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TERRAIN CORRECTIONS FOR BOREHOLE AND TOWER GRAVITY MEASUREMENTS

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INTRODUCTION

Many investigators have computed terrain corrections for gravity measurements made in vertical mine shafts (e.g., Rogers, 1952; Domzalski, 1954; Rische, 1957; Vaschilov, 1964) and on structures above ground (e.g., Hammer, 1938; Kumagai et al., 1960; Kuo et al., 1969; Fajklewicz, 1976). The need for a rapid method for calculating terrain corrections for borehole gravity surveys arose with the development of a high-precision borehole gravity meter (Howell et al., 1966; McCulloh et al., 1967). Hearst (1968) was the first to publish a reasonable scheme for rapid computation of terrain corrections to both tower and borehole gravity surveys. Beyer (1971) applied terrain corrections to both tower and borehole gravity measurements using a computational procedure that increased the versatility of Hearst's method. Specific procedures are given by Beyer and Corbató (1972).

Terrain corrections for gravity stations along the vertical line above, on, and below the ground surface can be calculated with the familiar zone and compartment scheme in which the surrounding terrain is described from topographic maps as average compartment elevations of a series of compartmentized concentric circulate zones (Hayford and Bowie, 1912; Hammer, 1939). Bowie (1917) doubled the number of inner Hayford-Bowie zones, and H. W. Oliver and S. L. Robbins of the U.S. Geological Survey (written commun., 1969) doubled the number of compartments in these inner zones. The modified Hayford-Bowie zones and compartments divide and average terrain elevations in more detail and extend to a greater distance from the borehole than do the popular Hammer zones and compartments.

As pointed out by Hearst and others (1978), errors in estimating terrain elevations are the principal source of error in the computation of terrain corrections. Map elevation errors are usually one-fourth to one-half of the map contour interval, depending on the severity of the terrain, and cannot be made smaller except through the construction of a topographic map with a smaller contour interval. Compartment elevation error is the elevation error that results from the visual estimate of the mean elevation of the compartment. Compartment elevation error is always larger than map elevation error and is a function of map scale, contour interval, complexity of the topography, and most critically, the size of the compartment. In general, the smaller the compartment, the smaller the compartment elevation error.

The modified Hayford-Bowie zones and compartments describe terrain elevations in detail sufficient to calculate terrain corrections accurately for all but the very shallow borehole and tower gravity measurements. Consequently, the modified Hayford-Bowie scheme has been used for all borehole gravity studies made by the author since 1967 in order to standardize the reduction of borehole gravity data and obtain more accurate terrain corrections for borehole gravity measurements made at shallow depths, even though the detail afforded by this scheme is not needed in many regions of low or moderate relief or a greater well depths. Accurate terrain corrections for very shallow borehole and tower gravity measurements may require subdivision of one or more of the inner Hayford-Bowie zones and a more detailed description of the local topography than is generally available from standard topographic maps of the U.S. Geological Survey. The modified Hayford-Bowie zones and subdivisions of zones B and C1 used by the author for calculation of terrain corrections for tower gravity measurements are given in Table 1.

Accurate terrain corrections for borehole and tower gravity measurements depend on accurate selection of a density or densities for the topography. Available geologic data can be used to assign densities to the topography (rather than assign a standard density) in order to increase the accuracy of the terrain corrections. The same density or densities should be used for the calculation of terrain corrections for surface, borehole, and/or tower gravity measurements when they are analyzed in a coordinated fashion.

Terrain corrections normally are applied directly to individual borehole or tower gravity measurements. A logical terrain-correction datum for borehole and tower gravity measurements is the elevation of the ground level at the top of the borehole or base of the tower. This situation gives rise to two types of terrain corrections that have positive signs (Fig. 1). As a consequence, terrain corrections for borehole and tower gravity measurements and their vertical gradients may have positive or negative signs, depending on the relative contributions of the correction types and the manner in which these contributions vary up or down the tower or borehole. A theoretical explanation of terrain correction variations in a borehole is given by Hearst and others (1978).

The vertical gradient of the terrain correction can be multiplied by $-1/4\pi k$ to determine the adjustments in borehole gravity density profiles caused by application of terrain corrections to the gravity measurements (k is the Newtonian gravitational constant). In the following examples, terrain corrections are expressed in Eotovos units and milligals/foot, and adjustments to the density profiles are given in grams/centimeter^3. By changing the signs of the density adjustments, one obtains a scale of the errors in borehole gravity densities that result from failure to apply terrain corrections. Vertical gradients are positive or negative when terrain corrections become more positive or less positive at successively lower elevations.

EXAMPLES OF CORRECTIONS MADE

Terrain corrections calculated along vertical lines piercing a hilltop (Fig. 2) and canyon bottom (Fig. 3) illustrate two contrasting types of corrections possible for shallow borehole and tower gravity measurements. Vertical gradients of the terrain corrections also are shown. The canyon-bottom example essentially is a mirror image of the hilltop example. The changes in sign of the terrain corrections are explained by the relative contributions of the four types of terrain corrections portrayed in Figure 1. Gravitational effects due to terrain change very rapidly and are very sensitive to the character of the local topography between the largest negative and largest positive terrain corrections in both the hilltop and canyon bottom examples. It is impossible to determine accurate terrain corrections and vertical gradients of terrain corrections in this region without a detailed description of the elevation and density of local topography. At greater distances above and below the ground surface, terrain corrections and vertical gradients can be calculated with greater reliability from standard topographic maps. The behavior of the vertical gradient curves very near the ground surface (datum) is shown in the insets A of Figures 2 and 3. The gradients are not discontinuous at the ground surface because the innermost zone is assumed to be level and at the elevation of the datum in both the hilltop and canyon bottom examples.

How large might terrain corrections be for borehole gravity measurements made in areas of extremely rough topography? To answer this question, terrain corrections and vertical gradients of terrain corrections were calculated for hypothetical boreholes at the bottom of Snake River Canyon located on the boundary between the states of Oregon and Idaho and atop Mount Rainier in Washington state. These are shown in Figure 4.

The Snake River Canyon example illustrates terrain corrections caused by a mass excess above the gravity stations and datum. Terrain corrections increase downward, at a decreasing rate, from about 33 milligals at the top of the borehole to about 76 milligals at a depth of 4,000 feet. The positive sign of the vertical gradient due to terrain would result in negative corrections to the density profile calculated from a borehole gravity survey.

The Mount Rainier example illustrates terrain corrections caused predominantly by a mass deficit below the gravity stations and datum for depths down to about 3,500 feet. Below depths of 3,500 feet, the terrain correction becomes negative because the dominant effect is caused by a mass deficit above the gravity stations and below the datum. The negative sign of the vertical gradient due to terrain would result in positive corrections to the density profile calculated from a borehole gravity survey. The magnitudes of the terrain corrections and associated vertical gradients in these examples greatly exceed those found in areas of lesser topographic relief.

The largest terrain corrections calculated by the author for an actual borehole gravity survey are shown in Figure 5; corresponding vertical gradients of terrain corrections relative to well depth for increasingly more distant topography are shown in part B. The changes in sign of the terrain corrections are explained by the relative contributions of the four types of corrections given in Figure 1. For example, below a depth of 850 feet, corrections are principally a function of a mass deficit above the station and below the datum. The large and rapidly changing terrain corrections and gradients over the upper several thousand feet of the borehole are a function of the high relief of the local land surface. In this particular case, topographic elevations vary by slightly more than 1,400 feet within an 8,000-foot radius of borehole. The negative vertical gradient of the terrain correction for topography out through Hayford-Bowie zone O causes positive adjustments to the densities calculated from the borehole gravity measurements that range from slightly more than 0.50 g/cm^3 near the top of the well to about 0.05 g/cm^3 at a depth of 12,000 feet. Note that corrections for topography beyond zone I affect the absolute accuracy but do not appreciably affect the relative accuracy of the densities calculated from the borehole gravity measurements.

Unlike the relatively large terrain corrections and gradients shown in Figure 5, the gravitational effect of topography in most boreholes is small, especially at greater depths. Vertical gradients of terrain corrections are shown in Figure 6 for eleven boreholes located in various topographic settings in California, Colorado, Wyoming, and Nevada and one mine shaft in Arizona. The names and locations of these boreholes are given in Table 2. The examples of Figure 6, and others not shown, indicate that, at depths below several hundred to several thousand feet, terrain corrections and their gradients generally are small and vary gradually with depth. Note that curve 11 in Figure 6 is taken from Figure 5 and that Figure 6 corresponds to the patterned area of Figure 4.

CONCLUSIONS

1. Four types of terrain corrections for gravity measurements made on towers and in boreholes (Fig. 1) explain the vertical variation of the gravitational attraction of topography when one acknowledges the inverse-square-of-the-distance law of gravity and that only the vertical component (with its angular dependence) is considered.

2. Terrain correction curves along vertical lines near the ground surface usually resemble more or less extreme variations of the hilltop or canyon-bottom example (Figs. 2 and 3), or some intermediate form. The scale of the correction curves varies with the magnitude of the topography. Terrain corrections and their gradients vary rapidly along vertical lines within tens of feet of the ground surface where the local topographic surface has relief of feet to tens of

feet or more. At these places, it is difficult to separate useful anomalous vertical gradients caused by geologic structure from gradients caused by topography in tower gravity measurements and to calculate accurate densities from borehole gravity measurements made at shallow depths. It may be impossible with standard topographic maps. The use of special zone and compartment schemes to model the topography will improve the accuracy of terrain corrections in these cases.

3. Terrain corrections and their gradients generally 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, then, terrain corrections usually are not critical to the determination of accurate relative densities from borehole gravity measurements or to the recognition of anomalous vertical gradients in boreholes. The absolute accuracy of densities calculated from borehole gravity measurements is improved, if only slightly in most cases, when terrain corrections are applied (Fig. 6).

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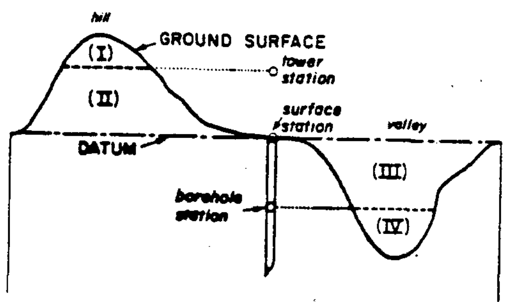

Type of Terrain Correction	Surface Gravity Station	Borehole Gravity Station	Tower Gravity Station
1. Mass deficit below station & below datum	+ (III & IV)	+ (IV)	+ (III & IV)
2. Mass excess above station & above datum	+ (I & II)	+ (I & II)	+ (I)
3. Mass deficit above station & below datum		- (III)	
4. Mass excess below station & above datum			- (II)

Sign of Terrain Correction (regions in parentheses) applies to the Surface, Borehole and Tower Gravity Station columns.

Figure 1. Four fundamental types of terrain corrections for borehole, surface and tower gravity stations. Correction datum is the elevation of the ground surface at the top of the borehole or base of the tower.

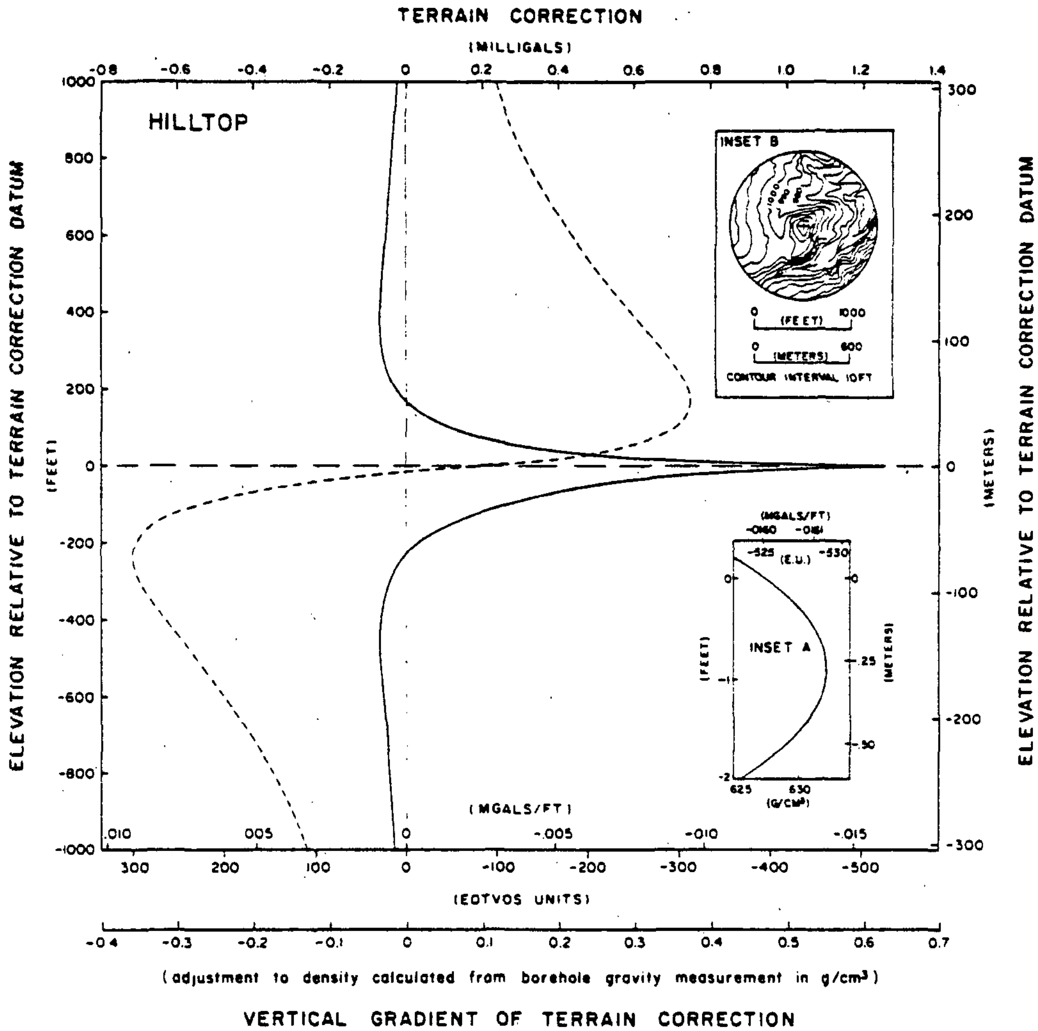

Figure 2. Terrain corrections (dashed curves) and vertical gradients of terrain corrections (solid curves) calculated along a vertical line that pierces a hilltop. Base diameter and height of hill are about 1,200 feet and 70 feet, respectively. Inset A shows behavior of vertical gradient near datum. Inset B shows the topography out through Hayford-Bowie zone C2. Corrections of this figure and Figure 3 are calculated for topography out through zone C2 using a density of 2.00 g/cm^3 and the subdivisions of zones B and C1 given in Table 1.

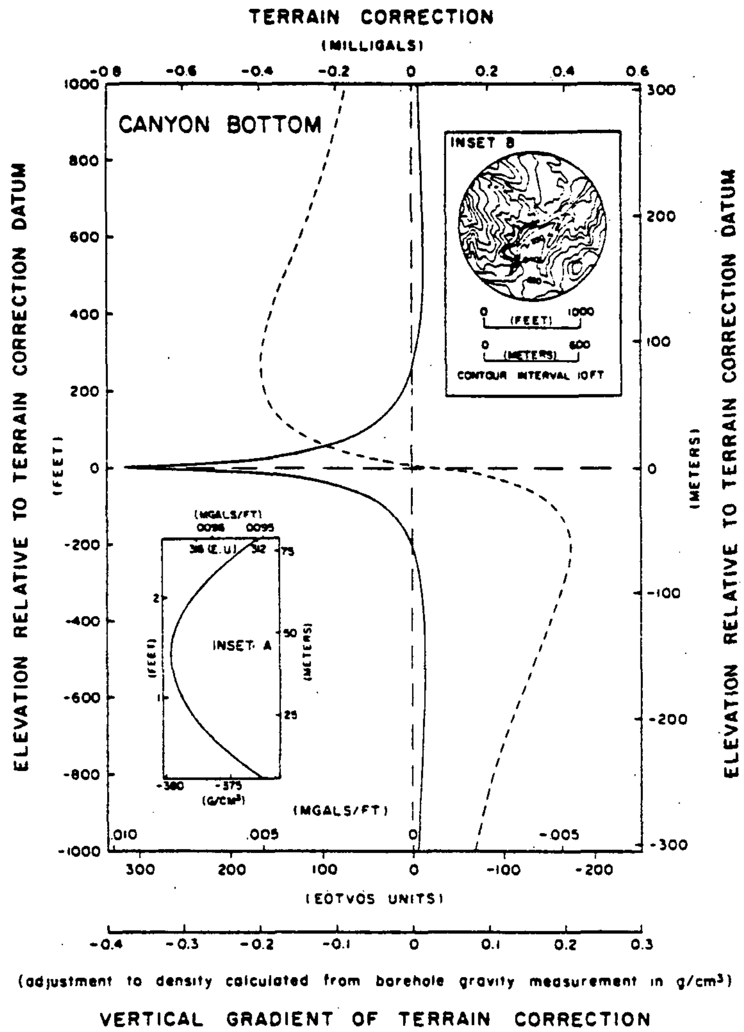

Figure 3. Terrain corrections (dashed curves) and vertical gradients of terrain corrections (solid curves) calculated along a vertical line that pierces a canyon bottom. Ridge-to-ridge width and depth of canyon are about 1,200 feet and 75 feet, respectively. Inset A shows behavior of vertical gradient near datum. Inset B shows the topography out through Hayford-Bowie zone C2.

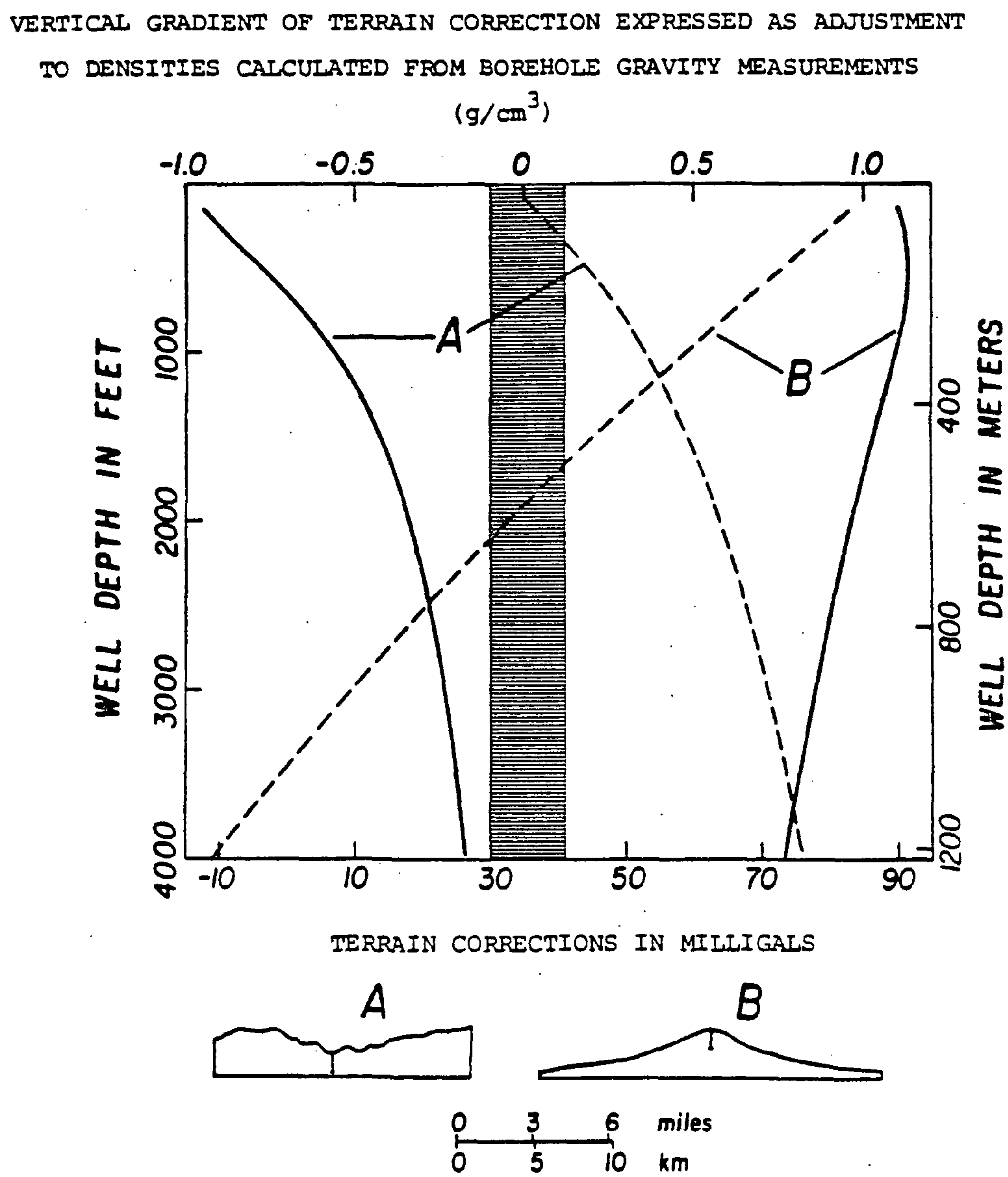

Figure 4. Terrain corrections (dashed lines) and vertical gradients of terrain corrections expressed as corrections to borehole gravity density profiles (solid lines) for two hypothetical 4,000-foot boreholes in different topographic settings. Example A is for a borehole located at the bottom of the Snake River Canyon on the boundary between the states of Oregon and Idaho at lat. 45°20' N. Terrain corrections are computed using a density of 2.55 g/cm^3 out through Hayford-Bowie zone O. Example B is for a borehole located atop Mt. Rainier in Washington state. Terrain corrections are computed using a density of 1.70 g/cm^3 out through Hayford-Bowie zone O. Topographic profiles without vertical exaggeration also are shown. The patterned area corresponds to the region covered by Figure 6.

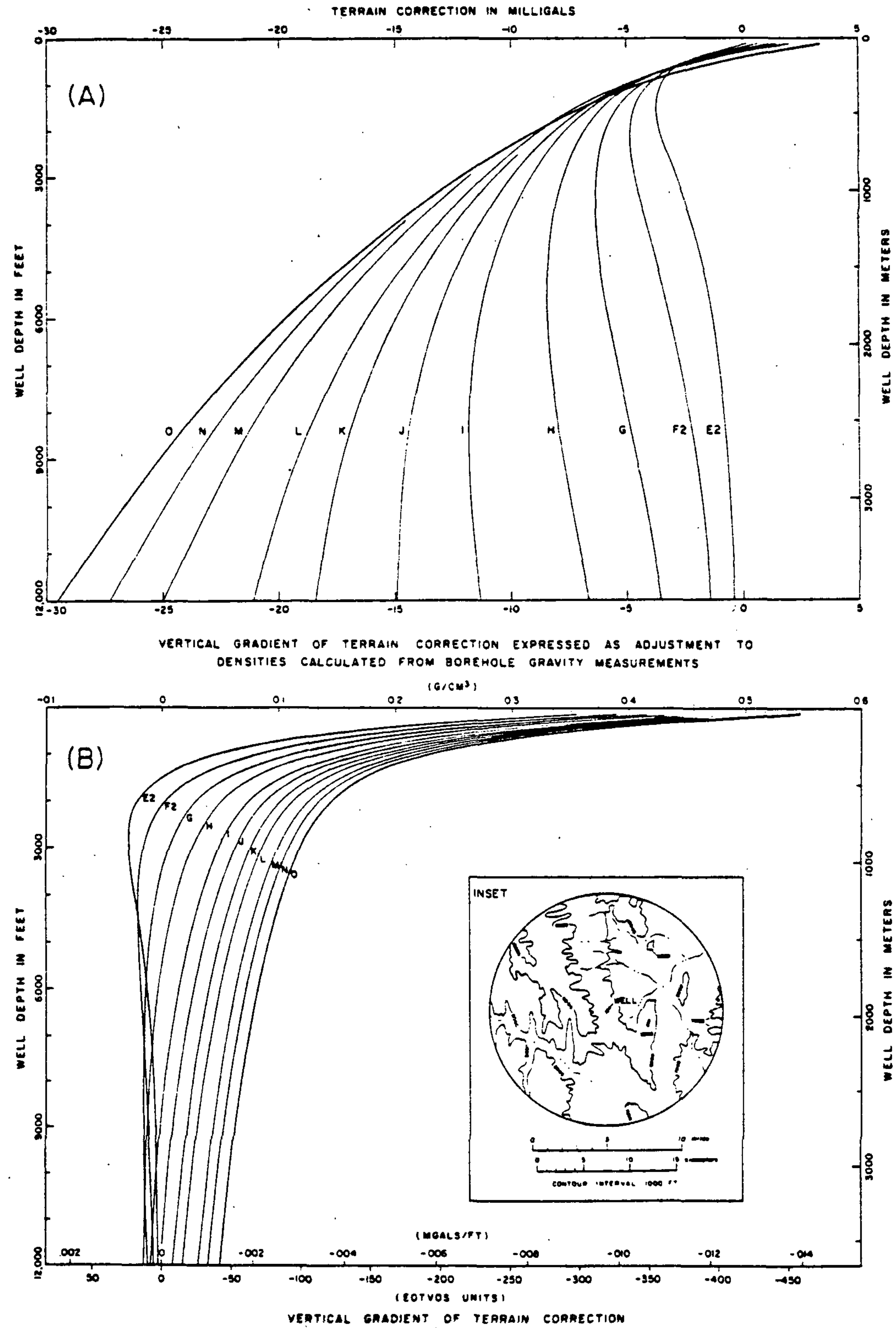

Figure 5. Cumulative terrain corrections (part A) and corresponding vertical gradients of terrain corrections (part B) out through modified Hayford-Bowie zones E2 to O in relation to well depth for the Mountain Fuel Supply Co. Dry Piney Unit 19, 15-27N-114W, Sublette County, Wyoming. Terrain corrections are computed using a density of 2.67 g/cm^3. Inset shows topography around well out through Hayford-Bowie zone J.

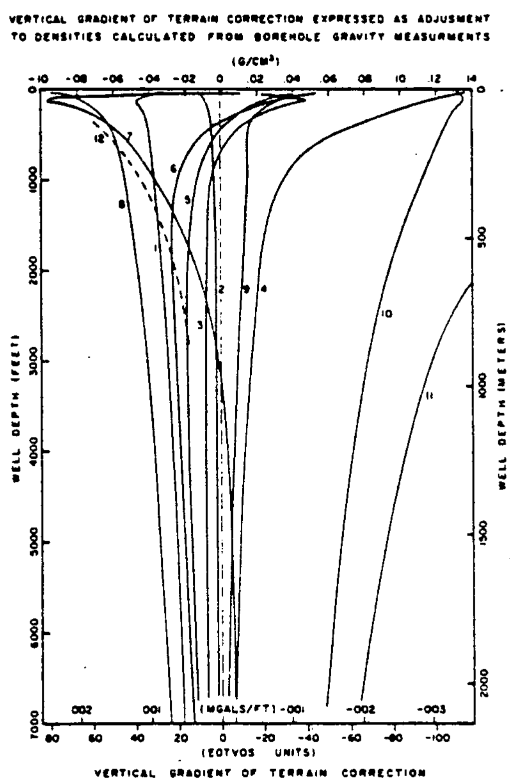

Figure 6. Vertical gradients of the terrain corrections for eleven wells and one mine shaft located in the Western United States. Name and location of these wells are given in Table 2.

PART A

Zone	Outer Radius (meters)	Compartments
A	2	1
B	68	4
C1	130	8
C2	230	8
D1	380	12
D2	590	12
E1	870	16
E2	1,280	16
F1	1,680	20
F2	2,290	20
G	3,520	12
H	5,240	16
I	8,440	20
J	12,400	16
K	18,800	20
L	28,800	24
M	58,800	14
N	99,000	16
O	166,700	28

PART B

Zone	Outer Radius (meters)	Compartments
A	2	1
BA	5	8
BB	10	12
BC	17	12
BD	27	12
BE	41	12
BF	61	12
BG	89	10
BH	130	8

Table 1. Modified Hayford-Bowie zones and compartments (Bowie, 1917) used to describe topography for calculation of terrain corrections for borehole gravity measurements (Part A). Subdivisions of zones B and C1 made by author to more accurately describe local topography for terrain corrections for tower and very shallow borehole gravity measurements (Part B).

Profile No.	Well	Location	Terrain Density g/cm^3
1	Standard Oil Company of California Anza Pacific Corp. 76	36-12N-24W Midway-Sunset oil field Kern County, California	variable 2.00-2.76
2	Standard Oil Company of California Jordan Community 9	6-3S-11W Santa Fe Springs oil field Los Angeles County, California	variable 2.00-2.76
3	Standard Oil Company of California Baldwin 180	6-2S-11W Montebello oil field Los Angeles County, California	variable 2.00-2.76
4	Shell Oil Company Vedder 431	9-27S-28E Mt. Poso oil field Kern County, California	variable 2.00-2.76
5	Texaco, Inc. Fee 28	32-32S-24E Midway-Sunset oil field Kern County, California	variable 2.00-2.76
6	Chevron Raven 1-A	30-2N-102W Rangely oil field Rio Blanco County, Colorado	2.30
7	Chevron W. P. Mellen 1-3	16-2N-103W Rangely oil field Rio Blanco County, Colorado	2.30
8	Atlantic Richfield Co. Leutholtz A-20	22-11N-23W Midway-Sunset oil field Kern County, California	variable 2.00-2.76
9	Tenneco Oil Company Fee A-121	25-28S-27E Kern River oil field Kern County, California	variable 2.00-2.76
10	Well UE19n Pahute Mesa	Lat. 37°20'14"N Long. 116°22'33"W Nevada Test Site Nye County, Nevada	2.00
11	Mountain Fuel Supply Co. Dry Piney Unit 19	15-27N-114W Dry Piney unit Sublette County, Wyoming	2.67
12	Vertical mine shaft	Arizona (data adopted from Rogers, 1952, p. 369)	2.60

Table 2. Name and location of wells and density used to compute vertical gradients due to topography shown in Figure 5.