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Delineating basement structure under sedimentary cover using Gravity Inversion

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Summary

We use data from a seismically well-studied structure to benchmark the performance of our Linear Programming (LP) based gravity inversion. The formalism had to be first modified to be able to deal with features associated with real data, and is now able to handle - and invert for - a dc component and a linear trend, which may be present.

The LP-based inversion, assuming a bi-modal lithology, yields a "sharp" image of the basement topography, confirming the presence of two hidden basins. The image is shown to be robust for reasonable variations in the model-parameterisation (cell-size). This also illustrates another advantage of our approach - that of avoiding detailed gravity modelling - which often need complex geometrical shapes. Our method does require a minimum depth to the top of the structure to be inverted for, but such information is often available, e.g. from seismics.

The formalism should also be applicable in other challenging exploration settings e.g. delineation of salt flanks, localization of metallic mineralisation etc.

Motivation & Introduction

Reflection seismics is the preferred technique for exploring the sub-surface of the earth down to the basin level, and provides most of the primary information pertaining to the structures inside potentially oil/gasbearing basins. Under problematic settings, however, interpretation of seismic reflection data can be leveraged by input from non-seismic sources, e.g. potential-field data (here, gravity anomalies). The better-constrained interpretation could, in turn, lessen exploration risks.

Geophysical inversion involves obtaining objective information about a part of the earth's interior based upon observation of some (geo)physical field(s) – normally measured at the surface. In conventional L_2-norm based inversions, a smooth image is aimed for, to avoid overinterpretation. In an earlier work (Van Zon & Roy Chowdhury, 2006), we presented an alternate approach to invert *absolute* gravity data using LP and L_1-norms, which yielded "sharp" images of the causative subsurface to facilitate their geological interpretation.

LP inherently searches for solutions on the external boundary of the so-called "feasible set", thus yielding a structural inversion (SI). In certain geological settings, e.g. salt-flanks, boundaries of ore-deposits, SI may, in fact, be the more appropriate approach. See Van Zon & Roy-Chowdhury (2006), for details about LP and SI.

Here, we use anomalies from a regional scale gravity survey to invert for basement topography, hidden below sedimentary layers. The sub-surface in this area has been extensively studied by multiple geophysical techniques – including seismics & magnetics - the "correct answer" is therefore known (see the section **Example** for details). If the validation exercise is successful, our formalism could be applied to explore other areas where deeper basins may be hidden below overlying sedimentary covers.

The approach

Our original formalism used absolute values of gravitational attraction; it had to be first modified to deal

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with characteristics of Bouguer anomalies resulting from a standard processing of field measurements, the details of which were unknown to us. We have extended the inversion to include an unknown (constant) offset and a linear trend possibly present in the (relative) anomalies.

Model parameterisation also needed to be modified, although we retained the use of uniform grids to describe the sub-surface. The target sub-surface is divided into equi-sized homogeneous cells, whose properties (say excess density) are sought. Such uniform grids do not pose an a-priori bias on the "shape" of the solution - the latter actually "emerges" out of the inversion. We assume the 2.5-D sub-surface to consist of homogeneous horizontal prisms of identical size and shape and finite in the strike direction. Their cross section below the measured profile can then be represented by a square grid. Our aim is to determine the (excess) density distribution on this grid, which will explain the observed gravity anomalies.

The example

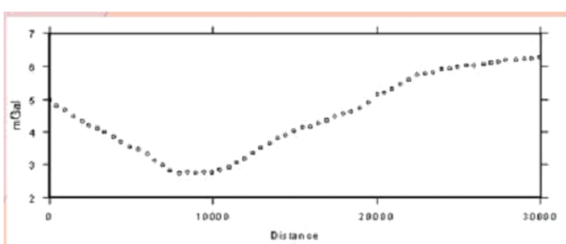
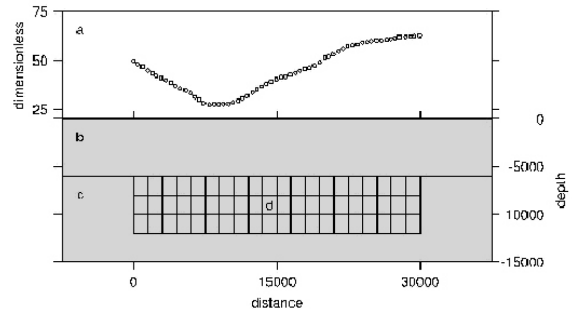


Figure above shows the data, (courtesy Shell), consisting of Bouguer gravity anomalies at 61 locations extracted from a 2-D regional survey in the North Sea. The line was selected so as to be nearly perpendicular to the regional structural trends, to justify the assumption of a 2.5D sub-surface. The measurements had been earlier corrected for time-varying, terrain and elevation effects. The unit of the spatial dimensions are not known to us (probably m). Magnetic measurements in the area gave some indication regarding the depth of the basement. Information obtained from some earlier gravity modelling work indicated the presence of a few gently dipping sub-parallel layers above the basement.



Panel a in the figure above shows the same data after scaling by an assumed constant error of 0.1 mGal, the sub-surface above the basement is represented by panel b, and the panel c represents the rest of the sub-surface (half-space). Panel d (part of panel c) is the area targetted for imaging by inversion and has been parameterised by horizontal prisms (each 90,000 units long) placed symmetrically in the strike direction to simulate the assumed 2.5D geometry -- with a square-gridded crosssection. Its minimum depth corresponds to the expected minimum depth of the basement.

Since LP yields only positive solutions (read: excess celldensities), whereas we want to test for possible basement depressions (indicating basins) i.e. mass deficiencies, we need an extra pre-processing step before applying the modified inversion procedure. We *fill-up* volume d with material of the maximum density contrast expected between basement and the basin (0.15 gm/cc^3), and add the corresponding *anomaly* to every data point. The result, shown in the figure on the right (panel a, top) is then the anomaly ready for inversion.

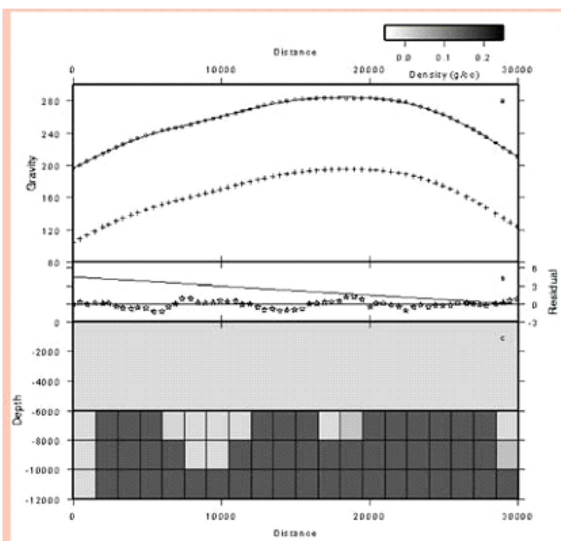
The modified LP-based inversion yields estimates of:

- A constant term, which will include, in addition to any possible dc offset originally present in the data, also the effects from the volumes b and c (figure above); this term is further of no direct interest to us;
- A gradient term, which will represent an eventual linear trend present in the data. Although of no direct interest for the current investigation, such a trend (figure on the right, panel b, top), may provide useful information regarding regional dips both above and below the target depth. It may be noted, that in our modified formalism, the direction of the trend is not assumed a-priori, but is also solved for.

- Optimum values for the densities in the parameterised (gridded) part of the sub-surface, as evaluated using an L-norm based objective function. This is of course of great interest to us and is the main motivation for the current investigation.

The figure below summarises the results from one inversion of the *data* shown at the top of panel a. Panel d shows the excess cell densities obtained (within the specified maximum of 0.15 gm/cc^3). Two *basin-like* structures are clearly visible, albeit along with some anomalous edge-effects. The latter are probably due to:

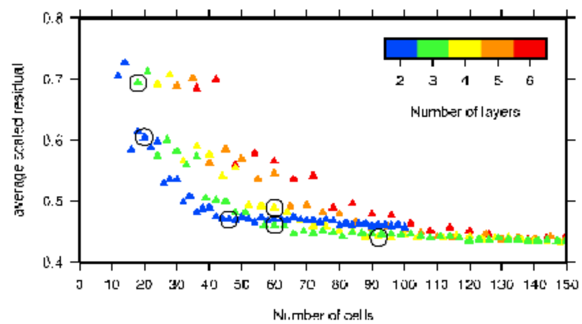
- wrong background density (assumped), and/or,
- inadequate availability (lateral coverage) of gravity measurements to constrain the result well.



Discussion

An important aspect of any inversion procedure is its robustness with respect to different parameterisations. We investigated this using different numbers and configurations of the cells; these varied from as few as 45 cells (15x3) to as many as 180 (30x6) to cover the gridded volume. Our earlier strategy of using as few cells as possible, which was shown to work for synthetic data corrupted with Gaussian noise, cannot unfortunately be used here. Panel b (above) shows a spatially correlated residual that cannot be modelled even by severe overparameterisation. Hence, we suggest using roughly as many cells as there are data points (here 61), which has some support from information theory. The above figure is indeed one such inversion, with 60 (20x3) cells.

To obtain some insight into the inversion process, a series of runs were done, combing through the space of parameterisation of the target-volume. Laterally, 6 to 50 cells were used, and vertically, 2 to 6 layers were studied. Out of these, the figure on the next page (left) summarises the global performance of the inversion procedure for all runs using 150 cells, or less. Underparameterisation (very-few cells) clearly results in a poor datafit, but the datafit does not seem to keep improving with more cells being used, and reinforces our preference for inverting for approximately as many parameters as there are data points (61 here).



While consistently showing the two basin-like features (results not shown here), some of the inversions yielded models containing density inversions – especially near the left edge. To investigate this further, we imposed an extra constraint in our LP-based formalism - not allowing *a decrease of density with depth.*

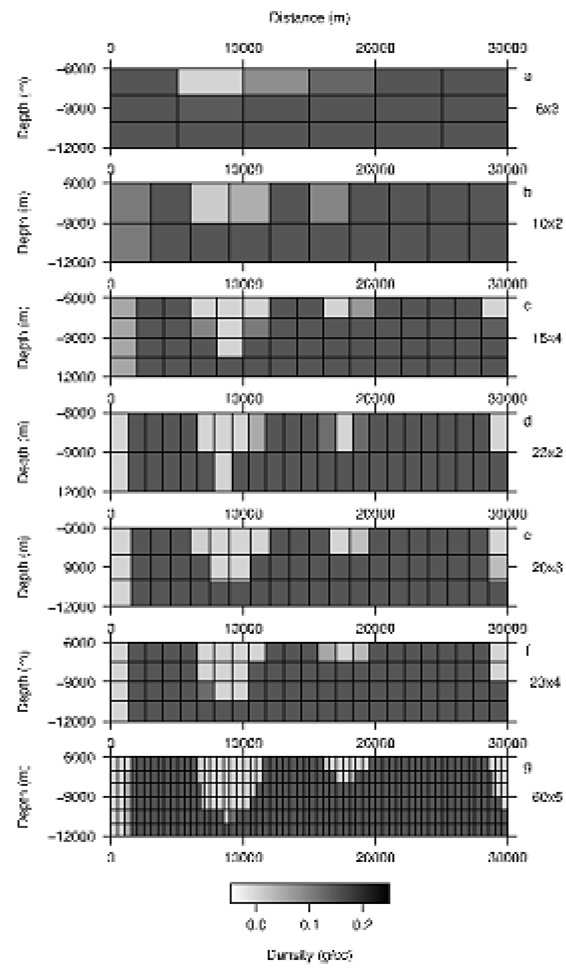
The sub-surface images resulting from seven runs of this constrained inversion, using the same set of parameterisations for the sub-surface volume as before, are summarised on the right. The data fit (circled in the figure above) worsened slightly – not unexpected, as there were extra constraints now to be satisfied. Note, that the 60 (20x3) cell solution, our favourite, did not change, as can be seen comparing it with the figure on the previous page. This too was expected, because the earler, unconstrained solution, already satisfied the constraint added later; it did indicate the robustness of the LP-algorithm used though, as it searches for the best solution through the feasible set.

All the constrained images, except the clearly underparameterised 18 (6x3) cell case, indicate two depressions in the basement topography. These appear to be robust features, their lateral extent better constrained than their depth. Many of the earlier geometrical gravity modelling (by Shell. Not shown), using a large number of thin bodies gave similar results.

During the pre-processing, the sedimentary overburden was treated as having a constant density. Fortunately, this does not seem to have affected the inversion for the target-volume in this case. The effective linear trend determined from this data agrees with the general dip of the sedimentary cover atop the basement.

Conclusion

- Structural Inversion of gravity data, using Linear Programming was able to image basement topography underlying sedimentary cover.
- The images, using different parameterisations, were robust, and indicated presence of two basins.
- The results are in agreement with gravity modelling studies, and give support applicability of *LP-based SI* to real data under suitable circumstances.
- The modifications to the formalism yield additional information and make it possible to process gravity data without accurate knowledge of their processing history; the need to know the depth to the top of the target volume, however, remains.



Acknowledgement

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