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Best Use of Drillhole Log Data for Geostatistically-Constrained Potential Field Inversions

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SUMMARY

This presentation will show some best-practice examples of maximising borehole petrophysical and geochemical log data together with geological and seismic data, to produce ideally constrained 3D starting geological models for inversion with magnetics, gravity and gravity gradients. Results have far-reaching implications for targeting of Uranium and Base Metal Mineralisation, as well as producing extremely well-constrained Basin and Basin Density models, and even predicting mineralisation away from known drilling. The presentation will highlight approaches to problem-solving for 3D inversion in different geological contexts with some recent modelling examples from both industries, using novel geostatistical modelling with domain kriging, wavelength and residual filtering, and gravity, gravity gradient and magnetics data. The presentation will also demonstrate how the results of inversion and modelling can be used in exploration targeting at earlier stages with significant application for the Uranium industry and other types of exploration.

Introduction

This presentation will show some best-practice examples of maximising drillhole petrophysical and geochemical log data together with geological and seismic data, to produce ideally constrained 3D starting geological models for inversion with magnetics, gravity and gravity gradients.
The majority of inversion algorithms currently in use for potential fields rely on deterministic methods similar to those of (e.g. Parker and Huestis, 1974; Li and Oldenburg, 1996; 1998a) These types of computations can be made very rapidly in 2D and 3D with modern computing methods, but often lack a priori knowledge of the geology and petrophysical properties, leading to high degrees of geological uncertainty. Solutions can be refined by drilling data, seismic horizon picks, rock sample analysis, iterative property weighting (Geosoft, 2013) and fast automated depth solutions such as Euler Deconvolution (e.g., Reid et al, 1990) or Tilt-Depth (e.g., Salem et al, 2007) amongst other techniques.
More recent stochastic inversion techniques (e.g., Guillen et al 2008) have advantages in that they typically use 3D voxel models of pre-defined geology or geological rock properties as input, which provide far better initialisation conditions. Probabilistic geological and geophysical misfit conditions are used to discard less likely solutions. With the advent of more powerful processors and the multi-threading of computations, it is now possible to construct very detailed input 3D geological models and retrieve and review modelling process in very reasonable time frames. More plausible geological starting models means that inversion has a much greater success in predicting lithological and petrophysical changes and testing model hypotheses. As this paper will demonstrate, taking advantage of geostatistical analysis of downhole drilling logs to generate and constrain geological models can significantly enhance the reliability of input geological models and provide a testing framework for inversion results in most geological scenarios.

Geological and Geostatistical Methods

The primary software for geostatistical and geological modelling and subsequent geophysical forward and inverse modelling used in these case studies is 3D GeoModeller**. However the methodology outlined here is intended to be more generally prescriptive for advanced inversion case studies. 3D GeoModeller software interpolates between geological boundaries, structural data and drill holes to generate easily adaptable 3D geological models. The geostatistical method of co-kriging uses observed geology contacts and geology gradients (dip and strike) to interpolate the geology in 3D (Calcagno et al, 2008). For the purposes of potential field inversion, the implicit function based geological model is discretised into a 3D structured grid or block model with dimensions that reflect the target spatial resolution of the potential field grid. Historically, geological information supplied for this type of modelling has come from field mapping and GIS, digital elevation and geophysical grid interpretation, structural cross sections and drillhole logs.
Geostatistics has long been used in resource modelling work and more recently hydrocarbon studies. However use of these techniques for more general 3D geological modelling has been less common. Interpolation of virtually any type of drillhole log data, for example geochemical logs, density, susceptibility, impedance, conductivity, temperature, amongst others, can predict, with an estimate of uncertainty, a great deal more information about the subsurface. It can be used to verify or identify geological and geophysical trends, provide the basis for generic 3D petrophysical models and provide links and substitution models for linked physical, chemical and geological inferences.

The modelling techniques involved in these studies included simple inverse distance modelling, radial 1D and 2D kriging, and Domain kriging. Of these, attention is drawn to Domain kriging, which exploits the geological pseudo-potentials trends generated by GeoModeller's implicit modelling functions (Guillen et al, 2011). Instead of classical kriging which is performed in 1, 2 or 3 fixed directions or by radial basis functions, the interpolation function follows the pseudo-potentials defining the shape, direction and thickness of specific geological units or series (Figure 1). When interpolating measured or derived data, the grid is filled according to the variogram function pertaining to each geological unit. This has a clear advantage in defining a 3D input petrophysical grid in areas of more complexly defined geology without having to resort to inferences about anisotropy, as the predicted geological trends inform the property interpolator. Where information about an important physical or chemical parameter is limited but related to another that has been more reliably measured by logging or chemical analysis of log samples, domain based interpolation can suddenly become critically important.

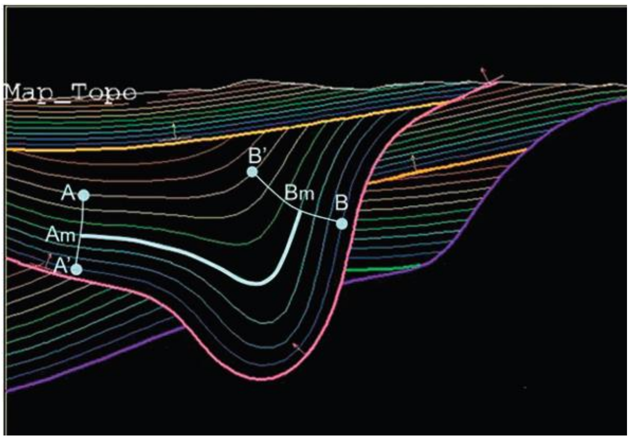

Figure 1 *Curvilinear distance between two points A and B: Point A is on the isovalue potA, point B is the isovalue potB. The distance dg (A,B) is the length of the arc AmBm (in blue) at isovalue potM = (potA + potB)/2. The distance dg (A, B) is therefore defined as dg (Am, Bm).*

Examples with Potential Field Inversion

In the rift basin modelling example shown in this paper, the geological input data comprised only 2D depth-migrated seismic horizon picks and 8 wells. The wells themselves act only as interface boundary fixed control points, highlighting the sparseness of geological information in basins, unless one is able to take advantage of the downhole log information as well as seismic. Interpolation from seismic horizons and wells was sufficient to build a fairly robust 3D geological model, which was later tested by inverting for the Gzz component of the FTG gravity data at the best resolution available at the time, 150x150x100m on a single processor notebook. Density information was originally obtained by statistical analysis of downhole logs from 6 wells. Means and standard deviations for each formation were extracted from the data and supplied into the geophysical modelling as constraints along with the model itself.
Re-visiting the project in 2013, the input density logs were instead converted to regularised 1D downhole grids and a variogram of the sequence densities computed for all the wells. This was used as a basis for Domain kriging of the basin densities throughout the model and creating a new initial 3D density model as input for stochastic inversion. Inversion was computed on 3 components of the FTG tensor simultaneously at 100x100x25m on 8 CPUs. Products produced were an optimised 3D basin and basement lithology voxet and a density cube. (Figure 2). There is compelling improvement in this work, which derives directly from the use of Domain kriging as well as multi-component inversion.

Another example shown is from a shallow Uranium deposit in South Australia, the Blackbush deposit. Uranium was discovered from drilling into Tertiary sediments above a strongly radiogenic basement granite between 60 and 80m depth. The Uranium lies in a palaeochannel flanking a local basement high in the granite. Although the mineralisation had been defined principally by pattern aircore drilling, gravity data had also been collected across the area at spacings between 100m and 25m. A study was commissioned to determine if gravity was able to play any role in defining either the deposit itself or at least the geometry of the basin and density contrasts defining palaeochannels and basement highs.

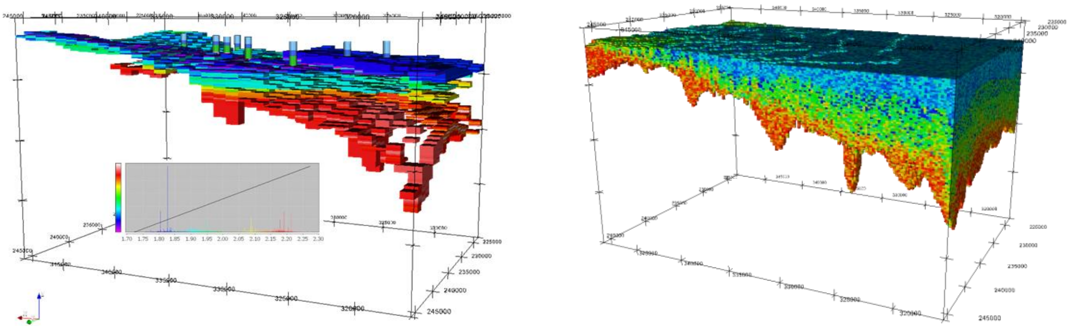

Figure 2 *Domain kriged basin well densities (Left) and basin densities post-inversion (Right).*

Gravity data were first terrain corrected, gridded with variable density techniques (Intrepid, 2013) and then residual filtered using power spectrum techniques (Spector and Grant, 1970) to create a residual grid containing shallow signals representative of the upper 200m. A 3D geological model was created over the deposit area using data from ~120 drill holes, all of which were logged for U3O8 abundance but only a dozen were logged for density. Statistical analysis of the limited density logs identified average density distributions for the individual formations, but although density spikes were present at the Uranium mineralisation intersections, there was not enough information to model the Uranium density. Comparison of the logs with U3O8ppm revealed consistent correlation of density spikes where U3O8 was greater than 1000ppm. Radial kriging of the U3O8 data above 1000ppm generated a 3D grid of Uranium mineralisation. This was converted to a 3D grid of assumed density using a linear regression function from correlation with the density logs.
In the addition to these processes, a Forward Gravity Model was computed from the 3D Geological Model generated from drilling, using the identified formation and granite densities, but not taking into account the Uranium density model. The misfit between the Forward Model and the Residual Gravity used as input for modelling revealed a prominent positive gravity anomaly in the centre of the model, which when compared to the 3D Kriged U3O8/Density models showed a near- identical shape and distribution (Figure 3). This was a clear identification of the Uranium deposit from the gravity data. A subsequent stochastic inversion of the model, using the gravity data and incorporating the 3D grid of Uranium Density into the model, reorganised and distributed the Uranium mineralisation in a consistent manner to that predicted from resource modelling. The implication of this study is that possibly for the first time, a subtle signature of a shallow Uranium deposit of moderate size can be detected from appropriately collected and treated gravity data, if the 3D geology is modelled first. This may lead to future pathways for exploration for shallow Uranium.

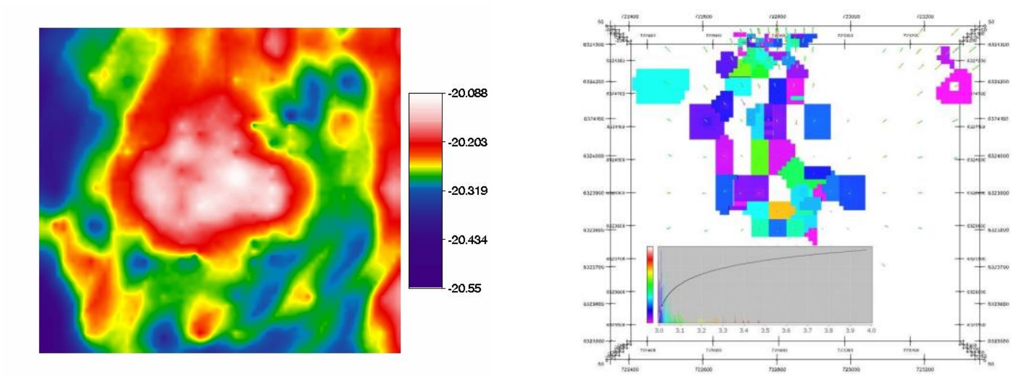

Figure 3 *Difference in Bouguer Anomaly between Input Gravity and Forward Modelled Gravity without Uranium (Left) and Top View of 3D Uranium Pre-Inversion Kriged Density (Right).*

Conclusions

These examples serve to illustrate that there are many ways to exploit downhole drilling data for the purpose of potential field modelling. Whilst this paper is not an examination of inversion techniques itself, it suggests very strongly that even if your data is fairly sparse, creating an initial 3D geological model and populating it with petrophysical properties is going to lead to a far more reliable set of solutions from inversion. At worst it can be used for hypothesis testing, at best it can extend as far as predicting mineralisation or geology related to in a well-constrained fashion, or even identify approaches to deposit detection and general exploration. Geostatistical property modelling can add significant quantitative evidence to geological scenarios and initial geological models where geometries and lithologies were previously unknown. It can also be used to assist in identifying impedance contrasts due to stratigraphic or facies changes in 3D, and provide geometrical and domain-bounded petrophysical models with more accurate trends. With some imagination and recognition of correlations between geochemical and geophysical log parameters, mathematical treatmeant of voxel grids can lead to much more improved model initialisations. The future of 3D potential field (and other geophysical) inversion modelling best practice is intimately linked to creating good 3D geology models and taking advantage of geostatistical methods.

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