6^{th} International Conference & Exposition on Petroleum Geophysics "Kolkata 2006"

Sharpening the Edges to Leverage Seismics

Kabir Roy-Chowdhury* and Tim van Zon
Applied Geophysics Group, Utrecht University, The Netherlands
E-mail : kabir@geo.uu.nl

Summary

Structural Inversion (SI) of potential field data can yield geologically reasonable models in seismically difficult settings, and thus enable an improved interpretation. We report on studies using a gridded model and an L_1-norm based objective function for inverting gravity anomalies associated with salt structures. The use of Linear Programming (LP) for the actual inversion results in "sharp" (geologically reasonable) models of the sub-surface due to an inherent property of the former. The improved lateral resolution should enable better interpretation of salt flanks. Prior-knowledge regarding the depth to the top is necessary; this however is generally available from the seismics. A true joint inversion - including a moderate amount of seismic first arrival times is expected to remove this requirement.

The formalism is applicable in other exploration settings too, e.g. surveying for (magnetic) minerals, mapping basement topography etc.

Introduction

Reflection seismics is the preferred technique for imaging the sub-surface of the earth down to the basin level, and thus provides most of the primary information pertaining to the structures inside potentially oil/gas-bearing basins. Due to the acquisition geometry, however, reflection seismics illuminates near-vertical features sub-optimally. This results, for example, in poor spatial resolution of flanks of salt structures. Additional types of seismic data (cross-well, turning ray etc.) thus needs to be acquired/processed and interpreted in order to properly assess the hydrocarbon potential associated with such regions, adding significantly to the costs.

Below, we report on the possibilities of using potential-field data (in our case, gravity anomalies) to provide extra information regarding the spatial extent of near-vertical structures. This can lower exploration risks by better constraining the interpretation of reflection data.

The approach

Geophysical inversion involves objectively obtaining information about a part of the earth's interior based upon measuremnts of some physical field(s), usually at the surface. The field to be used here is the vertical component of the gravitational attraction caused by masses distributed in the sub-surface. To make the problem simpler, we assume a bi-modal density distribution, such that the homogeneous anomalous body - e.g. a diapir, or a dike - is embedded in a homogeneoeus background medium. Further, we assume that the gravity data has been corrected for all temporal and spatial effects and represents only the effect due to the density difference of the anomalous body with respect to the background. Our aim is to determine the shape/ borders of this anomalous density distribution.

All geophysical observations contain noise, which impacts their inversion. Any inversion procedure must therefore be careful in dealing with this noise, so as to avoid the pitfall of fitting noise into the model (Jackson, 1972). We assume that all coherent noise has been removed, and that the remaining part is purely random. We then strive to find the anomalous density distribution which can explain the data to the level of noise.

Another important aspect of an inversion procedure is the parameterisation of that part of the interior about which information is sought (model), gridded and geometric parameterisations being frequently used.

In the geometric approach, the anomalous zone is configured roughly using some volume-fill scheme (e.g. Voronoi triangulation, vertical prisms etc.), and the nodes of this body are iteratively manipulated (Ditmar, 2002). This obviously needs a-priori knowledge as to the number and locations of anomalous "bodies". Optimising the update of the nodes remains a challenge though.

In the gridded approach, the target sub-surface is divided into equi-sized homogeneous cells, whose properties (say excess density) is sought. Uniform grids do not pose an a-priori bias on the "shape" of the solution, the latter actually "emerges" out of the inversion. Below, we assume the 2.5-D sub-surface to consist of horizontal homogeneous prisms (finite in the strike direction) whose cross-section can be represented by a square grid.

Lastly, our goal is a structural inversion, i.e. the density distribution should have sharp boundaries (transitions). Conventional schemes using an L_2-norm based objective function impose – via regularisation - some degree of smoothness, which in turn "destroys" the structure. Some earlier workers have constructed special objective functions to impose sharp boundaries. We choose the objective function to be the L_1-norm of the data-fit. The response of any cell at any observation point being a linear function of the (excess) density, we can use LP for the inversion. This imposes certain restrictions on the formulation of the "constraints" (linear relationships). On the other hand, LP inherently searches for solutions on the external boundary of the so-called "feasible set", thus yielding a structural solution. See van Zon & Roy-Chowdhury (2006), for further details about LP and SI.

Example (two diapir-like bodies)

Fig 1. shows the earth-model consisting of two vertical bodies simulating two-diapirs of unequal depth extent. Each 100x100m cell represents a horizontal prism 1000m "deep" in the strike direction. At the top are the gravity anomalies as measured at 80 locations uniformly spread above, and extending somewhat beyond, the anomalous zone. The two "diapir-like" bodies, shown by black cells, have a constant +ve density contrast (0.4 gm/cc) with respect to the background. As such this scenario has sufficient complexity to be interesting. Both the lateral resolution of the two structures as also their depth estimation are important and not easy.

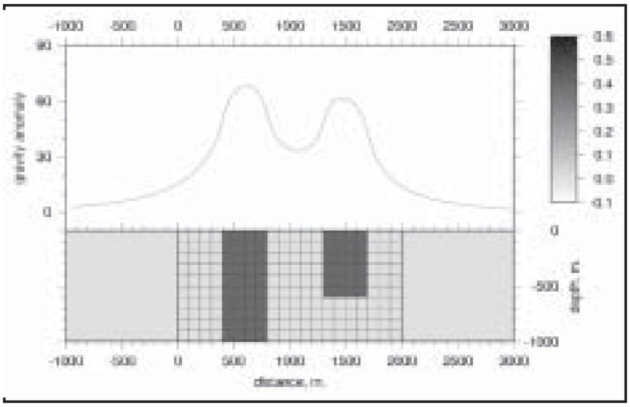

Figure 1: The two-diapir target and its gravity response

For testing the inversion formalism, the data was first scaled by a constant assumed measurement error, and then contaminated with zero-mean unit-variance random noise. The noise-level was about 16%. Fig. 2 (top panel) shows the data used after contamination. The result from the LP inversion is shown in the panel second from the bottom. For comparison, we also inverted the same data using the truncated SVD approach and the L_2-norm. The result shown in the bottom panel has the "anomaly" concentrated near the top of the sub-surface. This is a well-known problem in gravity inversion. Moreover, a large part of the cells at depth have light grey shades, indicating intermediate densities, and thus a non-structural image. By comparison, the L_1-norm based inversion using LP delineates the lateral extent of the bodies. Its performance regarding the vertical extent is somewhat inferior, but it does indicate the relative depth extents correctly. The cell

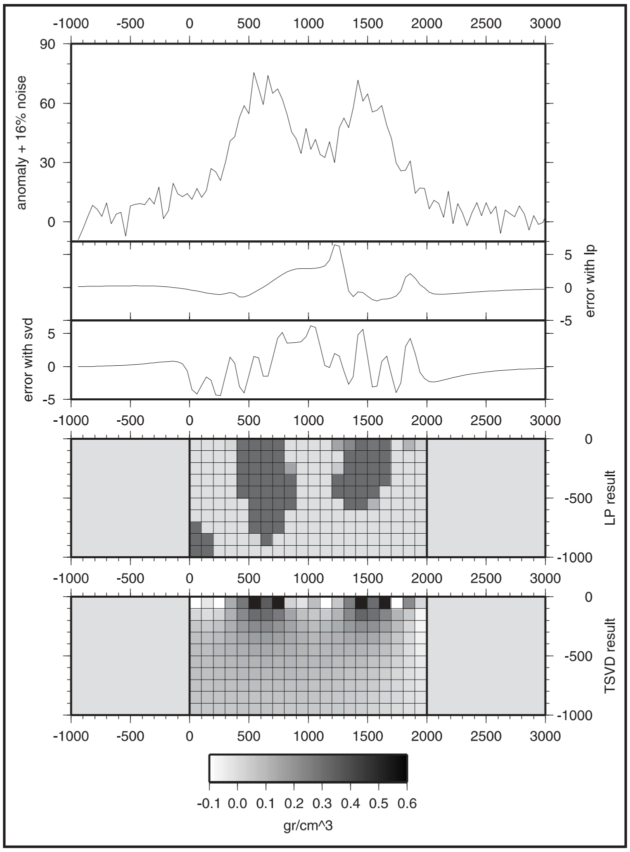

Fig. 2: L_1-norm structural inversion and L_2-norm TSV inversion of the two-diapir data. Top: data contaminated with noise; bottom two panels: inversion results; middle panels: residual error in the two cases

densities obtained show strong strong bi-modality, with only a few cells of intermediate shade. Thus the main objective of obtaining sharper images (SI) has been achieved.

Disscussion / Conclusions

For inversion, the actual target is not known, thus a strategy for optimum parameterisation is needed. Too coarse a parameterisation will yield a "smeared" image, whereas the opposite may make the problem severely underdetermined, as we have to determine densities for all the prisms. In case the noise-level is known (as here), a workable strategy is to use a range of cell-sizes, carry out the inversion, and then select the parameterisation with the fewest cells that fit the data to the noise level. For real data - where the noise level/distribution - may be unknown, we have obtained good results inverting for total number of cells in the order of the number of observations (van Zon & Roy-Chowdhury, 2005).

Additional tests (van Zon & Roy-Chowdhury, 2006) have shown that the performance of our method is sensitive to the a-priori knowledge of the minimum depth to the top of the anomalous body. This is not an acute problem though, because such information (top salt) is generally available from seismics. We are currently testing a joint-inversion using, in addition, some first-arrival times too; the first results are promising and may obviate the need for this a-priori information. ????invert????

The SI shown in Fig. 2, also includes some artifacts, especially in the lower left corner of the model. This is because the cells near the sides of the model are poorly constrained by the data. An effective way to test the robustness of the model is to invert several times with different realisations of noise. The mean and the variance of the models then yields valuable insight regarding the (less) dependable parts of the result.

Finally, we have tested the effectiveness of our formalism only in the case of known maximum density contrast and then only in a two-lithology setting. Actually, the maximum contrast may also be inverted for, although we have not tried it. Similarly, the case of multiple lithologies also needs to be tested.

The formalism described above is also applicable to exploration situations other than for hydrocarbons. (Inclined) dykes are often associated with mineralisation and possess excess density. Similarly, ore-bodies with sharp lateral boundaries, and heavier than the surrounding rock could also benefit from SI.

References

Ditmar, P., 2002, Finding the shape of a local heterogeneity by means of a structural inversion with constraints; Geophysical Prospecting, v 50, pp 209-223.

Jackson, D. D., Interpretation of inaccurate, insuffficient and inconsistent data; Geophys. J. of the RAS, v 28, pp 97-109.

Van Zon, T. and Roy Chowdhury, K., 2006, Structural inversion of gravity data using Linear Programming; Geophysics, accepted.

Van Zon, T. and Roy Chowdhury, K., 2005, Structural inversion of gravity data using Linear Programming - a case study; SEG tech. Prog. expanded abstracts 24; 75th ann. mtg, Houston.