



TECHNICAL PAPER

The use of different types of velocity data and their application to gravity modelling

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INTRODUCTION

Velocity measurements are available from a variety of sources, including well surveys (e.g. sonic log, vertical seismic profiling), velocity analysis (from seismic processing, e.g. stacking velocities, from seismic interpretation and well correlation, e.g. interval velocities), global crustal databases. In this note, we demonstrate three methods to prepare 3D velocity data for use in gravity modelling in Geosoft GM-SYS 3D modelling module. We first look at Crust 2.0 public data, then a SEG-Y volume of interval velocities, and finally interval velocities derived from isochore \ isochron grids. A detailed analysis is beyond the scope of this note, and the user should bear in mind relevant assumptions used in velocity analysis. For example, stacking velocities derived from seismic processing may be converted to interval velocities using Dix equation (**Dix, 1952**), which are more useful to convert to density. However, stacking velocities can be highly variable in seismic, and the Dix equation assumes horizontal seismic reflector horizons. If the user has a SEG-Y volume of interval velocities, these would provide more accuracy than equivalent stacking velocities.

There have been several papers over the years demonstrating crustal velocity-density conversion methods. These include Gardner's equation (**Gardner et al , 1974**), valid for sedimentary rocks (excluding evaporites) in a range of 1.5 to 6.1 kms⁻¹. Gardner's equation states: $\rho = 0.23v^{0.25}$, for use when primary wave velocity is in the range 1500- 6100 ms⁻¹.

Brocher (2005), quotes a series of P-wave (compressional –velocity) derived density formulae, for a range of crustal depths and lithological\ mineral composition, and quotes the Nafe Drake curve published by **Ludwig et al., 1970**, Brocher also provides an empirical formula for the Nafe-Drake graphical relationship between density and compressional wave velocity. This equation can be used in the Vp range 1500 to 8500 ms⁻¹. We have highlighted the use of this relationship in our methods presented below. The resultant density block model can be input to GMSYS3D to efficiently calculate the gravity response of the crustal block, or a specific interval of the model, in a one-step approach. Using the different forms of data in our 3 methods, we exemplify the calculation of local and regional gravity modelling.

GLOBAL CRUSTAL DATABASE, CRUST 2.0 PROVIDES MODELLING OPTIONS

Method 1

The recent addition of Crust 2.0 (Bassin et al., 2000) to Geosoft's DAP web client enables comparison of gravity modelling with other regional methods. The Crust 2.0 database provides a total of 7 global grids at 2 x 2 degree resolution for each of crustal structure, Vp (compressional wave velocity) and density. The grids form 7 layers defining crustal boundaries from ice, down to the Mohorovičić discontinuity resembling the crust – mantle boundary. The grids can be downloaded for any region of the world to aid interpretation work.

Vp and crustal thickness grids were downloaded from DAP for the area. The velocity grids were resampled and converted to an array distribution using Geosoft's database channel to array tool. This tool converts a time or depth series of measurements contained in separate channels to a (spectral) multi- channel array. The thickness grids were converted to elevation grids by hanging from topography, and then the elevation grids were converted to an array channel, using the same method as the velocity grids.

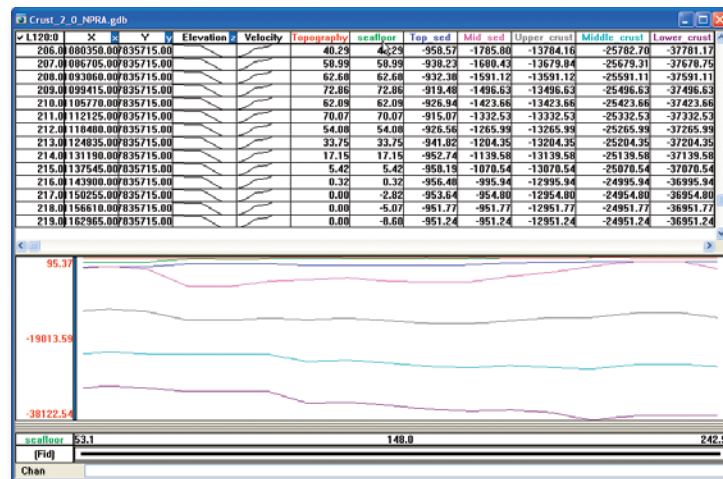


Figure 2-1

3D gridding with a variogram model based on 10km horizontal sampling and 250m vertical sampling was used to create the Vp voxel. **Figure 2-2** (all following 3D figures except 2-4 are looking due south west) shows the gridded Vp 3D model cut away with intersecting structural grid of surface topography. **Figure 2-3** shows the structural interfaces derived from Crust 2.0, and hung from the topography.

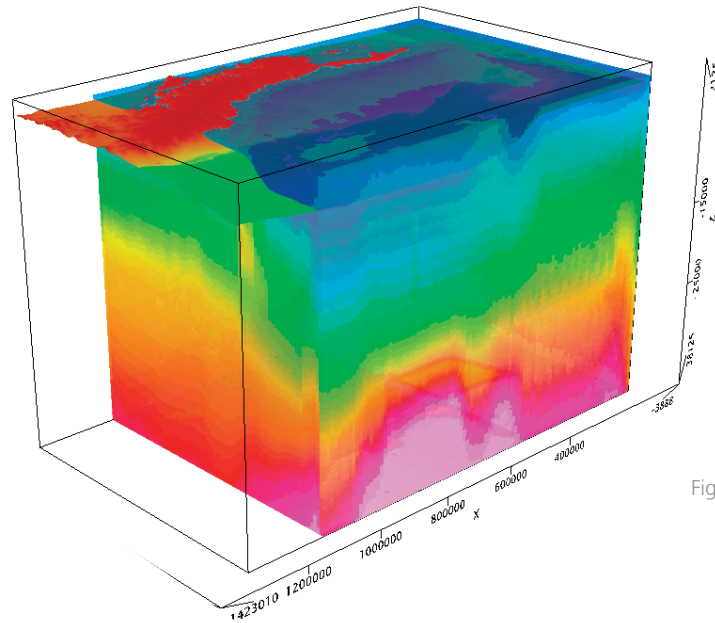


Figure 2-2

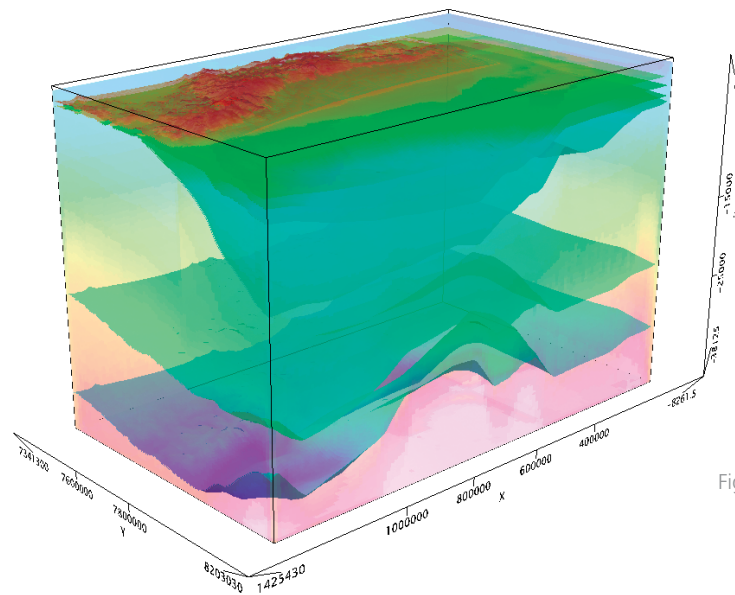


Figure 2-3

The resultant velocity block model has a range of approx 0.5 to 10.5 kms^{-1} . Using Voxel Math, values below 1.5 kms^{-1} and above 8.5 kms^{-1} were limited to the applicable range for use of Gardner's and Nafe-Drake's density conversion. i.e. V_p values $< 1.5 \text{ kms}^{-1}$ were converted to 1.5 kms^{-1} . Therefore, the sea-water interval velocity was a constant 1.5 kms^{-1} .

Refinements to the voxel output included clipping the model to topography, and in order to satisfy the requirements of the gravity calculation, the grid null value areas were filled with zeros.

Next Brocher's empirical formula for the Nafe-Drake graphical relationship was used to convert the velocity to density

$$\rho \text{ (gcm}^{-3}\text{)} = 1.6612V_p + 0. - 0.4721V_p^2 + 0.671V_p^3 - 0.0043V_p^4 + 0.000106V_p^5$$

where V_p (kms⁻¹)

The gravity response of the density model was then calculated at an elevation plane of 5000m. An existing observed free-air anomaly grid (upward continuation filter applied to same elevation) was available for comparison. The grids show a good comparison in response in the mountainous South over the Brook Range, whereas the Crust 2.0 model shows a prominent gravity anomaly peak in the central portion of the region, related to a core of high velocity around the middle crust layer in the model. **Figure 2-4** (looking north west) shows this anomaly in 3D with the calculated gravity response draped over topographic relief, and the anomalous high velocity \ density block in green. The upper crust layer is shown to intersect this density block. Note the figure displays the draped gravity grids with vertical offsets for illustrative purposes. Both grids in the offshore area show a gravity trough, consistent with the continental shelf structure, see **figure 2-5**.

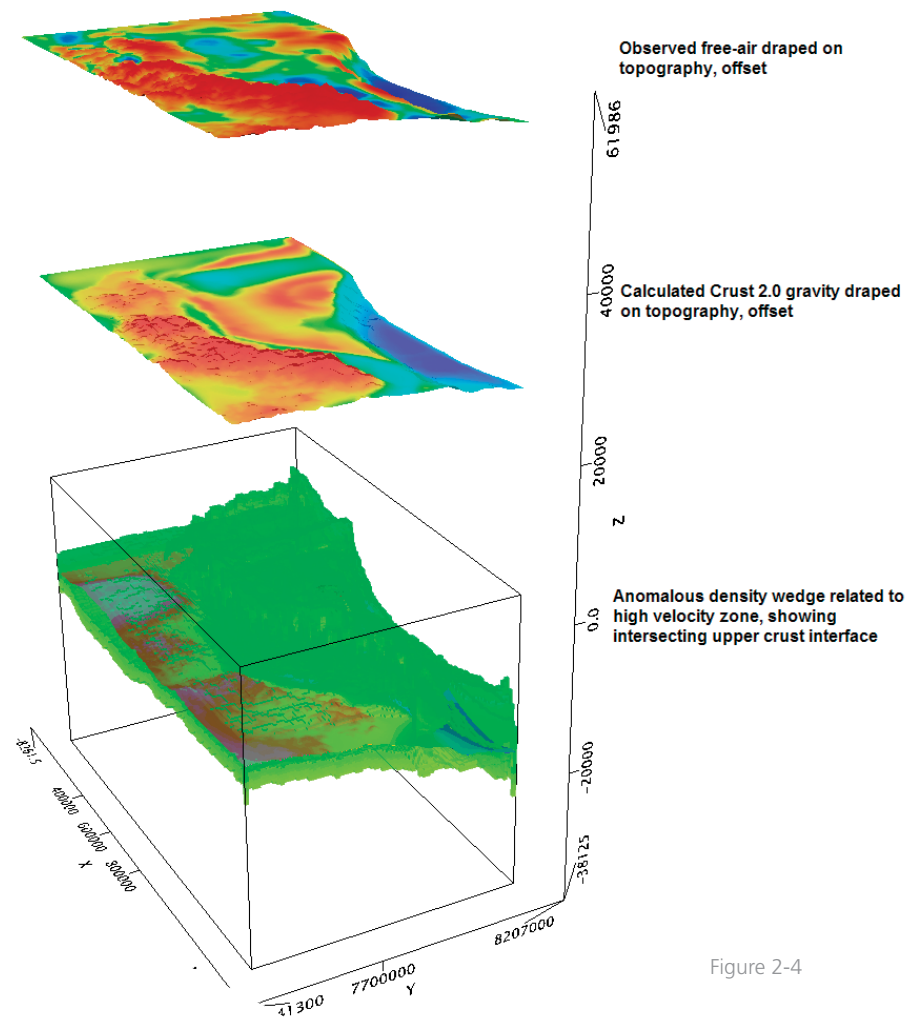


Figure 2-4

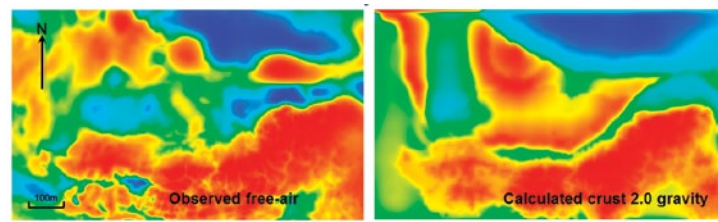


Figure 2-5

Lastly, a comparison was made between a regional isostatic response calculated using Geosoft's Isostatic Residual module, versus the lower crustal response of the Crust 2.0 density model. These methods should be comparable, since in both cases the distal response of regional gravity has not been accounted for in the modeling. First, the isostatic response of topography was calculated via Airy-Root using the Isostatic module. The input topography was not expanded for the area covering the block model. The resultant grid displays a partial response of the isostatic gravity component.

The voxel created above from the Crust 2.0 velocity data was split into a lower crust component using a topography clip at the lower crust structural interface derived from Crust 2.0. Again, the resultant Voxel was padded with zeros to satisfy the requirements of the gravity calculation. This is required, since the calculation does not allow the presence of null values, hence the nulls were converted to a value of zero, equivalent to background response of air. The GMSYS3D response to this lower crustal density voxel correlates well with that calculated via Isostatic Residual, see figure 2-6

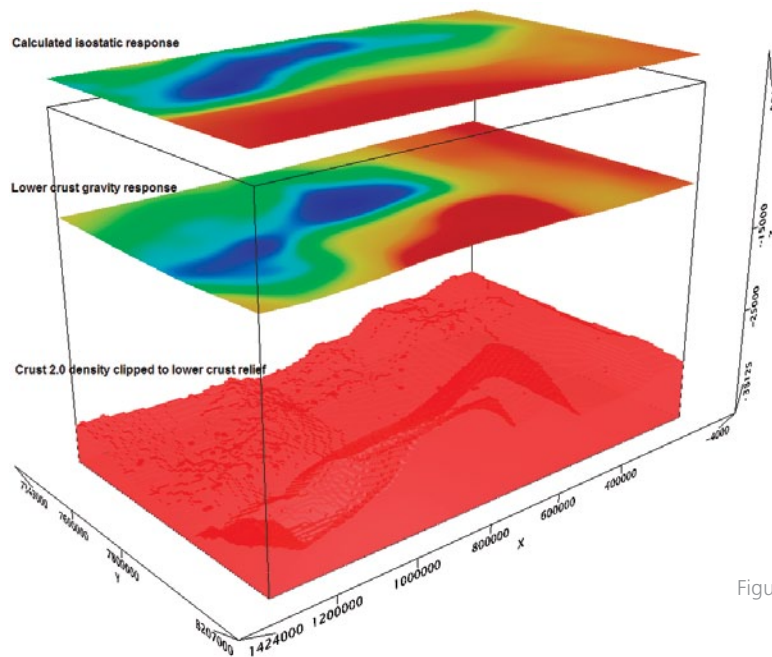


Figure 2-6

GRAVITY MODELING USING SEG-Y VELOCITY DATA

Method 2

The implementation of stacking velocities to density conversion to constrain a gravity model using Geosoft's Oasis Montaj has been described before (**Longacre, Connard, Johnson, 2008**). Using new technology it is now possible to convert a SEG-Y volume of interval velocity to density using velocity-density relationships.

If well data is available, the sonic log can be imported for quality control of the velocity volume, prior to density conversion. The well logs can either be displayed in 3D with the seismic data, else, a quantitative comparison can be made by comparing SEG-Y voxel values with well logs in database form.

In our example, we use an example SEG-Y consisting of smoothed pre-stack depth migrated interval velocity. This method looks at a region covering approximately 25 x 25km square, and to a depth of 10km.

Geosoft's SEG-Y Reader can import 2D and 3D seismic trace data and transform to different data formats. The tool can be accessed via the Database| Import menu option or the GMSYS menu within Oasis Montaj. The reader also automatically engages when selecting 2D SEG-Y as an overlay in GMSYS 2D Profile Modelling. Further information regarding the SEG-Y reader is contained in the manual. At present the Reader supports the most recent revision of the format (SEG-Y rev. 1), however it is not possible to read extended textual file headers.

The 3D SEG-Y data can be configured by inspection of the internal text and binary header information. The trace viewer enables the user to quickly inspect the format of the SEG-Y, and determine relevant fields that need to be set (including coordinate offsets, starting in-lines and cross-lines). The interval velocity data was configured using the 3-step process in SEG-Y Reader. The first step (**SEG-Y Config**) sets the disk format parameters including navigation information where available. Most of the parameters are automatically detected, and hence the user should review the values selected. For instance, the text header indicates the range and value of the line numbers present in the volume, and the user can enter these values in the Inline\crossline parameters window.

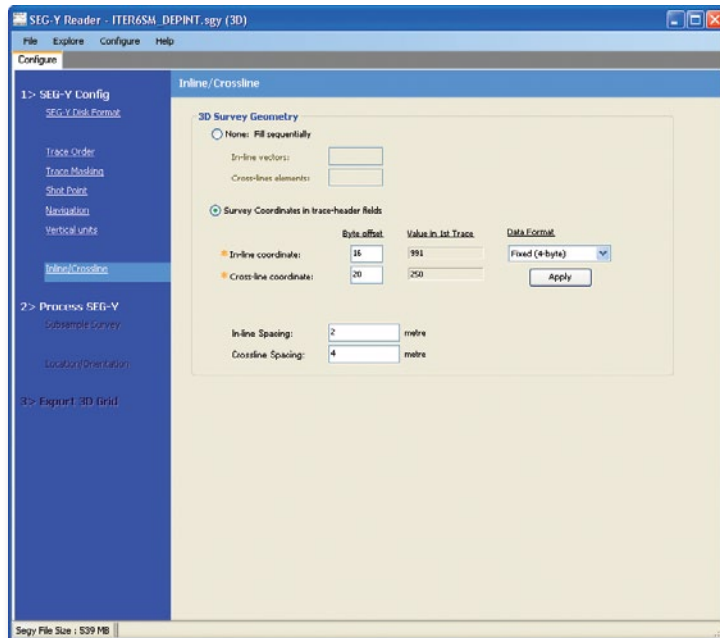


Figure 2-7

Commonly, the SEG-Y will be accompanied by a navigation file to correctly georeference the origin of the SEG-Y volume or section. In our example we did not have navigation data available, but instead, the coordinates for the origin of the volume were chosen to lie in an arbitrary location, offshore U.K. This can be set in step-2 of the 3D seismic formatting – Process SEG-Y.

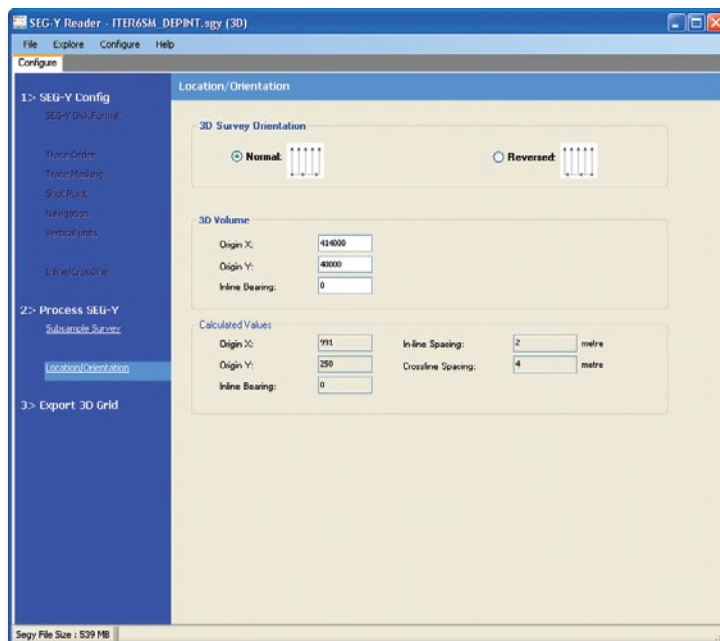


Figure 2-8

When importing 3D SEG-Y, the user has the option to create an index database of inlines for the survey area. This is a good means to review and verify the survey orientation has been configured correctly. At the minimum, plotting the line path of the index database enables the user to calculate

the survey's inline bearing, and adjust accordingly. Step-2 also offers sub-sampling options to keep data file sizes manageable, or otherwise to review and create a quick 3D voxel output.

Once the SEG-Y volume has been confirmed as correctly configured, with the survey outline and vertical sampling correctly configured, the user can export to a Voxel, using step-3 (**Export to 3D**). At this stage, the volume can also be exported to a Geosoft database for further analysis.

Once the interval velocity voxel has been created, the velocity units are converted to kms^{-1} , for use in Nafe-Drake's equation (as per method 1). Since the original vertical traces in the velocity volume are continuous functions, each cell in the output Voxel is filled with a valid value, so there is no need to fill null or dummy values in preparation for gravity calculation with GM-SYS 3D. The same expression as per method 1 was used to create a density volume.

Inspection of the velocity range of the velocity voxel reveals that the data is collected from a marine survey. Therefore it was assumed the seismic reference datum was 0m, coincident with the maximum elevation of the Voxel, at sea level.

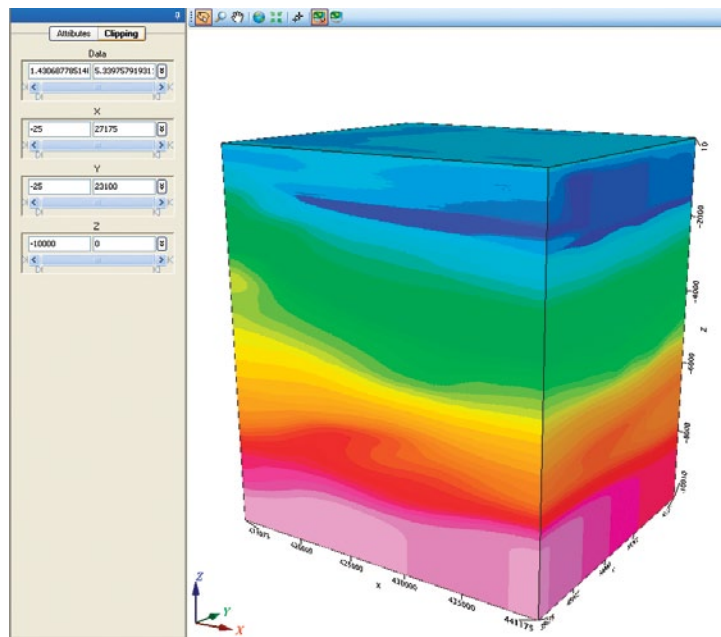


Figure 2-9

The GM-SYS 3D 1-step gravity calculation was set to a station elevation of 0m.

The resultant calculated gravity shows an expected correlation with the velocity variation in the region. A sloping continental shelf with increasing water column thickness (from West to East) is reflected in the velocity volume by a westerly-thinning wedge of water velocities in range 1.4-1.6 kms^{-1} .

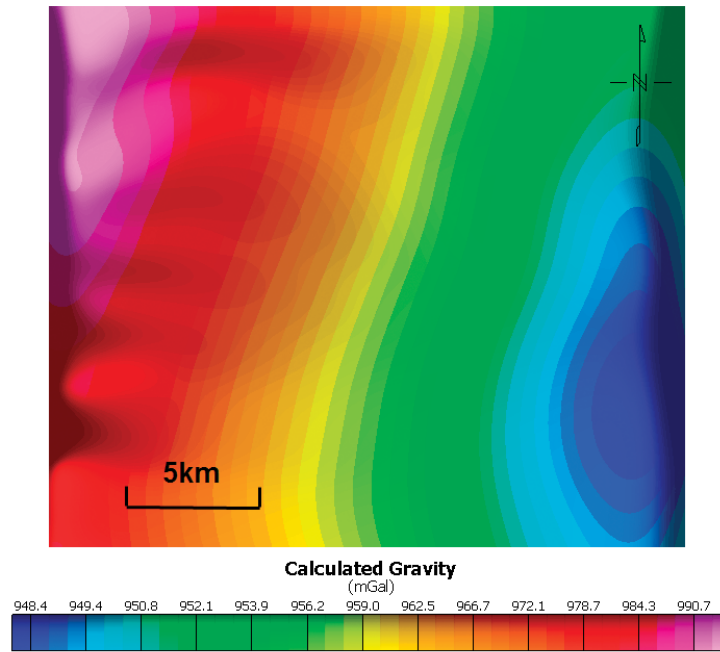


Figure 3-0

The calculated gravity, enhancing the near-surface response, also reflects the water column thickness with an approximate linear horizontal gradient of $-1.3 \text{ mGal} \setminus \text{ km}$ heading East. The calculated gravity neither reflects free-air anomaly nor a residual response, but using a simple grid layer model in GM-SYS 3D would enable the user to calculate deeper crustal and Moho response to combine with the calculated Voxel gravity for further analysis.

FIELD SCALE GRAVITY MODELLING, TEAPOT DOME, NAVAL PETROLEUM RESERVE 3, WYOMING

A large dataset recently made available to public, by (U.S.G.S. \ Rocky Mountain Oilfield testing Center), for the TeaPot Dome \ NPR-3 oil field near Casper, Wyoming provides 3D time SEG-Y with seismic interpretation, over 1000 wells with downhole logs and logged formation tops. This method looks at using interval velocity grids to create a density voxel for input to a local gravity calculation.

Method 3

Time migrated horizon interpretations were supplied, together with formation tops picked from well data. No depth interpretation was available. The method uses isochore and isochron grids to create interval velocities between prominent top picks from wells and known geology. Grid extent and resolution of the formation top picks decrease with increasing depth, due to the number of well intersections and logged core available at these well depths. Isochron grids were constructed from seismic horizon time interpretation provided in XYZ format. Formation top depth grids were created by first importing the well directional surveys to convert measured depth (MD) to depth relative to sea level (TVDMSSL). The formation picks were then gridded to yield depth (TVDMSSL) grids at lower resolution than the time grids. The interval velocities were derived from the simple division of isochores by isochrons. The TVDMSSL and velocity grids were then sampled to a database for the creation of a velocity layer model. The “database channels to array” tool was used as in method 2 to create a velocity \ depth array suitable for 3D gridding. In order to control the 3D model, a top layer of velocity was added (8 kms⁻¹), derived from a VSP well survey in the field. Also the last interval velocity between the 2nd Top reservoir pick and bottom reservoir pick was taken from synthetic time-depth log estimates.

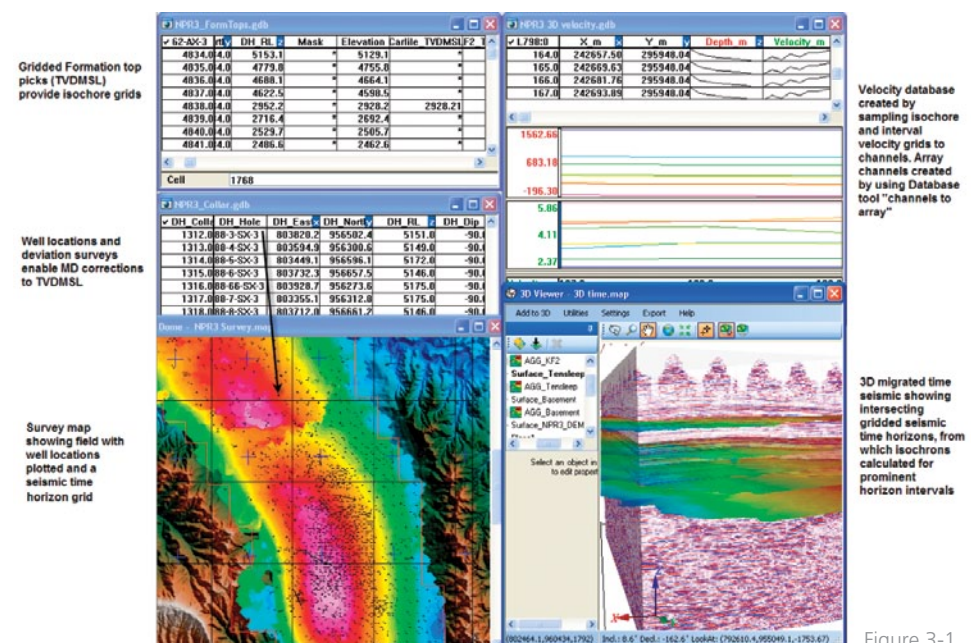


Figure 3-1

The construction of the 3D velocity model follows similar method employed for the Crust 2.0 data. 3D gridding with a variogram model based on 100m horizontal\ vertical sampling was used to create the velocity voxel model.

Refinements to the output velocity model included clipping the voxel to local topography, and using voxel math to constrain the interpolated velocity range in X,Y,Z space. Using the following formula:

```
//v0= (XYZ clipped velocity model voxel)
//vm=. \ (voxel gridding output)
@temp=vm;
@temp = (X)<793300?dummy:(X)>806600?dummy:@temp;
@temp = (Y)<949400?dummy:(Y)>968800?dummy:@temp;
v0 = @temp>25000?dummy:@temp<0?dummy:@temp;
```

This was necessary in order to prevent extrapolation of data at depth where well picks were more sparse.

Next Brocher's empirical formula for the Nafe-Drake graphical relationship was used to convert the velocity to density. As in method 1, input velocities in (kms⁻¹) yield densities in (gcm⁻³). Two voxels were created, the first calculated from the non-filled velocity volume. This voxel was used to ascertain the average density of the field model (2.35 gcm⁻³). The second voxel output was created from the filled velocity volume (null values padded as zero density, in order to satisfy GMSYS-3D calculation requirements), which could be used in the gravity calculation:

The gravity response of the density model was then calculated at an elevation plane of 2000m. The gravity response of the field shows a peak of 94mGal over the main field area.

A Bouguer approximation was calculated by setting the background density of 2.67 gcm⁻³ in the density model (replacing all values of 0 with 2.67).

The resultant calculated response shows a negative anomaly (-6mGal) over the field area, consistent with lower average densities related to the low velocity of the main reservoir zone in the field that had over 45,000 SCF of gas injected to yield 10.3 x 10⁶ stock tank barrels of oil (STB) and over 52,000 SCF of natural gas (as of January 2005, Source: Rocky Mountain Oilfield Testing Center). The low density anomaly is also reflected in the Voxel properties for the unfilled density model, having an average density of 2.35 gcm⁻³, versus the background density of 2.67 gcm⁻³.

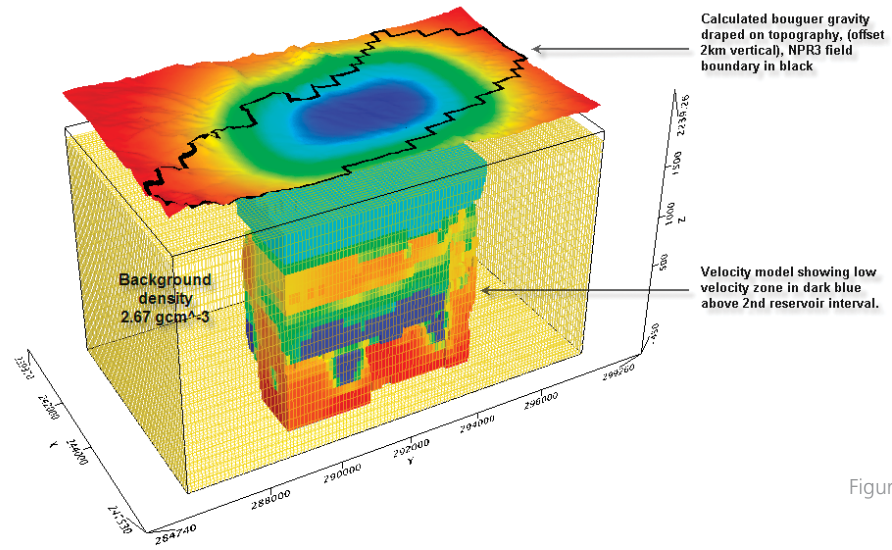


Figure 3-2

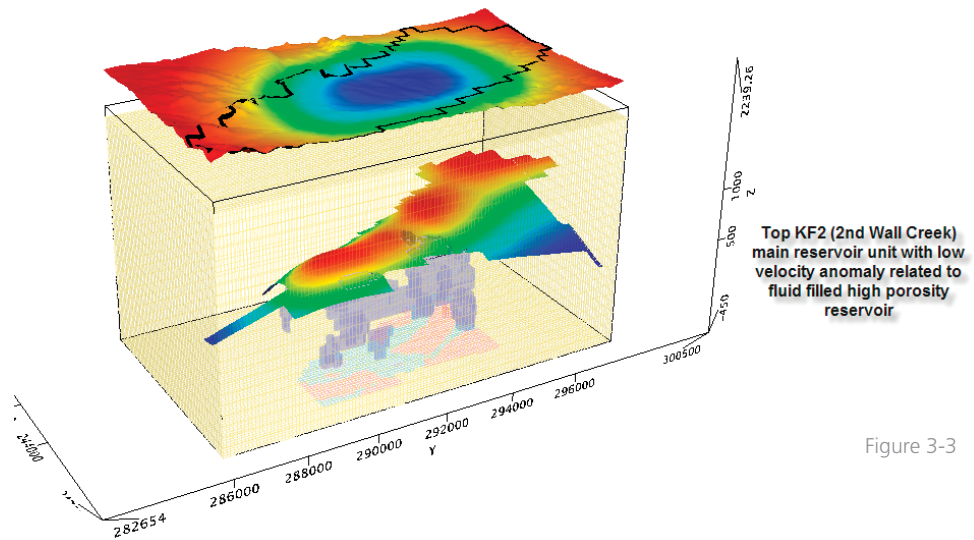


Figure 3-3

It has been demonstrated (for example, Brady et al, 2008) how changes in fluid properties related to production methods used during a field's life can be related to changes in local gravity, when 4D microgravity is acquired in a producing field, over a period of several years.

CONCLUSION

The uses of SEG-Y data, Crust 2.0 public data, and seismic interpretation grids have been discussed in application to density conversion and gravity modeling.

The gravity response of a density Voxel can be calculated in GM-SYS 3D's simple 1-step tool at any specified elevation, including within the density volume itself. This offers useful applications to model deep crustal isostatic gravity response, or by means of Voxel Math, the density volume can be discriminately "sliced" into intervals, for constrained gravity calculation. Alternatively, the density volume can be sliced using topography grids.

The use of interval velocities derived from a SEG-Y-volume enables quick calculation of a gravity response, using published velocity-density relationships. Our use of Crust 2.0 data demonstrates possibilities to quickly model regional gravity response. When combined with observed gravity, this can yield residual isostatic gravity for more localized modeling. This method can also be applied in larger scale, for example in an oil field to calculate local gravity by preparing isochore \ isochron grid pairings for prominent intervals defined by seismic reflector\ formation picks from seismic and well data respectively. In this latter method, It has been shown the resultant simple Bouguer calculation correlates with the velocity modelling.

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