Imaging the SEAM I base of salt with gravity gradiometer data

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Summary

The SEG Advanced Modeling (SEAM) I model incorporates a wide range of features that are a challenge to image with the seismic method. New software has been developed over the past few years for the inversion of gravity gradient data. This rapid development of potential field inversion algorithms and workflows provides an opportunity for improved recovery of base of salt (BOS) structures. A simplified version of the SEAM I density model was used to generate synthetic airborne survey data incorporating noise levels of current gravity gradiometer systems and lower noise systems under development. These data were used to successfully recover the broad BOS structure using three different inversion algorithms. A stochastic inversion approach using lower noise data was able to recover more detailed structures in the BOS.

Introduction

Recovering the BOS using the seismic method alone can be very challenging under certain circumstances. Gravity gradiometry data have shown promise in supplementing information and highlighting potential errors in the seismic interpretation of the BOS (O'Brien et al., 2005). Even with past successes gravity gradiometer data have not been widely adopted as an essential part of sub-salt exploration. This is largely due to the shortcomings in imaging the BOS with existing gravity gradiometer systems and in extracting and seamlessly integrating relevant geologic information into an exploration workflow. Fundamental challenges include poor signal-to-noise ratio for the BOS interface due to depth of burial or low density contrast with surrounding sediments, noise in the measurement and poor differentiation between signals from structures situated above and below the interface of interest.

The SEAM I consortium provided a high-resolution, realistic Gulf of Mexico type salt model to enable research and development of imaging technologies. The model incorporates a wide variety of salt features that are challenging for the seismic method. The ultimate goal of this study is to demonstrate how gravity gradiometry data can contribute information on the geometry of the BOS to a seismic workflow. The relief of the SEAM I BOS (Figure 1) is highly variable extending from 2,150 m below sea level (BSL) to the bottom of a salt keel at a depth of 12,500 m BSL. The salt has a density contrast with surrounding sediments ranging from +0.17 g/cc to -0.38 g/cc. The salt feeder situated between 8,000 m BSL and 12,500 m BSL is the most prominent feature in the BOS. The depth of burial of this salt keel results in a relatively low signal of 1.7 E and marginal signal-to-noise ratio (SNR) with operational airborne gravity gradiometer systems. There are low-noise, high-resolution gravity gradiometer systems being developed (Tryggvason, 2004)) that will improve the SNR by an order of magnitude or better.

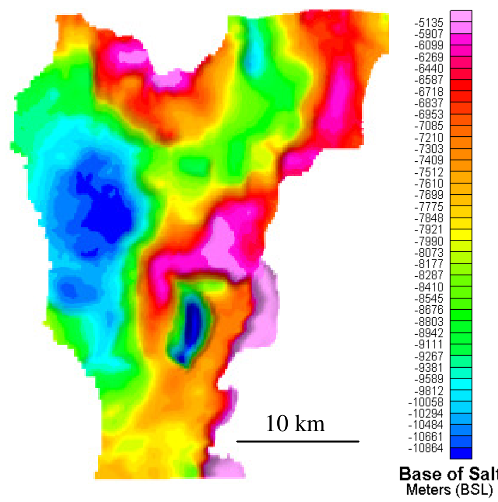

Figure 1. True base of salt interface in the SEAM I model

The gravity gradiometer response of the SEAM I model includes contributing signals from bathymetric relief, a highly variable top of salt (TOS) and surrounding sediments in addition to the BOS signal. With no prior geologic information it is well understood that gravity gradiometer data would not be able to provide detailed information about the BOS. The information required to some degree of accuracy includes a bathymetric model and estimation of the top of salt surface and density of surrounding sediments from seismic interpreters. In order to substantively contribute to imaging the BOS interface, information generated earlier in the exploration workflow are required to either constrain the gravity gradiometer inversion or be modeled and stripped out of the observed response.

The number and capabilities of software packages for inverting gravity gradient data have greatly increased over the past few years. The SEAM I data provides an ideal opportunity to conduct controlled testing and development of these algorithms. For successful BOS recovery all inversion algorithms must provide the ability to conduct an inversion that can be constrained by prior information either through static geologic interfaces or starting density models where specific voxels can have fixed parameters.

The progressive stages of this study are as follows; determine the SNR for the SEAM I BOS as would be measured by current gravity gradiometer systems and those under development, test the performance of various inversion algorithms in recovering the BOS using a simplified model, test assumptions and constraints used during the inversion and finally simulate a realistic BOS recovery workflow.

Simplified Model

The initial phase of the project was to demonstrate how well the SEAM I BOS can be recovered. To expedite and focus the initial analysis, assumptions were made to simplify the geology. A “background model” was generated by removing the allochthonous salt from the original SEAM I density model and interpolating across the gap. This background model was then subtracted from the

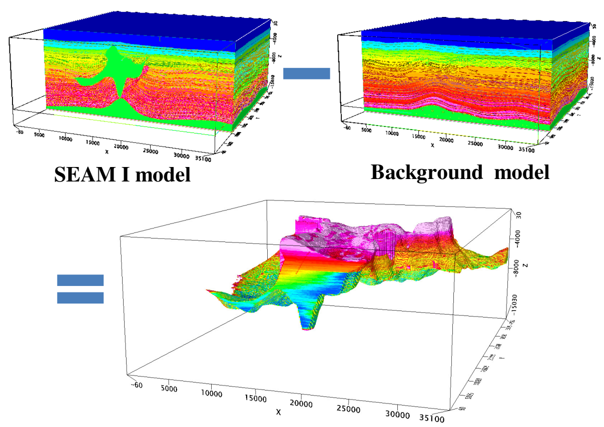

Figure 2. The salt contrast model was constructed by subtracting a background model from the SEAM I density model.

original density model to create a salt contrast model (SCM) (Figure 2). In the SCM, the density of all surrounding geology and the autochthonous salt now have a density contrast of zero. This is equivalent to assuming that all the geology, with the exception of the allochthonous salt, is perfectly known. This could also be accomplished in an inversion algorithm by setting this geologic information either as fixed interfaces or density voxels. By removing the response of this geology beforehand setting up the inversion is greatly simplified and the size of the model space reduces roughly to the size of the salt body. Additionally, the challenges associated with the edges are greatly reduced as the salt body tapers to a density contrast of zero around almost the entire model. The model is overly simplistic but expedited the feasibility analysis.

Survey Simulation

The simulated survey data over the salt density contrast model were computed at a survey altitude of 150 m and at regular grid spacing of 250 m. Noise simulating the performance of current commercial gradiometers systems and anticipated performance of those under development was then added to this response.

The noise level of gravity gradiometer survey depends largely on the accelerations experienced by the instrument. The noise level reported by Dransfield (2013) for fixed-wing gradiometer systems that are currently in commercial operation range from 1.5 to 4.7 E√km. The noise used in this study was 2.5 E√km which represents a good performance level for current systems collected in near ideal turbulence conditions. The systems under development are anticipated to have significantly improved performance. For this study the target noise level of the Gedex system of 1E/√Hz (0.25 E√km when mounted on a fixed-wing platform) was used.

A white noise character was used for all noise simulations. With the acquisition platform situated 1000 m over the known TOS, there is a large component of the noise that can be filtered without impacting the signal of the deeper BOS. A low-pass filter with wavelength of 2000 m was applied which did not affect the signal of interest. The vertical gravity gradient response of the SCM is shown in Figure 3 with 2.5 E√km and 0.25 E√km noise added and low-pass filtering applied. For this target depth there is little advantage in using multiple components so all inversions were done with only the vertical gradient of the vertical gravity component (Gzz).

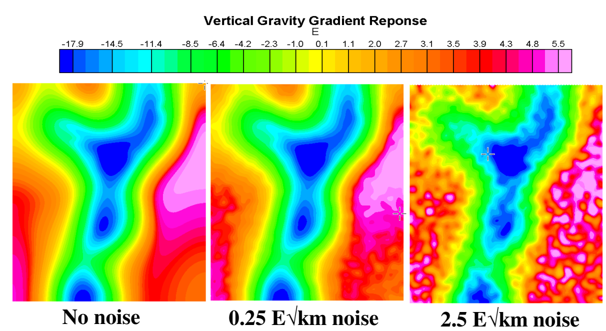

Figure 3. Vertical gravity gradient (Gzz) response simulated for an airborne survey flown at 150m ASL. The no-noise, 0.25 E√km noise and 2.5 E√km noise are shown. The noise added Gzz responses have been filtered with a 2000m low-pass filter.

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Inversion Algorithm Testing

Three different inversion packages were tested for imaging of the BOS in the SEAM I model; interface-based Geosoft GM-SYS 3D, binary voxel inversion BININV3D developed by the Colorado School of Mines and geologically-constrained, interface-based Intrepid Geomodeller. Generalized voxel inversion is not appropriate for this geologic scenario where the BOS interface must be represented by a sharp contact.

For all the inversions the starting model was setup as follows. The top of salt was provided as a known surface with the volume below being the BOS model space. The density values between the top of salt and BOS were also assigned. Here it was assumed that the change in density of the surrounding sediments with depth is known. This vertical density function was generated by calculating the average density of horizontal layers in the salt contrast model. The region outside the salt body was fixed at a density of zero. As indicated earlier this is equivalent to assuming that the density distribution of all surrounding geology is known perfectly. No prior information was supplied on the structure of the BOS. The starting model for this interface consists of a flat plane.

<u>GM-SYS 3D Interface Inversion</u>
Geosoft GM-SYS 3D is an interface-oriented inversion package which is well suited to this geologic scenario as the BOS is a sharp contact. A problematic area for inversions is at the depth where the salt density equals the density of the surrounding sediments (nil-zone). Adjusting the model within the nil-zone will not reduce misfit so the algorithm cannot move this interface across this region. To overcome this one would normally conduct a preliminary inversion and observe where the BOS has plateaued but where misfit (of the right sign) also remains. The interface needs to be manually pulled across the nil-zone for the inversion to proceed on the other side.

The BOS surface computed by GM-SYS for the lower noise and higher noise simulations are shown in Figure 4a.

<u>Binary Inversion</u>
The Colorado School of Mines binary inversion of gravity data (BININV3D) uses voxel model representation as in continuous density inversion but restricts the model values to one of two lithologic units as does interface inversion (Krahenbuhl and Li, 2006). Here the two lithologic units are salt and non-salt (or sediment). To maintain consistency between the inversion tests, the noise added in the BININV3D gravity inversion possessed an identical character as the noise used in the gravity gradient inversions.

The starting model sets each active voxel to randomly represent either salt or non-salt. These are then flipped using a genetic algorithm approach in an attempt to minimize the misfit between the model response and the observed data. The inversion package was run 10 times with a range of regularization parameters which balances the trade-off between closely fitting the observed data and smoothness in the model. A voxel was deemed to have a high probability of being salt if 3 or more runs of the inversion indicate that voxel to be salt. Rejecting the low-probability solutions created a sharp contact for the BOS. Although there are some erroneous non-salt cells within the salt body around the nil-zone, the BOS interface was able to successfully cross the nil-zone.

The inverted BOS surface computed by the binary inversion algorithm for the lower noise and higher noise simulations are shown in Figure 4b.

<u>Geomodeller Inversion</u>
Geomodeller is a 3D geologic model building tool that allows interfaces to be modified through geophysical inversion. In the inversion process Geomodeller uses a voxel representation but only allows changes in lithology to occur along defined geologic interfaces. Rather than halting the inversion at a prescribed misfit level Geomodeller uses a stochastic approach to continue the inversion to explore a range of allowable models. This allows the algorithm to successfully push a geologic interface through the nil-zone.

The BOS surface computed by the Geomodeller inversion algorithm for the lower noise and higher noise simulations are shown in Figure 4c.

Results and Conclusions

An important application of the SEAM I density model is to test the effectiveness of a number of inversion algorithms. Using the SCM simplifies the SEAM I model and allows rapid head-to-head comparison. Comparing the computed BOS surfaces using the various algorithms in Figure 4 with the true BOS in Figure 1 illustrates some similarities/differences between the algorithms tested. The broad structure of the BOS was relatively well recovered by all the algorithms with similar accuracy. GM-SYS 3D and BININV3D both did a good job in rejecting noise with the results from the lower and higher noise inversions being very similar. The Geomodeller inversion of the lower noise system did a much better job imaging the detailed structure in the BOS. In particular, the presence and position of the salt feeder is very well defined. The Geomodeller inversion of the higher noise data does not image the salt feeder and other important structures and adds short wavelength noise to the BOS surface.

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This exercise illustrated the SEAM I BOS can be broadly imaged using gravity gradient data. A lower noise system coupled with an appropriate inversion algorithm can extract important structure in the BOS. The next stage of modeling is to test the assumptions made in this initial testing and then to repeat the inversion using the full SEAM I density model and geologic constraints that would be available in typical exploration workflows. Initially developed to build 3-D geologic models, Geomodeller is very well suited to progressively adding constraints.

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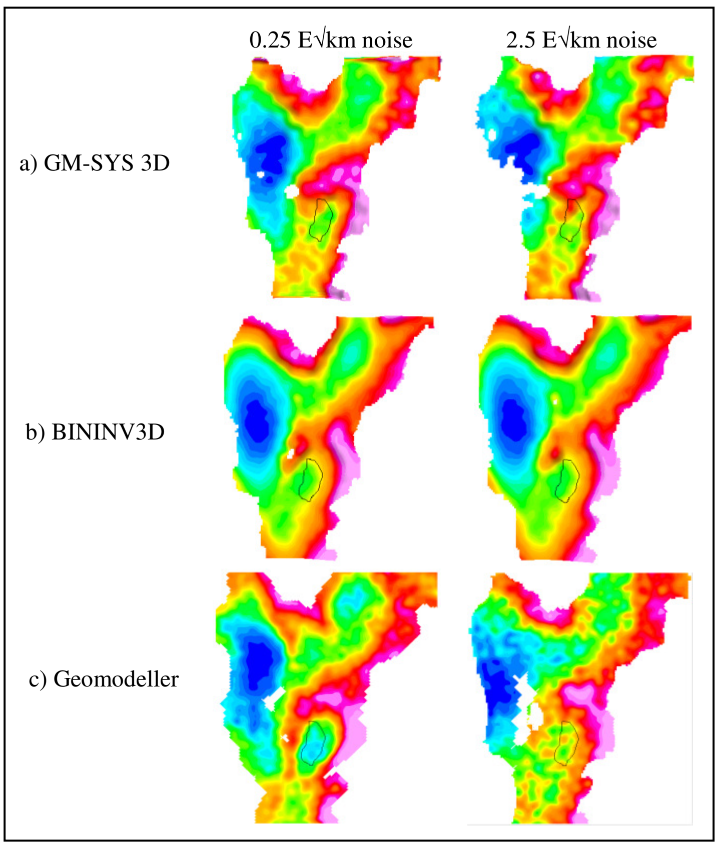

Figure 4. Base of salt surfaces computed by the a)GM-SYS 3D b)BININV3D and c)Geomodeller inversion algorithms. The true BOS surface is shown in Figure 1.