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Standardization in gravity reduction

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ABSTRACT

Gravity reduction standards are needed to improve anomaly quality for interpretation and to facilitate the joining together of different data sets. To the extent possible, data reduction should be quantitative, objective, and comprehensive, leaving ambiguity only to the interpretation process that involves qualitative, subjective, and geological decisions. The term "Bouguer anomaly" describes a field intended to be free of all nongeologic effects—not modified by a partial geologic interpretation. Measured vertical gradients of gravity demonstrate considerable variation but do not suggest, as often reported, that the normal free-air gradient is in error or needs to be locally adjusted. Such gradients are strongly influenced by terrain and, to a lesser extent, by the same geologic sources which produce Bouguer anomalies. A substantial body of existing literature facilitates the comprehensive treatment of terrain effects, which may be rigorously implemented with current computer technology. Although variations in topographic rock density are a major source of Bouguer anomalies, a constant density appropriate to the area under investigation is normally adopted as a data reduction standard, leaving a treatment of the density variations to the interpretation. A field example from British Columbia illustrates both the variations in vertical gravity gradients which can be encountered and the conclusion that the classical approach to data reduction is practically always suitable to account for the observed effects. Standard data reduction procedures do not (and should not) include reduction-to-datum. The interpreter must be aware, however, that otherwise "smooth" regional Bouguer anomalies caused by regional sources do contain high-frequency components in areas of rugged topography.

INTRODUCTION

Free-air and Bouguer reductions recently have been subject to serious criticism, partly resulting from an incomplete treatment by leading exploration textbooks and partly from an apparent misunderstanding of the term "Bouguer anomaly." The classical approach to data reduction is supported here with the caveat that comprehensive treatment—not the suggested alterations in fundamentals—leads to appropriate anomalies. Comprehensive and careful application of accepted procedures is especially appropriate for surveys in rugged topography or where high accuracy is required. Environmental studies, exploration for very subtle anomalies (e.g., salt overhang near the density crossover zone, stratigraphic effects, and mineralization anomalies) in oil and mining exploration, and, not least, integrated interpretations in production and field-development geophysics are examples justifying rigorous data reduction procedures.

It is our intent that the Bouguer anomaly be free of all nongeologic effects that are unavoidable components of the basic measurement. Toward that end, each step in the data reduction process is not a stand-alone contribution but is part of an integral strategy for producing the Bouguer anomaly.

Following tradition, the observed gravity measurement, g_{obs}, (after appropriate adjustment for meter calibration, drift, tides, and network ties) is

$$g_{obs} = g_0 + g_f + g_B + g_{geol} \tag{1}$$

or

$$g_{geol} = g_{obs} - (g_0 + g_f + g_B), \tag{2}$$

where g_0 is the latitude-dependent theoretical value of gravity at mean sea level, g_f is the elevation-dependent free-air term, g_B is the elevation- and topography-dependent Bouguer term, and g_{geol} is the geologic contribution to the measurement, i.e., the purpose of the survey. Equation (2) defines the gravity effects of the subsurface geology *at the point of measurement* as the difference between the gravity

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observed at that point and the gravity (also at that same point of observation) caused by a defined earth model. By adopting standards by which we determine the gravity effects of the defined earth model—the terms within parentheses in equation (2)—we simplify the joining together of different surveys and, moreover, provide interpreters with a clearly understood data set from which they may begin their work. Erwin (1977) states this thesis well.

THEORETICAL GRAVITY

The appropriate formula for the g_0 term in equations (1) and (2) is the International Formula of 1967 (Morelli, 1974).

FREE-AIR REDUCTION

The last three terms in equation (1) all contribute to local variations in the vertical gradient of gravity, a phrase which, unfortunately, is often used interchangeably with "free-air gradient." A view that the free-air reduction is invalid and/or requires local adjustment is frequently expressed.

Gumert (1985) wrote, "The free-air factor varies significantly with horizontal position and can affect the reduction of observed gravity data. Land gravity observations made at varying elevation in an area of rugged topography, processed using the standard accepted free-air factor, can produce highly erroneous maps," and Gumert and Stanacato (1985) wrote, "The data showed a variation in the free-air factor of as much as ±3 percent. Using an incorrect free-air factor while processing ground gravity data in areas of high topography leads to problems with the accuracy of the ground gravity data." Karl (1983) suggested that the free-air reduction is in error by no less than 14 percent. Ager and Liard (1982) stated that the very low measured vertical gradients in British Columbia require that we use there a free-air reduction value considerably lower than the normal. Gibb and Thomas (1980) said, "By far the largest potential source of error lies in the assumption that the value of F (the free-air correction) is 'normal' and equal to 0.3086 mGal/m." McCulloh (1965) reported on data that strongly support the normal value, but by using the phrase "Neglecting the possibility of an *abnormal* free-air vertical gradient . . ." casts doubt on the universal applicability of the free-air reduction. Robbins (1981) concluded that the normal value is "acceptable" but points out that ". . .determination of the local and regional variations of F is still a tenuous procedure, . . . " Thyssen-Bornemisza et al. (1972) also expressed concern about the standard free-air reduction and suggested a method for locally "improving" it by incorporating the measured vertical gradient of gravity.

The semantics alone can lead to the unfortunate notion that the "normal" free-air reduction is some sort of average which may be locally manipulated.

The free-air reduction accounts for the elevation-dependent effects of the main-earth term and may be thought of as a modification to g_0 in equation (1); it is not a method for "correcting" *local* variations in the vertical gradient of gravity. Because the radius of the earth is very large in comparison with elevation changes, this term is taken to be the product of a constant and the elevation. This condition may not be assumed for sources contributing to the g_{geol} term in equation (1), especially for those sources of exploration interest. We use 0.3086 mGal/m; very small additional corrections may be included for variations in latitude and high (or very deep, in the case of boreholes) elevations. An attempt to account for the actual vertical gradient of gravity (VGG) should not be included as part of the free-air reduction. Such an approach would require significant and undesirable changes in other phases of data handling. For both surface and subsurface surveys, the free-air reduction should be consistently applied, leaving a consideration of anomalous VGG to other data reduction steps *and to the interpretation of the data.*

The free-air value is based on well-known parameters (indeed, known better than many of the geological parameters which limit the accuracy of our final interpretive product) and is well discussed in the literature. The free-air reduction value as defined in the literature is determined with an error not exceeding 0.07 percent of its accepted value (and this only when we ignore variations due to latitude and second-order elevation effects: see, for example, Lambert, 1930). It is currently difficult to determine from field measurements the actual VGG with such precision; moreover, variations in the actual VGG arising from non-main-term sources (discussed below) are considerably greater *and are not satisfactorily treated as linear functions of elevation.* Interestingly, a large number of surveys (one of which is discussed in this paper) have been conducted in both surface and subsurface regions for which the actual VGG is substantially different from the normal free-air gradient. These data confirm the appropriateness of applying the normal free-air reduction without local modification (LaFehr and Chan, 1986).

TOPOGRAPHIC (BOUGUER) REDUCTION

Usually, a large part of an observed anomalous VGG is accounted for in the well-known Bouguer reduction. The classical Bouguer reduction is a three-step procedure (Swick, 1942): (1) apply the simple Bouguer slab formula ($2\pi\gamma\rho h$), where γ is the Universal Gravitational Constant, ρ the density, and h the elevation of the station, (2) add a curvature (Bullard B) correction to (1), and (3) apply a terrain correction for departures of the actual Earth's surface from an idealized spherical surface. The first two are functions of elevation and topographic density only, while the third is, in addition, a function of surrounding topography.

Curvature (Bullard B)

Recently improved curvature (Bullard B) corrections and a new exact formula are reported by LaFehr (1990). When added to the simple Bouguer term (Bullard A), the result is equivalent to determining the effect for the spherical cap of surface radius 166.7 km. This is also the outer radius of the Hayford-Bowie Zone O (discussed below). Leading exploration textbooks do not discuss this correction. Topographic reduction procedures in the exploration industry were established at a time when humans were "computers" and when few surveys were in areas of rugged topography. It is important now, however, to establish more comprehensive standards by which we can improve Bouguer anomalies. It is especially true in engineering and environmental studies that survey specifications are frequently stated in the low microgal range without an appreciation for larger sources of error resulting from inadequate reduction procedures. Seismic geophysicists are increasingly concerned with the improvement of their statics corrections in oil production studies. Microgal gravity surveys can aid the seismologists by an improved definition of the shallow density variations—if the gravity data are properly reduced.

Possible problems may be avoided by routinely applying the Bullard B correction, such as (1) the introduction of ficticious elevation-dependent anomalies. For example, in a survey whose elevations range from sea level to 1000 m, the maximum difference in curvature effects is 1.111 mGal, and for high-precision surveys in even moderate topographic relief, the effect near sea level is about 14 μGal/m of elevation difference between stations. This effect is not a function of the horizontal distances between stations. In relatively rugged terrain, where many exploration surveys have been conducted, large elevation changes do occur rather close together. Ignoring this correction may result in serious distortion of target anomalies. (2) If a topography/Bouguer anomaly analysis is used to help determine the Bouguer density, ignoring the Bullard B may contribute to inaccuracies in the determination of topographic density, though this effect is small in comparison with other uncertainties. (3) If the survey is tied to another (especially where new mountain stations are added to existing adjacent basin stations) where one survey uses the Bullard B and the other does not, misties between surveys will occur. Such misties between surveys may be as large as 1.5 mGal (greater for elevations greater than 5000 m) and may appear as a datum shift.

Terrain corrections (Bullard C)

Standards are needed in the exploration industry for removing the effects of terrain. Terrain features in even mild topography can have a significant influence on the observed VGG. The extent to which the effect of terrain is properly removed from the final Bouguer anomalies depends on the care and comprehensive nature of the corrections, about which a large body of literature (Hammer, 1939; Sandberg, 1958; Kane, 1962; Plouff, 1966; Krohn, 1976; Oliver and Simard, 1981; Cogbill, 1990; Zhou, et al., 1990; etc.) has been created over the last several decades. For exploration gravity surveys in moderately rugged to very rugged topography, terrain corrections continue to be the single most important source of error. However, nearly an order of magnitude in the improvement of terrain corrections has been demonstrated (LaFehr, et al., 1988) by the implementation of new field procedures and a more comprehensive approach. Four specific standards are responsible for the improvement with varying degrees of relative contribution as a function of terrain and station location: (1) the application of the Bullard B correction discussed above, (2) improvement in the determination of inner-zone topography, (3) extension of terrain corrections to the outer radius of the Hayford-Bowie Zone O (167 km), and (4) utilization of topographic slope as well as compartment relief in the calculations.

Inner-zone effects are typically kept to a minimum by careful placement of the gravity stations away from abrupt changes in elevation, and this continues as recommended field practice. Field operators usually fill out forms with estimates of the nearby elevations, but recent studies (LaFehr, et al., 1988) indicate the possibility for very large errors in areas of rugged topography. One traverse over the Continental Divide in Colorado produced statistics indicating up to 3 mGal of discrepancy (from inner zones alone) because of the difficulty in correctly estimating distances and relief in very rugged topography, even with the use of dip meters. Electronic surveying equipment coupled with automatic data loggers and Global Positioning Satellite (GPS) instruments enable the rapid acquisition of additional topographic control near each station. Both horizontal and vertical control is obtained and saved for subsequent computations. The locations of the auxillary control are determined in the field to minimize additional costs and to take advantage of the actual topography. The method yields considerably improved inner-zone corrections (Figure 1) as well as a means by which the uncertainty in the correction can be estimated.

Hammer (1939) introduced terrain-correction tables limited to an outer radius of 21 km at a time when the exploration industry was using the Gulf Coast as its model. These tables are still used in the industry and still published in modern textbooks (Dobrin and Savit, 1988) even though they are quite inadequate where significant topographic relief is encountered. It is no longer expensive to compute terrain effects out to the outer radius of the Hayford-Bowie system (167 km), and this should become a standard.

Compartment curvature adjustment (this is quite different from and in addition to the Bullard B curvature correction) is not always incorporated in published algorithms (e.g., Krohn, 1976) probably with the same historical basis as for

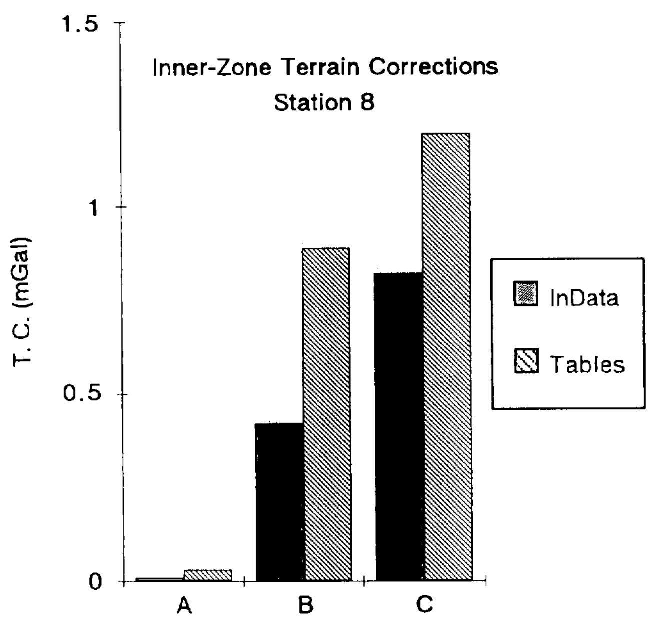

FIG. 1. Hayford-Bowie Inner Zones. Calculations "InData" are based on in-field surveying and a slope-based algorithm. Calculations "Tables" are based on in-field operator notes with inclinometer and standard tables.

the Hammer tables mentioned above, but this easily implemented adjustment should be a standard. By properly including this adjustment, negative total terrain corrections result for some stations, for example, in the Central Valley of California (Chapman, personal communication). Increased accuracy can also be obtained in the terrain-correction calculations for all zones from the station to Zone O (167 km) of the Hayford-Bowie system by utilizing slope information (Campbell, 1980; Blais and Ferland, 1984; Zhou et al, 1990) as well as average compartment elevations. Errors related to the topographic model typically are not random but may produce inadequate estimates. Positive errors in the terrain correction are generated when the average slope from the station to the compartment is in the same direction as the slope within the compartment; negative errors in the terrain correction are generated when the average slope from the station to the compartment is in a direction opposite to the slope within the compartment. Because computer memory and power are presently inexpensive, this problem can be economically approached if an adequate terrain (Digital Elevation Model) grid (Cogbill, 1990) is available.

Topographic effects beyond 167 km

Can we safely ignore the topography beyond 166.7 km? Complete Bouguer anomalies are defined as having taken into account all of the topography out to, but not beyond 166.7 km (Swick, 1942). In the Hayford-Bowie system, both topography and compensation beyond Zone O are taken into account in isostatic reductions, but not in Bouguer reductions. Almost all gravity exploration work, however, is based on Bouguer anomalies. Distant topography and/or bathymetry can be responsible for several milligals of absolute effect in a survey area, but we are only concerned to the extent that such effects vary as a function of station elevation. Figure 2 illustrates the differences in topographic effect (in mGal) for elevation differences ranging from 0 to 2000 m as a function of the average elevation of the continent out to a radius of 567 km from the station (not including any effects internal to Zone O). As the illustration shows, differences of a few tenths of one mGal may occur, and even a few mGal are possible in rugged terrain. However, there are reasons for not extending the Bouguer reduction to global proportions, as has been suggested, e.g. Karl (1971): (1) in cases where *relative* distant effects are large, errors from nearby terrain are far more significant than errors resulting from distant topography, (2) continental elevations over vast regions are generally low (averaging about 680 m), and (3) for many land surveys, much of the distant departure from the "normal" earth is actually sea water, producing a partial canceling of the effect. Nonetheless, for stations in rugged topography, measurable contributions to Bouguer anomalies arising from topographic effects beyond 167 km may occasionally be worth taking into account (as can be seen in Figure 2). The interpreter should be aware of such contributions (from both onshore and offshore) and be prepared to account for them in situations requiring such precision. A comparable situation does not exist for surface-ship measurements. Distant topography and/or bathymetry have negligible relative effects because changes in station elevation owing to tides produce such effects well below the noise level of marine surveys.

Rock density in the Bouguer correction

Variations in topographic rock densities can produce larger effects than some of those mentioned above. This may be a reason not to extend topographic corrections beyond 167 km. One of the standards applicable to all of the discussion to this point is that constant densities should be consistently applied to the Bullard A, B, and C contributions and clearly stated in the appropriate map and profile legends. The treatment of varible density should be left for the interpretation and not included as part of standard data

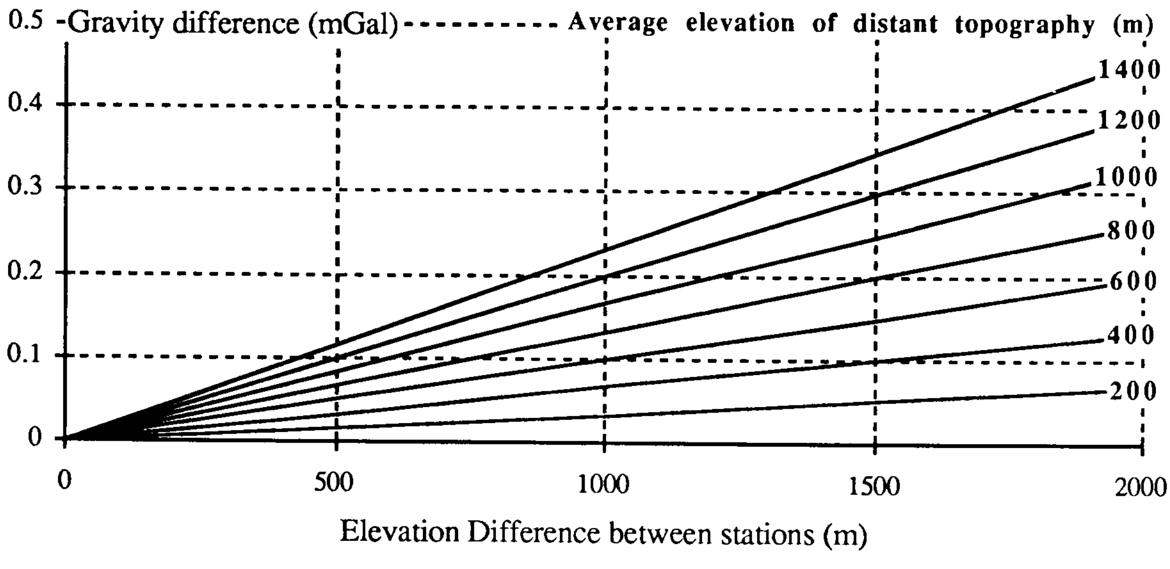

FIG. 2. Distant (beyond 167 km) topographic effects. Differential gravity effect (mGal) between two stations of different elevations owing to topography beyond 167 km. Distant topography has a width of 400 km and a thickness as given.

reduction. Many organizations use as a standard a Bouguer correction density of 2.67 g/cm^3. The exploration industry typically selects lower densities more appropriate to the rocks in the survey area. The interpretation of Bouguer anomalies may involve topographic sources whose appropriate interpretive density contrasts are the differences between actual rock densities and the constant density applied in the Bouguer reduction.

A FIELD EXAMPLE

I now return to Equation (2) and the classical approach to data reduction by selecting from the literature an area producing one of the most anomalous data sets that has provoked concern over standard data reduction procedures. This area of rugged topography clearly illustrates the multiple elevation-dependent gravity variations from free-air, topographic, and geologic contributions.

Observed VGG measurements are equal to the normal free-air gradient plus an anomalous VGG. In most cases, authors who wish to alter the free-air reduction are concerned about anomalous VGG. The uneasy theme common to those papers expressing concern about the standard reduction method has essentially gone unanswered. That theme and its serious claim is summed up by Ager and Liard (1982; E = Eötvös):

> This work also demonstrated that the normal free-air gradient of 3086 E is too high for most of the area surveyed in southern British Columbia. In fact, it appears that a value in the range of 2600–2800 E would be closer to reality and should be used as the free-air gradient for data reduction in this region. These results point out the validity of measuring vertical gravity gradients over large areas in order to map the free-air effect to be used in more local gravity survey work.

Ager and Liard's Figure 7 is reproduced here as Figure 3 and shows their measured vertical gravity gradients at several locations along Highway 1, British Columbia. Departures from the normal are striking. Their observations are very interesting because their traverse includes remarkable rugged topography, and their points of observation are located at elevations substantially lower than that of the average surrounding topography. We observe anomalous gradients for the same reason that we observe anomalous Bouguer fields and in addition because of the influence of terrain (the effect of which is supposed to be removed from Bouguer anomalies).

Causes of anomalous vertical gradients fall into two general categories: (1) terrain or bathymetry and (2) variations in the geology (including density differences within the upper mantle and crustal structure). The former can be substantial, sometimes more than 30 percent of the normal free-air reduction, and should be taken into account during the data reduction phase of exploration work, while the latter usually amount to less than 5 percent of the normal free-air reduction and may be considered during the interpretation phase.

Ager and Liard estimated the terrain effect at Boston Bar (where the deviation from the normal free-air gradient is greatest) to be only 130 E (3086 E or Eötvös units is

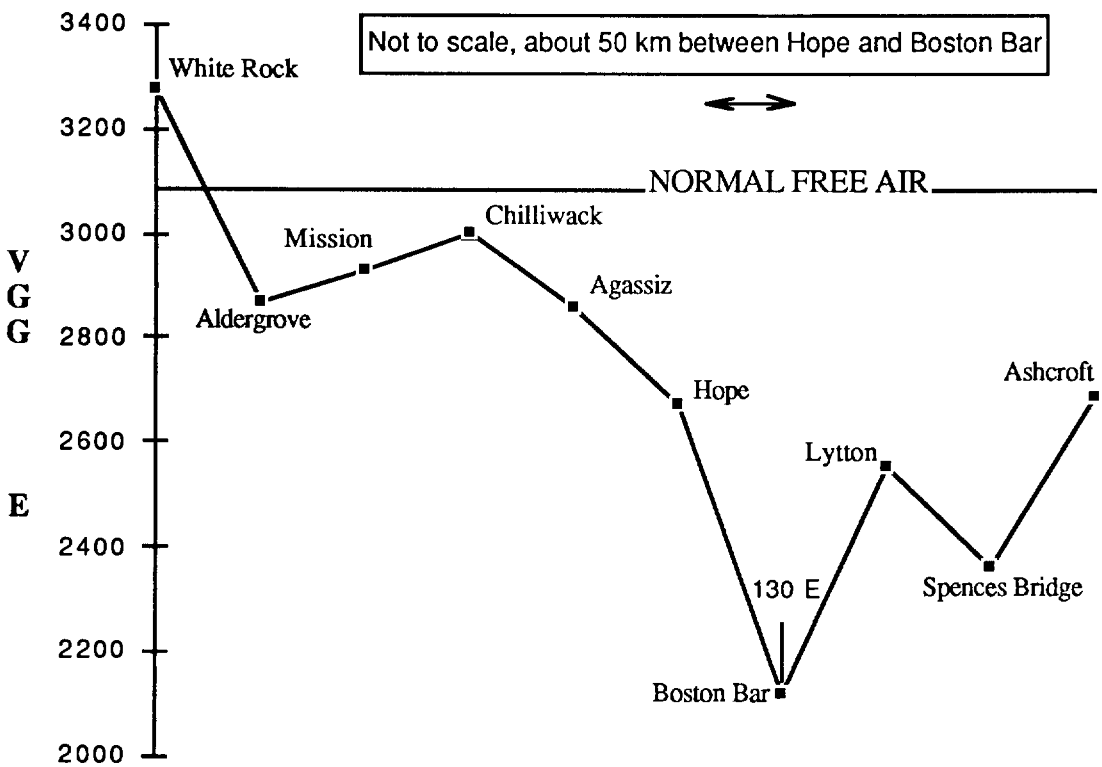

FIG. 3. Vertical gravity gradients measured along Highway 1, British Columbia: Ager and Liard (1982).

equivalent to the normal vertical gradient of gravity), and they did not calculate the effect of terrain at the other stations. VGG terrain effects resulting from the rugged topography of British Columbia were calculated here for each Ager and Liard highway station as depicted in Figure 3. These calculations are based on the estimated difference in elevation between the highway and Hayford-Bowie terrain zones (Swick, 1942) C through O (or outer radii ranging from 0.23 to 167 km) utilizing the published topography for British Columbia. All steps discussed above in the section on terrain corrections were incorporated except for the treatment of inner zones. Figure 4 shows that most of the anomalous VGG observations are caused by terrain effects, without recourse to the unknown elevation differences in Zones A and B.

These results are accumulated from Zone C through Zone O, expressed as a percent of the normal free-air reduction, and plotted in Figure 4. By conservatively estimating the terrain (the ground level near the stations is assumed to be flat), the calculated VGG is about the same as or less than the observed VGG (which is reversed in sign to facilitate a comparison).

Only terrain above sea level has been considered in these calculations. White Rock is close enough to the Pacific Ocean (negative density contrasts offset from and below the station) to produce anomalous VGG measurements of opposite sign. Simple model calculations confirm the magnitude of the White Rock anomaly. Aldergrove is situated with respect to both the sea and the mountains such that very little terrain/bathymetry-induced anomalous VGG is calculated. However, the published Bouguer anomaly map indicates a significant local mass to explain its observed VGG in terms of geology.

The discrepancy between observed and calculated VGG is greatest at Boston Bar, where two sources not included in the calculations that led to Figure 4 provide an explanation either separately or in combination: (1) near-station terrain effects (relief inside zone C) and/or (2) low-density rocks, such as a sand bar or highway fill, directly beneath the observations. Effects falling in the first category are indicated in Figure 5, while those associated with the second case are illustrated in Figure 6. Figure 5 shows the importance of near-station terrain corrections not included in Figure 4; by interpolation or extrapolation we see that the contributions to the VGG from inner zones may easily bring the total terrain effect at each station to the levels observed by Ager and Liard.

Alternatively, we may expect some contribution to the observed VGG from subsurface geologic variations. At Boston Bar, possible contributions from the existence of a sand bar at the surface or other mass (such as highway fill) of low density may partially explain the observations. Figure 6 illustrates a range of possible contributions by assuming a subsurface density contrast of -1.0 g/cm^3. Geologic contributions to the observed VGG are not removed in the data reduction process and should not be (as are contributions from topography). However, the interpreter must realize that the Bouguer anomaly values are *station anomalies* (not reduced-to-datum anomalies, discussed below).

Thus, terrain and/or local subsurface density contrasts can explain the observations of Ager and Liard without recourse to a modified free-air reduction. Of course regional geologic variations, such as masses required for isostatic compensation, also affect the VGG, but these effects cannot change sharply over short distances, as in this example taken from British Columbia, and their contributions to anomalous

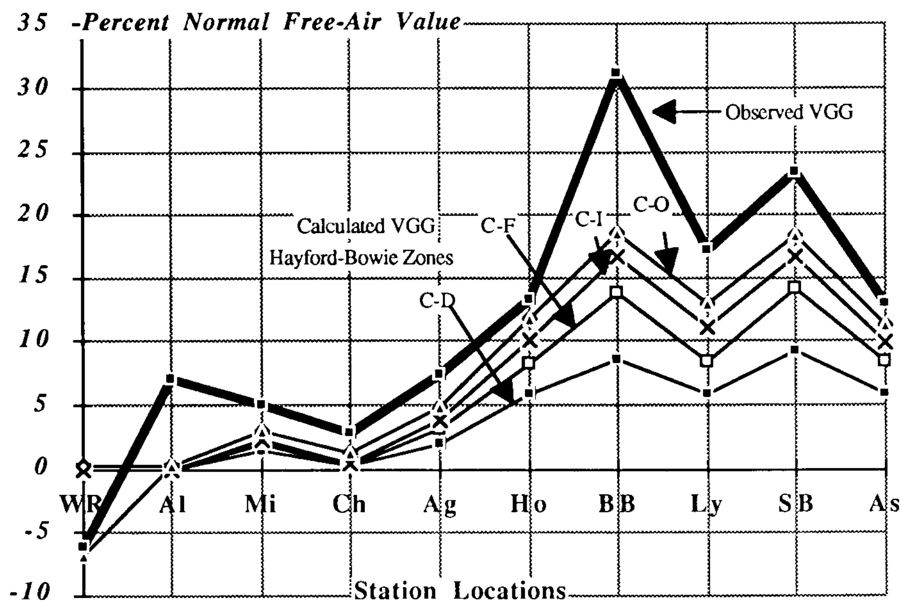

FIG. 4. Vertical gradient of gravity terrain effects, expressed as a percent of the normal free-air reduction, for all Hayford-Bowie terrain zones beyond zone B at 10 stations, British Columbia. The maximum distance for which the calculation is made is 167 km. The relief of each zone is taken from the topographic maps and varies from 0 to 4100 ft. The station symbols are: WR-White Rock, Al-Aldergrove, Mi-Mission, Ch-Chilliwack, Ag-Agassiz, Ho-Hope, BB-Boston Bar, Ly-Lytton, SB-Spences Bridge, As-Ashcroft.

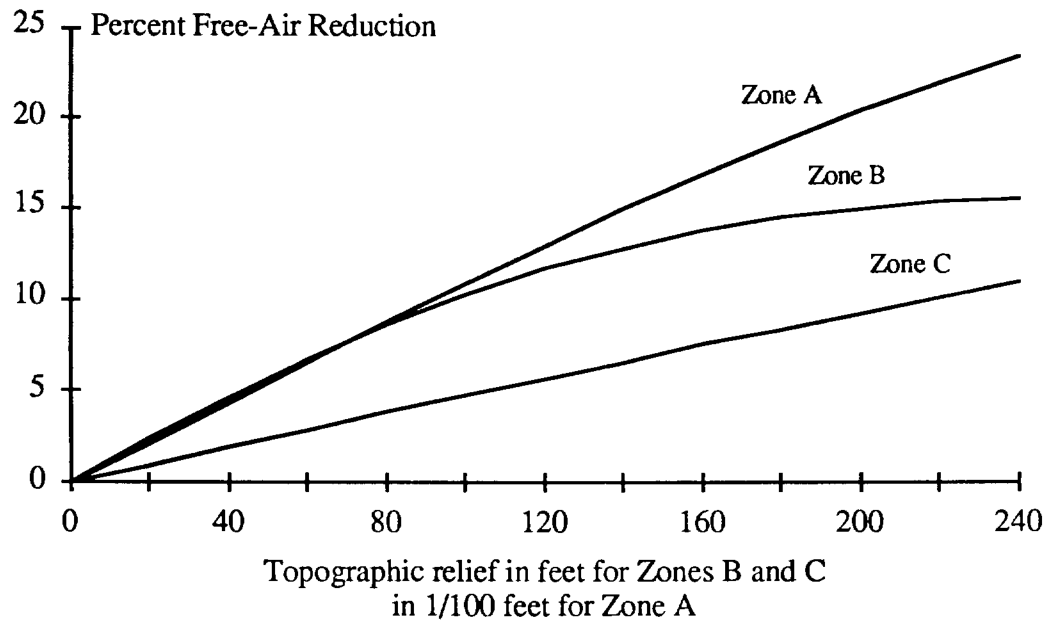

FIG. 5. Vertical gradient of gravity terrain effects, expressed as a percent of the normal free-air reduction, for Hayford-Bowie terrain zones A, B, and C. Gravity gradients are especially sensitive to any change in elevation within zone A, the horizontal scale for which is given in units of 0.01 ft. The scale for zones B and C is in feet.

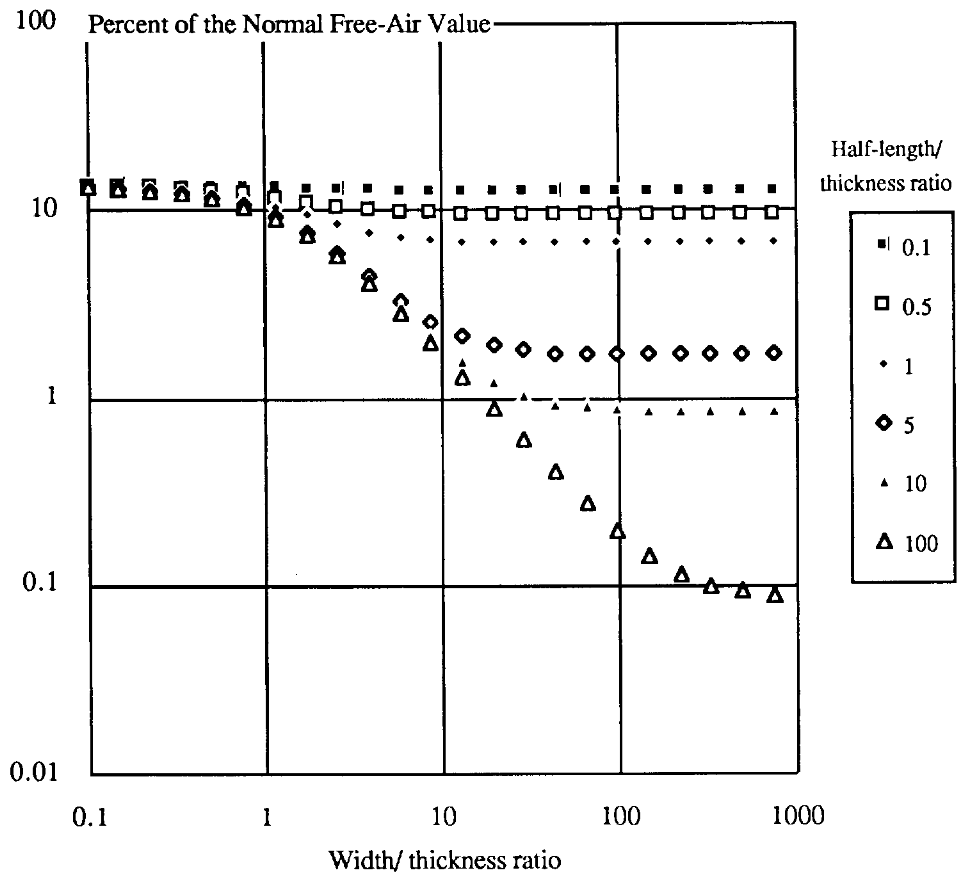

FIG. 6. Vertical gradient of gravity geologic effects, expressed as a percent of the normal free-air reduction, for a low-density (-1.0 g/cm^3) sandbar at the surface. These effects are calculated from a wide range of prismatic dimensions, having half-length/thickness ratios from 0.1 to 100 as a function of width/thickness ratios as shown on the horizontal axis.

VGG amplitudes are significantly smaller than the observations used in this illustration. For example, isostatic contributions to the actual VGG in Colorado (where such effects are quite large) are under 0.5 percent of the normal free-air gradient. VGG anomalies (because they are gradients) attenuate with distance from their sources much more rapidly than do Bouguer anomalies.

REDUCTION TO DATUM

Another difficulty is the notion that the free-air (and/or Bouguer) reduction reduces the data to a common datum [i.e., "to reduce them to the values they would have on some datum" (Telford et al, 1976)]; it is very important to note that the routine elevation-dependent reductions do not have as a purpose the reduction of the data to a common datum. How widespread this notion is can be seen by reviewing the major textbooks on the subject: of 15 English-language books which carry descriptions, no fewer than nine state or imply with Telford that our intent is datum reduction. However, a minority give clear and unequivocal explanations of this aspect of the data reduction process. Jeffreys (1962) notes that "the actual value on the co-geoid is of course appreciably different." Parasnis (1986) states, "The reader should also guard himself against the loose expression that the Bouguer anomaly is the gravity reduced to the datum level." Tsuboi (1983) says ". . . the free-air anomaly should be considered to be a station anomaly."

Figure 7 illustrates the problem. Both changing elevations and subsurface density contrasts are required to produce a difference between the measured complete Bouguer anomaly and the "reduced-to-datum" Bouguer anomaly. Henderson and Cordell (1971) have demonstrated a method which works on an irregular data set in two dimensions in which a Fourier Series approach is employed. Bhattacharyya and Chan (1977) developed an equivalent source technique, which, with modification can be applied to this problem. Dampney (1969) also proposed an equivalent-source technique which can be adapted to this problem. Xia's (1988) analysis favored the Dampney method; however, reduction to datum is not currently applied as a routine part of data reduction in modern gravity exploration.

Any solution, of course, requires adequate data sampling (station spacing) in order to define fully the anomaly—something that is difficult in rugged topography. Reduction-to-datum is implemented very differently from the standard free-air reduction: where the latter as a linear function of elevation is independent of surrounding stations, the former cannot be satisfactorily accomplished without a rather complete definition of the field. All reduction-to-datum methods produce some deterioration of anomaly quality, which may be the best reason for not including reduction-to-datum as part of standard data reduction procedures.

An important caveat for interpreters of data observed in areas of rugged topography is to be aware that regional

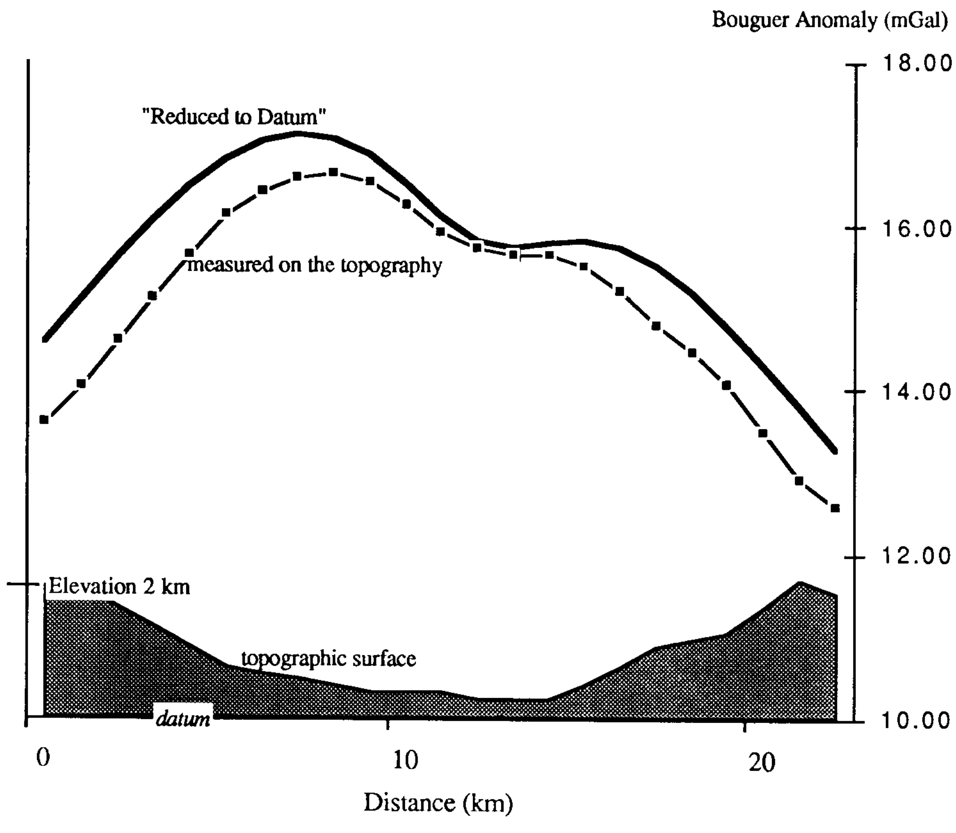

FIG. 7. Regional plus local Bouguer anomaly on both topography and datum.

fields, which would be "smooth" if measured on the datum, contain high-frequency components introduced by the irregular observational surface (LaFehr and MacQueen, 1990). This is true whether the source of the regional is deep or shallow. Most interpretations start with the separation from the observed Bouguer anomaly of the "regional" anomaly. This is to enable the modeling process to match the calculated anomaly arising from a proposed interpretation with the residual anomaly believed to be caused by the target structures. Thus an interpreter, who first removes a "smooth" anomaly (realizing that the data have not been reduced to a datum), models the residual station anomalies (albeit at their proper elevations) which may contain errors not properly removed during the anomaly isolation process. One solution to this problem is to include the regional geology in the model and calculate both regional and local effects at the actual station locations.

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