Methodology for interpreting 3-D marine gravity gradiometry data

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New high-resolution multicomponent gravity gradient data now becoming commercially available yield important subsurface information when properly modeled. Gravity gradients represent minute variations in the 3-D gravity field. T_{xx} represents the gradient in the x direction of the x component of the gravity (G_x). T_{yy} represents the gradient in the y direction of the y component of the gravity (G_y). T_{yz} represents the gradient in the y direction of the vertical component of the gravity (G_z). T_{zz} represents the vertical gradient of the vertical component of the gravity (G_z), and so forth. The measured gravity gradients thus provide a more detailed picture of the subsurface by reflecting the edges, shape, and approximate depth of dominant mass anomalies. An example of these data, the calculated wavefield produced by a single body, is illustrated in Figure 1.

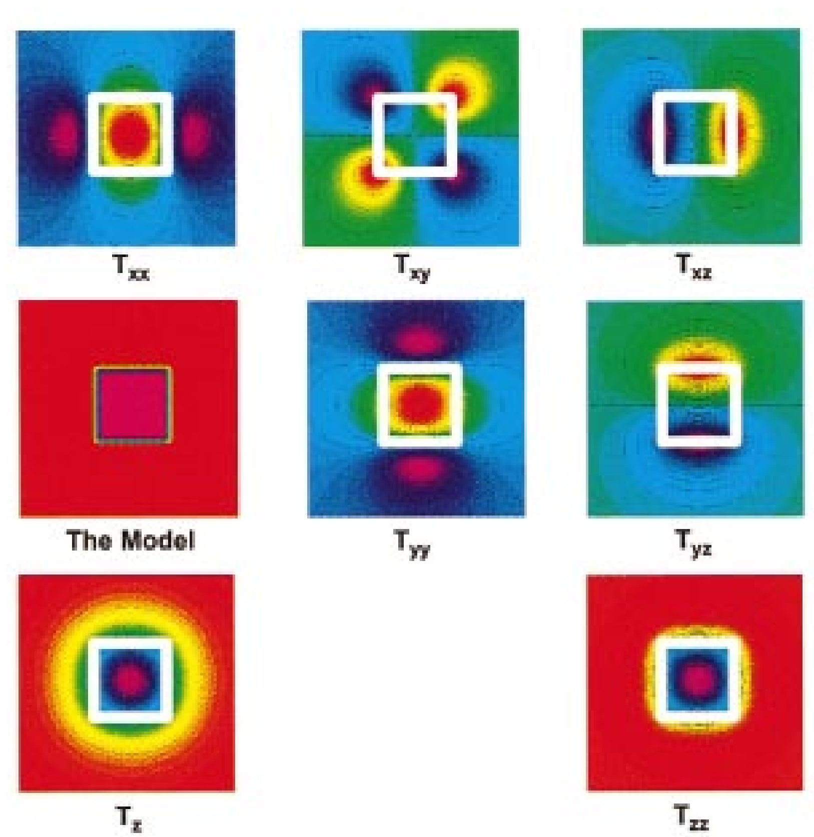

Figure 1. Gravity gradient response to a rectangular prism. Prism is 2500 ft square, center of prism at 10 000 feet. Prism's vertical dimension is 2500 ft. Density contrast is -.05 gm/cm^3, and the model is extended to 310 miles in all directions.

Methodology. This paper presents a "by the numbers" interpretation technique to aid explorationists in determining the source (and possible resource potential) of these very interesting and complex anomalies.

1) Determine model size. In order to maximize the use of the 3-D full tensor gradient (FTG) data one should model the measured gradient data while remaining within constraints imposed by seismic and well data. 3-D model size is critical. An accurate model should be large enough to calculate the full wavelength of the anomaly of interest. A general rule of thumb for modeling gravity and gradient data is that the wavelength is approximately four times the depth to its source (± 20%). Therefore, if an interpreter is interested in modeling a subsalt structure at 15 000 ft subsea, the model should be at least 60 000 ft in diameter. We also add an extra 10 000 ft for edge effects generated by the modeling algorithm. Horizons and density grids must cover the entire model area.

The model should consist of several horizons and density grids.

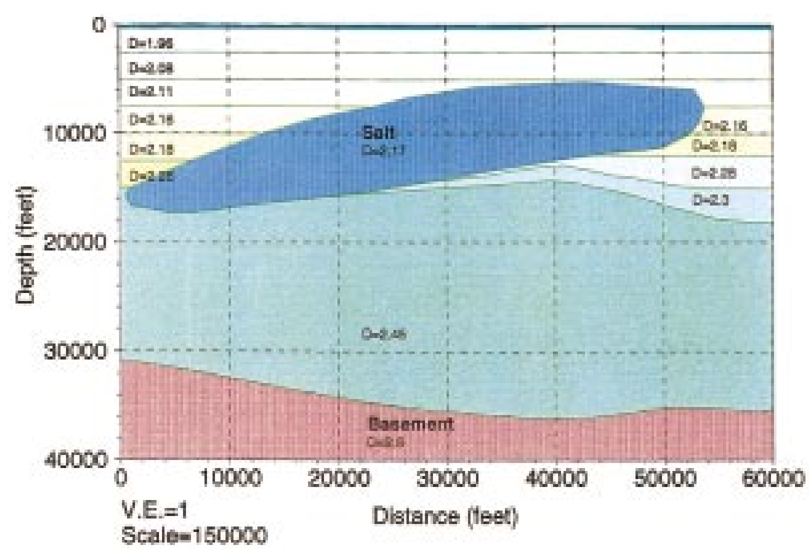

Figure 2. Profile from 3-D geologic model showing surfaces and average densities.

Typical horizons include bathymetry, top of salt, base of salt, subsalt surfaces (if known), and basement. Several flat surfaces are constructed on intervals (i.e., every 500-2000 ft) and clipped to the top of salt and base of salt. Stacked density grids are applied to these flat surfaces, thus providing a density cube that surrounds the salt body (Figure 2). Constant densities are used for salt water, salt and basement.

2) Build density grids from well data. Laterally varying density grids are built for interval isopachs. Calculating density values and constructing density grids from well data may involve several steps. Initially, we calculate an average density value for every interval at each well. Contouring the results and posting log signatures enables us to see anomalous areas and note if any posted density values average both salt and sediment over one interval (Figure 3). If they do, we exclude or edit those values. To edit the values, we create a new density curve, then recalculate the average density values using this new curve. Crossplots of depth versus density allow us to extrapolate sediment-only densities over the salt interval (Figure 4). After all zones are completed, we compare the contoured density maps for the entire depth range and make adjustments as necessary to compensate for areas with no well control.

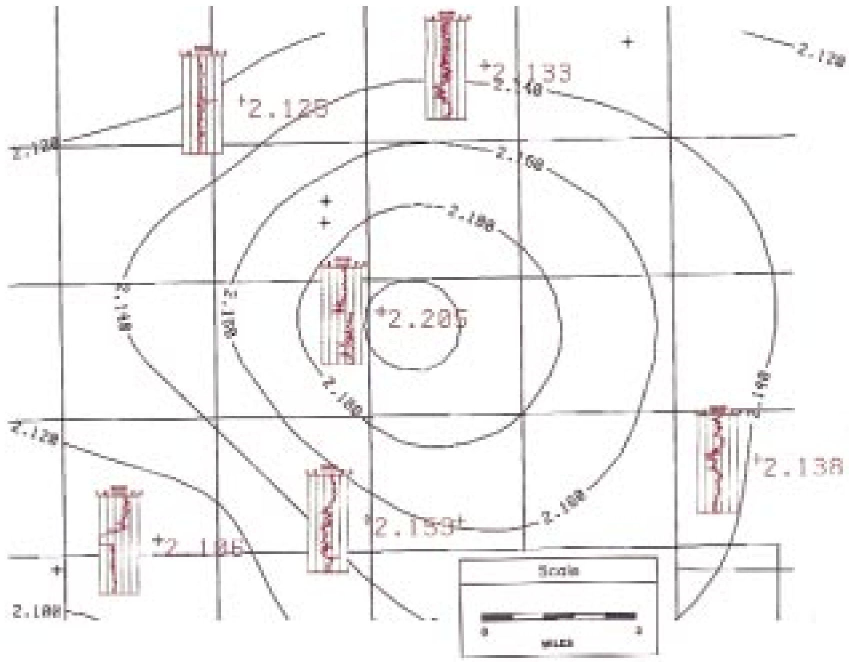

Figure 3. Density grid showing density log and posted values over isopach interval.

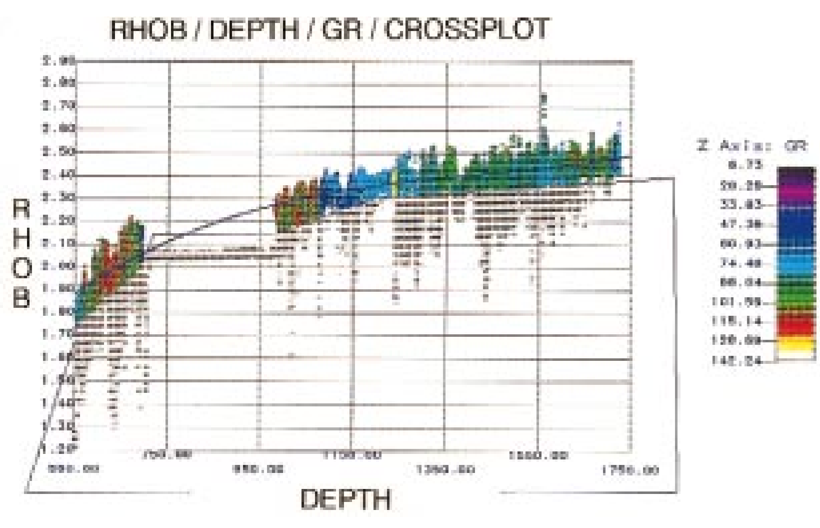

Figure 4. Crossplot of depth versus density showing extrapolation of curve through salt and scatter.

3) Build density grids from velocity data. Density grids can also be constructed by using apparent densities calculated from interval velocities. Velocity values can be extracted along flat horizons from a velocity cube (Figure 5) in much the same way that amplitudes are extracted along interpreted horizons from a 3-D seismic cube. The translation from velocity to density can be derived from the Gardner equation. Figure 6 shows an alternative equation using the generalized form of the Gardner relationship. Bain and Weber term this relationship the LASA equation, named after the Louisiana Southern Addition. This equation is useful for calculating apparent densities in the Gulf Coast region because the data were derived from this area.

4) Forward modeling and interpretation techniques. Several modeling techniques can help interpret 3-D FTG data, such as inversion modeling or filtering the data before forward modeling. We will only discuss 3-D forward modeling of the free-air 3-D FTG data after standard corrections and equivalent source gridding.

Once the initial geologic model is constructed, a 3-D forward gravity gradient model can be calculated and subtracted from the 3-D FTG data leaving "residual anomalies" of all sizes, shapes, and amplitudes. The residual or difference map indicates areas where mass needs to be increased or decreased within the geologic model. With the 3-D FTG data, it is important to first model the short wavelength residual anomalies, i.e., those produced by sources shallower than the zone of interest. These short wavelength residual anomalies interfere with the longer wavelength residual anomalies that are presumably generated from sources at a depth of exploration interest. This method of modeling the short wavelength anomalies and then modeling the longer wavelength anomalies can be referred to as "geologic stripping." You are removing the gravity gradient effects from the known geology by constraining the model with seismic and well data and also removing the residual anomalies from the top down as you go through the iterative modeling process. As the residual anomalies at shallower depths are modeled, the long wavelength residual anomalies will become much more apparent. This method helps the explorationist interpret what changes need to be made in the deeper portions of the geologic model. Obviously it is important to refer to the seismic data when changing the densities of an area or the attitude of a horizon. The interpreter must ask:

- "Are there indications that might suggest the base of salt is wrong for this particular area?"
- "Could I have a gas chimney instead of shallow salt?"
- "Are the seismic data ambiguous beneath the salt, leading to alternate subsalt interpretations, if so, which one is in better agreement with the gradient data?"
- "Does there appear to be a seismic anomaly where I need to increase mass or decrease mass over an area; could these anomalies represent sediment compaction, overpressured shale, or even gas?"

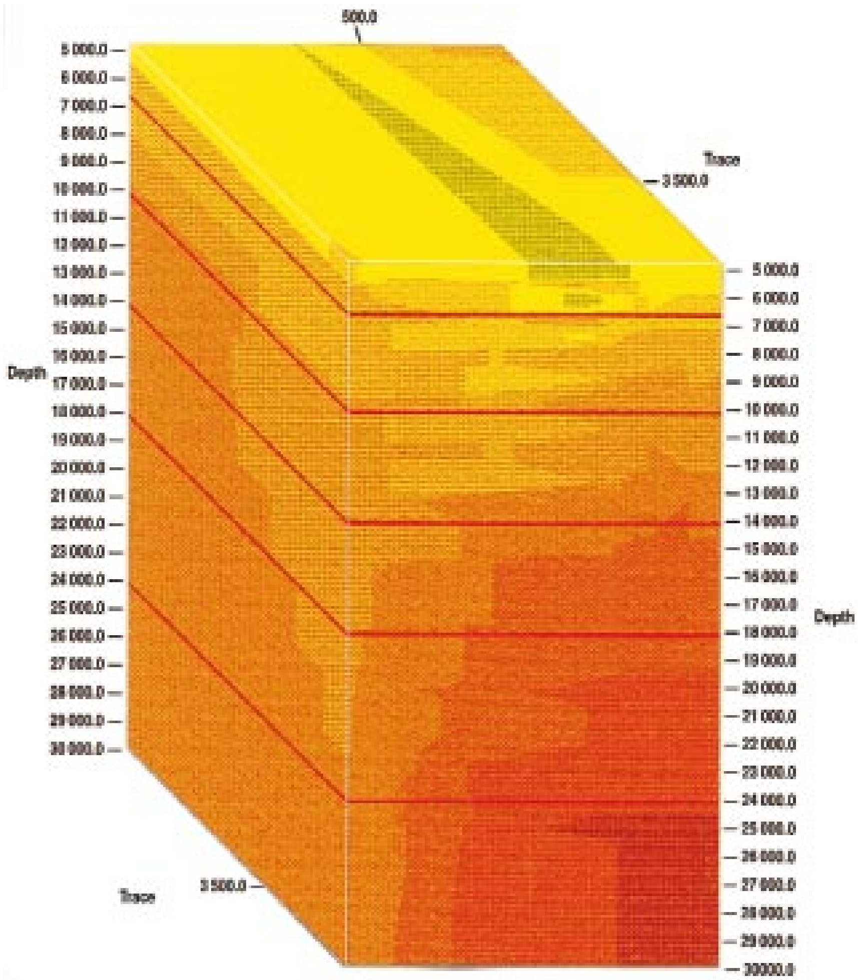

Figure 5. Velocity cube showing flat horizons in red.

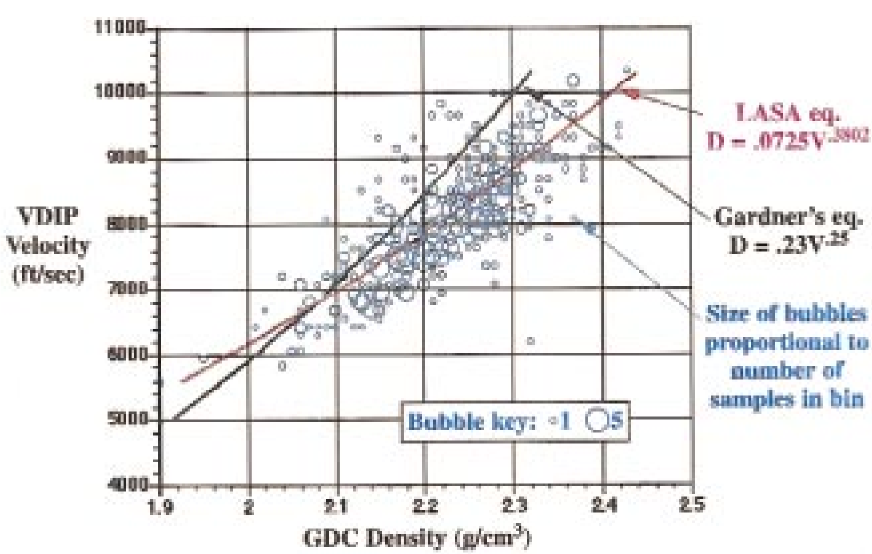

Figure 6. Crossplot of velocity versus density.

Figure 7 shows a gravity gradient case study that we believe indicates gas-saturated sands between 1500 and 6000 ft. The free-air T_{zz} gradient shows a 15 Eötvös anomaly low. Initially we used densities ranging from 1.90 gm/cm^3 and 2.12 gm/cc between the bathymetry and 6000-ft isopach intervals. As an example, we show the initial density grid applied to the 1500-2000 ft isopach. After the initial run, the T_{zz} gradient residual shows a large negative anomaly indicating mass in the model needs to be decreased from what was used for the initial model. The density grids were altered between the 1500-6000 ft isopach intervals and the model recalculated. We show the final density grid applied to the 1500-2000 foot isopach as an example. For the final model, the T_{zz} residual anomaly shows only a very short wavelength residual low. This remaining residual probably indicates gas-saturated sands that still need to be modeled at or just below bathymetry. The bulk densities of the gas sands used in the final model reflect gas saturation ranges between 80% and 20% with a porosity of 35% based on Schlumberger charts CP5 and POR5.

To summarize, the key steps in a 3-D forward gravity gradient modeling project are:

- Compile well, seismic, and 3-D FTG data.
- Determine 3-D model size and build the model. (Interpret structural horizons and build grids. Verify density data and build laterally varying density grids from well log and/or velocity data.)
- Start forward modeling and interpretation processes. (Calculate 3-D gravity gradient model. Subtract the calculated model from the measured data to determine the residual. Interpret the sources of residual anomalies. Adjust density grids and/or structure grids while remaining within the constraints of seismic and well data. Recalculate

the 3-D model. Repeat until a best fit is obtained.)

Conclusions. Multicomponent gravity gradient data provide excellent density information for the upper 6000 ft of the subsurface model as well as interpretable signal from 15 000 ft and below. It is essential that accurate density data be used for the upper portions of a 3-D model.

Incorrect densities used for modeling shallow layers will impact the greatest error on the modeling results for deep subsalt structures. In areas where seismic data are ambiguous, the integration of the 3-D FTG data can help resolve interpretation problems through the forward modeling process.

While this paper was being written, a well drilled from a nearby platform tested gas on the northern fringe of the anomaly in Figure 7. As a result, the operators are considering production of the relatively shallow zone.

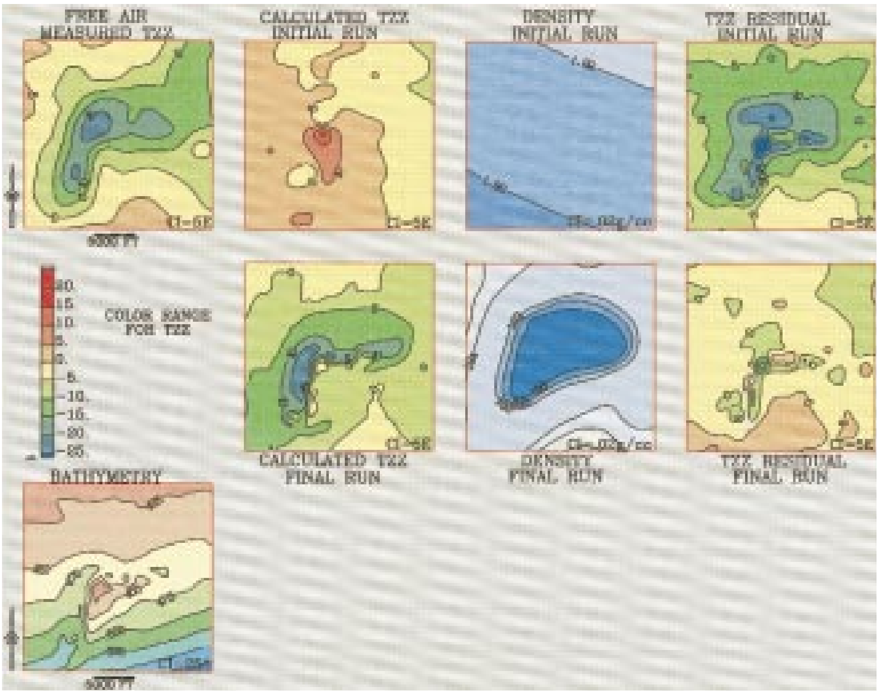

Figure 7. Montage of free-air T_{zz}, calculated T_{zz} for initial model and final model, residual T_{zz} for initial model and final model, density grid for 1500-2000 ft isopach for initial model and final model, and bathymetry.

Suggestions for further reading. "Complex salt features resolved by integrating seismic, gravity and magnetics" by Bain et al. (EAEG/EAPG *Expanded Abstracts*, 1993). "Formation velocity and density—the diagnostic basics for stratigraphic traps" by Gardner et al. (GEOPHYSICS, 1974). **E**

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