

# Resolving Complex Salt Features Using Gravity and Magnetics

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## Introduction

In the past the role of gravity and magnetics data was largely for basin identification and delineation in frontier areas, and was used only peripherally in mature areas, giving way instead to the greater imaging power of the seismic method. However, many complex geologic environments have not yielded all of their secrets to the seismic method. A revival is underway in the use of gravity and magnetics data to produce better geologic interpretations from seismic data. This revival includes a growing portion of 3-D seismic surveys acquiring coincident gravity and magnetics, with applications ranging from linkage of seismic faulting, testing of play concepts, as well as some recent applications at the reservoir engineering level.

The seismic method measures changes in acoustic impedance, which is a product of velocity and density. The easiest geology to image using the seismic method has a flat layered geometry, with an acoustic impedance contrast across each layer boundary. The gravity method measures lateral changes in density, thus, the previous example of flat density layers would be essentially invisible to the gravity meter. Similarly, the magnetics method measures lateral changes in magnetic mineral content, and would also yield an expressionless data set for the flat layer case. Conversely, the seismic expression of complex geology such as overthrust strata, volcanic layers, buried reefs, and salt structures, can oftentimes be difficult to interpret around the features, with perhaps little or no signal below the features. However, it is precisely in these complex geologic environments where the gravity and magnetics fields often have their greatest expression. Accordingly, the close cooperative integration of these methods produces substantially better interpretative results than will any of one these methods when used in isolation.

Gravity and magnetics data can, when integrated with the full detail obtained from the seismic results, be used to discriminate between alternative and equally viable seismic interpretations. This multi-disciplinary integration can also provide valuable information where seismic data alone may be difficult to interpret. For example, integrated gravity, magnetics and seismic modelling has been used in the Gulf of Mexico to provide information about salt geometries and dip angle to the seismic processors so that the seismic data processing methods can be focused using the most likely structural geometries. In addition, gravity and magnetics data can be used to improve velocity models below tabular salt sheets, where velocities derived solely from seismic data are typically interpolated over large distances. Recent advances in workstation software now include real-time dynamic-linking between seismic, gravity and magnetic interpretation and modelling sessions, allowing multiple (yet equally viable) seismic interpretations to be tested and either eliminated or corroborated quickly and efficiently.

## Concept Of "Bootstrapping"

One philosophy which has been employed in the field of gravity and magnetic modelling and interpretation since its beginning is the concept of "bootstrapping". Bootstrapping is defined by Sheriff (1991) as follows: "To attempt the impossible, as "to lift oneself by one's bootstraps". Stated geophysically, "Derive an earth model, test it, refine it, test it...". This philosophy is fast-becoming routine for many aspects of seismic exploration. Methods such as AVO modelling, pre-stack depth migration, turning wave analysis, etc., all have an inherent structural and/or velocity model as the starting premise. Tuning of this initial model is then performed and used as a refinement on the seismic processing parameter selection. Other independently measured geophysical techniques, which respond to the same (or are linked to the same) lithological parameters as the seismic method, can be used to provide important input and constraint to the selection of these starting point models.

This point is summarized with the following Q & A:

Question: Can a single earth model be derived which satisfies all of the geophysical and geological data?

Answer: Yes, but a single "perfect" answer is typically not achieved in practice, nor is it necessarily an essential conclusion.

A large amount of useful information is obtained in the process of answering this question, with oftentimes some of the most beneficial findings being those where the individual geophysical data types do not support each other. These mismatches should allow (force?) the interpreter to go back to each assumption for additional scrutinization, so as to more clearly identify the error bars in the data sets and the flexibility for change in the model assumptions.

## Density Analysis

### General Density Versus Depth Functions

Density data are a critical component which limits the resolving power of the gravity method. **Figure 1** shows a density versus depth plot, where the background shading is a generalized density vs. depth function derived from 30 wells in the Vermilion area, offshore Louisiana. The linear trace is the local density vs. depth trend derived from compensated formation density (FDC) logs at a point (A-2) located in 120 feet of water. Note the dramatic differences between the local density variations and the general function, particularly at and below the first geopressure pick. All too often, a generalized function such as that shown here is used to represent the density distribution over a considerable spatial area.

## The Nil Zone

The vertical depth interval over which the density of the surrounding sediments is within the range of salt densities has been termed by previous authors (Bain and Weyand, et. al, 1993) as the "Nil Zone", given that the salt/sediment density contrast is nil. For this example, salt was assumed to range from 2.16 to 2.20 g/cm<sup>3</sup>. Thus, the gravity method would be essentially blind over this thickness interval. It is important to identify these zones where the gravity method would not be anticipated to assist the modelling process. Typically, magnetics can be useful for interpreting through these zones.

## Apparent Density Computed From Velocity

Figure 2 shows the density log from A-2, along with an apparent density computed using sonic log-derived velocities, and the velocity/density relationship of Gardner, et. al. (1974). While the shape is similar, the sonic-derived apparent densities are considerably lower than the actual densities measured with the FDC tool. Indeed, had the sonic-derived densities been used for gravity modelling, two Nil Zones would have been predicted; one essentially overlapping the FDC-derived Nil Zone from 4,000 to 5,000 feet, and a second deeper and substantially thicker Nil Zone between 9,000 and 13,000 feet. Figure 3 is a profile of density versus depth with the leftmost point (A-12) located onshore north of West Cameron and the rightmost point (A-1) located in 600 feet of water, in South Marsh Island. The local density versus depth is very similar to the general density/depth function for portions near shore, whereas large departures are noted going seaward.

Thus, an important ingredient in gravity modelling is the pursuit of a "perfect" density cube, as indicated in Figure 5. The importance of density has recently been gaining attention from seismic practitioners, including renewed density interest for AVO work and acoustic impedance analysis. We recommend that the optimum approach to a study of densities for gravity modelling is: 1) develop a macro-level model of the regional density framework and 2) refine the regional density model locally for detailed study by developing a micro-level density model.

## Construction of a Micro-Level Density Cube

Macro-level density models can be used to perform a wide range of model studies, and can be of particular importance for high-grading purposes. When focusing in on a particular play, the macro density model should then be refined on a localized basis. It is suggested that this refinement include the following components:

- retrieval of all available log data sets in the local study area
- verification and editing of the log data
- construct localized refinements for the velocity to density relationships
- in-fill the density data using apparent densities derived from interval velocities, and from deep resistivities (Loren, 1992)
- construct an updated micro-level density cube of the local area

## **Salt Density**

The density of salt must also be assigned in the modelling process. Previous studies by Jackson and Talbot (1986) suggest that salt tends to decrease in density with depth, as the salt's volume increases with increasing temperature faster than it contracts from the increase in overburden pressure. Jackson and Talbot's work, based on onshore salt coring, suggests a range for salt density between 2.15 to 2.20 g/cm<sup>3</sup> ( **Figure 4**). Salt cores obtained by the authors from the near-offshore of Mexico indicated a density of 2.15 g/cm<sup>3</sup>, averaged over a substantial depth range. Indications were presented by Gardner et. al (1974) for salt in the range of 2.0 to 2.2 g/cm<sup>3</sup>. Gravity modelling performed by the authors in numerous areas both onshore and offshore suggests that there is a general trend for salt densities to decrease seaward. This point is also supported by several of our clients, based on independent studies. The salt density selected for our ISSIP (Integrated Sub-Salt Interpretation Project) area discussed below was 2.08 g/cm<sup>3</sup>. This is admittedly lower than what is found in some of the literature, but is supported (again, in a bootstrapping sense) based on model studies and limited petrophysical information. With a large number of wells slated to drill through considerable thicknesses of salt in the next decade, it is hoped that more data on salt densities will become available. Of particular utility would be apparent density derived from borehole gravity surveys, particularly if coincident with VSP surveys.

Maps for the offshore U.S. Gulf of Mexico have been created by Geophysical Development Corporation (GDC) to identify variations in the depth to the top and thickness of the Nil Zone. It is important for the modelling process that the density data be refined to provide this level of detail.

## **Integrated Geophysical Modelling of Complex Subsalt Features: Case History from the Southern Additions, Offshore Louisiana**

Recent significant discoveries beneath tabular salt masses have re-established the Gulf of Mexico as a world class oil and gas province. Many of the recent sub-salt discoveries have been a direct result of high-resolution 3-D surveys and advanced processing and interpretation methodologies which combine multiple geophysical data types. Imaging the base of tabular salt structures is an expensive effort using the seismic method and, while new processing techniques show great promise, the signal of events below the salt is oftentimes corrupted in the process.

A project was undertaken to produce an integrated interpretation of the sub-salt play area in the Southern Additions of offshore Louisiana (the Integrated Sub-Salt Interpretation Project, or ISSIP). The primary intent of the project was to build, test and verify a geological model which integrates multiple geophysical and geological data. This model would facilitate testing of alternative models, and would provide a robust framework for performing detailed analysis on a localized, prospect-level basis.

The initial model was used to perform geological stripping, thereby removing the gravity effects of the assumed model, to simplify the identification and interpretation of density anomalies beneath the tabular salt masses. The gravity data were then used to interpret the distribution of low density material (salt roots, overpressured shales, and under-compacted sediments), below the tabular salt. The depth to the low density zone (LDZ) is useful for identifying sub-salt sediment fairways. Also, determining the distribution of rooted salt and overpressured shales aids in the interpretation of hydrocarbon migration pathways. The integrated model results can also be valuable for developing and testing alternative velocity models used to obtain increased resolution of the base of tabular salt and structures below the salt from seismic data.

## Project Methodology and Input Data

The goal of the project was to: 1) build a geological model which contained all of the known control and assumptions, 2) calculate the theoretical gravity effect of the model, 3) remove this effect from the observed gravity field, 4) evaluate the remaining (or difference) gravity field in terms of potential distributions of deeper salt, errors in the initial density model, errors in the seismic interpretation of tabular salt, or combinations of all of these. The steps for performing this project are summarized in [Figure 6](#).

The model included data from several independent sources:

- Top and base of tabular salt in depth- provided by TGS-CALIBRE & Geco-Prakla
- Density grids derived from FDC logs - provided by GDC from the Rock Properties Catalog
- Apparent density grids derived from velocity - provided by TGS-CALIBRE & Geco-Prakla from the VDip Cube
- Bouguer gravity and bathymetry - provided by Sidney Schafer & Associates
- Additional data and information in the public domain

The gravity data are individual water-bottom gravity stations located on a nominal 7/10 mile grid, with an accepted accuracy of better than 0.25 mGal. The gravity data set was extended well beyond the actual study area using the same quality Schafer data to the north, east and west, and south to the 600 foot water line where this data set stops. Public domain gravity data were then used to provide additional extent to the south. Edge effects were thus minimized.

### Construction of a Macro-Level Density Cube for the Southern Additions, Offshore Louisiana

In our Gulf of Mexico work we have utilized the digital Rock Properties Catalog produced by GDC for our macro-level model. While this Catalog includes a wide range of products, the primary data we used are average bulk density derived from compensated formation density (FDC) logs. These densities were used to construct a series of horizontal density grids covering the whole of offshore Louisiana from 5,000 to 15,000 feet below sea level. Very few wells had been logged shallower than 5,000 feet, and not many extended deeper than 15,000 feet. The number of wells contributing densities varied between 90 and 1,700 for different 1,000 foot depth intervals.

The density data "gap" between water bottom and 5,000 feet subsea was filled using apparent densities calculated from interval velocities derived from the TGS-CALIBRE/Geco-Prakla VDip project. The VDip cube provides average velocities on a regularized grid, with a vertical sampling of 200 milliseconds. The translation from velocity to density was derived using a cross-plot of interval velocity versus density as shown in [Figure 7](#). These data were obtained from a series of wells for which velocity surveys had been run, and for which the FDC logs were available from the GDC Catalog. The familiar velocity/density relationship of Gardner, et. al. (1974) does not provide a good fit to the observed data in this study area ([Figure 7](#)). An alternative relationship was derived using a best-fit approach to the data,

using the generalized form of the Gardner relationship (i.e., density as a function of velocity to a power). The resulting function has been termed by the authors as the LASA Equation; named after the Louisiana Southern Additions from which the data were derived. Interested readers should also consult the work presented by DiSiena (1994). With this locally-derived empirical relationship between velocity and density, the VDip velocities were converted to apparent density.

The density data gap below 15,000 feet and extending to the bottom of our model (40,000 feet) was filled by using a multi-step approach. Firstly, the deepest density layer in the model was chosen to represent the overall character of the lateral density variations for deeper layers. Higher levels of low pass filtering were applied to the progressively deeper grids. Secondly, a generalized density versus depth profile was constructed using the available FDC log data below 15,000 feet. Eight wells with a good spatial distribution contributed density information between 15,000 and 19,500 feet. This generalized density versus depth function was then used to apply a bulk density shift to the respective density "shape grid" derived in the first step.

In this manner, a macro density cube was constructed which included 30 stacked density grids thus providing macro-level density control from the water bottom down to 40,000 feet subsea level. This density cube became an important component for follow-on work, including both regional and localized projects. As salt models are derived from seismic interpretations, these top and base of salt features can be inserted into the density cube quickly, allowing detailed modelling of specific regions of interest.

### **Gravity Effect of the Density Cube**

The regional density cube discussed above provided the framework for computing and removing the gravity effects of the horizontal and vertical variations in tabular salt derived from seismic alone. The theoretical gravity effect of the density cube was calculated using 3MOD (an LCT software tool for full 3-D gravity and magnetic modelling). Two profiles across the area are displayed in [Figure 8](#), which shows the calculated gravity effect of the density cube (without salt) and the residual gravity anomaly along the same profile. The top figure shows a profile from south to north; the bottom figure shows a profile from west to east. Note the agreement in shape and amplitude between the observed gravity anomaly and the gravity effects solely due to the density cube. The localized differences are attributable to shallow and deep salt, gas chimneys, local sedimentary anomalies, and other lateral variations in density which were not sampled in the macro density model. [The residual gravity anomaly was derived from the Sidney Schafer & Associates water-bottom Bouguer anomaly by removing a long wavelength (200,000 foot lowpass) regional field component.]

## Geological Stripping via Gravity Modelling

As stated above, the goal of the project was to: 1) build a geological model which contained all of the known control and assumptions, 2) calculate the theoretical gravity effect of the model, 3) remove this effect from the observed gravity field, 4) evaluate the remaining (or difference) gravity field in terms of distributions of deeper salt, errors in the initial density model, errors in the seismic interpretation of tabular salt, or combinations of these. In an ideal world, with a perfect density cube, a perfect seismic interpretation (including all the salt) and perfect gravity data, the difference gravity field would be zero.

The top and base of tabular salt had been mapped by TGS-CALIBRE and Geco-Prakla using an extensive 2-D seismic data base. This data set was converted to depth using the VDip Velocity Cube, described above. While newly-acquired 3-D data indicate some shortcomings of the 2-D interpretation, the consensus of the project participants was that the 2-D results were suitable for the project purposes. These top and base of salt depth surfaces were injected into the macro-level density cube. That is, density cells in the cube were replaced with the defined salt density of 2.08 g/cm<sup>3</sup> where salt was interpreted from the seismic. The theoretical gravity effect of the composite model was computed and removed from the observed gravity field. The difference field was then interpreted to resolve the apparent distribution of deeper salt masses or other low density material.

## Gravity Modelling Using Constrained Inversion

The difference gravity field ("Difference Field") was then operated on using LCT's 3MOD package for both the forward and inverse gravity modelling. 3MOD operates on a geologic model, which in this case is made up of the macro-level density cube plus the injected seismic horizons for top and base of tabular salt. In the forward modelling mode 3MOD passes numerous horizontal slices through the model to yield a series of composite density (or magnetization) grids. The gravity and/or magnetic field of each of these layers is calculated using an FFT technique, and the individual layer effects are summed to compute the theoretical gravity or magnetic field of the model. In the inverse modelling mode, the Difference Field is operated on to determine (automatically, but within user-defined constraints) adjustments to the structural model which will minimize the difference field between the calculated model effects and the observed gravity effects.

The initial model is shown in [Figure 9](#), where each of the previously discussed components of the density cube are annotated. In addition to the horizontal sections of the density cube, the tabular salt model derived from seismic is indicated, along with a deep horizontal layer labeled "Low Density Zone" or "LDZ" for short. The LDZ represents low density material located below the tabular salt, and may be deeper salt cores or remnant salt feeder stocks, unmapped extensions of the tabular salt, overpressured low density shale masses, or unmapped low density sands, to name a few. This deep horizontal low density zone is the starting point for the inversion process. The inversion algorithm will make successive automated, constrained "guesses" for changes in the depth to the top of the LDZ which will minimize the Difference Field.

The constraints for the inversion are: 1) the seismic interpretation of top and base of salt are assumed to be perfect in depth, and 2) the gravity data are assumed to be perfect. Obviously, each of these have an accompanying error budget which will need to be re-evaluated during the process. However, initially, these constraints are assumed to be inflexible. Therefore, changes are made to the top of the LDZ but the LDZ is not allowed to pierce the tabular salt features interpreted from seismic. [Figure 10](#) illustrates the outcome of the inversion process where the LDZ was allowed to shallow-up to accommodate a gravity

minimum in the difference field below some of the tabular salt features, as well as between the salt features.

### **Evaluation of the Inversion Results**

The defined goal of the gravity inversion process is to yield a final post-inversion Difference Field (or, as we prefer to call it, the "Left-Over Map") which is zero everywhere. In practice, this is seldom attained. Instead, the Left-Over Map typically provides valuable information regarding problem areas in the initial model assumptions which must be re-evaluated. The primary checks involve re-evaluation of the tabular salt interpretation and the density cube, in areas where convergence to a zero field is not possible. These left-overs may represent areas where the base of tabular salt interpretation is in error (perhaps primarily in depth), necessitating changes to the depth conversion process. They may also represent poorly sampled areas in the macro-level density cube.

In the study area, the pre-inversion Difference Field ranged from  $\pm 35$  mGal. After numerous inversion sequences were conducted and evaluated, the majority of the post-inversion Difference Field was below  $\pm 1$  mGal, with 80% being less than  $\pm 0.5$  mGal.

To evaluate the inversion results, a number of seismic lines (both 2-D and 3-D data) were studied, together with the project participants both during the selection of optimum constraints and inversion parameters, as well with the final inversion results. This proved to be an extremely valuable and professionally enjoyable process, as the seismic interpreters were excited about the results coming from the gravity inversion process. The method was typically a "close to the vest" approach, wherein we would suggest an area below the tabular salt where the gravity results indicated an unmapped area of low density material, the seismic data would be displayed on a workstation. In nearly all cases, the seismic interpreter was willing to accept the possibility for either a remnant or pinched off feeder stock, or a mass of low density overpressured shales. In some cases, the seismic interpreter had indications of velocity anomalies, but was unable to derive a coherent boundary. In other cases, the 3-D data provided a better image than the 2-D, and alterations were identified for the base of tabular salt interpretation.

**Figure 11** and **Figure 12** illustrate the evaluation process. **Figure 11** indicates the seismic interpretation of two tabular salt features in time. In **Figure 12**, the results of the gravity inversion process have been converted from depth to time using the VDip Cube, and the results overlaid on the time interpretation. In this example, a low density mass is indicated in the gravity inversion results. An inspection of the 2-D seismic data did not preclude this from being a remnant salt feeder stock. However, 3-D seismic data indicated the mass was unlikely to be salt, given the better definition of a salt weld. The density cube was verified to be well sampled and of good quality in this region precluding density errors to be the primary culprit. The final interpretation of this feature was it is a low density overpressured shale mass situated beneath and between the interpreted tabular salt features. This should enhance the play given that gravity corroborates the lack of additional salt beneath the tabular salt features suggesting prospective section may be found, and the shale wall may serve as an additional trapping mechanism. In either event, the velocity model used in the next iteration for pre-stack depth migration of the seismic can be upgraded to include both the new as well as corroborative information below and around the tabular salt features.

Thus, the integration of these geophysical methods to produce viable geological models lowers exploration risk.

Near the end of the ISSIP Project we were able to review preliminary results of 15 second seismic data recently acquired by TGS-CALIBRE & Geco-Prakla. The correlation between deep LDZ features and events on the 15 second seismic records was, in several cases, quite clear. It is anticipated that these deep seismic data will benefit from the combined multi-disciplinary approach discussed herein. These deep seismic data can then be used to further improve and constrain the gravity inversion results. [And thus the concept of bootstrapping continues!]

### **Interpretation of the Final Unresolved Gravity Difference Field**

A longer portion of the cross section illustrated in [Figures 11 and 12](#) is shown as [Figure 13](#). The observed gravity field is shown, along with the composite calculated gravity field due to both the tabular salt effects and the gravity effects of the deeper low density zone (LDZ). Notice the good overall agreement between the observed and calculated fields. However, midway on the leftmost tabular feature there is a fairly large discrepancy between the calculated and observed gravity, reaching a maximum difference of about 2 mGal. What is most diagnostic about this difference is not so much the magnitude of the differences, but rather, the wavelength. Simple modelling quickly indicates that the anomaly cannot be matched with changes in depth to the LDZ; i.e., the changes must be made in the depth range of the tabular salt features. Therefore, either the density cube or the tabular salt interpretation must be in error (the seismic interpretation may be in error in depth, but not necessarily in time).

To assist the interpretation of the unresolved gravity Difference Field a number of sensitivity models were generated and analyzed to provide possible alternatives to the final model which would minimize or eliminate the post-inversion Difference Field. These possible alternatives include:

- modifications to the top and/or base of tabular salt
- modification of the density cube over 1 to 4 block regions
- modification of the LASA equation for regional variation
- modification of the LDZ density (salt or overpressured shales)
- modification of the model to include relief on basement

## **Summary: Integrated Subsalt Interpretation Project, Southern Additions, Offshore Louisiana**

A project was undertaken to produce an integrated interpretation of the subsalt play area in the Southern Additions of offshore Louisiana (the Integrated Subsalt Interpretation Project, or ISSIP). The primary intent of the project was to build, test and verify a geological model which integrates multiple geophysical and geological data. This model would facilitate testing of alternative models, and would provide a robust framework for performing detailed analysis on a localized, prospect-level basis.

The initial model was used to perform geological stripping, thereby removing the gravity effects of the assumed model, to simplify the identification and interpretation of density anomalies beneath the tabular salt masses. The gravity data were then used to interpret the distribution of low density material (salt roots, overpressured shales, and under-compacted sub-salt sediments). The depth to the low density zone (LDZ) is useful for identifying deep sediment fairways. Also, determining the distribution of rooted salt and overpressured shales aids in the interpretation of hydrocarbon migration pathways. The integrated model results can also be valuable for developing and testing alternative velocity models used to obtain increased resolution of the base of tabular salt and structures below the salt.

### **Integration of Magnetics to Aid the Interpretation of Salt Features**

Magnetics has a clear role to play in the exploration of salt features. The ISSIP project did not incorporate magnetics owing to data ownership constraints amongst our participants. A project is now in progress which will produce a depth to magnetic basement model as one of the products. This will then be folded back into the ISSIP model and the low density zone (LDZ surface) will be updated accordingly.

Magnetics data can be useful in a number of ways:

- mapping of basement, tectonic fabric (the more conventional usage)
- independent indicator of salt wall dip angle
- provides a crutch for gravity through the density Nil Zone
- together with gravity, provides an independent (from seismic) means to identify
- overhanging salt features.
- enhances our ability to define offset on listric faulting

One of the primary difficulties in deriving accurate modelling results from magnetics data is the very low amount of sedimentary susceptibility measurements that have been made. Schlumberger is reportedly working on a tool which could make logging of magnetic susceptibility a part of their standard log suite. They should be encouraged to complete this development, and our petrophysical colleagues should then be encouraged to request (and find budget for) this service. Another method for deriving susceptibility data is to make laboratory measurements on unoriented sidewall cores.

An example is shown in **Figure 14**. Note the high variability in susceptibility values, indicating higher levels of magnetite content in penetrated sand channels. Some valuable work has been performed by Flanagan et. al. (1988) in tying the magnetic sedimentary susceptibilities to paleo data, to construct accurate models of the magnetic effect of sedimentary sequences.

In the absence of local susceptibility measurements, we utilize magnetics data as an accurate and independent indicator of depth to the causative source (sediment/salt interface, for example), as well as an accurate indicator of salt boundary and salt wall dip angle. Several examples are provided below:

### **Shallow Sand Channel and Salt Mapping via Seismic/Magnetic Modelling**

The magnetization of shallow Gulf of Mexico sediments typically varies between 0 - 300  $\mu$  CGS units, with 70  $\mu$  CGS being a useful average. Salt, by comparison, is slightly diamagnetic (minor negative susceptibility), but virtually zero or non-magnetic. Accordingly, much of the salt-prone areas are characterized by small amplitude, high frequency magnetic lows, owing to the replacement of low magnetization sediments with non-magnetic salt.

**Figure 15** (after Saad, 1993) illustrates the aeromagnetic signature over two salt plugs. The associated magnetic lows have amplitudes in the range of 4 - 10 nT (gammas), with excellent correlation between the high anomaly gradients and the seismic-derived salt interfaces. Interesting to note is the sand channel in the center of the seismic display, which correlates with a subtle (2 - 4 nT) positive magnetic anomaly. While small in amplitude, the signature is easily correlated with seismic and then used as an additional independent guide for linking up the seismic events. This signature is well within the limits of current high resolution airborne magnetics (where tenths of nT are commonly repeated). Note also, the apparent velocity push down below this sand channel, in response to the less consolidated channel fill.

This example shows that high resolution magnetics can be helpful in the corroboration and delineation of sand trends and can be used to differentiate between salt masses and thick sands.

### **Overhung Salt Dome Example**

The use of magnetics data for mapping salt interfaces is of most benefit with salt features shallower than about 15,000 feet (Flanagan et. al.), owing to the small magnetization contrast typically associated with salt/sediment interfaces. Gravity data, also of use in mapping shallow salt features, provides information over a greater depth range. These important differences can be used to aid in the identification of overhanging salt features, independent of the seismic data. **Figure 16** (after Saad, 1993) shows an overhanging salt dome, along with the residual gravity anomaly. The magnetic anomaly of the salt dome is sharper than the gravity anomaly, and is centered over the shallowest of the salt mass. The gravity anomaly is broader and has its axis located over the center of the total salt mass. This offset between the magnetic and gravity anomaly axes indicates the shallow salt is not coincident with the center of mass, i.e., the shallow dome overhangs and is offset from the central stock. This axial offset can oftentimes be readily observed in both map and profile form.

This example shows that gravity and magnetics can help seismic imaging of salt overhang and steep flanks, and can differentiate between rooted and non-rooted salt.

### **High Resolution Gravity and Magnetics Data**

For studies of the types described above to be successful, the gravity and magnetics data must be of high fidelity. While water-bottom gravity data continue to produce high quality results, the high cost factor has nearly removed this method from routine practice. However, recent studies (LaFehr, et al, 1992) suggest that accuracies of dynamic shipborne gravity data are approaching and, in some cases, exceeding that of static water-bottom surveys. High precision gravity surveys are capable of producing +/- 0.1 to 0.5 mGal in calm to moderate sea states. Also, water-bottom stations are typically acquired on a grid, with oftentimes large gaps between discrete stations.

Shipborne gravity data on 3-D seismic surveys benefit from the extremely high sample rates along-line (3 meter sampling on the LCT - ZLS systems) and the tight line spacing on 3-D seismic programs. This high density of gravity samples results in a large redundancy of data. This redundancy, when coupled with high accuracy Eötvös and horizontal acceleration corrections from high precision GPS, has allowed the evaluation of short wavelength, low amplitude anomalies which would previously have been filtered out with conventional processing. This new level of anomaly resolution is encouraging a closer link between the seismic and potential field methods.

One extremely important factor in high resolution marine gravity and airborne magnetics is that the data can typically be processed in a much shorter time frame than the 3-D seismic data. Accordingly, the potential field data can (and should) be used at the earliest stages of seismic processing parameter selection.

### **Summary and Conclusions**

The interpretation of seismic data in complex sub-salt areas can be greatly enhanced through the close cooperative integration of gravity, magnetics and petrophysical data sets. Gravity and magnetics data can, when integrated with the full detail obtained from the seismic results, be used to discriminate between alternative and equally viable seismic interpretations of the base of tabular salt. This multi-disciplinary integration can also provide valuable independent information where seismic data alone may be difficult to interpret.

Integrated gravity, magnetics and seismic modelling has been used in the Gulf of Mexico to build, test and verify a geological model which integrates multiple geophysical and geological data. This model facilitates testing of alternative (yet equally-viable) models, and provides an efficient framework for performing detailed analysis on a localized, prospect-level basis. The gravity data were then used to interpret the distribution of low density material (salt roots, overpressured shales, and under-compacted sub-salt sediments). The depth to the low density zone (LDZ) is useful for identifying deep sediment fairways. Determining the distribution of rooted salt and overpressured shales aids in the interpretation of hydrocarbon migration pathways. The integrated model results can also be valuable for developing and testing alternative velocity models used to obtain improved seismic images of the base of tabular salt and structures below the salt.

A revival is underway in the use of gravity and magnetics data to produce better geologic interpretations from seismic data. This revival includes a growing portion of 3-D seismic surveys acquiring coincident gravity and magnetics, with applications ranging from linkage of seismic faulting, testing of play concepts, as well as some recent applications at the reservoir engineering level.

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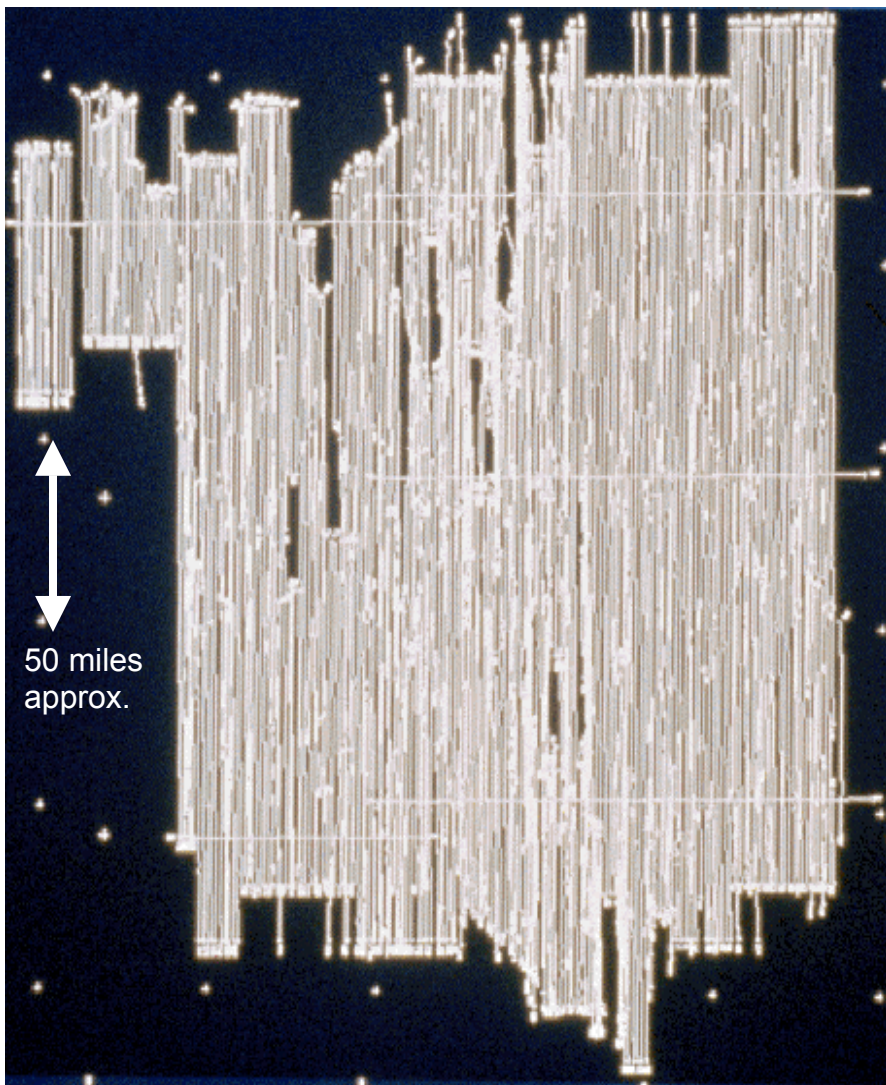
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**Fig. 1** Gulf of Mexico 3-D Seismic Survey, Line Location Map  
Spatial Sampling of Typical 3-D Seismic Survey

# Velocity-Derived Density vs. Depth

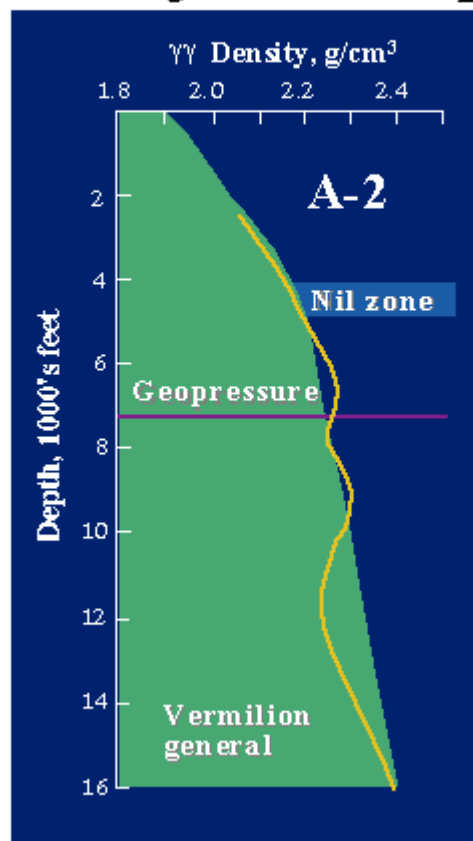


Figure 2

# Density vs. Depth Profile

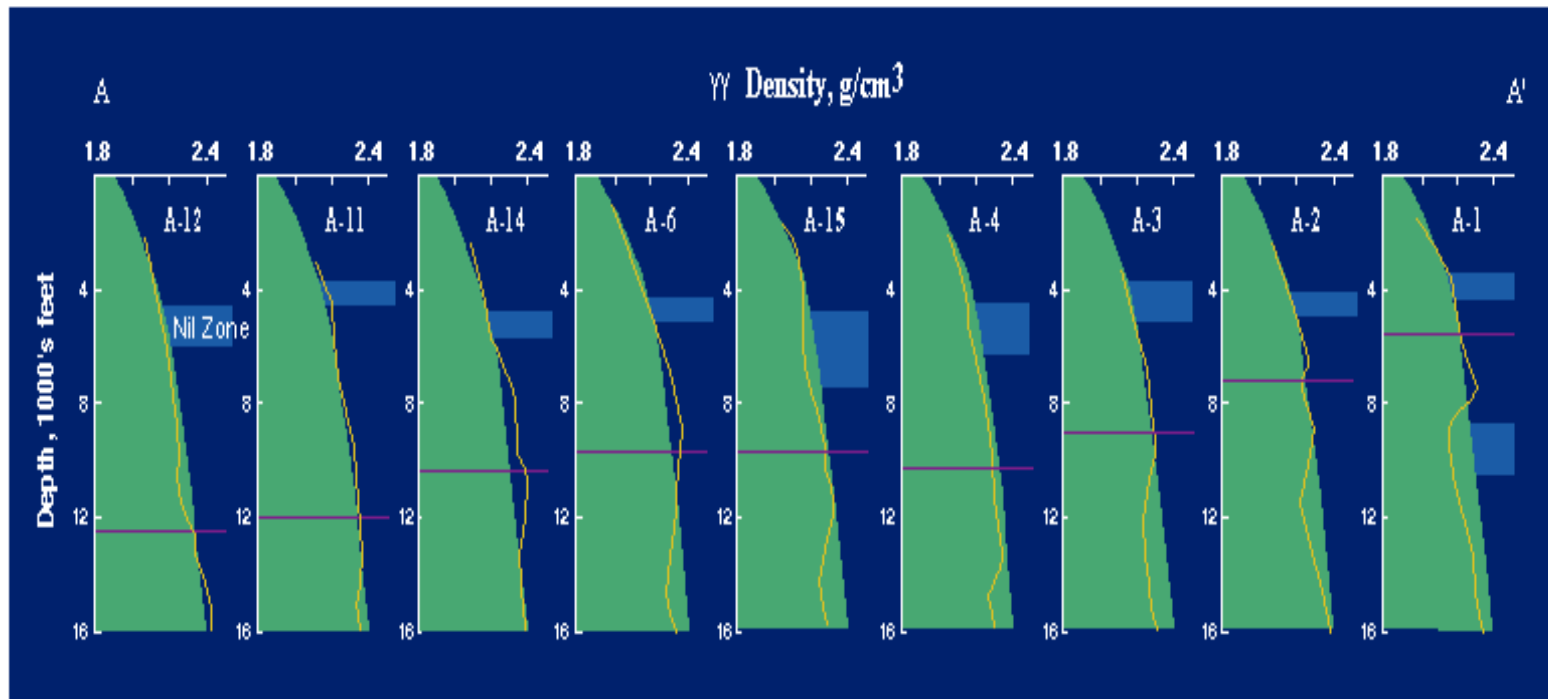


Figure 3

# Salt Density vs. Depth

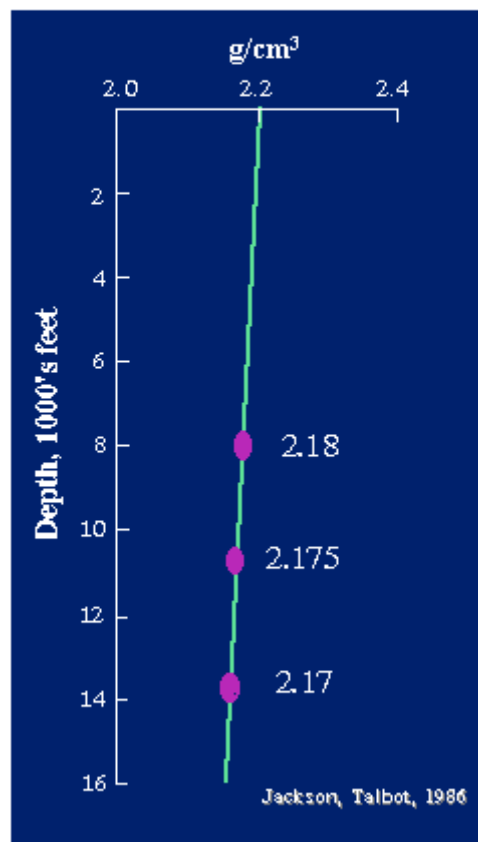


Figure 4

# In Pursuit of the Perfect Density Volume

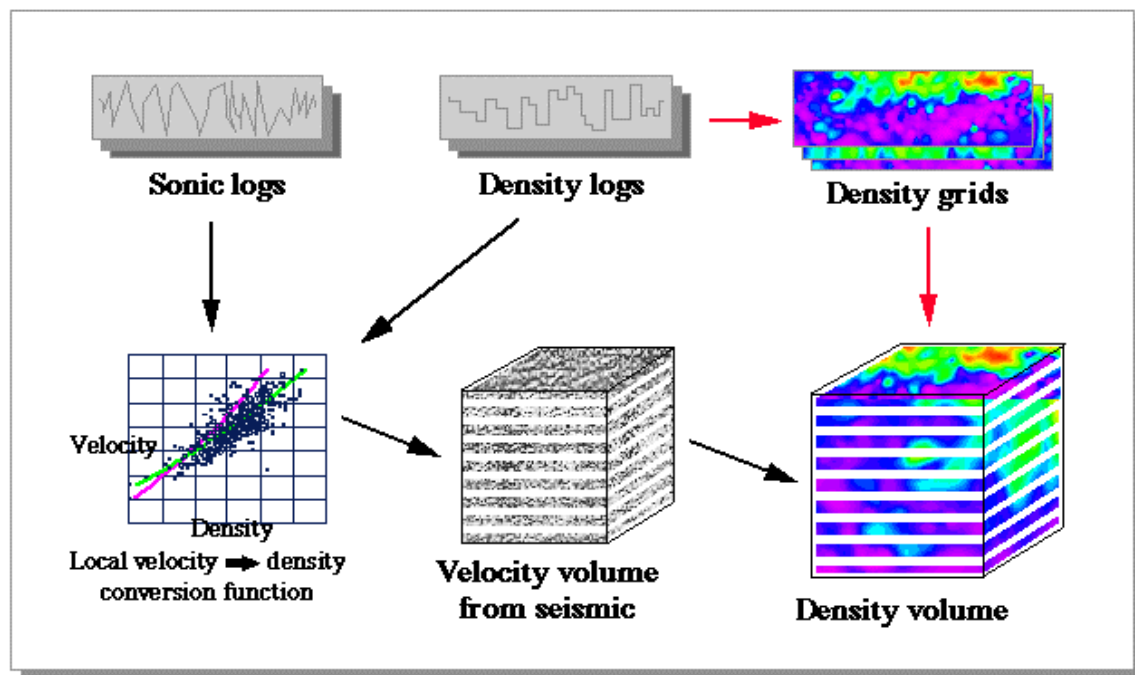


Figure 5

# Project Methodology

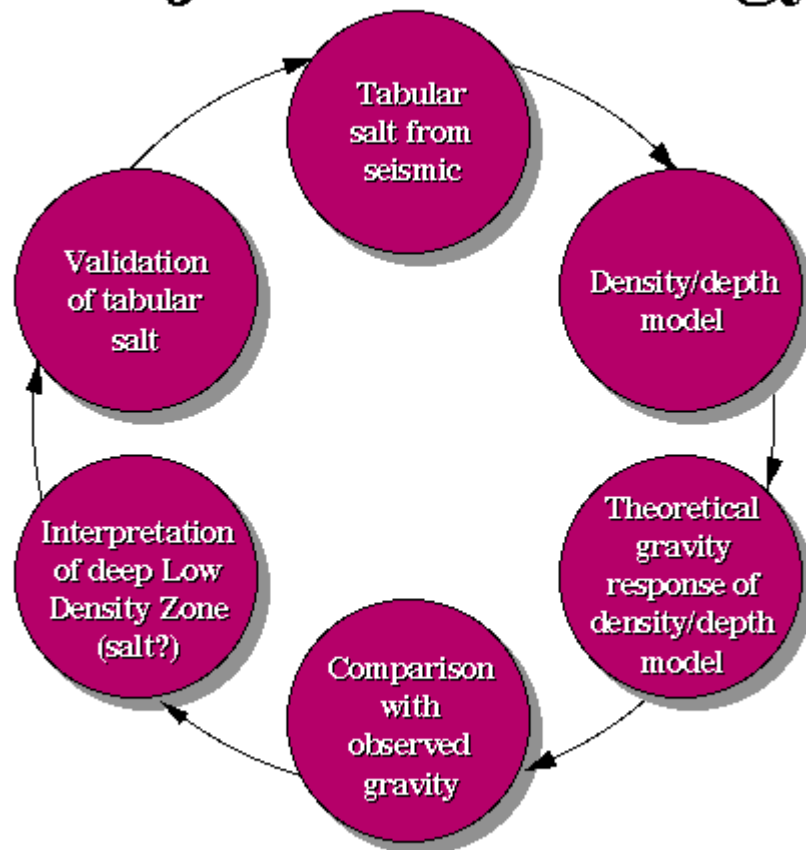


Figure 6

# Density vs. Velocity

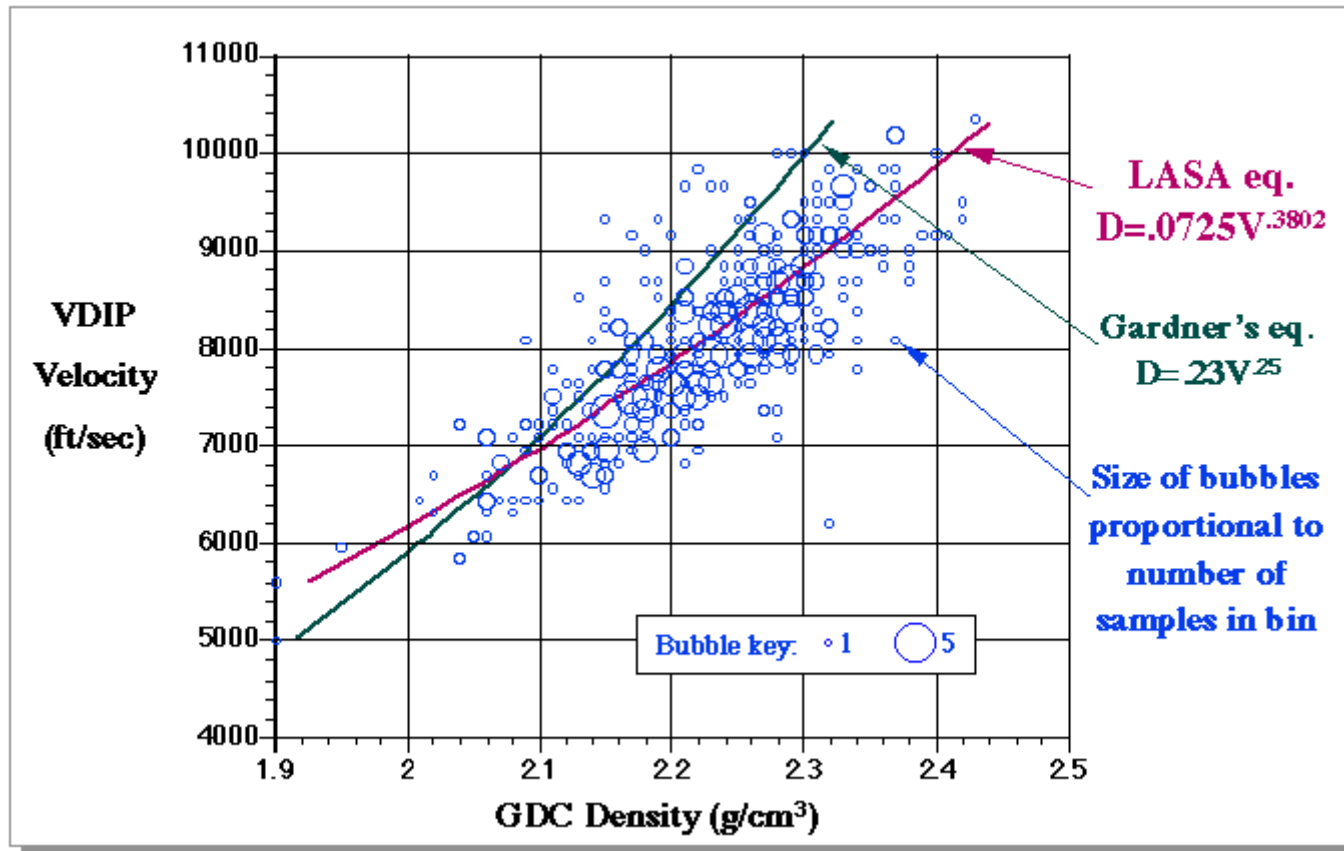


Figure 7

# Calculated Density Effect versus Residual Anomaly

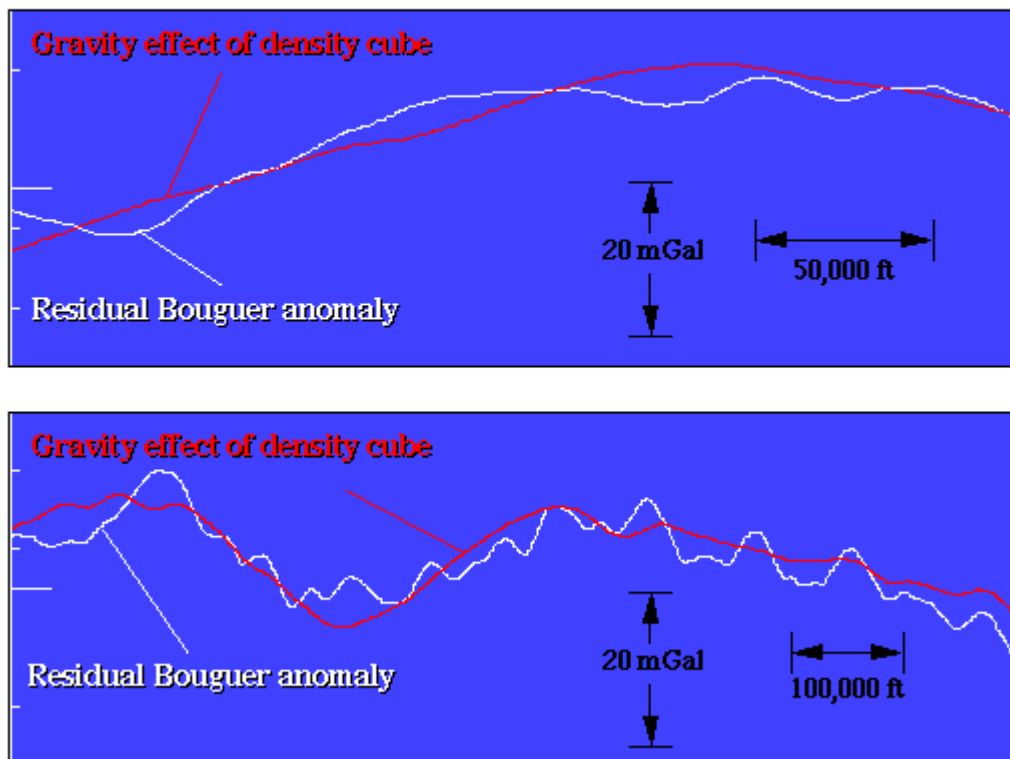


Figure 8

# Initial Pre-Inversion Model

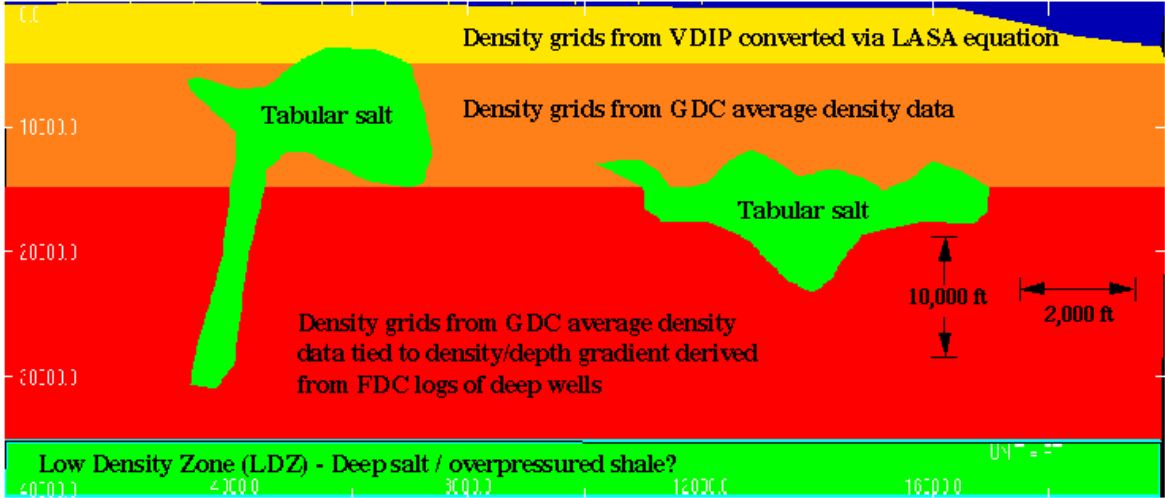


Figure 9

# Post-Inversion Model

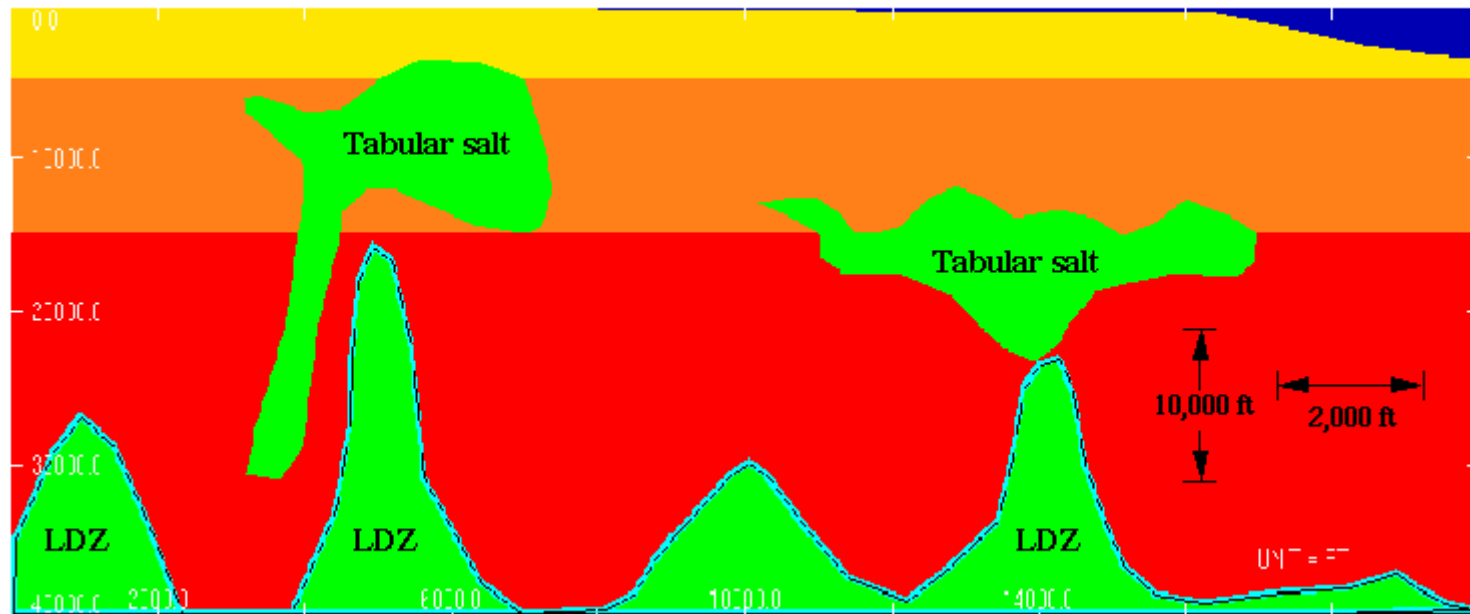
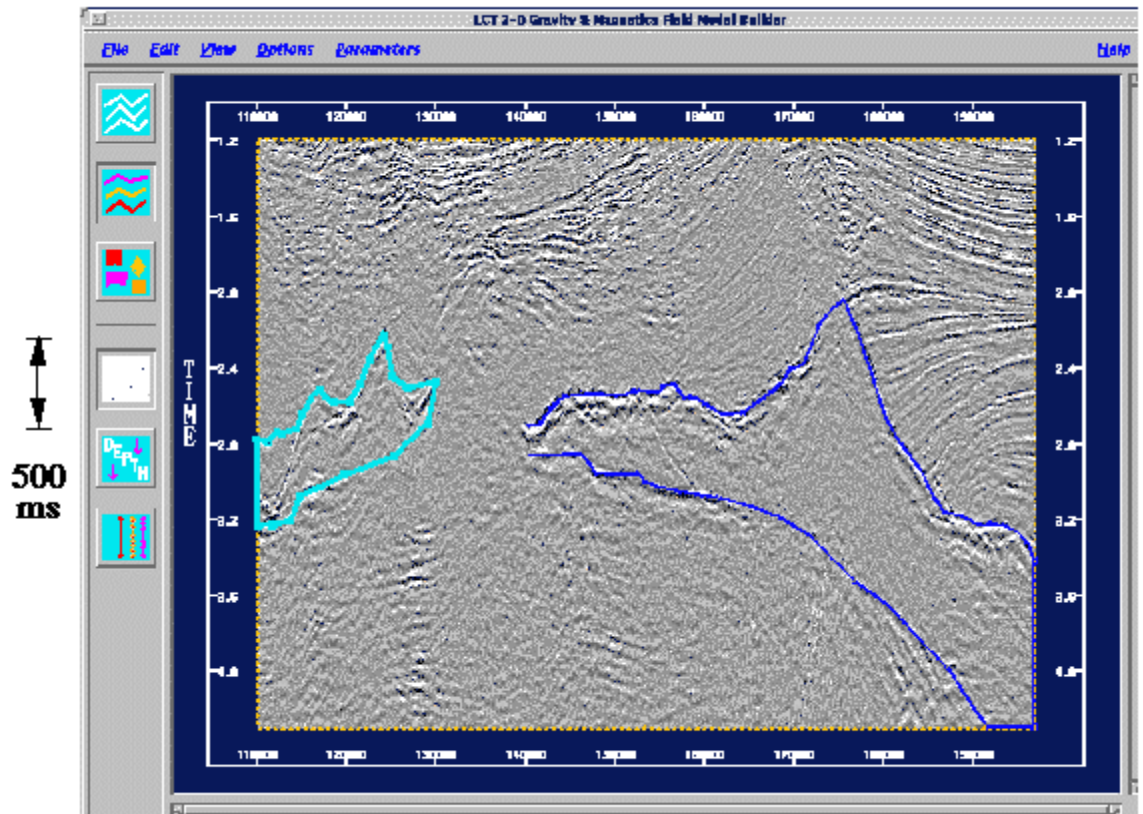


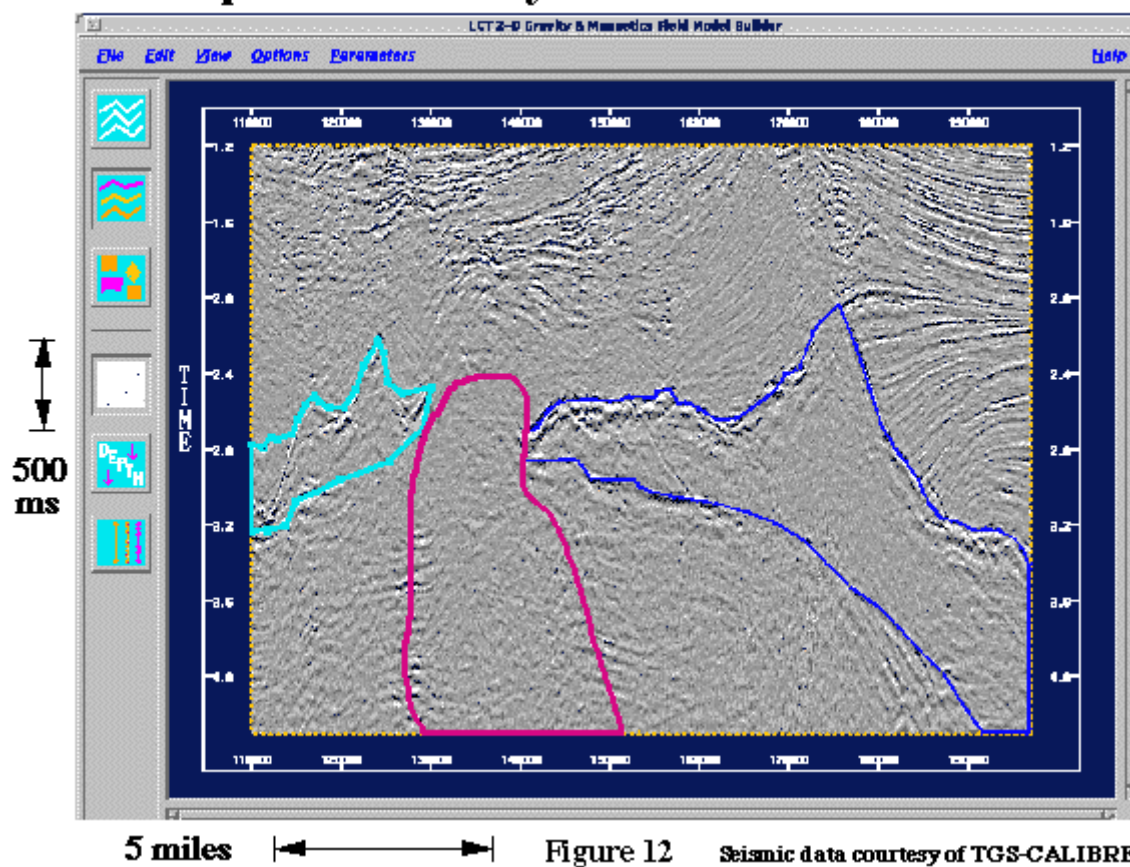
Figure 10

# Original Seismic Top and Base of Salt

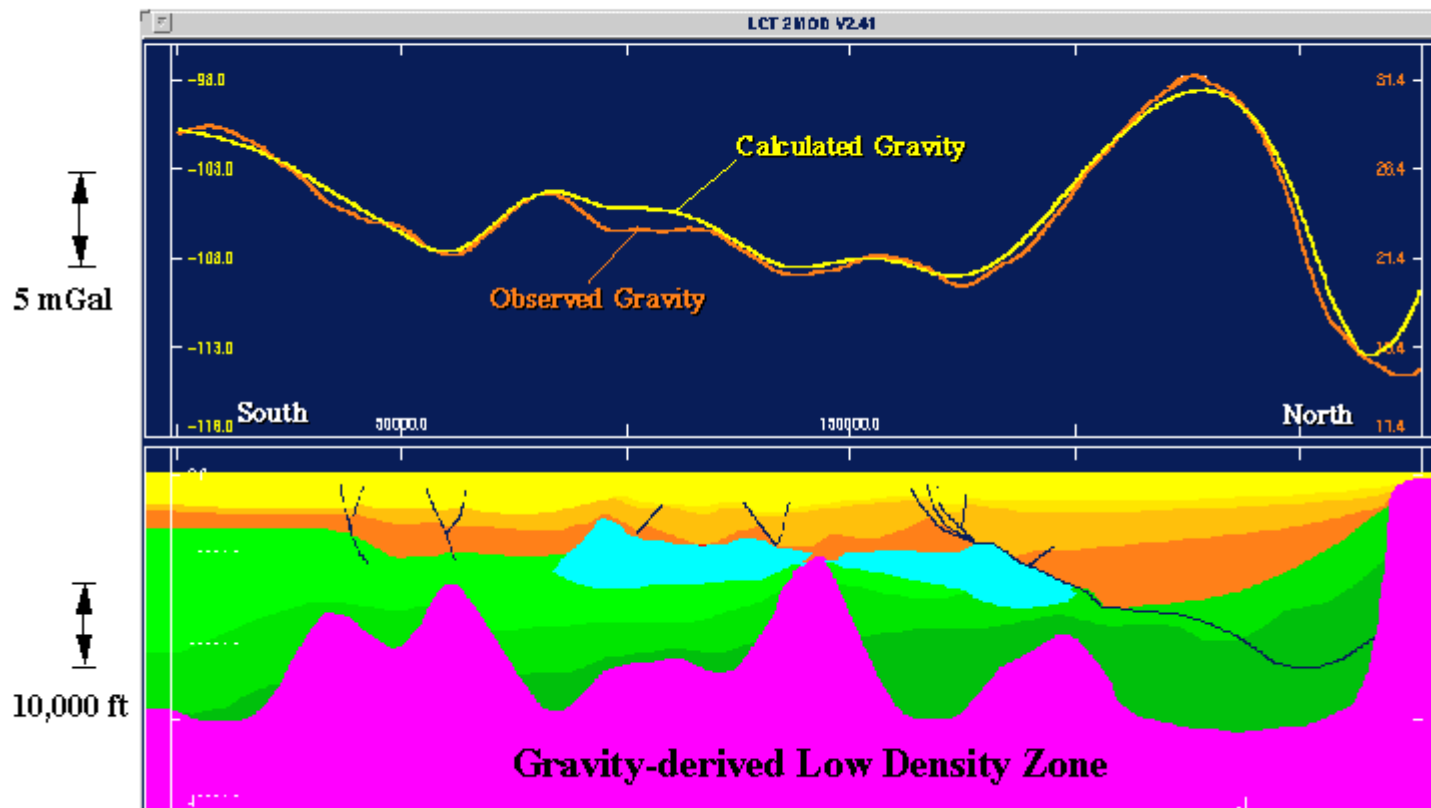


5 miles ←————→ Figure 11 Seismic data courtesy of TGS-CALIBRE

## Overlay Gravity-Derived Deep Low Density Zone on Time-Section



# Overlay Gravity-Derived Deep Low Density Zone on Depth-Section



10 miles      Figure 13

# Susceptibility Profile – Garden Banks

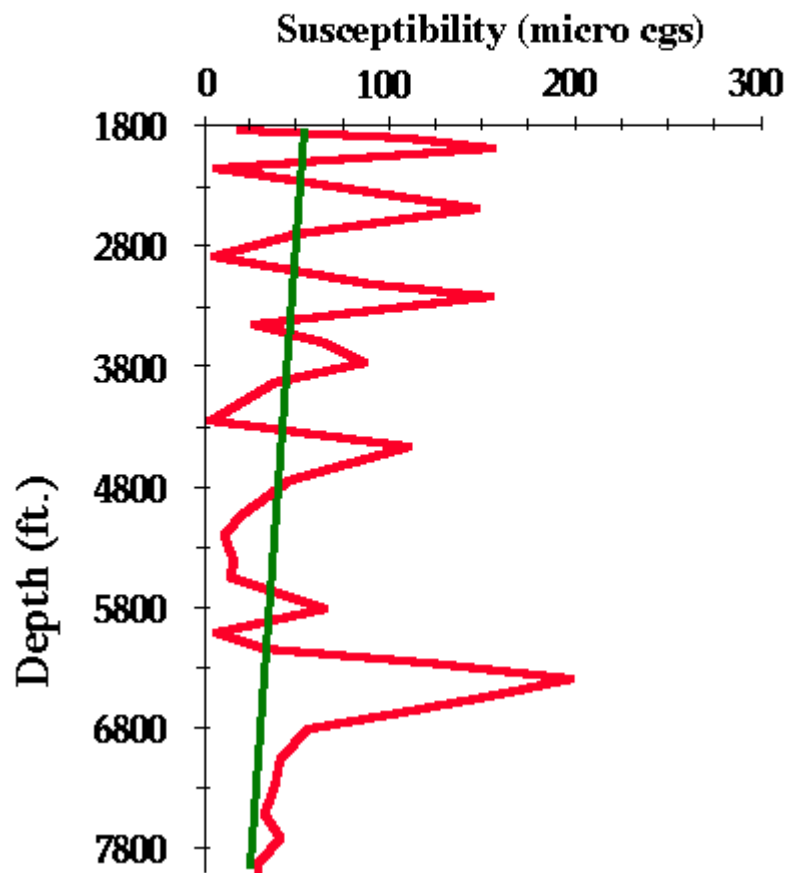
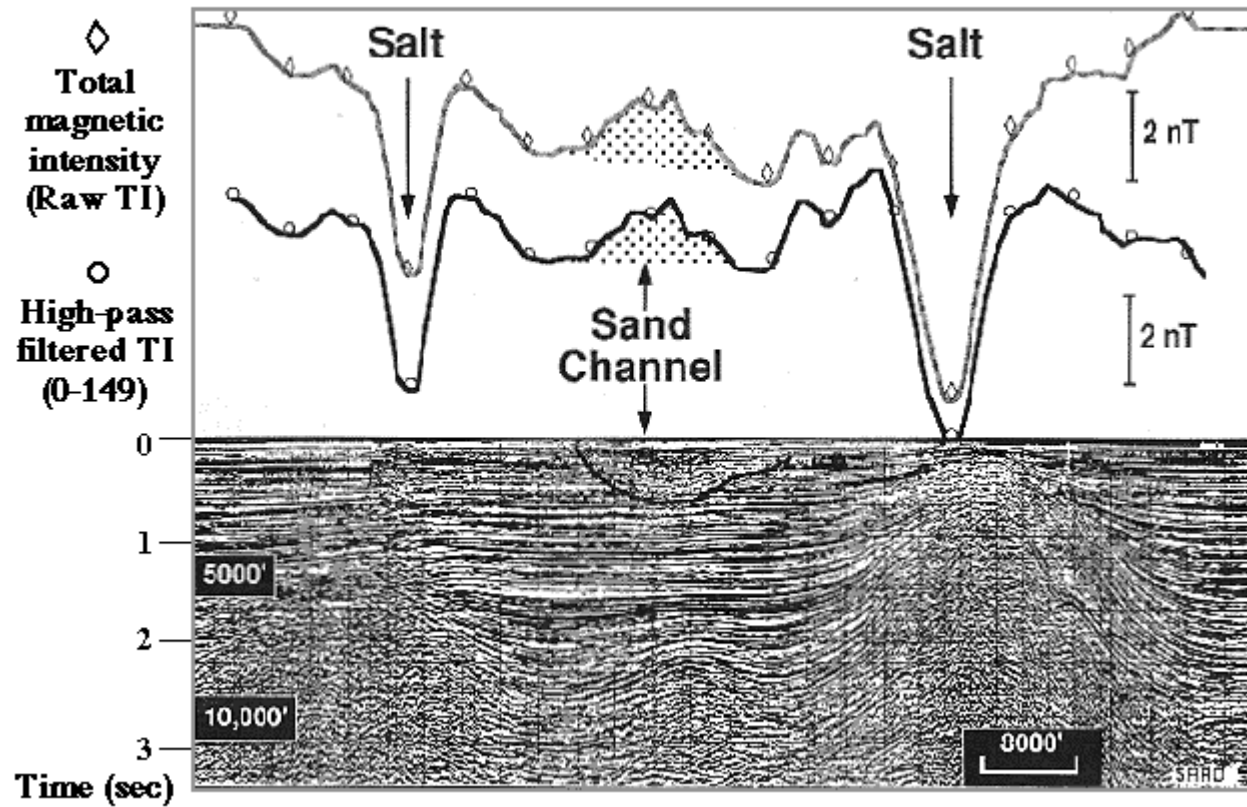


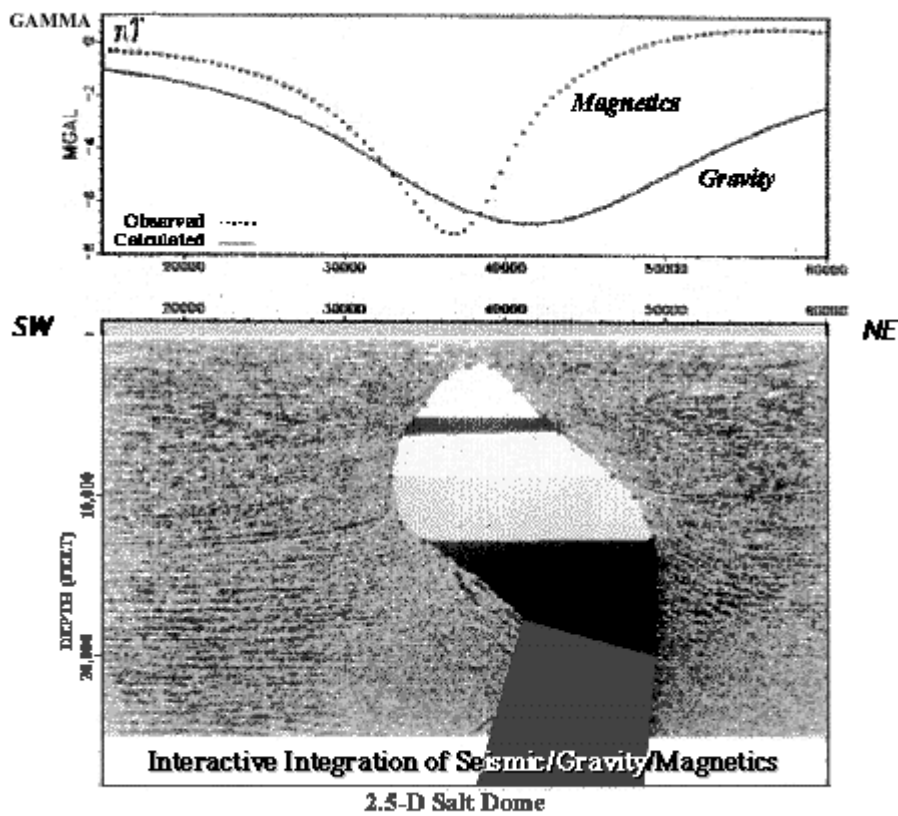
Figure 14

## Magnetic Anomalies Due to Shallow Sand Channel and Salt Structures in the Gulf of Mexico



© OTC Paper 7079 (A. Saad), 1993 Figure 15

# Salt Overhang Model



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