic Well Measurements

Borehole gravity surveys are conducted by stopping and reading the borehole gravity meter (BHGM) at a series of downhole stations that have been previously selected from examination of well logs to meet the survey objectives. This technique leads to a series of gravity difference (Δg) and depth difference (Δz) measurements that constitute the interval vertical gradient of gravity ($\Delta g/\Delta z$) between successive stations (Figure 2-6).

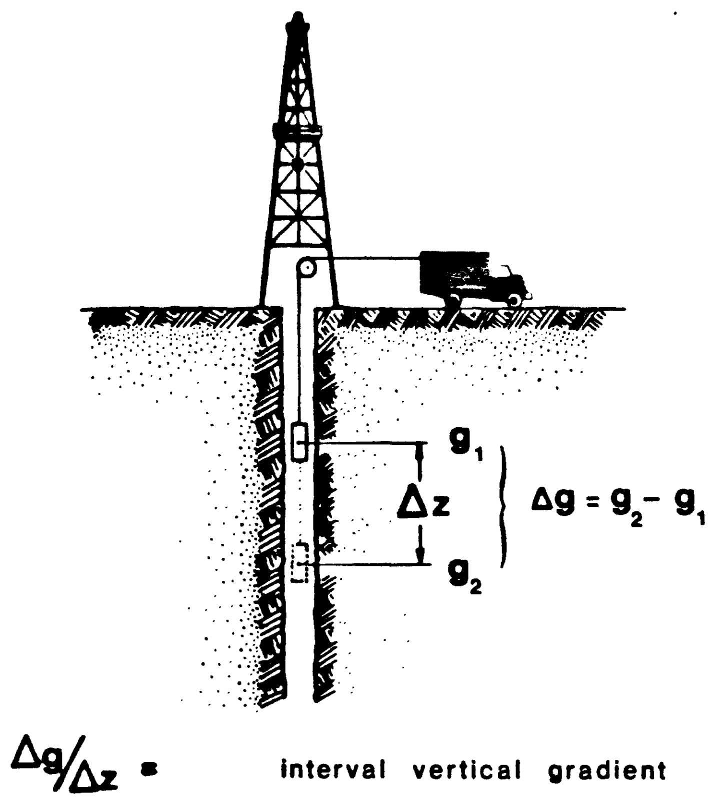
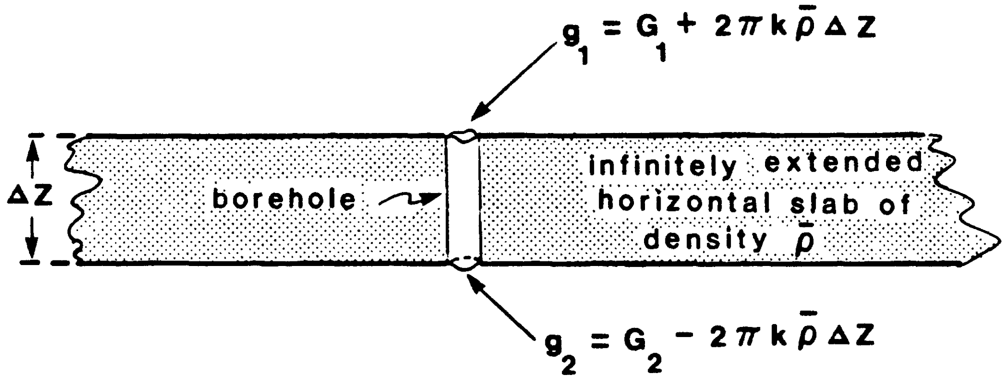


Figure 2-6. Schematic diagram showing measurement of interval vertical gradient of gravity. The interval vertical gradient is given in units of milligals/foot (mgals/ft), or other convenient units of acceleration/length.

The fundamental equation of borehole gravity (eq. 1-23) becomes

$$\Delta g = F\ \Delta z - 4\pi k\bar{\rho}\ \Delta z \tag{2-1}$$

when written as a gravity difference. According to eq. (2-1), gravity increases downward at a rate determined by the difference between the free-air vertical gradient (F), which is essentially a constant, and a gradient of opposite sign ($4\pi k\bar{\rho}$) that varies as the density of the adjacent rocks changes. The positive $F\Delta z$ term is the increase in gravity downward caused by closer approach to the center of mass of the earth. The negative $4\pi k\bar{\rho}\Delta z$ term is twice the attraction of an infinitely-extended horizonal layer of thickness Δz (see eq. (1-11)) and is explained by Figure 2-7.



$$\Delta g = g_2 - g_1$$

$$\Delta g = \left(G_2 - G_1\right) - 4\pi k\bar{\rho}\Delta Z$$

Figure 2-7. Schematic diagram of cross section of infinitely-extended horizontal slab showing how $-4\pi k\bar{\pi}\Delta z$ term arises in eq. (2-1). G_1 and G_2 represent all other gravitational accelerations felt by the gravity meter at the top and bottom surfaces of the slab except those due to the slab itself. When the gravity meter is at the bottom of the slab, the acceleration due to the slab is directed upward and therefore has a negative sign.

As the density ($\bar{\rho}$) of the horizontal layer increases in eq. (2-1), the gravity difference (Δg) decreases, and vice versa. Or, returning to the fundamental equation,

$$\Delta g/\Delta z = F - 4\pi k\bar{\rho} \qquad (2\text{-}2)$$

increases in layer density correspond to decreases in the interval vertical gradient ($\Delta g/\Delta z$), and vice versa. <u>This simple relationship between the measured interval gradient ($\Delta g/\Delta z$) and the density ($\bar{\rho}$) of the horizontal layer is, for practical purposes, valid in many geologic settings. Thus, it is often possible to accurately determine very small variations in the density of rocks bracketed by different Δz intervals with little or no analysis beyond the simple reduction of the basic gravity and depth measurements</u>.

2.3 Factors That Affect Borehole Gravity Measurements

The fundamental equation of borehole gravity is not strictly correct when applied to the real earth. Departures of the earth's surface and deviations of the density layering in the subsurface from the horizontal contribute to the variation of gravity down the borehole.

Unwanted or extraneous accelerations caused by topography or mass disturbances connected with the well usually are negligibly small, can be avoided by moving the borehole gravity station a few feet, or can be easily calculated and corrected for with sufficient accuracy. In general, these types of mass disturbances are so small in magnitude that the gravitational accelerations they generate are negligible when compared with the accelerations generated by the mass of the subsurface rocks surrounding the well. This is one of the advantages of borehole gravity logging over conventional density and porosity logging methods: The measurements are essentially unaffected by casing, formation damage surrounding the borehole, and other drillhole-related influences. Extraneous influences on borehole gravity measurements are discussed in more detail in Section 2-5.

Measurable variations in gravity down the borehole can be caused by deviations of the density layering in the subsurface from the horizontal (lateral density variations). In some circumstances, benefits to exploration can be gained from the determination of "anomalous" or "structural" effects in the borehole gravity data.

2.4 Practical Formulas

The fundamental equation of borehole gravity can be modified to include mass disturbances in the real earth:

$$\Delta g/\Delta z = F - 4\pi k\bar{\rho} + \Delta G_b + \Delta G_t + \Delta G_g \qquad \text{(McCulloh, 1966b)} \quad (2\text{-}3)$$

$\Delta g/\Delta z$ is the measured interval vertical gradient; F is the normal free-air vertical gradient, 0.09406 mgals/ft; $4\pi k\bar{\rho}$ is the interval vertical gradient due to the laterally adjacent infinitely-extended horizontal layer of interval density $\bar{\rho}$; ΔG_b is the fractional part of the observed interval vertical gradient due to mass disturbances that may be caused by variations in borehole diameter, cement columns outside the well casing, changes in casing size or weight, casing shoes, or fluid columns in the borehole; ΔG_t is the fractional part of the observed interval vertical gradient due to the surface topography or marine bathymetry relative to a datum that usually is taken as the elevation of the top of the borehole; ΔG_g is the fractional part of the observed interval vertical gradient due to local and regional lateral density variations (called the anomalous vertical gradient).

Corrections for terrain and borehole effects usually are determined and applied as corrections to individual gravity measurements. When Δg values reflect these corrections, eq (2-3) becomes

$$\Delta g/\Delta z = F - 4\pi k\bar{\rho} + \Delta G_g \qquad (2\text{-}4)$$

Solving for interval density $\bar{\rho}$ and substituting values for the constants F, π, and k,

$$\bar{\rho} = 3.680 + 39.127(\Delta G_g - \Delta g/\Delta z) \qquad (2\text{-}5)$$

(units of feet, mgals, g/cm^3)

$$\bar{\rho} = 3.680 + 11.926(\Delta G_g - \Delta g/\Delta z) \qquad (2\text{-}5a)$$

(units of meters, mgals, g/cm^3)

The usual objective of a borehole gravity survey is interval density $\bar{\rho}$ (sometimes called "apparent" density) or the anomalous or structural effect ΔG_g. ΔG_g often is negligibly small so that accurate values of $\bar{\rho}$ can be calculated from eq. (2-5) by setting $\Delta G_g = 0$. When ΔG_g is of measurable magnitude, frequently it varies only slightly over the intervals of interest so that relative values of $\bar{\rho}$ can be accurately determined even if ΔG_g is ignored. Reliable evaluation of ΔG_g, when it is of measurable magnitude, requires independent density data (e.g., an accurate gamma-gamma log or core density measurements). Some authors claim filtering techniques can be used to separate $\bar{\rho}$ and ΔG_g without independent density information.

Gravity gradients are usually expressed in units of mgals or μgals per foot or per meter. Sometimes Eotvos units (E.U.) are used. Table 2.4 incorporates the latest value for the gravitational constant k and summarizes the constants and conversions used in BHGM surveys.

TABLE 2.4

CONSTANTS AND CONVERSIONS USED IN BHGM SURVEYS

A. Constants used in fundamental equation

$4\pi k = .025558 \pm .000002\ (cm^3/g)(mgal)(1/ft)$
$1/4\pi k = 39.127 \pm .003\ (g/cm^3)(1/mgal)(ft)$
$F = 0.09406\ (mgal/ft)$

units of feet, mgals, g/cm^3

$4\pi k = .083850 \pm .000006\ (cm^3/g)(mgal)(1/m)$
$1/4\pi k = 11.926 \pm .0009\ (g/cm^3)(1/mgal)(m)$
$F = 0.30859\ (mgals/m)$

units of meters, mgals, g/cm^3

B. Conversions used in fundamental equation

1 mgal/ft = 10^3 μgal/ft = 3.2808 mgal/m
1 mgal/m = 10^3 μgal/m = 0.3048 mgal/ft
1 E.U. = 10^{-4} mgal/m = 3.048×10^{-5} mgal/ft

Note: A 0.01 g/cm^3 change in interval density ($\bar{\rho}$) corresponds to a change in $\Delta g/\Delta z$ of .000255 mgal/ft = .000837 mgal/m = 8.4 E.U.

2.5 Corrections to borehole gravity measurements

2.5.1 Introduction

There are several standard corrections that must be applied to borehole gravity measurements and several non-standard corrections that infrequently may need to be applied before $\Delta g/\Delta z$ values can be calculated or anomalous gravity determined.

2.5.2 Calibration correction

Measured gravity values from presently-used BHGMs are in instrument or "counter" units. The manufacturer provides a calibration table from which numerical factors are taken to convert counter units to milligals. Each presently-used BHGM has a unique calibration table. The calibration table for LC&R BHGM #6 is given in Table 2-5 along with a description of how the conversion from counter units to milligals is made.

Table 2-5

CALIBRATION TABLE FOR
LaCOSTE & ROMBERG INC. BOREHOLE GRAVITY METER BH-6

COUNTER READING	VALUE IN MILLIGAL	FACTOR FOR INTERVAL	COUNTER READING	VALUE IN MILLIGAL	FACTOR FOR INTERVAL
000	000.00	.86674			
50	43.33	.86619	1500	1296.96	.86534
100	86.64	.86570	1550	1340.23	.86549
150	129.93	.86532	1600	1383.50	.86564
200	173.19	.86496	1650	1426.78	.86579
250	216.44	.86469	1700	1470.07	.86593
300	259.68	.86447	1750	1513.37	.86604
350	302.90	.86430	1800	1556.67	.86617
400	346.12	.86418	1850	1599.98	.86627
450	389.33	.86410	1900	1643.29	.86636
500	432.53	.86403	1950	1686.61	.86644
550	475.73	.86399	2000	1729.93	.86648
600	518.93	.86397	2050	1773.26	.86651
650	562.13	.86399	2100	1816.58	.86650
700	605.33	.86402	2150	1859.91	.86643
750	648.53	.86405	2200	1903.23	.86646
800	691.74	.86412	2250	1946.55	.86662
850	734.94	.86420	2300	1989.88	.86672
900	778.15	.86426	2350	2033.22	.86674
950	821.37	.86428	2400	2076.55	.86670
1000	864.58	.86431	2450	2119.89	.86666
1050	907.80	.86436	2500	2163.22	.86664
1100	951.02	.86446	2550	2206.55	.86662
1150	994.24	.86462	2600	2249.88	.86662
1200	1037.47	.86475	2650	2293.21	.86660
1250	1080.71	.86480	2700	2336.54	.86653
1300	1123.95	.86487	2750	2379.87	.86642
1350	1167.20	.86496	2800	2423.19	.86625
1400	1210.45	.86508	2850	2466.50	.86604
1450	1253.70	.86519	2900	2509.80	.86579
			2950	2553.09	.86555
			3000	2596.37	

<u>Conversion of gravity meter counter units to mgals:</u>

For a counter reading of 957.892

1) subtract next lower even 50-unit value (column 1 or 4):

$$957.892 - 950.000 = 7.892$$

2) multiply by the calibration factor opposite 950 (column 3):

$$(7.892)\ (.86428) = 6.821$$

3) add the result to the cumulative milligal value opposite 950 (column 2):

$$6.821 + 821.37 = 828.191 \text{ mgals (relative)}$$

<u>Optional Exercise:</u>

Given counter readings between two borehole stations of

1398.021 and 1401.769

find the gravity difference in mgals.

Ans. <u>3.244</u> mgals

2.5.3 Tidal gravity

Variations in the gravitational attraction with time of the moon (primarily) and sun (secondarily) on a point on the earth occur because the positions of these bodies (relative to a point on the earth) change with time. The maximum rate of change of gravity can be as large as about 0.3 mgal per 6 hours, during full or new moon phases, but is much less during quarter phases (see Figures 4-1 and 4-2; Nettleton, 1976). A summary of the requirements for tidal gravity corrections for borehole gravity surveys is given by Edcon (1977). These corrections are routinely made from computer programs (e.g., Cabaniss and Eckhardt, 1973; Harrison, 1971) and are routinely applied to borehole gravity measurements in a somewhat more careful way than they are applied to surface gravity measurements.

2.5.4 Instrument drift

All gravity meters are subject to drift - a change in gravity reading with time at a given location that is caused by changes in instrument response. Each instrument has its own drift characteristics that vary with time, depending on such factors as age of the gravity meter, temperature gradients around the sensor, mechanical shocks, vibrations, etc. With rare exception, the more stable the temperature and inertial environment of the gravity meter, the smaller the drift. In the borehole, temperature fluctuations and logging tool movements cause drift in addition to a usually small long term drift component that is characteristic of the instrument.

The drift is ascertained by re-occupying selected gravity stations during the survey (Figure 2-8). Occasionally, "tares", instantaneous "sets" or very rapid discrete changes in gravity readings occur, especially when the gravity meter is subjected to shock or strong vibrations, or subjected to large, rapid temperature changes (Figure 2-9). Small tares (.003 to 0.015 mgals) are less readily detected and often are interpreted as part of the repeatability or precision of the gravity measurements (Figure 2-10).

Correction for instrument drift is the only correction to borehole gravity measurements that is somewhat difficult and prone to error (Caton, 1981). As pointed out by Rasmussen (1973, Fig. 10) incorrect drift corrections can lead to very misleading results in some cases. Sufficient repeated measurements and predictability in the response of the gravity meter to ambient temperature changes are key elements to the construction of an accurate drift correction curve. The corrections themselves are simply added to or subtracted from the observed gravity readings, depending on where the baseline of the drift curve is located.

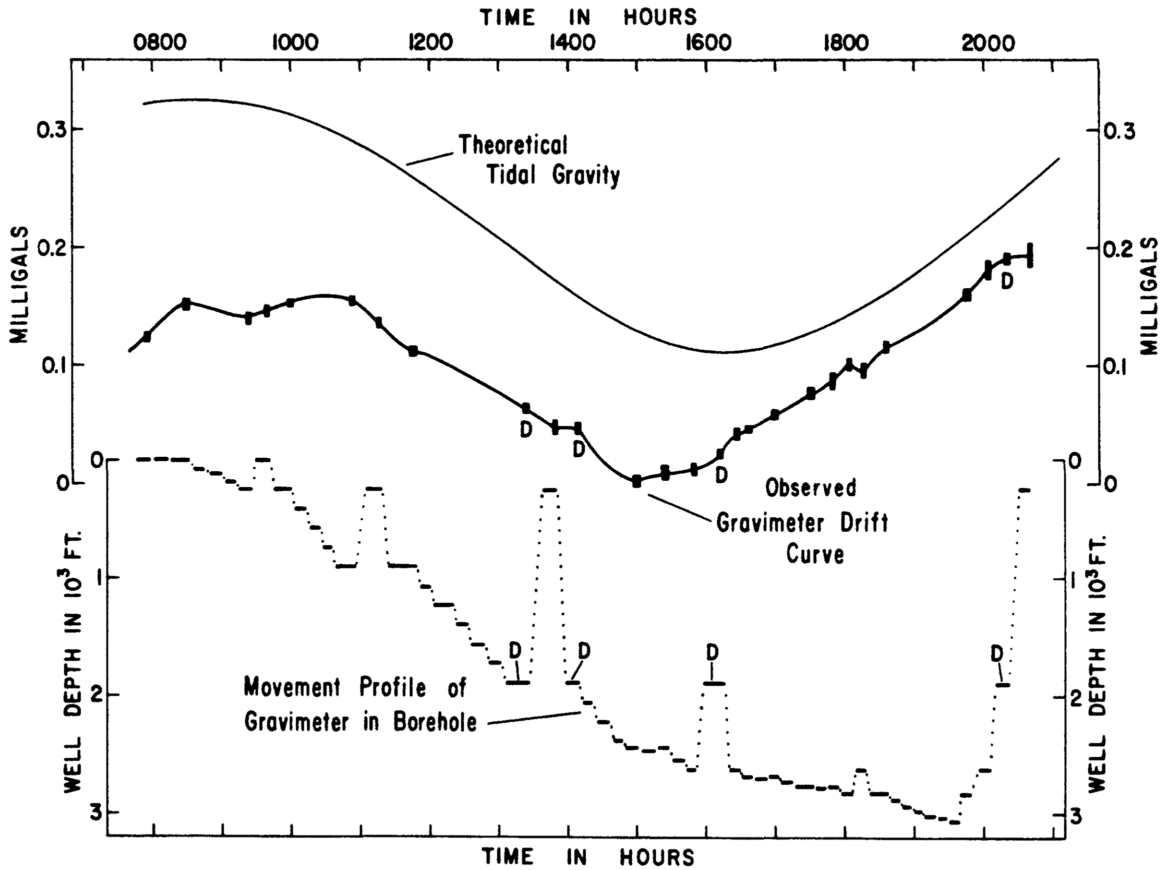
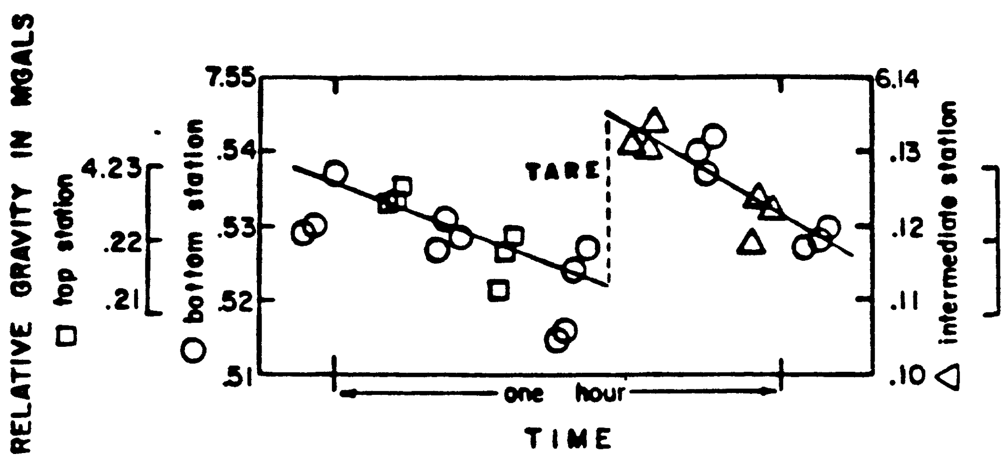


Figure 2-8. Observed gravity meter drift curve and movement profile for the borehole gravity survey in well 104-33D, 33-32S-24E, Midway-Sunset Oil Field, Kern County, Calif (Beyer, 1971). The observed drift curve is constructed from all sets of two or more repeated surface and subsurface borehole gravity observations. The height of each solid rectangle along the drift curve represents the uncertainty in determining the gravity reading from the analog readout. The width of each rectangle denotes the time over which the reading was averaged. The horizontal lines in the movement profile indicate the intervals of time that the gravimeter was stationary at each station. The letter D denotes the contribution of one borehole base station. Theoretical tidal gravity is adjusted for latitude and local time.



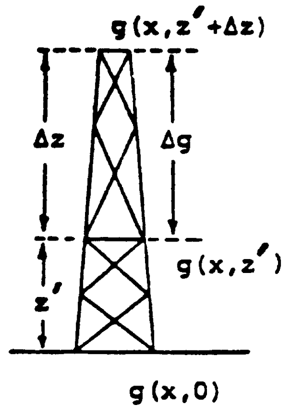


Figure 2-9. Repeated gravity measurements made with a surface gravity meter at bottom, intermediate and top stations of a 40-foot double tower (Beyer, 1971). Note obvious tare probably due to shaky foundation of tower gravity stations.

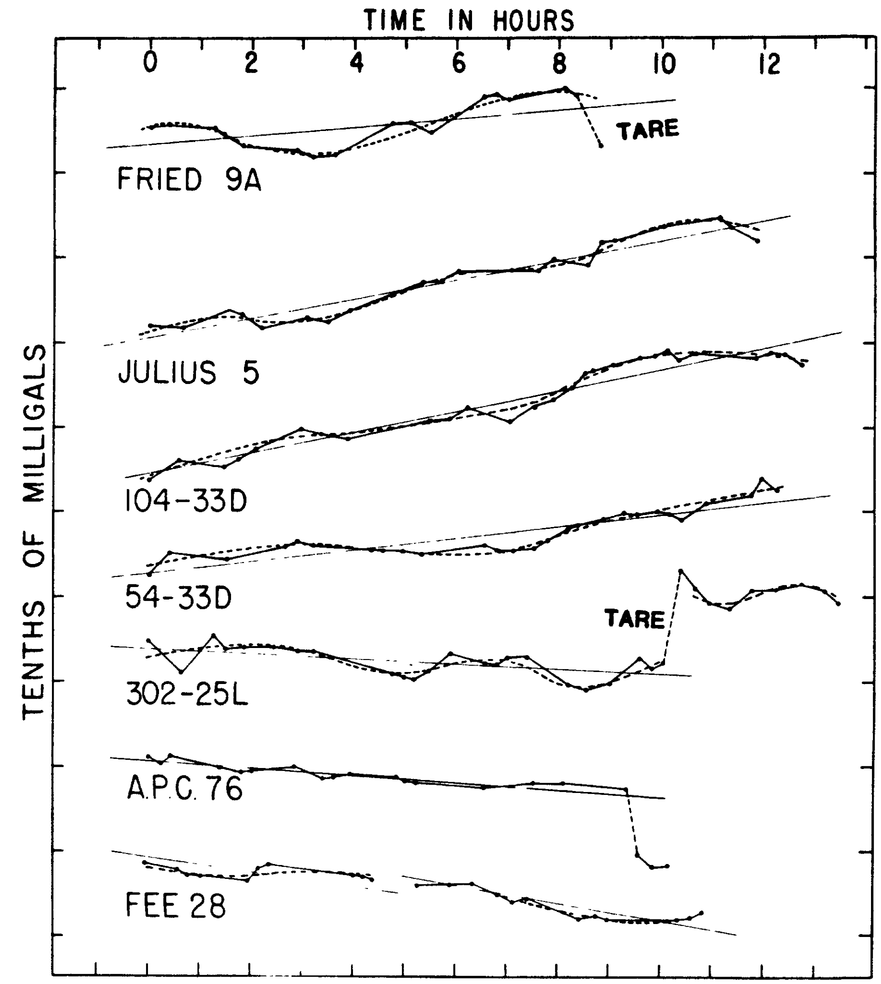


Figure 2-10. Gravity meter drift after removal of tidal gravity for seven wells in which gravity measurements were made (Beyer, 1971). Straight lines are fitted by least squares to the sets of repeated readings (dots). Dashed curves are estimates of systematic drift. Tares are evident in drift curves for the Fried 9A and 302-25L wells; micrometer screw counter synchronization was momentarily lost toward the end of the survey in the A.P.C. 76 well.

2.5.5 Corrections for Borehole Effects -- ΔG_b

The borehole void, its contained fluids, cement columns and plugs, casing and casing shoes, and the surrounding annulus of flushed and invaded rocks are mass disturbances of the idealized horizontal layer on which the vertical gradient term $4\pi k\bar{\rho}$ is based. In boreholes of conventional diameters in which these mass disturbances are relatively uniform up and down the well, no ΔG_b corrections are necessary because the effect is extremely small and is cancelled during the subtraction of successive borehole gravity values. Corrections may be necessary for borehole gravity stations located within 5 borehole diameters of the top or bottom of the borehole, a cement column, a casing string, a liquid column in the borehole or an extremely large sharp change in borehole diameter. In boreholes of conventional diameter, usually it is possible to relocate borehole gravity stations 1 to 3 feet away from these types of features by careful study of the drilling history, caliper log, and well completion record.

When corrections are necessary, one way to estimate the disturbing mass is with a series of stacked discs whose densities should be the density contrasts relative to the adjacent formation density (as best as it can be estimated) (Fig. 2-11a). Gravity and vertical gradients determined from gravity differences can be calculated along the vertical axis (the assumed center of the borehole) of the stack of discs. The gravitational attraction of one disc at a point along its axis is given by

$$2\pi k\rho(dz - rad_1 + rad_2) \qquad (2\text{-}6)$$

where the terms are as shown in Figure 2-11b (e.g., Garland, 1965, p. 67). A simple computer program can calculate the gravitational attraction of the discs at a series of points along the axis of the stack of discs by summing, with proper algebraic sign, the effects of all discs above and below. Interval vertical gradients and corrections to interval densities can be determined by dividing the gravity difference between points along the axis by the vertical distance that separates the points.

An example of borehole corrections for the effects over the length of a drillhole is shown in Figure 2-12. In this example from the Nevada Test Site, the borehole was uncased, air filled, and assumed to penetrate rocks whose densities are shown. It is apparent from Figure 2-10 that, even though severe caving has enlarged this air-drilled borehole, corrections are necessary only for gravity stations near or at the top and bottom of the well. Small corrections (<.005 mgals) may be necessary directly opposite sharp boundaries between rock units of large density contrast where boreholes are badly washed out. In the vast majority of cases, however, this correction is unnecessary.

Corrections for the gravity meter being off-center in the borehole in an irregular manner during a survey are not significant in drillholes of conventional diameters and can be avoided in ultra large diameter holes by using a centralizing device on the logging tool. Smith (1950, pp. 630-635) discusses borehole corrections in considerable detail.

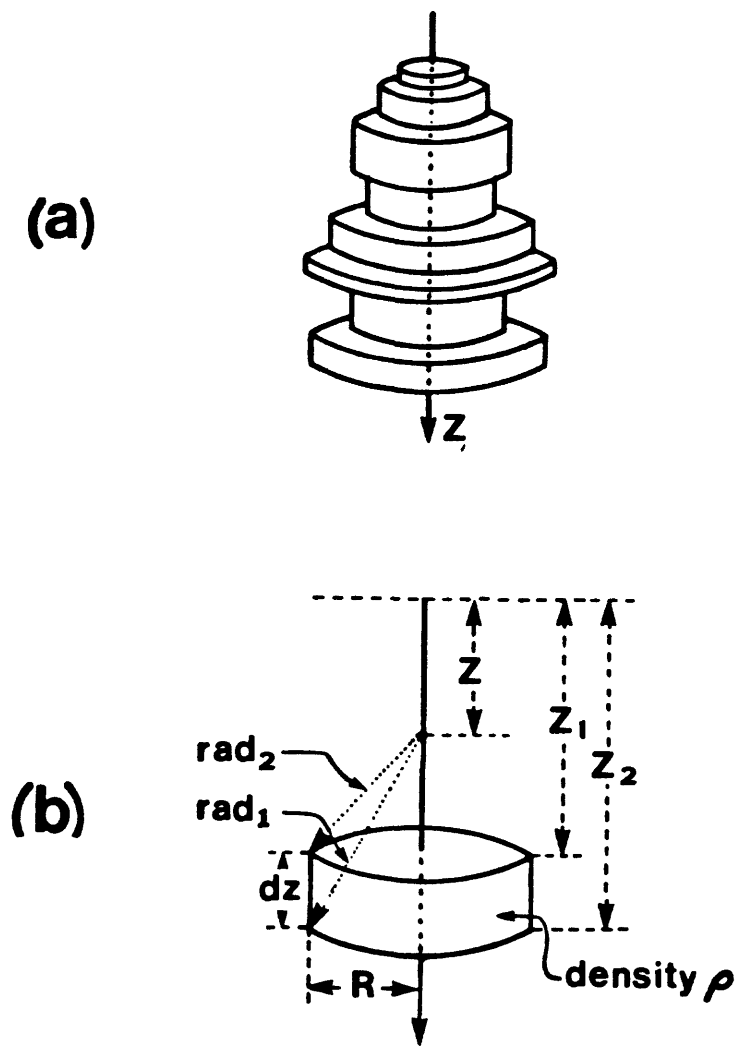


Figure 2-11. (a) Series of stacked discs to model a borehole caliper log for calculation of gravity effects of caved borehole. (b) Schematic of parameters used to calculate the gravity effect of stacked discs at a series of points along the axis of the discs.

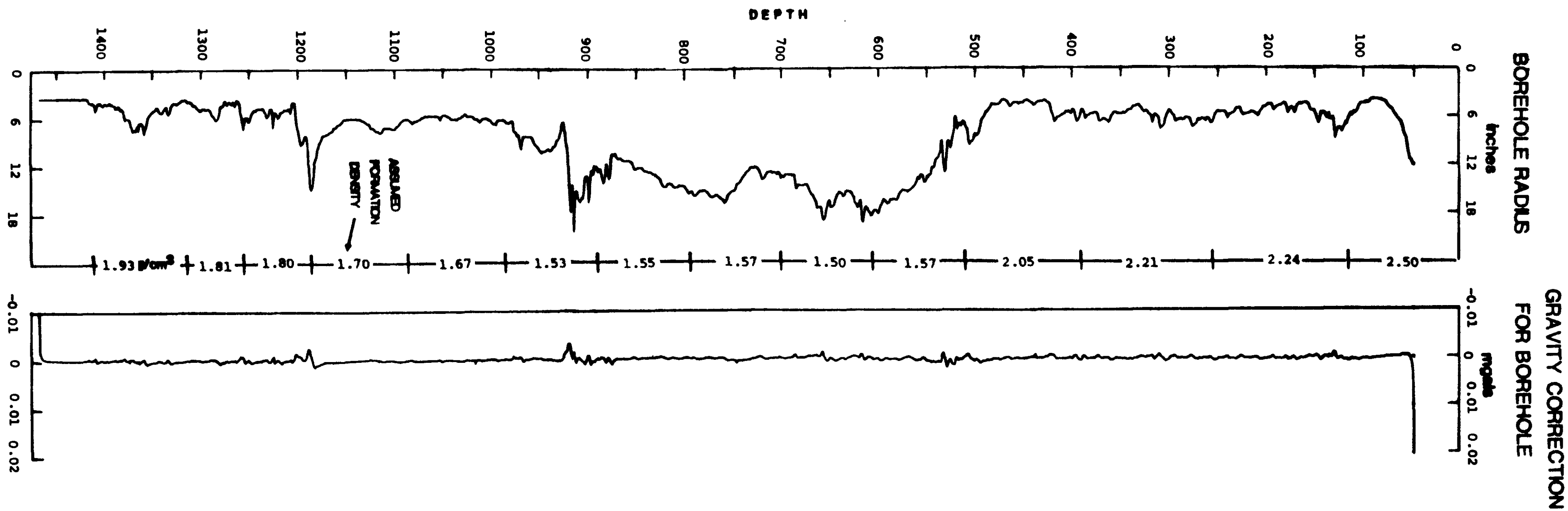


Figure 2-12. Calculated gravity corrections (right) for borehole whose caliper log is shown (left). Density contrasts used to calculate gravity corrections are between formation densities shown and air-filled (ρ=0.00 g/cm^3) borehole. Gravity corrections are extremely small (<.005 mgal) over entire length of borehole (except near top and bottom) in spite of badly caved intervals. Drillhole is UE19n, Nevada Test Site, and was air-drilled through unsaturated Tertiary volcanic rock (see Hearst, 1969, Fig. 10; Healy, 1970, Fig. 5).

2.5.6 Terrain Corrections -- ΔG_t

Terrain corrections are calculated in a straightforward manner and are applied directly to individual borehole gravity measurements for the same reasons they are applied to surface gravity measurements. The explanation for these corrections can be found in any general geophysics book (e.g., Nettleton, 1976). The aim is to calculate the gravitation effects of mass above the datum (hills) or deficiencies of mass (valleys) below the datum. The datum is usually the elevation of the ground at the wellhead or sea floor.

Hearst (1968) presented a computational scheme for calculating borehole gravity terrain corrections which Beyer and Corbato (1972) improved. The zone and compartment method of calculating terrain corrections is suitable for borehole gravity surveys and is based on the gravitational attraction of a hollow right circular cylinder at a point on the axis of the cylinder (see e.g., Heiskanen and Vening Meinesz, 1958, p. 152). Each concentric hollow cylinder is called a zone. If the cylinder is divided into N equal compartments by vertical planes that extend outward from its axis, the vertical component of attraction of the i^{th} compartment of the j^{th} zone is

$$g_{ij} = \frac{2\pi k\rho}{N}\left[\sqrt{r_1^2 + h^2} - \sqrt{r_1^2 + h_1^2} - \sqrt{r_2^2 + h^2} + \sqrt{r_2^2 + h_1^2}\right] \qquad (2\text{-}7)$$

where k is the gravitational constant, ρ is the density of the rocks enclosed by the compartment, and r_1, r_2, h, and h_1 are as defined in Figure 2-13.

The terrane is described from topographic maps by estimating an average elevation to each compartment. For a given gravity station in the borehole expression (2-7) is evaluated for each compartment of each zone and the results algebraically summed. The process is repeated for all specified gravity stations down the borehole. The proper magnitude and sign for the terrain correction is obtained regardless of the relative elevations of the compartment, gravity station, and datum, if in expression (2-7)

$$h^2 = (A - C)^2 \qquad \text{and} \qquad h_1^2 = (B - C)^2$$

where A is the terrain compartment elevation, B is the datum elevation, and C is the gravity station elevation (Fig. 2-13).

Prior to the evaluation of expression (2-7), each compartment elevation may be corrected for curvature with the expression

$$\Delta h \approx d^2/2R$$

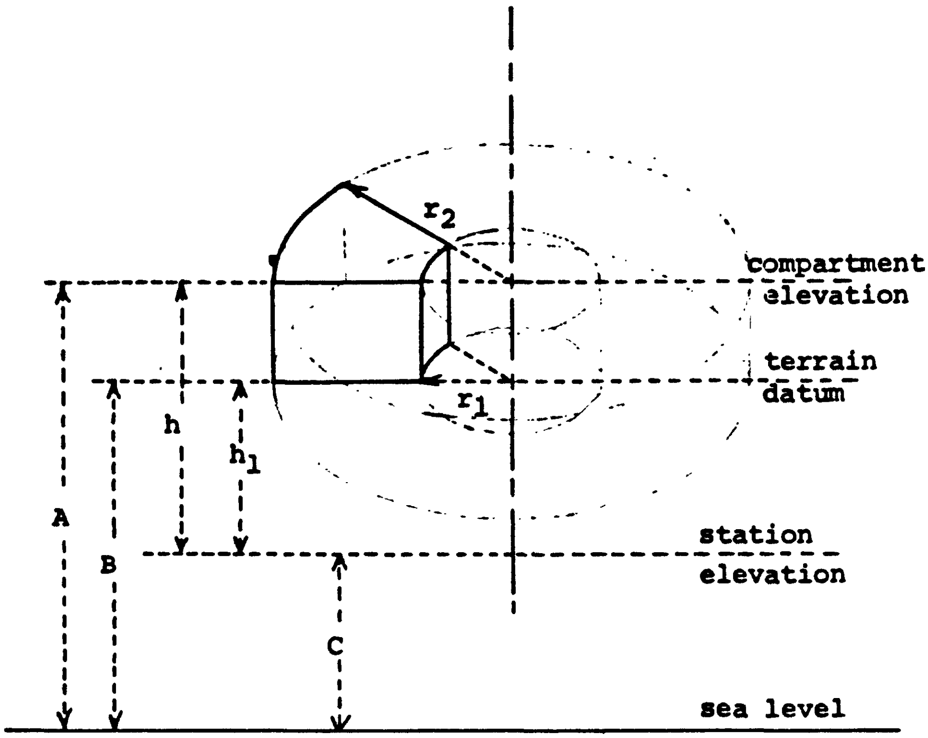
where $d \approx D = (r_1 + r_2)/2$ is the mean radial distance of the zone, R is the mean radius of the earth, and Δh is computed for each zone and subtracted from the compartment elevations (Fig. 2-13). For d and Δh expressed in feet,

$$\Delta h \approx 2.39 \times 10^{-8} d^2.$$

Beyer (1979a, 1979b) presented examples of terrain corrections made for 11 wells in various topographic settings (Figure 2-14). Generally speaking, terrain corrections and their gradients are small and change slowly and uniformly at depths greater than several hundred feet in areas of low to moderate relief and at depths greater than several thousand feet in areas of moderate to high relief. Over hundreds or, in many cases, thousands of borehole feet, terrain corrections usually are not critical to the determination of accurate relative densities from borehole gravity measurements or to the recognition in boreholes of anomalous gravitational effects due to geologic structure. The absolute accuracy of densities calculated from borehole gravity measurements is improved, if only slightly in most cases, when terrain corrections are applied. There are notable exceptions in extremely mountainous terrain.

Hearst and others (1980) studied in more detail the nature of terrain corrections for borehole gravity measurements. Practical implications of their work are that the effect of terrain features from 21.9 to 166.7 km from the well on calculated formation density is nearly constant with depth (like a dc shift) and that corrections for topography beyond 166.7 km are not likely to shift calculated densities by more than 0.01 g/cm.

Schmoker (1980) presents a simple method to estimate if the gravitational disturbances due to cultural features, such as basement excavations, gravel pits, mine dumps, etc., will significantly affect densities calculated from the borehole gravity measurements. Such disturbances are rarely significant below well depths of several hundred feet and often not significant below depths of several tens of feet (Figure 2-15).



$$\Delta h = D\cos\beta$$

$$D = 2R\cos\beta$$

$$\Delta h = D^2/2R$$

but since $D \approx d$

$$\Delta h \approx d^2/2R$$

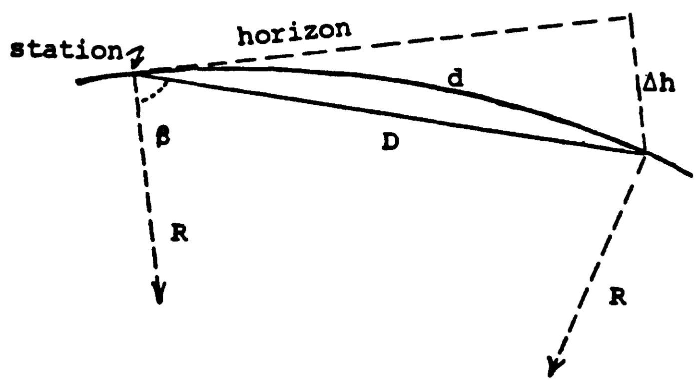


Figure 2-13. Schematic representation of zone and compartment nomenclature used to calculate terrain corrections for borehole gravity measurements (above) and to correct terrain elevation for earth curvature (below).

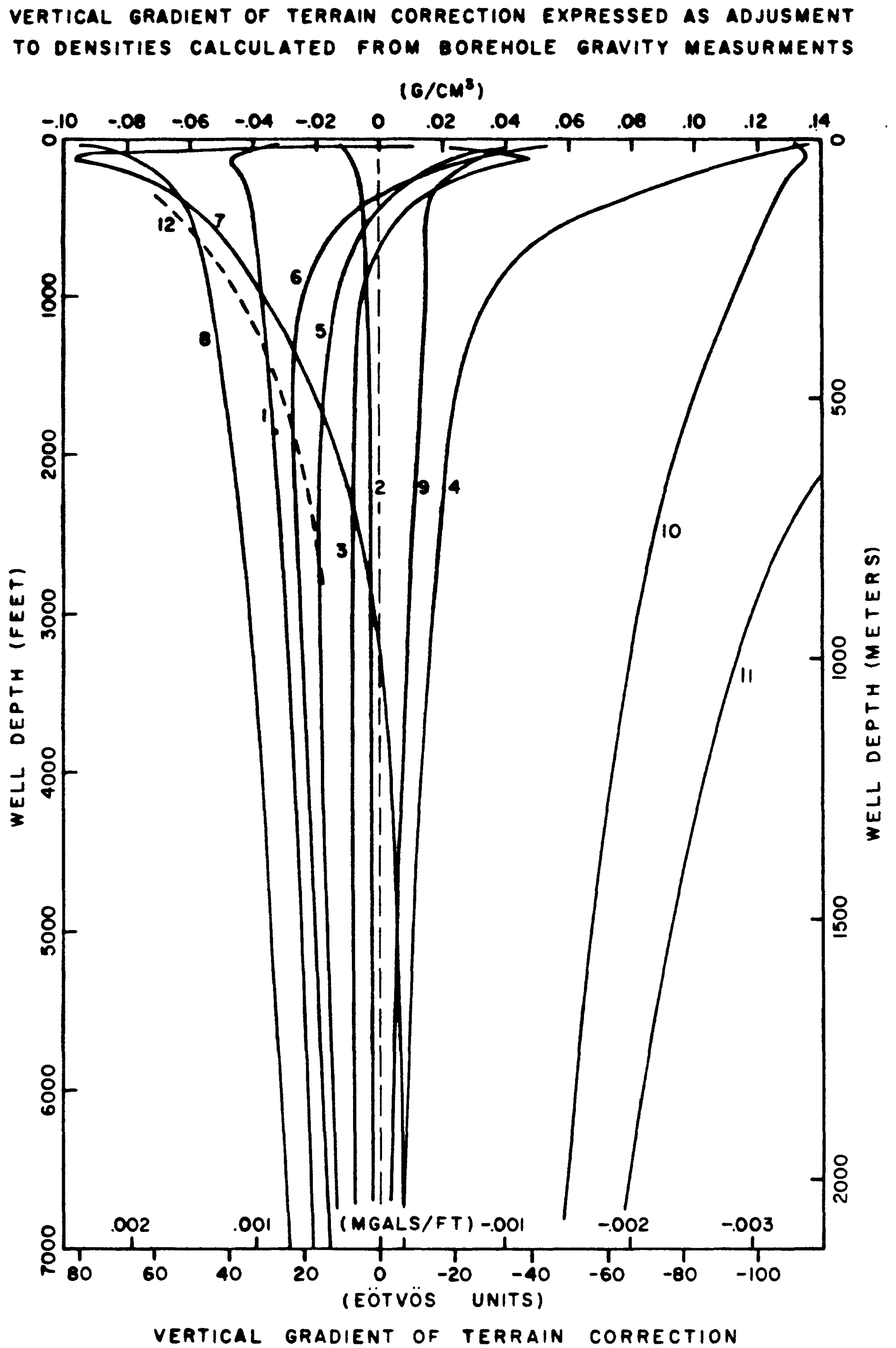


Figure 2-14. Vertical gradients of the terrain corrections for eleven wells and one mine shaft located in the western U.S. (Beyer, 1979a).

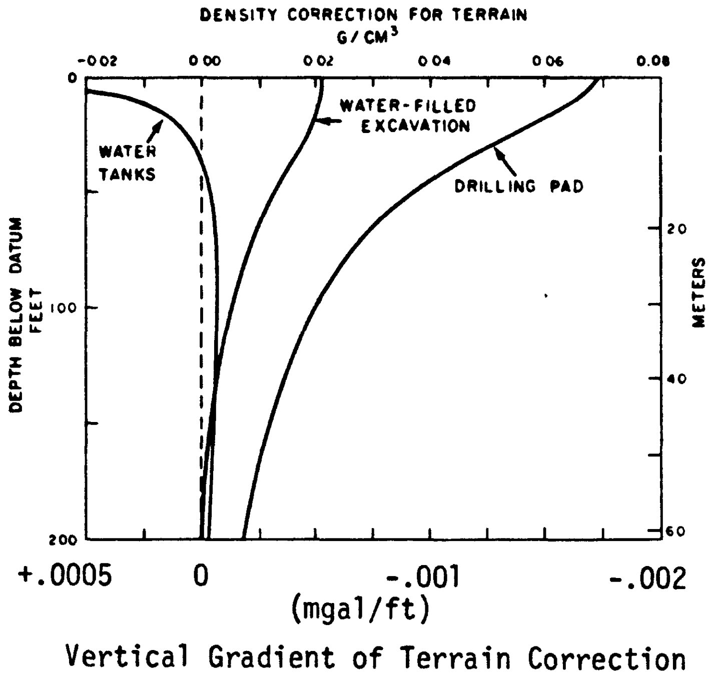


Figure 2-15. Examples of the terrain effect of selected cultural features upon densities computed from subsurface gravity measurements. Data are from borehole gravity surveys in south Florida. The rectangular drilling pad measured 200 x 380 x 7 ft (61 x 116 x 2.1 m), with an estimated density of 1.9 g/cm^3. The irregularly shaped water-filled excavation had an average depth of 29 ft (8.8 m), a surface area of 193 x 10^3 ft^2 (18 x 10^3 m^2), an estimated density contrast of -0.9 g/cm^3, and was centered 325 ft (99 m) from the well. Two above-ground water tanks contained 113 x 10^3 ft^3 (3.2 x 10^3 m^3) of water centered 90 ft (27 m) from the well and 63 x 10^3 ft^3 (1.8 x 10^3 m^3) of water centered 140 ft (43 m) from the well (from Schmoker, 1980).

2.5.7 Borehole deviation from the vertical

Corrections for boreholes deviated from the vertical by θ degrees usually involve only conversion of measured depth to true vertical depth using the equation,

$$\Delta z_{\text{true vertical}} = (\Delta z_m) \cos \theta$$

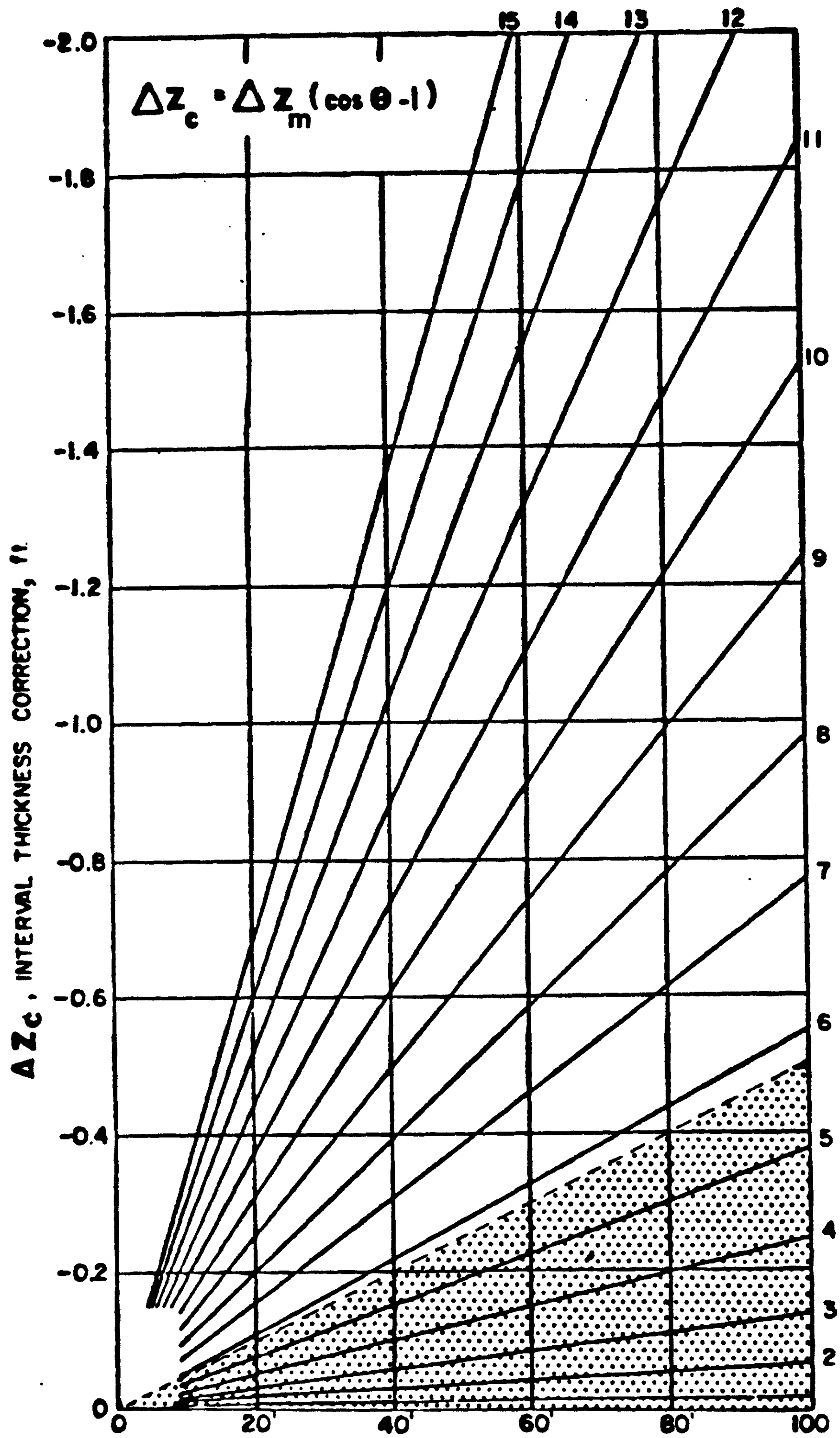
or a more involved formula if a severe dogleg is involved (Rivero, 1971; Fitchard, 1981). Figure 2-16 gives corrections that must be subtracted from measured depth intervals to obtain true vertical depth intervals, as a function of deviation angle. Based on a required minimum error of 0.5 percent in Δz, corrections for deviations less than 6° are unnecessary. If corrections are not made for deviations greater than 6°, the interval gravity gradient will be erroneously low and calculated interval densities will be erroneously high (interval porosities erroneously low).

Present-day BHGMs can be operated in wells that deviate by not more than about 14°. Neglect of a 14° deviation, causes a 3% error in Δz, which, in turn, can cause errors in calculated interval density that range from about .033 g/cm^3 for a formation density of 2.6 g/cm^3 to .050 g/cm^3 for a formation density of 2.0 g/cm^3.

In significantly deviated boreholes, the theoretical latitude-dependent horizontal gradient of total gravity and any anomalous horizontal gradients of total gravity will contribute to gravity variations measured down the borehole. The theoretical latitude-dependent gradient does not exceed 1.3 mgal/mile ($\approx$.0002 mgal/ft), applies only to north-south components of borehole deviation, and is given with sufficent accuracy by

$$0.8122 \sin 2\phi \quad \text{mgal/km}$$
$$1.307 \sin 2\phi \quad \text{mgal/mile}$$

where ϕ is latitude (Nettleton, 1976, p. 80-81). Anomalous horizontal gradients in total gravity occasionally are greater than 10 to 20 mgal per mile (.0019 to .0038 mgal/ft) on surface gravity maps and presumably are of similar magnitude underground. Values of the theoretical latitude-dependent horizontal gravity gradient together with estimates of anomalous horizontal gradients taken from surface gravity maps can be analyzed with hole azimuth and hole angle data from the well directional survey to determine if corrections for horizontal gradients are necessary. McCulloh and others (1968, p. 5) concluded that corrections should be made for horizontal gradient effects "of 0.008 milligals/foot or more per 20 feet" of depth which corresponds to an error of .0004 mgal/ft in the measured interval vertical gradient (or in the anomalous vertical gradient calculated from it) and an error of 0.15 g/cm^3 in calculated interval densities. A more general indication of the magnitude of horizontal gradient effects is shown in Figure 2-17. In the vast majority of cases, corrections for these effects are unnecessary or very small.



ΔZ_m Measured interval thickness (ft)

Figure 2-16. Correction Δz_c to measured interval thickness Δz_m for various degrees of borehole deviation (modified from EDCON, 1977). Stippled area shows region where corrections are unnecessary if an error of 0.5 percent or less in Δz is acceptable.

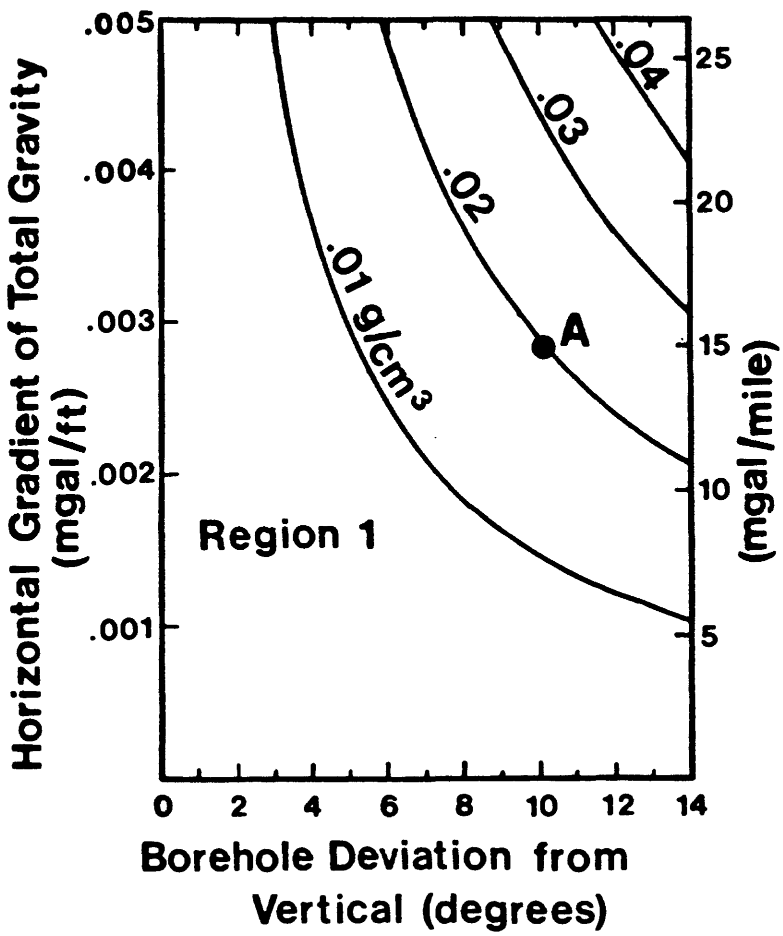


Figure 2-17. Borehole deviation from vertical in degrees versus horizontal gradient of total gravity (due to sum of latitude and anomalous gradients) that shows effect of horizontal gradients on calculated interval density. Combinations of borehole deviations and horizontal gradients in Region 1 cause errors in calculated interval density of less than 0.01 g/cm^3 if horizontal gradients are ignored. Higher values of the horizontal gradient can combine with greater borehole deviation to cause significant errors in interval density. For example, point A shows that, for a borehole interval deviated from the vertical by 10 degrees, a horizontal gradient of about 15 mgal/mile or .00285 mgal/foot, requires a 0.02 g/cm^3 correction. If the borehole azimuth and deviation and horizontal gradient combine to increase gravity with increasing depth, then the sign of the correction to the calculated interval density is positive, and vice versa.

2.5.8 Summary

Corrections for calibration and tidal gravity are routine and automatically calculated with high accuracy. Corrections for terrain and borehole deviation are often unnecessary but routine when needed. The most difficult and important correction, the one that depends heavily on the condition of the BHGM, the manner of the survey, and the borehole environments, is the instrument drift correction. Even if the performance of the BHGM and its telemetry system are optimized, accurate drift corrections are possible only if

(1) a sufficient number of repeated downhole BHGM measurements are made by carefully returning the instrument to the same locations, and

(2) the response of the BHGM to the temperatures and temperature gradients in the well is known. Calculation of (and correction for) the temperature response of the BHGM during a given survey requires that

   (a) sufficient temperature data be recorded during the survey, and

   (b) the response of the BHGM to ambient temperature fluctuations be known from careful, systematic laboratory tests of the BHGM (Fig. 2-18).

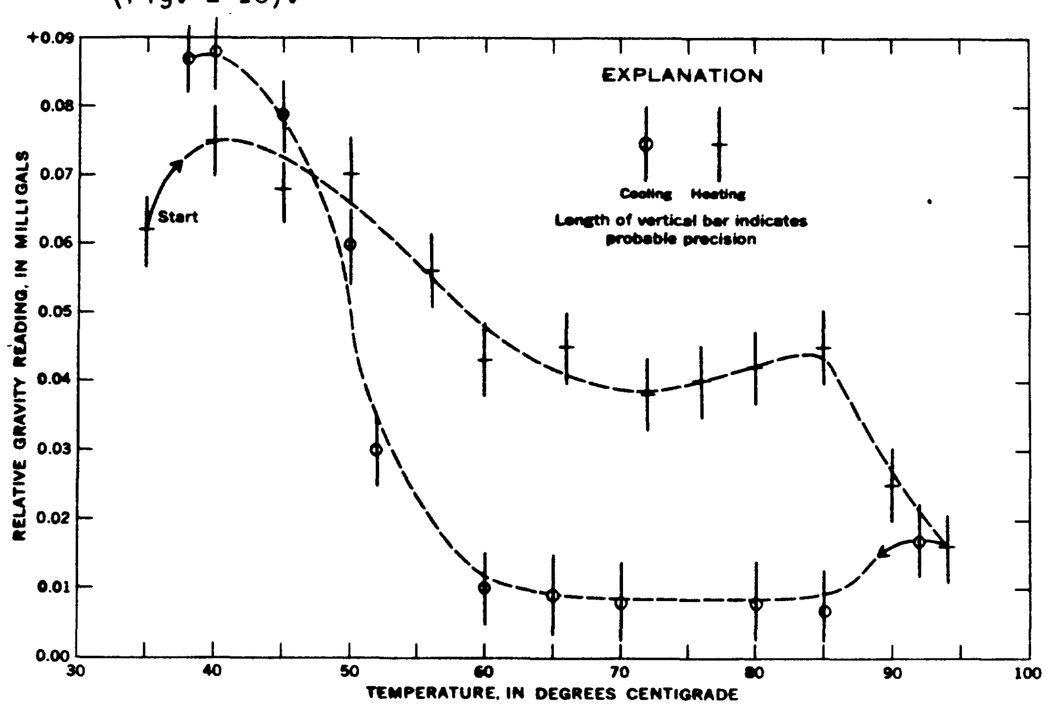


Figure 2-18. Relative gravity values (corrected for tidal gravity) of BHGM #1 as a function of variation of environment temperature from a laboratory test designed to simulate borehole temperature conditions during a BHGM survey (McCulloh, 1967).

2.6 Significance of Measurement Errors

2.6.1 Introduction

Errors in gravity and depth measurements translate directly through simple relationships to errors in calculated interval density. High-precision borehole gravity surveys involve high accuracy measurements and often short vertical intervals (less than 30 to 50 feet). Caton (1981) has presented a systematic approach to the error analysis of borehole gravity measurements and some of what follows is patterned after his approach. Basically, errors fall in these catagories; (1) repeatabilities or precisions of Δg (independent of depth errors) and Δz measurements, (2) errors in gravity station readings because of depth mislocation upon reoccupation which can cause errors in the instrument drift curve, (3) and errors in calculated interval densities that result from depth mislocation relative to the strata.

2.6.2 Error in Δg and Δz

Errors in calculated $\bar{\rho}$ occur when there are errors in the value of Δg. For example, if a Δg value of 1.0 mgal is in error by 0.04 mgal, then Δg_{error} = 0.04 mgal, and there will be an error in the calculated $\bar{\rho}$ whose magnitude depends on the magnitude of Δz.

Common causes of Δg_{error} include

1. Improper gravity meter calibration
2. Improper leveling of gravity meter
3. Improper "tuning" of the gravity meter
4. Improper function of the electronic telemetry and control system
5. Improper corrections for instrument drift
6. Human reading errors
7. Improper surveying procedures

The effect of Δg_{error} on $\bar{\rho}$ is illustrated in Figure 2-19 which is modified from Byerly (1977). The inset equation is modified from eq. (7) of Caton (1981) who considers errors in individual gravity measurements. In the inset equation, $\lfloor \Delta g_{error} / \Delta g \rfloor$ is simply the decimal percent error in Δg. Note that the Δg's cancel from numerator and denominator, making this relationship somewhat different from the relationship in the following section between Δz_{error} and $\bar{\rho}_{error}$. Here Δg_{error} is discussed not as a percent but directly in fractions of mgals. Figure 2-19 shows clearly the decrease in reliability of $\bar{\rho}$ with either a decrease in Δz or an increase in Δg_{error}. It is especially important to try to make Δg_{error} as small as possible and practicable, and to estimate its magnitude, which will depend on the individual errors in the two associated gravity readings.

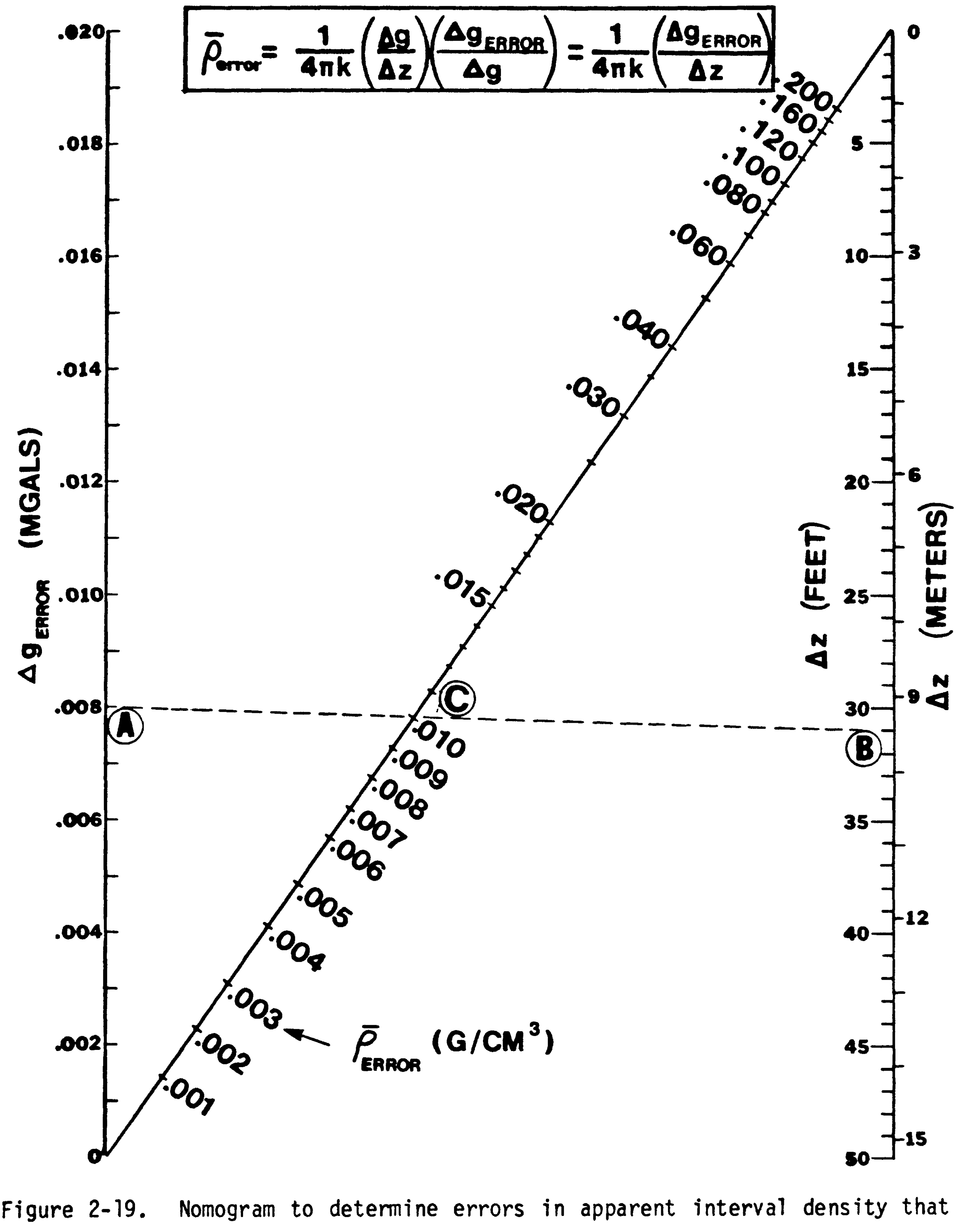


Figure 2-19. Nomogram to determine errors in apparent interval density that result from errors in Δg. Nomogram may be used for errors in Δg that range from 0 to .020 mgals for vertical intervals up to 50 feet thick. For example, an error in Δg of .008 mgal (A) over an interval of 31 feet (B) causes an error in apparent interval density of .01 g/cm^3 (C). Errors in Δz are assumed to be zero.

Errors in calculated $\bar{\rho}$ arise when there are errors in the value of Δz. If a Δz value of 50 feet is in error by 0.4 feet, then Δz_{error} = 0.4 ft, and there will be an error in the calculated $\bar{\rho}$ whose magnitude depends on the density of the formation.

Causes of Δz_{error} include

1. Incompletely or improperly conditioned wireline
2. Improper calibration or malfunction of depth measuring equipment and instruments
3. Lack of sufficient reading resolution on depth odometers and verniers
4. Human reading errors
5. Failure to account for significant borehole deviation from vertical

The effect of Δz_{error} on $\bar{\rho}$ is illustrated in Figure 2-20. The inset equation is similar to eq.(11) of Byerley (1977) and a modification of eq.(8) of Caton (1981) who considers errors in individual depth measurements. It is evident from Figure 2-20 that for high-precision BHGS, ($\Delta z_{error}/\Delta z$) < .005; that is, errors in Δz should be less than 0.5 percent. Based on this conclusion, Figure 2-21 shows the maximum tolerable Δz_{error} for Δz ranging from 1 to 1000 feet. This suggested maximum tolerable Δz_{error} is normally achievable, especially in cased wells, but requires careful attention to depth measuring equipment and depth measurements. Wireline hoist operators may be unfamiliar with this requirement.

If depth readings on cable odometers can be repeatedly read to the nearest 0.1 foot and the maximum 0.5 percent error in Δz is accepted, Δz intervals less than about 30 to 40 feet should be measured by hand-taping between marked points on the cable at the ground surface between the hoist and wellhead. This procedure seems to work well in most boreholes even though it depends on the assumption that the downhole tool moves the same incremental distance as the marked point on the cable at the ground surface.

Quality of Δz measurements in some mud-filled open-holes may be degraded by the tool or wireline sticking which can cause unpredictable cable elongation and irregularities in depth odometer readings due to variations in wire-

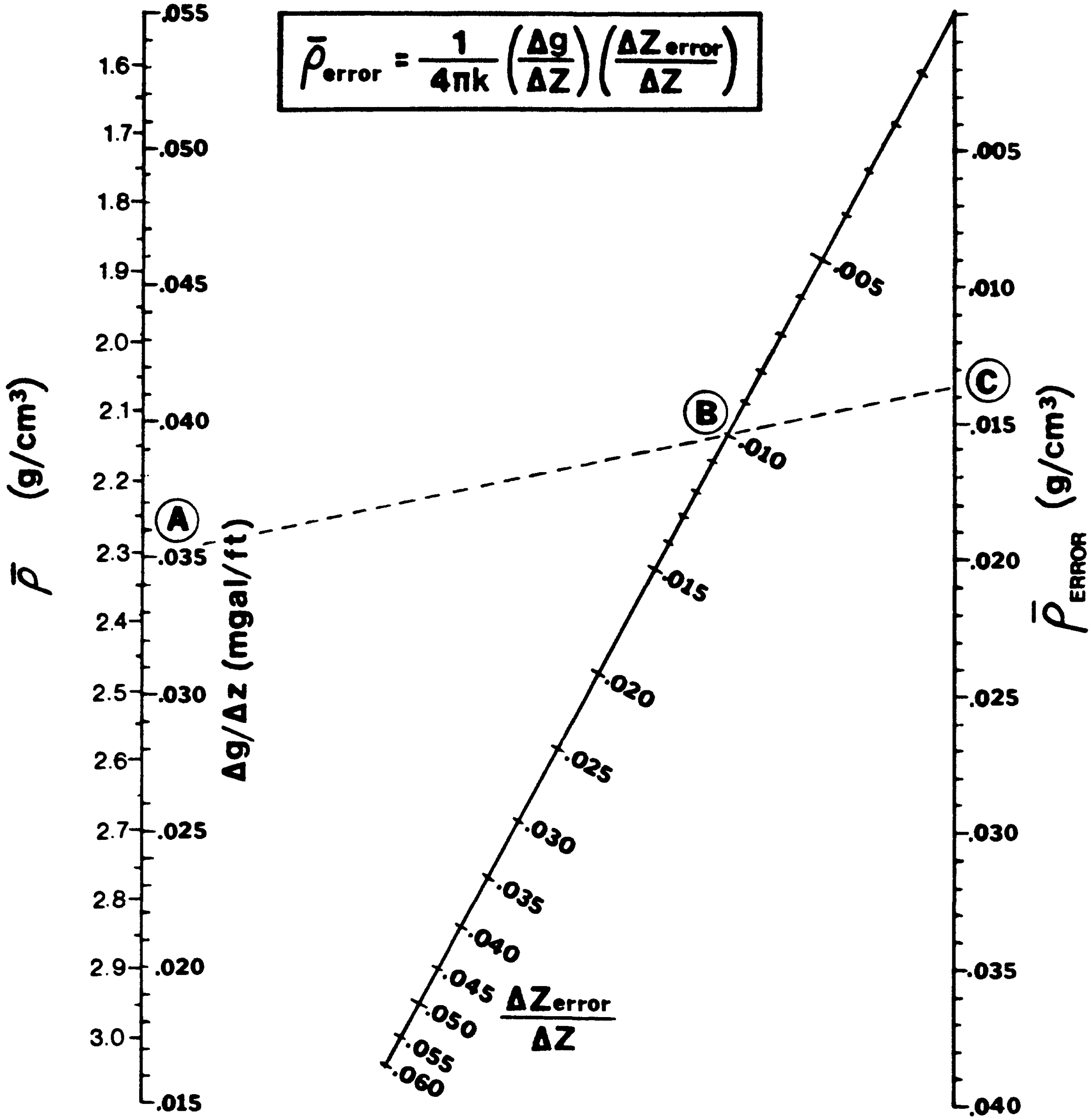


Figure 2-20. Nomogram to determine errors in apparent interval density that result from errors in Δz. Nomogram may be used for fractional errors in Δz that range from 0 to .06 where the interval gravity gradient ranges from .015 to .055 mgals/ft. For example, where the interval gravity gradient is .035 mgals/ft (A), a fractional error in Δz of .01 (B) causes an error in the apparent interval density of about .014 g/cm^3 (C). Errors in Δg are assumed to be zero.

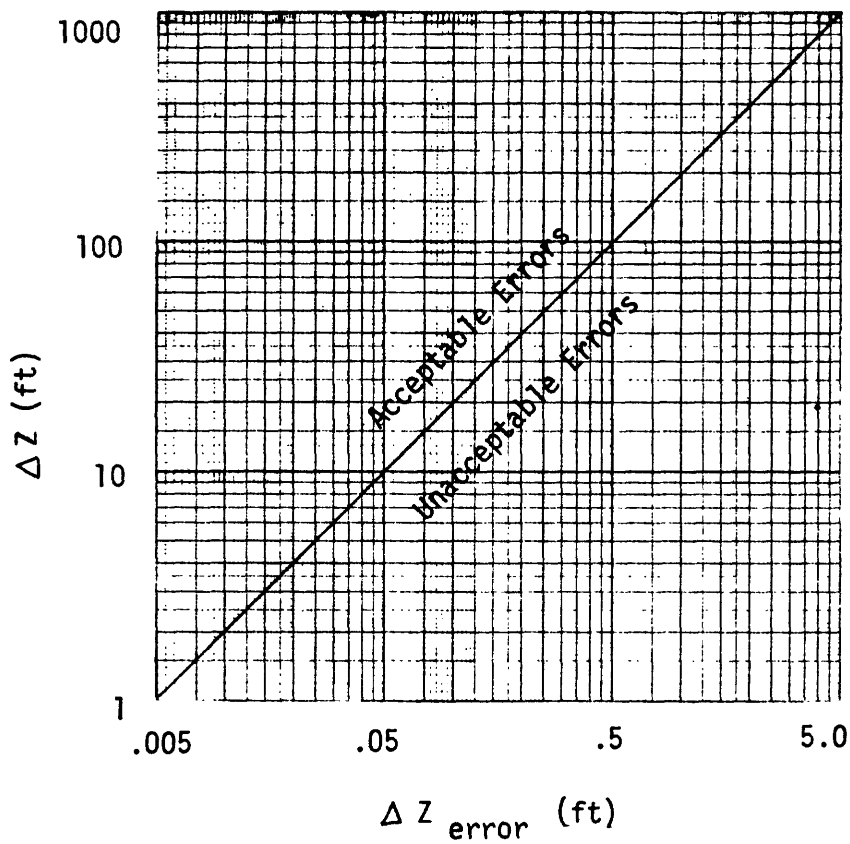


Figure 2-21. Region of acceptable errors in Δz measurements defined by a maximum allowable error of 0.5 percent; that is $\Delta z_{error}/\Delta z = .005$.

line tension. The logging tool may also stick or refuse to go down cased wells in which there is little clearance between the casing and logging tool and/or low gravity oil is present.

2.6.3 Depth mislocation of the borehole gravity station upon reoccupation

Differences in repeated gravity readings may be caused by depth mislocation when the gravity meter is returned to a downhole station (Caton, 1981). The gravity error (g_{error}) that results from a depth mislocation (z_{error}) for a range of rock densities is summarized in Figure 2-22, which was developed from Caton's eq. (9). Depth mislocation during re-occupation of a downhole gravity station is normally small or insignificant when equipment is operating properly, wireline is well conditioned, and careful survey techniques are employed. Sources of z_{error} are the same as for Δz_{error}. Minimal mislocation errors are essential to the construction of accurate correction curves for instrument drift.

Some indication of the minimum-depth error achievable during re-occupation of a downhole gravity is given by Allen (1969) who investigated subsurface compaction (related to surface subsidence) caused by fluid withdrawal in the Wilmington oil field, California (Figure 2-23). Careful remeasurements of casing points by Allen suggests that ±.05 feet is the maximum depth error upon re-occupation using casing collar locators (CCL). In practice, re-occupation error after traversing up and down a portion of the borehole can be several to many times larger, especially if the cable odometer or a marked point on the wireline is used for re-occupation. Use of a CCL or gamma-ray to reposition downhole or return to the surface to reset the cable odometer to eliminate counter "backlash" and cable stretch should result in smaller re-occupation errors.

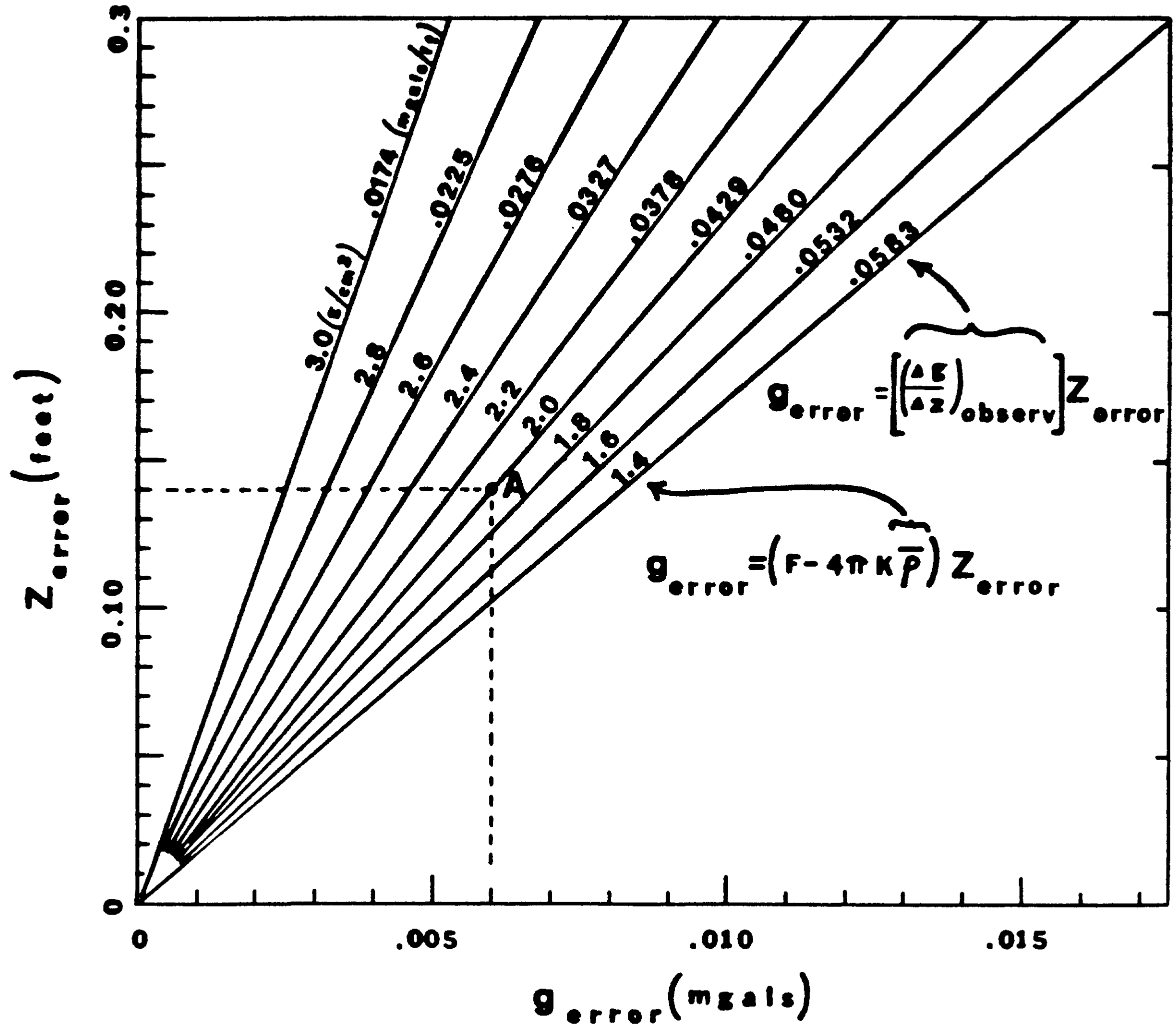


Figure 2-22. Error in gravity readings, g_{error}, caused by a depth mislocation, z_{error} for interval densities ranging from 1.4 to 3.0 g/cm^3. Point A shows that while logging through rocks with a density of about 2.0 g/cm^3, a depth mislocation error of 0.14 feet will cause a gravity error of .006 mgals.

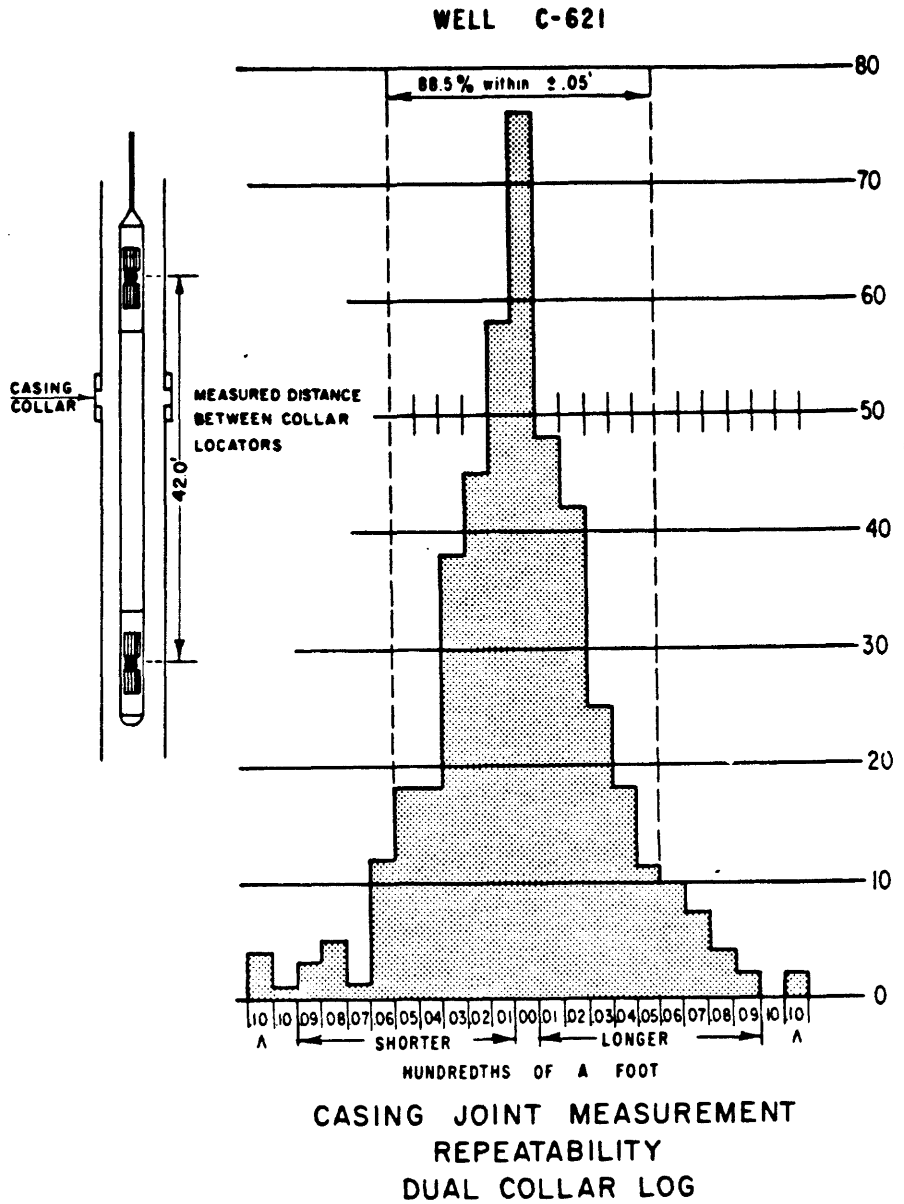


Figure 2-23. Frequency distribution of the measurement and remeasurement of pipe joint length on successive logging runs using a specially-built double casing collar locator (CCL). The spacing of the two CCLs was within the range of lengths of casing so that pairs of collars would be recorded about at the same time, thereby minimizing odometer, cable, and cable bounce errors (from Allen, 1969)

2.6.4 Depth mislocation relative to strata

Downhole gravity stations must be chosen carefully so that they actually bracket the stratigraphic intervals of interest. If gravity stations bounding a lithologic unit are mislocated into the intervals above and below, the calculated interval density for the unit will be a simple linear average of the density of unit A and density of the fractional parts of the intervals above and below. For example, in Figure 2-24, the calculated density for interval A is

$$\bar{\rho}_{calc} = \frac{\bar{\rho}\Delta z + \rho'\Delta z' + \rho''\Delta z''}{\Delta z + \Delta z' + \Delta z''}$$

where

$\bar{\rho}$ = interval density of interval A

$\bar{\rho}'$ = interval density of interval above interval A

$\bar{\rho}''$ = interval density of interval below interval A

Δz = thickness of interval A

$\Delta z'$ = depth mislocation of upper gravity station into overlying interval

$\Delta z''$ = depth mislocation of lower gravity station into underlying interval

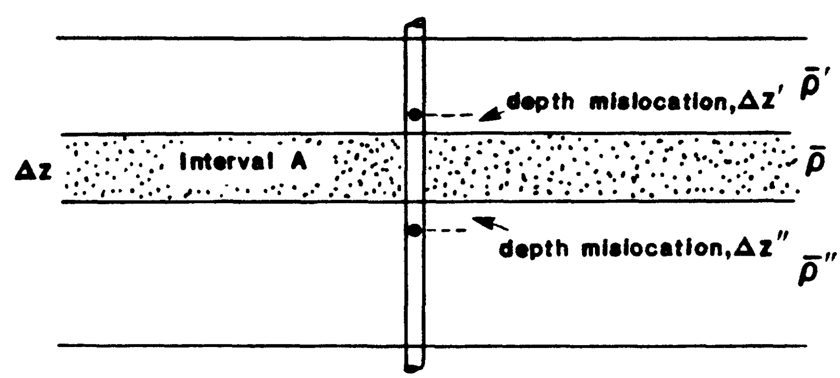


Figure 2-24. Schematic diagrams showing mislocation of borehole gravity stations above and below interval of interest.

A quantitative measure of the possible errors in calculated density that can arise from mislocation of borehole gravity stations relative to strata is shown in Figure 2-25 If the intervals above and below interval A have the same density and the total mislocation error is expressed as a percent of the thickness of interval A, the error in density contrast ($\Delta\bar{\rho}_{error}$) between interval A and the surrounding rocks is

$$\Delta\bar{\rho}_{error} = \left(\frac{P}{100 + P}\right)\Delta\bar{\rho}_{true}$$

where

P = depth mislocation into intervals above and below of gravity stations chosen to bound interval A, expressed as a percentage of the thickness of interval A

and

$\Delta\bar{\rho}_{true}$ = the true density contrast between interval A and the intervals above and below.

Errors due to depth mislocation relative to strata are only significant for relatively small Δz and large density contrasts between successive intervals.

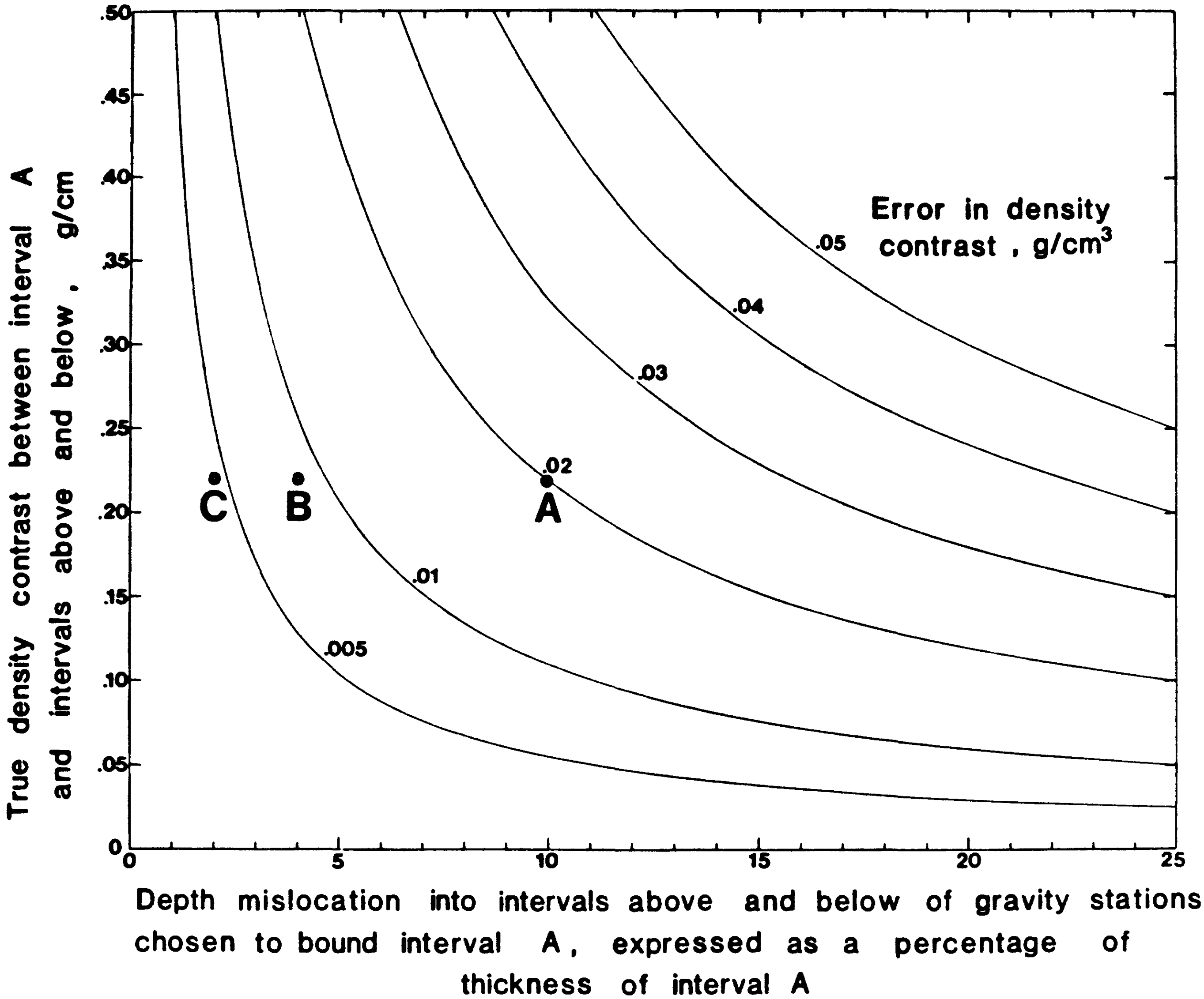


Figure 2-25. Errors in calculated interval density as a function of depth mislocation relative to the interval for a range of density contrasts between the interval and rocks above and below. For example, a 10% depth mislocation for a 10-foot sandstone interval causes a 0.02 g/cm^3 error in the calculated density contrast between the sandstone and surrounding shale when the true density contrast is 0.22 g/cm^3 (Point A). This is the case if the upper and lower gravity stations were each mislocated 0.5 feet into the shale, or one station had been mislocated 1.0 foot into the shale. The same 1.0-foot depth mislocation error for a 25-foot thick sandstone (with the same density contrast) causes a .009 g/cm^3 error in the calculated density contrast (Point B); for a 50-foot thick sandstone the error is about .004 g/cm^3 (Point C).

2.6.5 Summary

Care must be exercised during BHGM surveys to make errors in Δg and Δz measurements small enough to insure that calculated interval densities have the required precision. Figure 2-19 and 2-20 provide the basis to establish acceptable errors in Δg and Δz measurements and to convert these errors to uncertainties in calculated density. As the Δz interval becomes smaller, given errors in Δg or Δz are proportionally larger and, consequently, errors in calculated densities are larger. Errors caused by depth mislocation with respect to strata are small or negligible for larger Δz intervals and become important only for small Δz intervals (less than about 20 feet) and large density contrasts (>0.2 g/cm^3) between successive intervals. Repeated downhole gravity measurements to establish gravity meter drift curves and evaluate repeatability require that the instrument be returned to the same downhole location to within a fraction of a foot. Three of the four possible sources of error discussed here are related to depth measurements which are more stringent for high-precision BHGM surveys than for most other downhole work.

2.7 Repeatability of Borehole Gravity and Depth Measurements

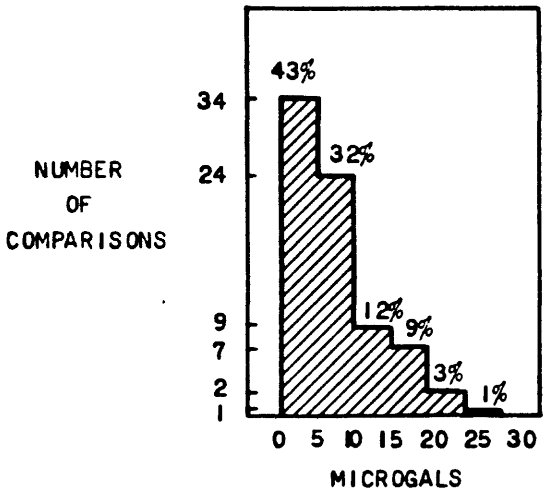
The repeatability or precision of gravity and depth measurements in boreholes has been a major (if not principal) concern of investigators from the beginning of high precision BHGS in the 1960's. Much time and effort has been spent devising proper evaluations of the response of gravity meters to thermal, inertial, magnetic, and pressure effects, and then "fine-tuning" (and frequently retuning) each instrument to insure a minimal and, most importantly, predictable response to these effects. Similar and equally important efforts have been devoted to progress in electronic telemetry and control systems, improved electro-mechanical components, mechanical systems, increase in maximum temperature tolerance, and reduction in the size of the gravity sensor itself.

The properly functioning BHGM of today is an almost miraculous mechanical device that represents nearly 20 years of gradual improvement. However, if improperly maintained and operated, the BHGM can perform so poorly that only worthless data are obtained.

The following published results of performance tests give some indication of repeatability or precision of borehole gravity surveys. It should be remembered, however, that different investigative groups have entered this field at various times since 1966 and each has had to re-discover the proper methods and procedures that result in truly high-precision surveys. Also, each borehole gravity meter responds according to the manner in which it is operated and maintained, and its performance can be strongly influenced by the logging procedures and environment of the borehole.

Earliest discussions of repeatability of LC&R BHGMs were those of McCulloh (1967) who concluded that the precision of (1) depth measurements ranged from 0.05 to 0.2 ft between the surface and 9,500-ft depth and (2) downhole gravity measurements ranged from 0.008 to 0.020 mgal with an average of 0.016 mgal. Beyer (1968) concluded that interval vertical gradients were repeatable to 0.00025 mgal/ft or better, based on repeated interval measurements in wells up to 3000 feet deep and improved performance of the BHGM.

Extensive tests at AMOCO Production Research during the early and mid-1970's produced results given by Rasmussen (1973), Brown and others (1975), and Jageler (1976) (Figure 2-26).



Bottom (ft)	Top (ft)	Thick (ft)	ΔG_1	ΔG_2	Dev.	Den_1	Den_2	Dev.
5,635	5,300	335	8.808	8.811	+ 3	2.66	2.66	0.0
5,300	5,250	50	1.365	1.372	+ 7	2.62	2.61	0.01
5,250	5,240	10	0.288	0.290	+ 2	2.557	2.550	−0.007
5,240	5,200	40	1.012	1.023	+11	2.70	2.68	−0.02
5,200	5,060	140	3.671	3.672	+ 1	2.66	2.66	0.0
5,060	4,980	80	2.273	2.248	−25	2.57	2.56	+0.01
4,980	4,850	130	3.950	3.956	+ 6	2.50	2.49	−0.01
4,850	4,800	50	1.388	1.388	0	2.60	2.60	0.0
4,800	4,620	180	4.564	4.550	−14	2.69	2.70	+0.01
4,620	3,950	670	19.131	18.183	+52	2.57	2.56	−0.01
3,950	3,165	785	25.228	25 183	−45	2.43	2.43	0 0
3,165	3,080	85	2.685	2 690	+ 5	2.45	2.45	0.0
3,080	3,050	30	0.971	0.971	0	2.42	2.42	0.0
3,050	2,970	80	2.289	2.290	+ 1	2.56	2.56	0.0
2,970	2,550	420	15.482	15.485	+ 3	2.24	2.24	0.0
2,550	2,100	450	16.469	16.481	+12	2.25	2.25	0.0
2,100	1,865	235	7.759	7.749	−10	2.39	2.39	0.0

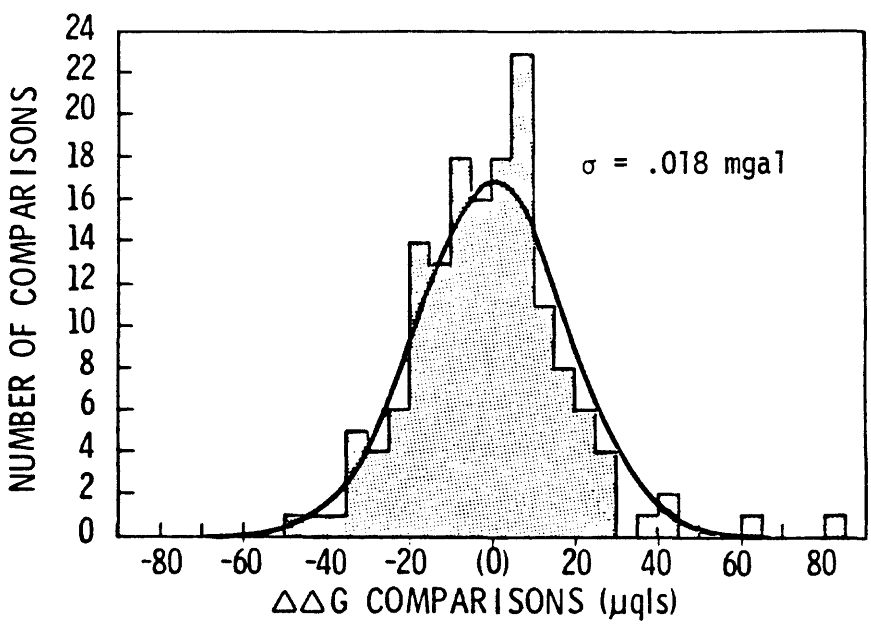


Figure 2-26. Differences between repeated Δg measurements. Seventy-seven repeated interval gravity measurements from Rasmussen (1973) (upper left); 17 repeated intervals from Jageler (1976) (upper right); and 154 repeated intervals from Brown and others (1975) (lower). Rasmussen's data appear to be deviations from averages of repeated Δg values rather than simple differences.

Schmoker (1978) repeated 132 Δg measurements during 1975-1976 and computed a mean of zero and a standard deviation of .019 mgals. He found that larger differences between repeated Δg measurements seemed to correlate with greater vertical separations between borehole stations and greater time intervals between the repeated measurements (Figure 2-27).

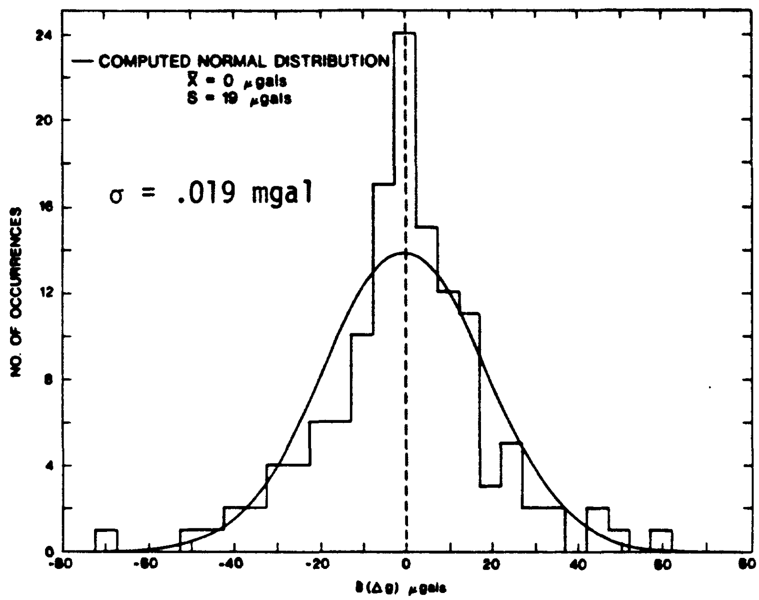


Figure 2-27. Distribution of mis-ties between 132 duplicate subsurface interval measurements. A computed normal distribution is also shown (from Schmoker, 1978).

Caton (1981) discusses in detail his statistical approach to the analysis of repeated borehole gravity measurements, using up to four repeated measurements of some intervals. The unadjusted differences in interval density between various repeats are rather large but Caton delves into the probable causes of the discrepancies and arrives at a statistical best fit to which he assigns a 90% confidence level (see Figure 2-28). His paper is highly recommended for those who want more information on the statistical treatment of borehole gravity measurements even though the data set he presents has atypically low precision and some of his conclusions are controversial.

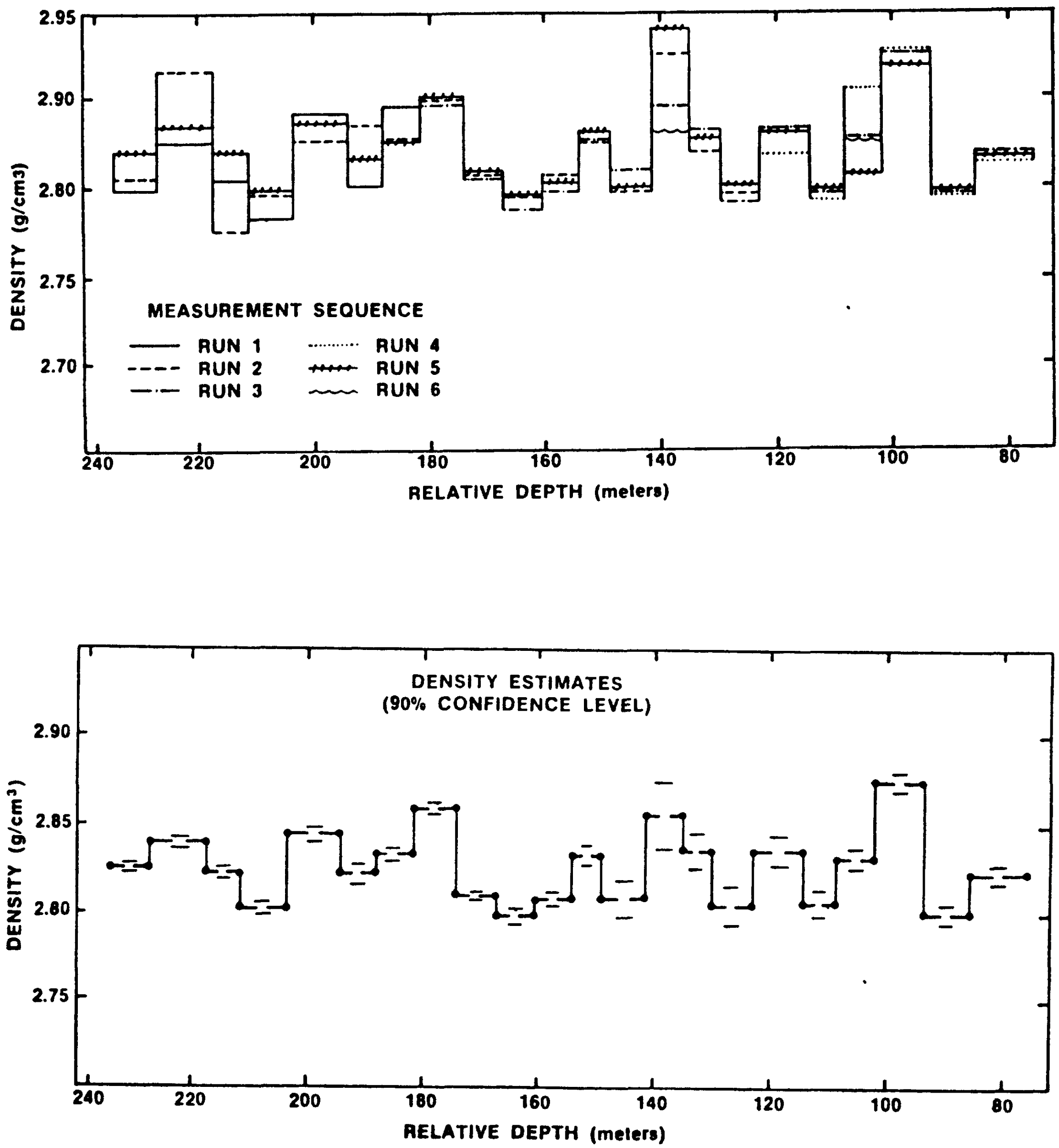
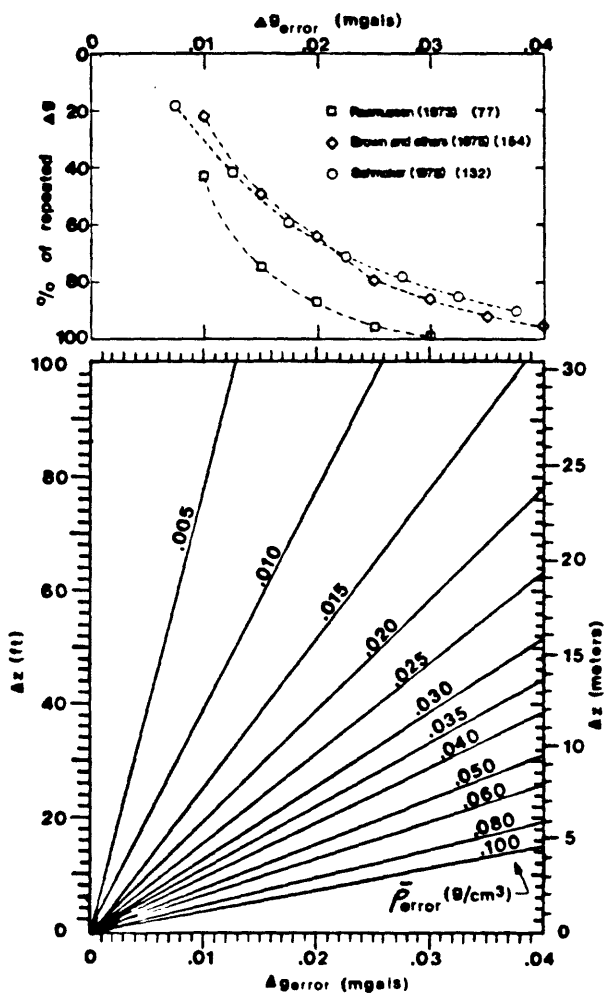


Figure 2-28. Density values obtained from uncorrected sequences of BHGM measurements within a Texas well (top). Improved density estimates at the 90% confidence level after statistical treatment (bottom) (from Caton, 1981).

The repeatability studies presented by Rasmussen (1973), Brown and others (1975), and Schmoker (1978) are combined in Figure 2-29 to project downward into an error diagram that relates Δg_{error} to $\bar{\rho}_{error}$ for Δz values up to 100 feet.

Some of the results of repeatability studies, ranging from the earliest to the most recent tests, conducted by the author at the U.S. Geological Survey are shown in Figure 2-30. Under optimum conditions, precisions of Δg measurements ought to be ±.008 to ±.012 mgals or better as Beyer (1971) concluded. Multiple repeated measurements of Δg with favorable borehole conditions and an optimally operating BHGM should lead to Δg_{error} that approach ±.002 to ±.004 mgal. Future instrumentation developments undoubtedly will also improve repeatability.



$$\bar{\rho}_{error} = \frac{1}{4\pi k}\left[\frac{\Delta g_{error}}{\Delta z}\right]$$

Figure 2-29

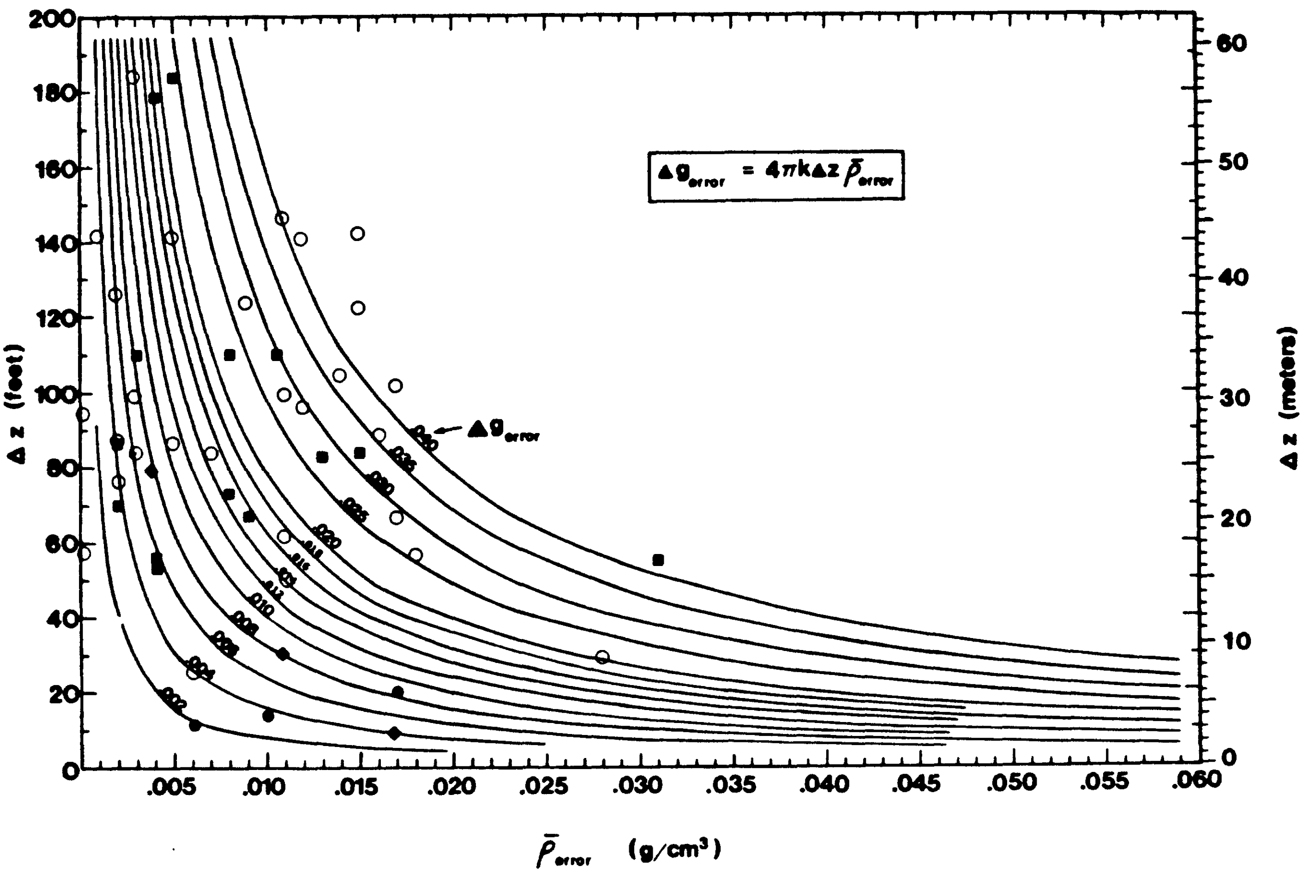


Figure 2-30. Differences in repeated interval vertical gradient measurements expressed in mgal/ft and as interval densities (g/cm^3) as a function of interval thickness (Δz). Open circles (○) are for intervals repeated six months apart in a well in the Santa Fe Springs oil field, California, in 1967 during the early development period of the prototype LC&R BHGM; diamonds (◆) are intervals repeated in the Midway-Sunset oil field in 1968; solid circles (●) are for intervals repeated in Texas in 1980. The solid squares (■) are differences between interval gradient measurements made by the U. S. Geological Survey in July 1967 with LC&R BHGM #1 and measurements made by Gravilog Corporation in January 1973 with LC&R BHGM #2 at the same stations in a well at the Nevada Test Site.

3.0 NATURE OF BHGM MEASUREMENTS

3.1 Interval and apparent density

Interval density $\bar{\rho}$ is calculated from the fundamental equation of borehole gravity

$$\bar{\rho} = 3.680 + 39.127(\Delta G_g - \Delta g/\Delta z) \qquad (2\text{-}5)$$

where ΔG_g is negligible or known and the units are feet, mgals, and g/cm^3. Interval density is the gravitational average density of the horizontal layer and, in theory, can be caused by an infinite number of different density distributions in the horizontal layer. In practice, $\bar{\rho}$ is a representative measure of the density in situ of individual beds or groups of beds in which density is reasonably constant in horizontal directions for radial distances of at least 5 to 10 times the interval thickness Δz. Under these circumstances $\bar{\rho}$ can, in effect, be considered a linear average of any vertical variations of density over the Δz interval.

The $4\pi k\bar{\rho}$ term in the fundamental equation (2-4) is the interval vertical gradient due to a horizontal layer of thickness Δz that, in theory, extends away from the borehole to an infinitely great distance. In practice, $4\pi k\bar{\rho}$ is mostly generated by that portion of the horizontal layer that is closer to the borehole than 5 to 10 times the layer thickness (see Figure 3-1).

From Figure 3-1, is it seen that for a horizontal layer of constant density $\bar{\rho}$ and thickness Δz,

65%	of the total $4\pi k\bar{\rho}$ effect occurs within a radial distance of	$\sim 1\Delta z$
75%	of the total $4\pi k\bar{\rho}$ effect occurs within a radial distance of	$\sim 2\Delta z$
90%	of the total $4\pi k\bar{\rho}$ effect occurs within a radial distance of	$\sim 5\Delta z$
95%	of the total $4\pi k\bar{\rho}$ effect occurs within a radial distance of	$\sim 10\Delta z$
99%	of the total $4\pi k\bar{\rho}$ effect occurs within a radial distance of	$\sim 50\Delta z$

It is apparent from Figure 3-1 that values of interval density represent the densities in situ of very large volumes of rocks that extend for considerable distances away from the drillhole, much farther in fact than the investigative distances of conventional open-hole logs.

Interval density is defined in the Glossary of Geology (Bates and Jackson, 1980) as "in a wellbore, the density of an interval integrated from gamma-gamma log data or determined by a borehole gravity meter." Apparent density is defined in the Glossary of Geology as "rock density calculated from gravity measurements in boreholes." The term apparent density should be reserved for those cases where, if ignored in eq. (2-5), ΔG_g is large enough to significantly affect calculated $\bar{\rho}$. Interval density should apply to cases where ΔG_g is negligibly small or its value has been determined and inserted in eq. (2-5).

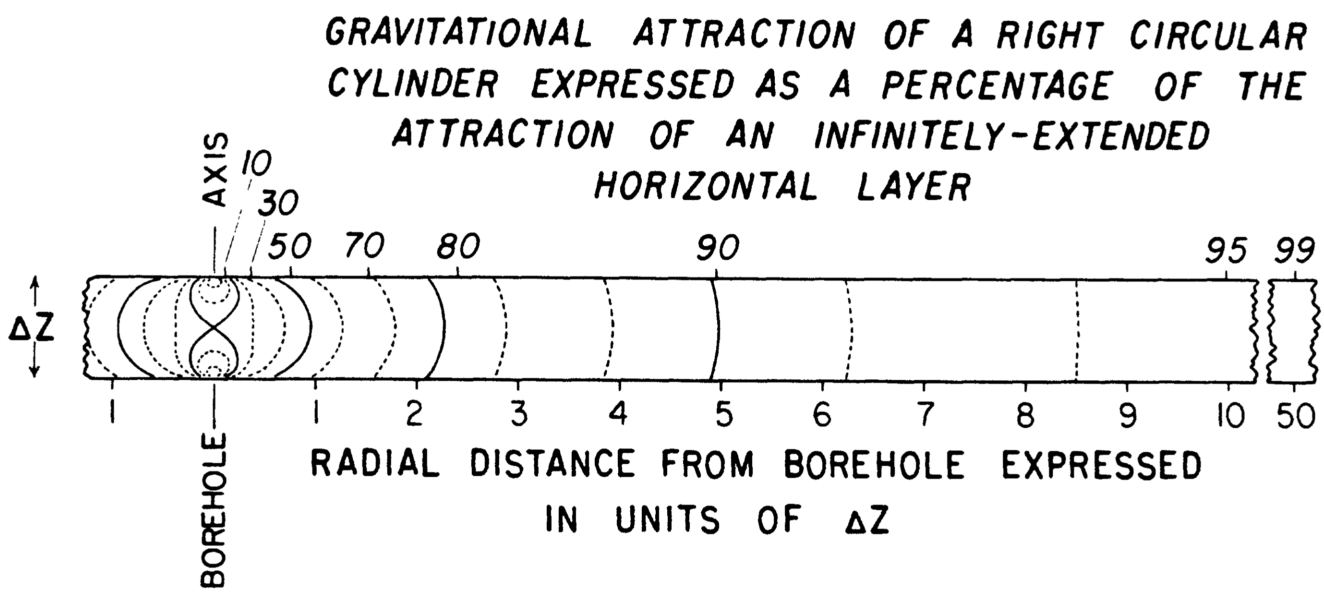


Figure 3-1. Schematic cross section of a portion of an infinitely-extended horizontal layer of thickness Δz, showing the radial distances from the borehole (in terms of layer thickness Δz) within which 50%, 70%, 80%, 90%, 95%, and 99% of the attraction of the infinite-layer occur. Curvilinear lines in the layer, moving away from the borehole, represent points at which a unit mass has decreasing gravitational acceleration on the BHGM.

3.2 Radius of investigation of BHGM measurements: Detection limits

Considerable discussion has appeared in the literature (e.g., Brown and others, 1975; Jageler, 1976; Hearst, 1977a) about the range of investigation and detection limits of BHGM measurements since McCulloh and others (1968) published Figure 3-2 along with the following statement:

> "As R (radius) increases, the gravimetric effect of the progressively larger cylinders approaches that of the infinite sheet . . . the greater the thickness of the layer, the greater the radius of that cylindrical part of the infinite sheet that will produce a given percentage of the total effect of the infinite sheet. Figure 4 ⌊3-2⌋ portrays graphically the very great radius of investigation of borehole gravimetric measurements of density, the fact that this radius is variable and controllable within limits, and the particularly favorable biased (for reservoir evaluation) distribution in space around the borehole of the volumes of rock contributing to the total measured effect for any given vertical measurement interval."

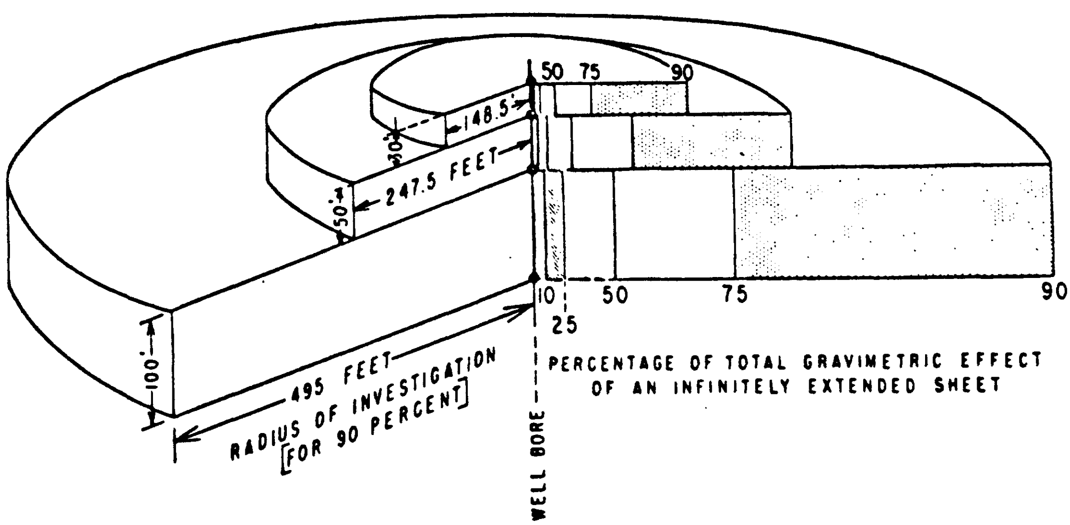


Figure 3-2. "The region investigated . . . is dominantly the tabular cylindrical region extending horizontally from the wellbore a radial distance equal to the vertical measurement interval" (McCulloh and others, 1968).

Figure 3-2 has been misinterpreted to mean that the greater the spacing between BHGM stations, the greater the radius of investigation for lateral density anomalies. As clearly pointed out by Jageler (1976), the detection of anomalous gravity in the borehole due to lateral density variations depends on the volume and shape of the anomalous mass, the magnitude of the density contrast, the distance from the borehole, the sensitivity of the BHGM, and the spacing of the borehole gravity stations. The situation is identical to that for surface gravity measurements except that the anomalous gravity measured in the borehole must be isolated from the borehole gravity variations due to the vertical density variations in the section penetrated by the well and the shapes of the anomaly curves are different. Detection limits can easily be determined for simple geometric (see e.g., Jageler, 1976; Hearst, 1977a).

If the rocks can be effectively considered as homogeneous horizontal layers of great lateral extent, the representations of Figures 3-1 and 3-2 are valid provided layers above and below are also homogeneous and horizontal. In this case, smaller volumes of rock near the wellbore have the same effect as larger volumes of rock more distant from the borehole. Schmoker (pers. comm., 1975) pointed out that there is some effective volume (a right circular cylinder) beyond which the gravitational effects are less than the precision of the BHGM measurements (Figure 3-3). For example, if the precision of the $\Delta g/\Delta z$ measurement is ±0.00025 mgal/ft (corresponds to an interval density precision of ±0.01 g/cm^3), the portion of the layer beyond a radial distance of about 100Δz contributes 0.00025 mgal/ft to the measured gradient for a layer density of 2.0 g/cm^3 (see dotted line in Figure 3-3). This is one conceptual way of viewing the radius of investigation for the case of infinitely-extended homogeneous layers.

It can be concluded that borehole gravity surveys examine volumes of rock that extend at least tens to hundreds of feet outward from the borehole. This is in sharp contrast to conventional well log methods whose radius of investigation is measured in inches from the borehole (see Figure 3-4 and 3-5). Borehole gravity measurements by virtue of their large radius of investigation are not significantly disturbed by formation damage caused by drilling--a common problem with conventional density and porosity well logging devices.

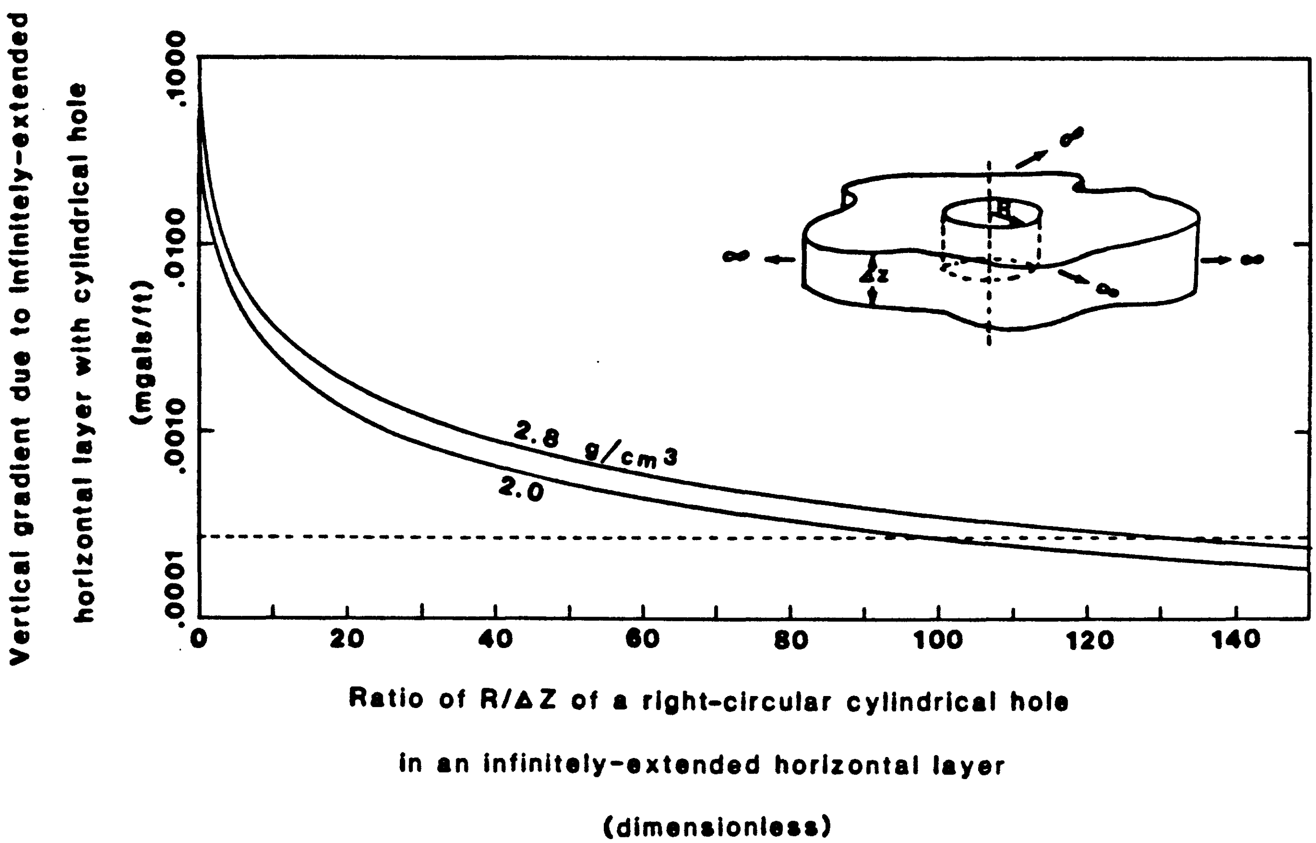
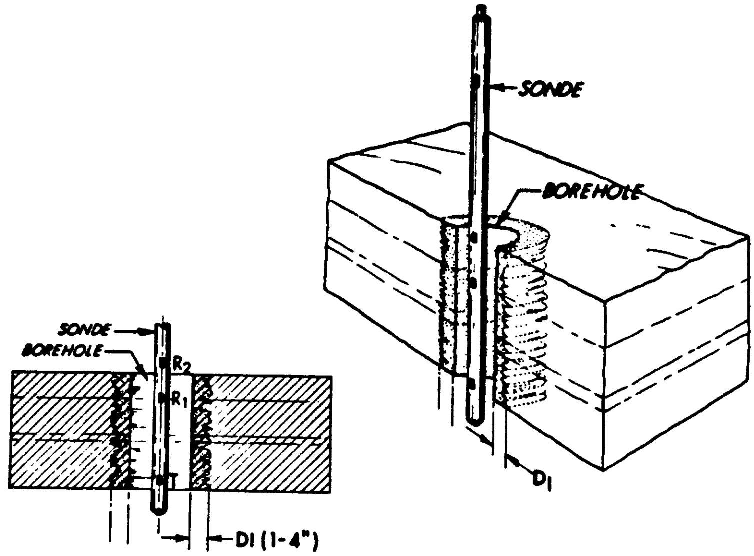
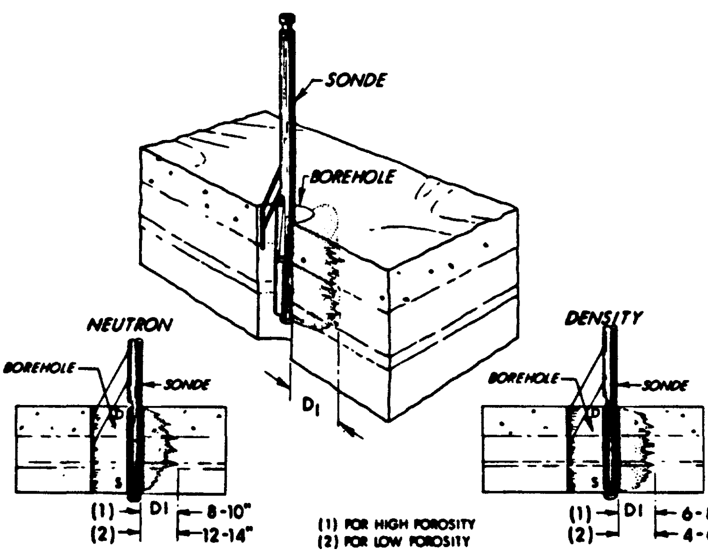


Figure 3-3. Region investigated by BHGM based on the radius of a right circular cylindrical hole in an infinitely-extended horizontal layer. As the radius of the cylindrical hole is increased, the vertical gradient due to the remaining portion of the infinitely-extended horizontal layer diminishes and approaches the precision of the $\Delta g/\Delta z$ measurements (modified from Schmoker, unpublished, 1975).



(A)



(B)

Figure 3-4. Approximate volume and depth of investigation (DI) of (A) acoustic devices (3- to 5-ft TR spacings) and (B) neutron and density devices as a function of porosity (from Jageler, 19/6).

Descriptions of Sondes Investigated

Sonde	Measurement	Remarks
FDC	Apparent bulk density	Detects gamma rays. A long-spacing detector is used for formation density. A short-spacing detector is used to correct for effect of mud cake.
SNP	Apparent porosity	Single detector counts epithermal neutrons. Detector has preferential response to neutrons from forward (formation) direction.
CNT-A	Apparent porosity	Detects thermal neutrons; uses two detectors. Measures spatial decay of neutrons.
CNT-X	Apparent porosity	Detects epithermal neutrons; uses two detectors. (Detectors and spacings are different from CNT-A.) Also measures spatial decay of neutrons.

Experimental Depths of Investigation

Tool	90-percent Depth of Investigation (inches)
FDC	5.0
SNP	6.7
CNT-A	10.3
CNT-X	9.3

(A)

		Near Detector	Far Detector
5 1/2 in. casing + 1-in. cement annulus	Fresh-water invasion	8.0 in.	8.7 in.
	Salt-water invasion	10.6 in.	12.4 in.
Uncased	Fresh-water invasion	8.8 in.	8.8 in.
	Salt-water invasion	11.7 in.	13.1 in.

Depth of investigation of the dual-spacing thermal neutron decay time log.

(B)

"To quickly summarize the results highlighted in this talk, we can say that the body waves, P and S, are the best indicators of unaltered formation properties, and their depth of investigation is approximately n inches away from the borehole if the source-to-receiver separation is n feet."

(C)

Figure 3-5. Three recent depth of investigation studies of well log devices: (A) Sherman and Locke (1975), (B) Antkiw (1976) and (C) Baker (1981).

4.0 SUMMARY

Borehole gravity measurements are responsive primarily to the vertical density variations in the rocks surrounding the drillhole and secondarily to lateral rock density variations of detectable magnitudes that may occur in the region around the well. Frequently borehole gravity data are easily converted to highly accurate interval density profiles because formations surrounding the drillhole often are level or nearly so and possess relatively uniform densities in lateral directions. Gravimetric interval density profiles, can be used for petroleum reservoir and ground water aquifer evaluation, well log and core analysis, surface gravity and seismic studies, or engineering and rock property investigations.

Currently-used borehole gravity meters are housed in logging tools with diameters of about 4 1/8 inches. They can be operated in boreholes that are deviated as much as 14° and to depths where ambient temperatures approach 125°C.

Borehole gravity surveys are conducted by stopping and reading the borehole gravity meter and cable depth odometer at a series of downhole stations that have been previously selected from well logs to meet survey objectives. Gravity (Δg) and depth (Δz) differences measured between successive stations constitute the interval vertical gradient of gravity ($\Delta g/\Delta z$) which varies inversely with the density of the rock layer bracketed by the measurements.

Measurements of Δg must be corrected for calibration of the gravity meter, tidal gravity fluctuations, instrument drift of the gravity meter, borehole effects, terrain effects, and borehole deviation from the vertical. The latter three corrections frequently are negligibly small. Instrument drift correction usually is the most important and requires frequent repeated gravity measurements at reoccupied stations as well as thorough laboratory tests of the response of the gravity meter to ambient temperature changes.

Errors in the measurements of Δg and Δz, the depth mislocation of the gravity meter station upon reoccupation, and depth mislocation of the gravity meter station relative to strata can introduce errors in calculated density. Many repeatability studies of borehole gravity measurements have been conducted by a number of groups using different instruments and equipment. When the borehole gravity meter is operating optimally, depth measurements are carefully made with a well-conditioned logging cable, and sufficient repeated measurements are made, densities can be calculated with relative errors of one percent or less.

Borehole gravity surveys examine volumes of rock that extend at least tens to hundreds of feet outward from the borehole and are essentially unaffected by casing or formation damage caused by drilling. Conventional well log methods generally have investigative distances measured in inches and can be hampered by metallic casing and formation damage caused by drilling.

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