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Generalized gravity gradient analysis for 2-D inversion

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ABSTRACT

Gravity gradient profiles across subsurface structures that are approximately 2-D contain diagnostic information regarding depth, size, and structure (geometry). Gradient space plots, i.e., plots of horizontal gradient versus vertical gradient, present the complete magnitude and phase information in the gradient profiles simultaneously. Considerable previous work demonstrates the possibility for complete structural interpretation of a truncated plate model from the gradient space plot. The qualitative and quantitative diagnostic information contained in gradient space plots is general, however. Examination of the characteristics of gradient space plots reveals that 2-D structures are readily classified as extended or localized. For example, the truncated plate model is an extended model, while the faulted plate model is a localized model. Comparison of measured or calculated gradient space plots to a model gradient space plot catalog

allows a rapid, qualitative determination of structure or geometry. "Corners" of a polygonal cross-section model are then determined as profile points corresponding to maxima on the vertical gradient profile.

A generalized approach to structural interpretation from gravity data consists of (1) determining vertical and horizontal gradient profiles perpendicular to the strike of a 2-D gravity anomaly, (2) determining the structural geometry from the gradient space plot, and (3) locating profile positions of structural corners from the vertical gradient profile. This generalized inversion procedure requires no quantitative information or assumption regarding density contrasts. Iterative forward modeling then predicts the density contrasts. Application of this generalized gravity gradient inversion procedure to high quality gravity data results in an effective density prediction consistent with measured near-surface densities and the known increase in density with depth in deep sedimentary basins.

INTRODUCTION

The importance and usefulness of the spatial gradients of potential fields have long been recognized. Gradients of potential fields have greater spatial resolution, better definition of lateral boundaries, added depth discrimination and filtering properties, and better structural or geometric indicators than the measured fields alone. Measurement or determination of the spatial gradients of potential fields is a natural step toward understanding the 3-D nature of the fields and determining the cause of the fields. Early papers, such as Evjen (1936) and Heiland (1943), emphasize the role of gravity gradients in structural interpretation of gravity data. Numerous publications describe procedures for calculating gravity gradients and higher-order derivatives from measured gravity data using various "center point and ring" numerical filtering methods (e.g., Agarwal and Lal, 1972a,b;

Baranov, 1975). Recent papers, such as Nabighian (1984), Moon et al. (1988), and Pederson (1989), emphasize the usefulness of spatial gradients for potential fields analysis in general. Many authors have explored the use of gravity gradients for detailed 2-D structural interpretation of the truncated plate model; for example, Hammer and Anzoleaga (1975), Green (1976), Stanley and Green (1976), Stanley (1977), and Klingele et al. (1991). Other authors, such as Fajkiewicz (1976) and Butler (1984b), have used the detectability and resolution advantages of gravity gradients for detection and mapping of shallow geologic and cultural features. Several PhD dissertations are devoted exclusively to the theory, measurement, and applications of gravity gradients; i.e., Mueller (1960), Trommer (1964), Beyer (1971), and Butler (1983).

Gravity gradients can be measured in the field with gravimeters and gradiometers or determined from existing

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gravity field data. Gravity gradients measured with gravimeters are determined as interval or finite difference gradients. Butler (1984a) examines interval horizontal and vertical gravity gradient determination procedures and the relation of interval gradients to true gradients. Stephen Thyssen-Bornemisza, a tireless advocate of the importance of direct measurement and application of gravity gradients, is the author of 18 contributions to GEOPHYSICS during the period 1956-1978 on the subject. For existing gravity survey data in the form of profiles and/or contour maps, interval horizontal gradients can be determined. Vertical gradients are then calculated as the Hilbert transform of horizontal gradient profiles or as the result of a numerical filter applied to a gridded representation of contoured data.

In this paper, the procedures for 2-D structural interpretation using gravity gradients are reviewed. Two classes of 2-D structural models are introduced, and distinctive, diagnostic features of gradient-space plots are emphasized. A systematic approach for complete structural interpretation (depth, size, geometry, density contrast) using gravity gradient profiles is proposed. Finally, the gravity gradient structural interpretation procedures are illustrated by way of a detailed case history.

BACKGROUND AND CONCEPTS

Two-dimensional structural analysis using gravity gradient profiles

Diagnostic characteristics of gravity gradient profiles for subsurface 2-D structure definition are discussed by many of the authors listed previously. Gravity gradient profiles have greater structural "resolving power" than gravity profiles; and under certain conditions, gradient profiles can give direct depth information without density measurements or assumptions. The vertical and horizontal gradients of potential fields on the surface, as a result of a 2-D subsurface source, are related by a Hilbert transform (Sneddon, 1972). The Hilbert transform relation and its application to magnetic interpretation are discussed in Nabighian (1972) and Shuey (1972). Green (1976) and Stanley and Green (1976) use the Hilbert transform relation between the horizontal and vertical gradients of the gravity field for complete structural definition of a truncated plate model; they introduce the gradient analytic signal and use profile plots of the amplitude (modulus) of the analytic signal and gradient space plots as interpretive tools.¹

As an example, the normalized gravity and gravity gradient profiles over a truncated plate model are shown in Figure 1 for two values of dip of the sloping face relative to horizontal. A peak in the $g_{z,z}$ curve and points of maximum slope in the $g_{z,x}$ curve occur close to the horizontal locations of the two corners of the model. Plots of the modulus of the

analytic signal for the two cases in Figure 1 are shown in Figure 2. The modulus plot, which does not contain the phase information in the analytic signal, is clearly not as effective as the individual gradient profiles, particularly the $g_{z,z}$ profile, for indicating the number and horizontal locations of structural corners. The g_z curves are not very diagnostic regarding locations of the structural corners or the dip.

FIG. 1. Gravity and gravity gradient profiles over truncated plate models where $\Delta\rho$ = density contrast and k = gravitational constant; (a) $\alpha = 5^\circ$ (b) $\alpha = 30^\circ$ degrees.

FIG. 2. Plots of the square of the modulus of the analytic signal for the two cases in Figure 1.

¹ $A(x) = g_{z,z}(x) + i s_{z,x}(x)$, where $A(x)$ is the analytic signal, $g_{z,x}$ and $g_{z,z}$ are the horizontal and vertical gradients of the vertical component of the gravitational acceleration, z is the vertical axis (positive downward), and x is the horizontal axis and profile coordinate. Alternatively, $A(x) = a(x) e^{i\phi(x)}$, where $a(x)$ and $\phi(x)$ are defined as the amplitude and phase, respectively, in the usual manner. $A'(x) = iA(x)$ is used by some authors as the analytic signal. In $g_{z,z}(x) = H(g_{z,x}(x))$, where $H(\cdot)$ symbolizes the Hilbert transform operation. The gradient space plot is a representation of $A(x)$ in the complex plane, i.e., $g_{z,x}$ versus $g_{z,z}$.

The complete structural definition of a truncated plate model for a positive density contrast (from the gravity gradient-space plot, i.e., $g_{z,x}$ versus $g_{z,z}$) is illustrated in Figure 3. The gradient-space figure is an ellipse, inclined to the $g_{z,z}$ axis at the same angle as the truncated plate face to the horizontal, where each point on the ellipse corresponds to a profile point x . The ellipse closes smoothly on the origin, proceeding from the origin at $x = -\infty$ clockwise to the origin again at $x = \infty$. A key parameter that emerges immediately is the dip angle α , which is an elusive parameter to determine from gravity or gravity gradient data separately. Details of the complete structural analysis for this illustrative case are given by Green (1976) and Butler (1983); analytical expressions relate the four coordinates of $A(\chi_2, \zeta_2)$ and $B(\chi_1, \zeta_1)$ to the four parameters, a , C , M , and Q . An alternate, though less rigorous procedure is to (1) determine C and α from the gradient-space plot, (2) draw line CR (Figure 3), (3) determine χ_1 and χ_2 (horizontal locations of the corners) from the vertical gradient profile, and finally (4) draw vertical lines χ_1T and χ_2S (Figure 3). The intersections of the vertical lines in step 4 with CR locate A and B. Application of these gradient analyses techniques are not limited to the truncated plate model. However, for models with more than two structural corners, analytical expressions relating diagnostic profile points to structural corner coordinates become virtually intractable (Butler, 1983), and the alternate gradient analysis procedure is used.

Both amplitude and phase of the analytic signal are included in the gradient-space plot. Thus, analyses of gradi-

FIG. 3. Illustration of key profile points for a general truncated plate model and associated gradient space plot.

ent-space plots makes full use of the simultaneous information content in the two gradient profiles. Also, *no quantitative assumption of density contrast is required for the complete structural interpretation*. The fundamental ambiguity (nonuniqueness) in this case is that the reciprocal truncated plate with negative density contrast (same absolute value) will give the same gradient-space plot. Also, *the analysis explicitly assumes that the source of the gradient anomalies can be approximated by a polygonal cross-section model*.

Extended and localized 2-D models

The truncated plate model is a member of a class of 2-D models that are *extended* in either the $+x$ or $-x$ -direction as well as they-dimension. The faulted plate model, however, is a member of another class of 2-D models that are completely *localized* in the x -dimension with regard to the geometric structure producing the gravity and gravity gradient anomalies. Other localized 2-D models include the circular horizontal cylinder, tabular-shaped horizontal "cylinders," and the graben.

As an example of the localized class of 2-D models, a faulted plate model is illustrated in Figure 4 along with the

FIG. 4. Gravity and gravity gradient profiles and plot of square of modulus of the analytic signal for a faulted plate model.

gravity and gravity gradient profiles and the modulus of the analytic signal plot. Again, the gradient profiles can be used to determine the number and approximate horizontal locations of structural corners in the model. The magnitude and spatial wavelength of the vertical gradient and modulus peaks are clearly related to the depths of the structural corners, but because of the superposition there is no simple or obvious way to use this information to determine depths. The modulus plot clearly indicates peaks corresponding to three of the corners, but a peak corresponding to corner A is not readily discernible.

The gradient space plot for the faulted plate model (Figure 4) is shown in Figure 5. Two fundamental differences are immediately obvious for this localized 2-D model. Whereas the gradient space plot for the truncated plate (extended model) does not cross the $g_{z,z}$ axis and approaches the origin smoothly at $x \rightarrow \pm \infty$, the plot for the faulted plate (localized model) crosses the $g_{z,z}$ axis and forms a cusp at the origin. Simplistically, however, the gradient space plot for the faulted plate is recognized as the superposition of two ellipses, one for each of the truncated plate halves of the total model, and qualitatively the relative sizes of the ellipses are indicative of the relative depths of the truncated plates.

Catalog of gravity gradient space plots

The two fundamental characteristics of the gradient space plots for the faulted and truncated plate models (whether or not the plots cross the $g_{z,z}$ axis and whether or not the plots form a cusp at the origin, respectively) are true in general for all members of the localized and extended classes. A

FIG. 5. Gradient space plot for the faulted plate model in Figure 4.

“catalog” of gradient space plots is presented in Figure 6, showing three examples of each class of 2-D models.

PRACTICAL APPLICATION OF GRAVITY GRADIENTS FOR STRUCTURAL INTERPRETATION

The previous discussion suggests procedures for deducing model parameters from gravity gradient data, but in each case the model itself is known. In practice, the appropriate model will be unknown. The real power of the proposed gradient interpretive techniques is the diagnostic nature of the gradient-space plots. *If the gradient anomaly is caused by a subsurface feature (structure) that can be considered approximately 2-D*, then processing the field data to yield a gradient space plot will suggest a specific class of 2-D models (localized or extended). Examination of properties of the gradient space plot as well as plots of the vertical gradient and/or the modulus of the analytic signal allows specification of the geometry.

Two approaches for determining the gravity gradients are: (1) determine both the vertical and horizontal gradients from field measurements; and (2) determine the horizontal gradient from field measurements or existing gravity survey data, and then calculate the vertical gradient using the Hilbert transform. Approach (1) is practical primarily for shallow anomalous features or structures (e.g., < 10 m) and relatively large gradients (Butler 1984a; Hammer 1979). Approach (2) is possible for good quality gravity data sets with relatively uniform data density. Under approach (2), the horizontal interval for calculating horizontal gradients can be selected to enhance the gradient anomaly for the depth range of interest (Butler, 1984a) but should not be less than the mean gravity measurement interval. For existing gravity survey data, a gravity profile is selected approximately perpendicular to the trend of an anomaly that indicates a feature that can be considered approximately 2-D (along the selected profile, in particular, the data density should be relatively uniform).

Once the vertical and horizontal gravity gradients are determined across the subsurface feature or structure of interest, the gradient analysis proceeds as follows:

- 1) Prepare the gradient space plot;
- 2) Determine the class of 2-D models represented by the measured gradient space plot (Figure 6);
- 3) Determine the dip angle(s) and horizontal location of the surface projections of the dipping faces from the gradient space plot;
- 4) Determine the number and approximate horizontal locations of structural corners of the model, representing the subsurface feature, from the vertical gradient profile;
- 5) Using the gradient model, determine the density contrast(s) by iteratively adjusting the model density until gravity calculated from the gradient model matches measured gravity.

The possible sources of ambiguity and nonuniqueness in the gradient analysis procedure are many, as with any gravity interpretation procedure. The reciprocal plate ambiguity was mentioned in association with the truncated plate model (Figure 1). Similarly, the gravity and gravity gradients pro-

files for the faulted plate model in Figure 4a are indistinguishable from the profiles for a faulted plate with half the thickness and full downdip offset. Other possible sources of ambiguity and nonuniqueness are (1) subsurface features that are not adequately characterized by a 2-D polygonal model, (2) poor quality data, (3) poor data distribution in the vicinity of the profile, (4) influence of inadequate terrain correction and/or near-surface heterogeneities, and (5) superposition of closely spaced *distinct* subsurface features. Only items (1) and (5) are fundamentally beyond the control of the interpreter. Negative impacts of items (2) and (3) can be diminished by judicious selection of profile locations and the gravity data sets to which the interpretation technique is applied. Problems associated with item (4) can be diminished to some extent by proper selection of Δx (Butler 1983, 1984a). The gradient analysis procedure will now be applied to an existing gravity data set, specifically to a profile approximately perpendicular to the strike of an elongated gravity anomaly (also see Butler 1983, 1984b).

GRAVITY-GRADIENT ANALYSIS OF A SELECTED GRAVITY PROFILE ACROSS DRY LAKE VALLN, NEVADA

Background

Dry Lake Valley is located in central Lincoln County, Nevada, approximately 170 km north-northeast of Las Vegas, and oriented with its long axis north-south. A

gravity survey, consisting of 1069 stations in and around Dry Lake Valley, was conducted by the Defense Mapping Agency (DMA) in the summer of 1977. The portion of the valley encompassed by the gravity survey is approximately 65 km by 22 km. Approximately one-half of the stations were more or less uniformly distributed throughout the valley with a mean station spacing of 1.5 km. The remainder of the stations were placed along roads and trails with a spacing of approximately 0.4 km or around the periphery of the valley on rock outcrops (see Figure 7a). Correction of the gravity data was performed by DMA and Fugro National, Inc., to produce a Bouguer anomaly map. The estimated uncertainty in the Bouguer anomaly values is 0.3 mGal. A regional field was derived by fitting a second order polynomial surface to Bouguer anomaly values on bedrock outcrop stations around the valley. Subtracting the derived regional field from the Bouguer anomaly map yields the residual anomaly map shown in Figure 7b. The Bouguer and residual anomaly for profile AA' (Figure 7b) are illustrated in Figure 7c. Complete details of the site, gravity survey, and data correction procedures are given in a technical report, Fugro National, Inc. (1980) and McLemore and Walen (1979).

Dry Lake Valley exhibits typical basin and range structure, with the valley occurring above a graben between two high angle normal basement faults on the east and west sides of the valley. Outcrops in the mountains on the western side of the valley are predominantly Tertiary ash flow tuffs with

FIG. 6. Catalog of gradient space plots for various 2-D models.

FIG. 7. Gravity survey, Dry Lake Valley, Nevada (Fu ro National, Inc., 1980): (a) gravity stations, (b) residual gravity map, Contour Interval = 2 mGal, (c) Bouguer and residual gravity for profile AA'.

some Paleozoic carbonates, while the mountains on the eastern side are predominantly the Paleozoic carbonates with only minor amounts of the Tertiary tuffs. The valley fill consists of unconsolidated to partially consolidated silt, sand, and gravel derived from adjacent highlands. At the surface, the fill materials are primarily Tertiary and early Quaternary alluvial fan deposits (72% by area), fluvial and stream terrace deposits (16%), playa and older lacustrine deposits (6%), and undifferentiated deposits (6%).

McLemore and Walen (1979) use an interactive, 3-D gravity inversion program developed by Cordell (1970) to determine a subsurface model that yields a gravitational field to approximately match the gravity anomaly shown in Figure 7b. The model is constrained by results of two long, intersecting refraction lines in the north end of the valley (<300-m depth to carbonate bedrock), seven shallow (<300-m) boreholes throughout the central portion of the valley (Phillips, B.R., 1979, Data Report, U.S. Army Engr. Waterways Exper. Sta.), and a knowledge of the structural style of the region. A density contrast of -0.45 g/cm^3 (between alluvium and carbonate bedrock) was determined by trial and error gravity interpretation to yield the best "tie" with the seismic refraction results. This density contrast is consistent with published density values for bedrock

($2.6\text{--}2.8 \text{ g/cm}^3$ range for the carbonates) and shallow alluvium ($2.1\text{--}2.4 \text{ g/cm}^3$ range) materials in the area (McLemore and Walen, 1979). An interesting feature of their interpretation is that the placement of the faults was determined from an examination of the second vertical derivative of the gravity field, i.e., the faults are placed along the zero contour of the second derivative field. This procedure places the surface trace of the eastern boundary fault about 1.5 km west of the surface cracks in the alluvium, which have been mapped as a fault.

Gradient interpretation

Profile AA' in Figure 7 is chosen to illustrate the gradient analysis procedure, and the average gravity measurement station interval along AA' was 0.4 km. The gravity profile was digitized at 1-km intervals (approximately 2.5 times the average basic measurement interval along the profile line), and horizontal gravity gradients were calculated for $\Delta x = 1, 2, 3,$ and 5 km , where Δx is the horizontal interval between gravity values used for the horizontal gradient determination. Vertical gradient profiles were then computed from each of the horizontal gradient profiles (Figure 8). The gradient profiles in Figure 8 clearly become smoother and

FIG. 8. Horizontal (dashed lines) and vertical (solid lines) gravity gradient profiles along AA' for four values of Δx .

exhibit fewer “complexities” as Δx increases because of the filtering properties discussed by Butler (1984a). The gradient profiles for $\Delta x = 5$ km closely resemble those for a horizontal cylinder (the simplest 2-D structure). The gradient profiles for $\Delta x = 1$ km, however, exhibit features in the central portion that closely resemble the profiles for a graben-like structure. Gradient-space plots for the $\Delta x = 1$ and 5 km cases, which further illustrate the qualitative features discussed above, are shown in Figure 9.

For purposes of gradient interpretation, the gradient profiles and gradient-space plot for $\Delta x = 1$ km are used; this selection for Δx will strongly attenuate gradient anomalies for shallow features (<0.5 km) while preserving amplitude and spatial wavelength of gradient anomalies for deeper features. While the diagnostic features are only slightly attenuated in the profile plots for $A = 2$ km (compared to the $A = 1$ km case), the features are severely attenuated in the profiles for $A = 3$ km. Assuming a best case uncertainty for the digitized gravity values of 0.3 mGal and a location uncertainty of 3 m, the horizontal gradient uncertainty is 0.0004 mGal/m (4 Eötvö). For a more conservative uncertainty estimate of 0.6 mGal for the gravity values, considering the additional uncertainty associated with digitizing the profile constructed from the contour map, the horizontal gradient uncertainty is 0.0008 mGal/m. Figure 10 is a larger size plot of the gradient profiles for $\Delta x = 1$ km. It is evident from an examination of Figures 9a and 10 that the structure causing the gradient anomalies is more complex than ex-

pected for a simple, symmetric graben-like structure that has nearly equal side slopes and a horizontal bottom boundary. Six points are labeled in Figure 10, with points E, F, G, and H assumed to be associated with the central graben structure. Points D and I are located at profile positions corresponding exactly to locations of vertical gradient peaks, while points E, F, G, and H are shifted by $\Delta x/2$ relative to the associated vertical gradient peaks to qualitatively compensate for gradient profile “broadening” because of sampling and superposition effects.

Angles of -48° and 68° relative to counterclockwise rotations from the $g_{z,z}$ axis, are defined in Figure 9a for the lower and upper ellipses, respectively. Also, points labeled C' and C'' are shown for the lower and upper ellipses, respectively; these points are assumed to be the surface projections of the sloping side faces of the graben structure. The slope angle and C' for the upper ellipse are fairly well defined. However, the slope angle and C'' for the lower ellipse are not as well defined; there is clearly subjective judgment involved in the definition of C''.

Using the parameters defined in Figures 9a and 10, the structural geometry shown in Figure 11a is constructed. Points D and I are assumed to be at or very near the surface and connected to points E and H, respectively, by straight lines. Maximum depth to rock of 5.4 km is predicted at point G. The structural model of the valley fill-bedrock geometry is deduced directly from the gradient data with no assumptions regarding magnitudes of density contrasts.

FIG. 9. Gradient space plots for profile AA'; (a) $\Delta x = 1$ km; (b) $\Delta x = 5$ km.

FIG. 10. Gradient profiles for $\Delta x = 1$ km (solid line-vertical gradient, dashed line-horizontal gradient). Selection of profile locations of structural "corners" based on vertical gradient profile.

FIG. 11. Structural models deduced from Dry Lake Valley gravity profile AA' using two different interpretive methods. (a) Structural model deduced by 2-D gradient methods. (b) Structural model from 3-D gravity inversion.

Comparison of gradient and 3-D gravity interpretations

The 3-D iterative gravity inversion model for the graben structure represents an independent and traditional approach to gravity interpretation, requiring the assumption of a density contrast. The result of the 3-D gravity inversion along profile line AA' is shown in Figure 11b (a polygonal approximation). Qualitatively, the two interpretations shown in Figure 11 are very similar, and the slope angles of sides EF and GH in Figure 11a and their counterparts in Figure 11b differ by only 1° and 5°, respectively. The primary quantitative difference is the dramatically larger depth to the carbonate bedrock predicted by the gradient model. Profile locations of points D and I are approximately the same in both models; however, profile locations of points E, F, G, and H in the two models differ by amounts as large as 1.5 km.

Although several explanations can be advanced to explain the discrepancies between the two models in Figure 11, only two will be discussed: (1) possible errors in the locations of points E, F, G, and H in the gradient model, and (2) errors in depth in the 3-D gravity model as a result of selection of density contrast. Small errors in location and hence spacing of the points E, F, G, and H could produce significant errors in depths to corners of the structural model, because of the relatively steep slopes of the sides of the graben structure. If the model shown in Figure 11b from the 3-D gravity inversion is correct, then using the depths to the corners E and H as a measure of the parameter ζ_0 , the "depth" to the model, results in $\Delta x/\zeta_0 \sim 2$ ($\Delta x = 1$ km, $\zeta_0 \sim 0.5$ km). From the considerations in Butler (1984a), amplitude attenuation and increase in spatial wavelength of the horizontal gradient profile become significant for $\Delta x/\zeta_0 = 1$ and become very pronounced for $\Delta x/\zeta_0 = 2$. Because of the sampling process, these distortions of the horizontal gradient profile will be reflected in the computed vertical gradient profile by increased separation and broadening of the peaks (relative maxima) corresponding to corners E, F, G, and H, leading to values for the distances EF and GH which are too large. It is noteworthy, however, that the location of the surface projection C' of segment GH for the gradient model in Figure 11a is more consistent with mapped surface cracks in the alluvium [Fugro National, Inc. (1980)], than the corresponding location in Figure 11b).

An equally plausible explanation for the differences in the two models in Figure 11 is that the predicted depths in Figure 11b are too shallow as a result of the use of a density contrast which is too large. The density contrast of -0.45 g/cm³ used for the 3-D gravity inversion corresponds to the density contrast for very shallow sediments relative to rock in the basin. Since the sediment density will increase with depth, primarily because of compaction, -0.45 g/cm³ must be viewed as a maximum density contrast (Fugro National, Inc., 1980). Thus, the depths calculated from the 3-D inversion are likely to be too small, particularly for the base of the graben. Additional modeling with different density contrasts or a density contrast function (decreasing with depth; Cordell, 1973; Litinsky, 1989) was not considered to be justified because so little is known about the actual density distribution in and around the valley.

Without further information, such as a deep boring in the center of the valley or a long refraction line in the center of the valley, it is not possible to resolve the discrepancy between the two models in Figure 11; however, density contrast considerations favor a valley model with greater depth than in Figure 11b. Using the gradient structural model (Figure 11a) and iteratively adjusting the density contrast, a constant density contrast of -0.22 g/cm³ is required to fit the gravity data. This seems to be a reasonable value for a depth-averaged or effective density contrast. Litinsky (1989) proposes a hyperbolic depth-density relation for basins in the Basin and Range Province and defines the concept of effective density. Assuming a hyperbolic depth-density relation for Dry Lake Valley and using the known surface density contrast and the residual gravity values, an effective density of -0.17 g/cm³ is predicted using the procedure proposed by Litinsky (1989), in reasonable agreement with the relative density contrast determined directly from the gradient model.

It is important to emphasize that the comparison of the gradient model to a 3-D model is *not* intended in any way to (1) argue for the superiority in general of a 2-D interpretation or (2) imply that the results of a 3-D inverse are a standard for comparison.

SUMMARY AND CONCLUSIONS

A general procedure for classifying and analyzing gravity gradient profile data over 2-D structures is presented. The procedure can be applied to case (1) where both vertical and horizontal gravity gradients are measured (finite difference approximations) in the field and case (2) where the horizontal gradient is measured or determined from existing gravity survey data and the vertical gradient data is calculated as the Hilbert transform of the horizontal gradient data. The 2-D structure is assumed to be approximated by a polygonal cross-section model, and two classes of such models are identified—extended and localized. Briefly, the procedure consists of identifying corners in the structural model from the vertical gradient profile and then using the gradient space plot to determine structural dips and other key points defining the model. A "catalog" of gradient space plots is presented for representative extended and localized 2-D models. This procedure can be used to completely define the geometry of a subsurface structure without any assumptions regarding densities. The structural model can then be used to determine density by assuming and iteratively adjusting a density value for the model until the computed gravity anomaly reproduces the measured gravity anomaly. The gradient analysis procedure can be applied to any existing gravity data that exhibit anomalies satisfying the 2-D criteria.

The gradient analysis procedure (inversion) is applied to the gravity survey data over a sedimentary basin (graben) in the basin and range province. A horizontal gradient profile is determined from a gravity profile that strikes perpendicular to a gravity anomaly that indicates approximately 2-D subsurface conditions. The gradient analysis procedure results in a structural model that is qualitatively consistent with the results of an independent 3-D interpretation of the gravity anomaly, however, depths to the graben bottom are larger

by a factor of two in the gradient model. It is easy to envision scenarios that could lead to overestimation of depths from the gradient inversion procedure. However, the density contrast used for the 3-D inversion is based on densities of very shallow sediments relative to exposed "bedrock." Since densities in sedimentary basins increase with depth, the 3-D model likely underestimates depths. A density prediction resulting from the gradient model is approximately one-half that used in the 3-D inversion, a feasible value for the depth-averaged or effective density of the sediments in the basin and consistent with the larger depth prediction from the gradient analysis.

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