A STUDY OF PARAMETER COUPLING IN MT AND GRAVITY JOINT INVERSION FOR GEOTHERMAL EXPLORATION

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Keywords: *Magnetotellurics, gravity, resistivity, density, joint inversion, geothermal exploration, sub basalt imaging*

ABSTRACT

Joint inversion techniques may be used to refine the geological model derived from the analysis of different geophysical techniques. In geothermal exploration, magnetotellurics and gravity data are among the most common data acquired to characterize the geothermal resources. The problem of non-uniqueness of magneto-tellurics and gravity inversion can be addressed through joint inversion of both data with a proper choice of parameter coupling techniques between density and resistivity. While there is no obvious reason to correlate one to one electrical resistivity and density values, there may be geological clues to expect similar resistivity and density features. We test a series of stochastic correlation techniques between the parameters and their spatial gradients to provide the required constraints to obtain a distribution of density and resistivity values. The approach is tested on field data from different geological settings.

1. INTRODUCTION

The purpose of joint inversion is to combine the advantages of two or more techniques in order to improve a geological model by the joint analysis of the different techniques carried out separately. Joint inversion between various types of geophysical data (MT, EM, gravity, seismic, …) is actively developed in the oil&gas industry (e.g. Colombo et al. 2008 , Tarits et al. 2015) while not yet much used in geothermal exploration.

Geothermal exploration relies partly on geophysics to identify potentially valuable reservoirs. Among the geophysical techniques available, magnetotellurics (MT) is cost effective and an efficient technique to image resistivity at depths over several 100 m and is commonly used in geothermal exploration to help understand the distribution of permeability and hydrothermalism associated with geothermal reservoirs. Gravity surveys often complete MT surveys to help map the geological units and the fracture zones. The basic conceptual model of volcanic high temperature geothermal systems includes the presence of a highly conductive clay cap above the geothermal reservoir resulting from the alteration of the embedding rock matrix through which water and gas flow (e.g. Cumming 2009). Knowledge of the geometry of this cap is important to understand the geothermal system. Thus the primary target of EM techniques is to map the base of the clay cap.

The diffusive nature of the induced electromagnetic field measured by MT makes the resolution of the resistivity decreases with depth. Furthermore the highly conductive top layer makes it difficult to accurately image the structures below the cap. It is through the combination of these data with other geophysical, geological and geochemical data that a suitable conceptual model is produced, which helps evaluate the resource and decrease the drilling risk.

Gravity is another type of data commonly acquired in geophysical exploration. Density models derived from the analysis of gravity survey results provide insights in the geological units and fracture networks provided significant changes in density exist in relation with the geology. For instance in geothermal studies density derived from logging is observed to vary within the alteration zone and is a good indicator of the maturity of the geothermal system (e.g. Frolova et al. 2010).

Here we address the joint inverse problem of gravity and a 3-D imaging technique such as magnetotelluric. Gravity is a potential field with no vertical resolution because it is the result of the sum of attraction of all masses on a single point. As a result, gravity data (once reduced to a free air anomaly for instance) may be exactly modelled by a surface sheet of variable mass. In order to obtain information on the actual depth of the mass distribution, hypotheses must be introduced or external data must provide a 3-D (or 2-D) geometry of areas in depth with density contrasts. This problem is often treated through the joint analysis with a 3-D imaging technique such as seismic which provides interfaces between which the density may change. One downfall of this approach is that there might not be a one to one relationship between the electric (or other) properties contrasts and the density contrasts.

In order to progress with this problem, we developed techniques derived from the joint inversion in which the geometrical constraint is provided by MT through various coupling between parameters and their spatial gradients. In other words, the MT model provides a framework of interfaces supplied mathematically to the 3-D gravity inversion. Density values are determined to match the free air gravity anomaly while satisfying on average a relationship with the MT resistivity model or its gradients. The difficulty of joint inversion stands in the definition of proper coupling laws between parameters namely resistivity and density in this study. Under the assumption that there must be some degree of correlation between the distribution of resistivity and density, we designed a series of geometrical coupling terms spanning various correlation scales both on the parameters and their spatial gradients. Because these couplings are enforced only as an average over the study area, the resulting density model is not a reproduction of the resistivity model but instead combines features mainly resolved by density (such as vertical fractures) and structures with common features in resistivity and density (such as the low resistivity low density structures).

We present two case studies in a different geological environment. The former case study is in Afar and addresses the problem of sub basalt imaging in oil&gas exploration with the unusual situation of a conductive volcanic mask. We reveal with the joint inversion that the conductive volcanics mask sediment depot centers. The second case study is a geothermal target in the Caribbean region. We test how the resolution of the clay cap description may be improved with the joint inversion.

2. METHOD

2.1 Tri-dimensional Magnetotelluric inversion

The MT method is very sensitive to three-dimensional (3-D) heterogeneities in the underground structure which is a great advantage because it offers the opportunity to characterise complex geological structures. We use our inversion algorithm MINIM3D (Hautot et al., 2000; 2007), a robust full tensor 3D MT data inversion scheme that was tested on several real data sets. The parametrization of the study area is driven by the number of sites and the frequency band of the MT data. The technique allows providing a detailed 3-D image of complicated geological contexts such as rift basins beneath thick basaltic screen covers. Since our 3-D inversion scheme does not require MT tensor decomposition, static distortion correction and heavy smoothing technique, it is possible to image upper crustal structures such as border faults, volcanic intrusion or clay caps for example.

2.2 Joint inversion

The basis of any inversion is to define a cost function to be minimized. This cost function is in general the sum of a misfit function which measures the departure of a model from a given set of data and a regularizing term which maintains the model parameters under some constraints (minimum energy, minimum gradient, minimum variance …..). In joint inversion problems, a similar cost function may be designed with additional terms which couple the resistivity and density. If no relationship is known between them, which is in general the case, then a cross-gradient technique may be applied (e.g. Gallardo & Meju 2004):

$$Crossgradient = \sum|\nabla d \times \nabla \rho|^2 \qquad (1)$$

The sum is over all the model cells. Each gradient is a spatial vector and the minimization of this term leads to a minimum angle between the two gradient vectors. This operation means that parameter contrasts are parallelized whenever both gradients are none zero. Compared to other joint inversion procedures published, we use a fully non-linear minimization technique which allows computing exactly the cross-gradient product. This term is actually one end member of a series of coupling terms based on gradients (Tarits et al. 2015). In cross gradient coupling, the gradients are led to be parallel for each node of the grid parameters. The other end member encompasses the whole parameter domain and may be interpreted as a correlation coefficient between both gradients summed over the whole domain:

$$covar^2\,(\nabla\rho, \nabla d)/var\,(\nabla\rho)/var\,(\nabla d) \qquad (2)$$

Depending on the problem considered, the covariance can be computed at different scales from a single node to the full model. In the next sections, this coupling approach will be named "Grad Corr". Finally, when a possible relationship is expected between two parameters, for instance clay content that may decrease both resistivity and density, the correlation between the parameters can be easily enforced in the cost function with

$$\boldsymbol{covar^2\,(\rho, d)/var\,(\rho)/var\,(d)} \qquad \textbf{(3)}$$

In all inversions, and most importantly for the unconstrained (or No Joint) inversion, the grid plays a central role in stabilizing the inversion process. In general 3-D gravity inversion must include grid constraints to be performed (LaFehr and Nabighian, 2012). Here the grid is derived from the MT grid, same slicing vertically and similar mesh grouping with depth so that the product of constant density times the position kernel does not vary much with depth and distance. An example is given in Figure 6. This approach is somehow equivalent to the popular depth weighting function first introduced by Li and Oldenburg (1998) and used in modern 3-D gravity inversion. Our approach is however better suited for the joint inversion than the weighting technique while efficient in unconstrained inversion

3. SUB BASALT IMAGING CASE STUDIES

The Republic of Djibouti belongs to the Afar Depression, in the East-African Rift. Over the past 30 Myr, the Afar Depression has formed the triple junction between three extensional systems, the Red Sea, the Gulf of Aden, and the Main Ethiopian continental rift. Intensive volcanic and tectonic activity affected the region and resulted in a series of basalt and sedimentary sequences (Daoud et al., 2011). In the framework of the geophysical exploration of onshore concessions in Djibouti, Oyster Oil & Gas Ltd has carried out a regional geophysical survey. The objectives were to obtain information on the volcanic and sedimentary units across the Territory. A gravity and magnetotelluric (MT) survey was carried out along a series of 8 profiles across three blocks, with a total of 120 MT and 843 gravity sites (Figure 1).

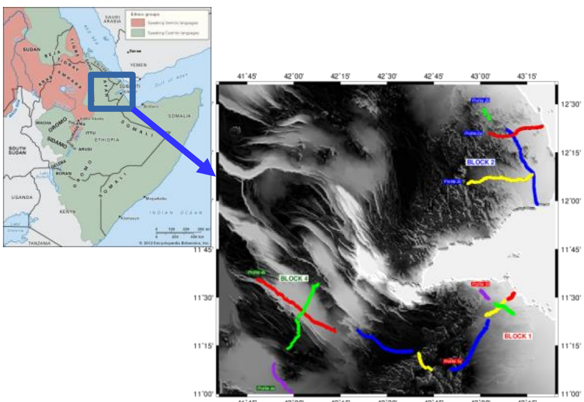

Figure 1: Region of Djibouti and MT/gravity profiles

The heterogeneous nature of the crust in this very active region suggested carrying out 3-D MT inversion along the profiles rather than 2-D inversion. The MT tensors at all sites were indeed highly 3-D. For each profile, the full MT tensor data at all available frequencies were modeled and provided resistivity models with contrasted regions of high and low values. In order to understand the geological nature of these structures, we performed a joint analysis of the MT data with the gravity data acquired along the profiles.

Concerning the gravity data, after reduction to free air anomaly, we considered using the deepest part of the resistivity models to provide a structural framework to obtain the topography of the Moho and remove its effect from the gravity data. Thus the joint inversion was used first to remove the long wavelength in the gravity data using the deep long wavelength structures seen in the MT resistivity model (Figure 2). Starting from the Bouguer anomaly (since local effects are not accounted for in the long wavelengths) we computed the long wavelength apparent Moho topography constrained by the deepest part of the MT resistivity model. Here the resistivity model is not changed while searching for the deep topography with a density 2.67 g/cm3 above and 3.0 g/cm3 below. In Figure 2 we present an example for one of the profiles. The gravity anomaly reduced from the long wavelength effect was used in the subsequent analysis. The plateau and topographic effect were included in the inversion. The density model was mapped onto the same grid as for MT in order to compute the vector gradients for both parameters (density and resistivity).

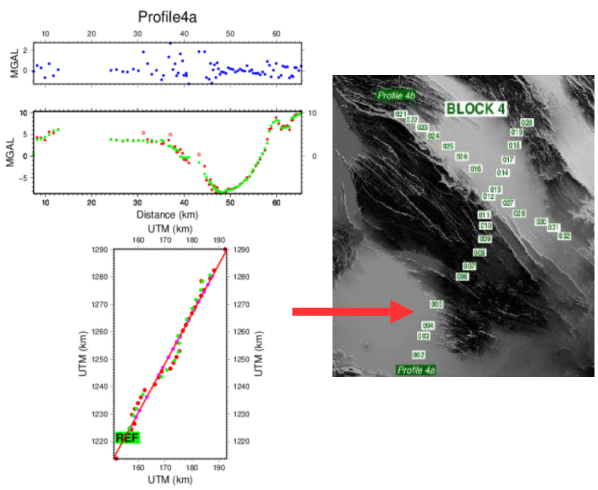

Figure 2: Middle: reduced gravity along profile 4a (red arrow) – data in red, model in green – Top: residual values – Bottom: positions of gravity (green) and MT (red) sites.

The reduced gravity data was modelled using the MT grid and a model of density contrast distribution was sought to fit the gravity data and minimize the cross gradient between the density and the resistivity (Figure 2). The surface of the resistivity model was adjusted to the SRTM topographic model used to compute the Bouguer correction in order to account for the shallow resistivity structures and the shortest wavelengths in the reduced gravity data. The inversion was carried out on the gravity data and the joint resistivity and density coupling term. The control of the effect of resistivity model on the MT responses showed that the changes were negligibly small as long as the MT misfit was kept less or equal to the starting MT misfit alone.

The resistivity model (Figure 3) obtained from the 3D MT inversion shows a heterogeneous conductive shallow layer correlated with the basalt cover in the topographic high. The recent sediments overlaying the volcanics are of similar resistivity. The joint inversion with gravity data provided a density model (Figure 3) that differentiates the dense partly conductive (blue) volcanics. Note that we use here the oil&gas convention for resistivity palette. Furthermore, the rather homogeneous and resistive medium below ~1.5 km (reddish) appears contrasted in the density model with a structure interpreted as a depot centre of resistive pre-rift sediments (Figure 3). The results for the shallow formations show that the structure corresponding to the large negative density anomaly (distance 40-50 km) is not seen in the MT model because there is no significant resistivity contrast.

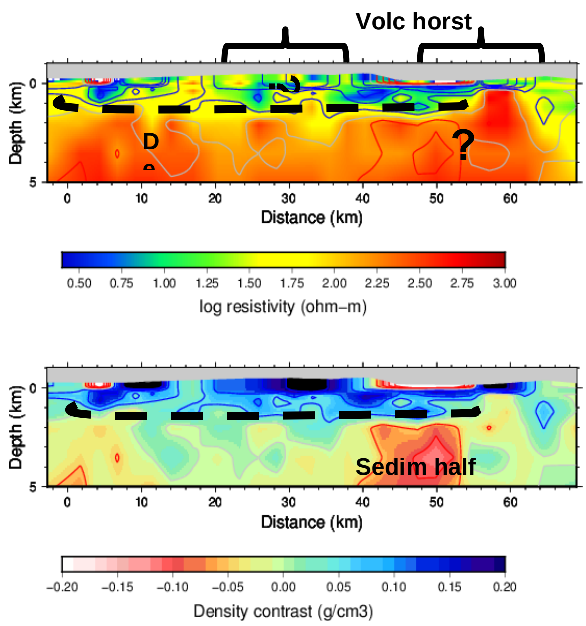

Figure 3: Top - resistivity section along the profile 4a. The contours reproduce the density contrast distribution shown in the bottom panel. Bottom - density contrast model obtained from the joint inversion of MT and gravity data. Oil&gas red/resistive blue/conductive convention used.

4. GEOTHERMAL EXPLORATION IN CARIBBEAN ISLANDS

In the framework of a deep volcanic geothermal project in the Caribbean Sea, MT results (data and 3D resistivity model) as well as gravity data acquired in one of the Caribbean islands were made available to us to test this approach (Figure 4).

A total of 68 MT soundings were inverted in 3-D (Hautot et al., 2000, 2007). The examples of resistivity model results presented in Figures 4,7,8 show the main characteristics of the resistivity structure, namely a low resistivity layer of highly variable thickness across the survey region. The resistivity values are in agreement with the usual clay cap resistivity (Ussher et al. 2000). A database of 279 gravity points is available within the area covered by the MT survey (Figure 4) including the free air anomaly and the complete Bouguer correction. The latter was calculated with a high resolution topography map (5x5 m) and bathymetry data to account for the nearby Caribbean Sea. Finally, a residual anomaly map was computed by removing a mean value. The residual gravity at all sites makes the database for the inversion (Figure 5).

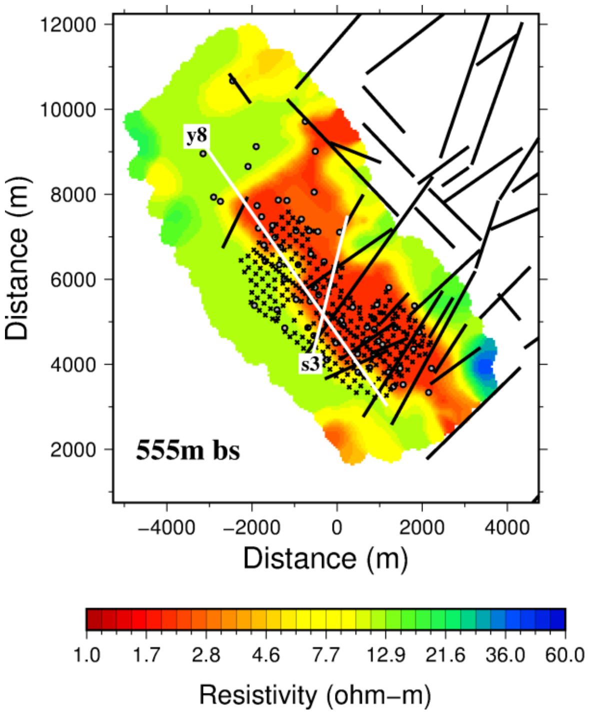

Figure 4: Distribution of MT (circle) and gravity (crosses) data. The background is the 3-D resistivity model 555 m below surface (bs). The black lines are known faults. The white line labeled s3 is the profile described in Figure 8. The label s3 indicates the zero of the profiles.

Once we define the area of gravity data to be analysed, we must decide on a grid for the density model. We tested some mesh sizes for the whole area and found that 100 m was a good compromise between resolution and number of gravity data per mesh. In order to find a density model that fits the gravity data, we defined a 3-D grid and assigned a density value for each mesh. In fact, we seek the density contrast (with respect to a reference density) distribution that fits the residual gravity data. Thus the starting model has zero density contrast. The reference density value chosen for this analysis is 2.80 g/cm^3, a value minimizing the correlation between topography and the complete Bouguer anomaly.

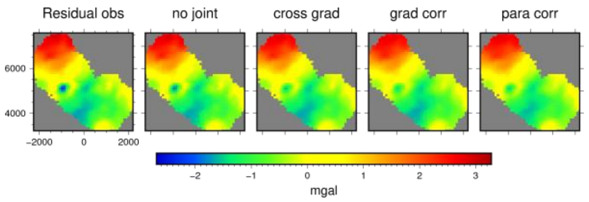

Figure 5: Left most panel – observed reduced gravity field (distances in m). To the right, responses of the density model for all four inversions with mean rms <0.2 mgal. Cross grad from Eq.1, grad corr from Eq.2 and para corr from Eq.3.

The vertical parametrization is critical for the gravity inversion. We used the gridding defined for the 3-D MT inversion (Figure 6) with layer thicknesses increasing with depth to account for the decrease in resolution with depth of the MT field.

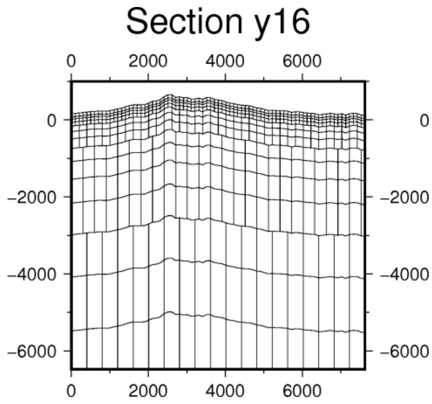

Figure 6: Example of the vertical gridding imported from the MT inversion to the gravity inversion. The vertical axis is the depth below sea level in meter. The horizontal axis is the distance in meter. The unit cell is 100x100m and is regrouped progressively with depth.

Section s3 (Figure 8) presents a thick low resistivity structure which shows up mostly in the density model param corr (Eq.3). The other three density models are rather featureless and not so well correlated with the resistivity at depth. We also note that the thickness of the less dense layer in the param corr model is much thinner than the low resistivity layer, of more limited lateral extent and more clearly centred on an interpreted geothermal up flow. In this density model, we observe structures below the low density medium that are blurred in the resistivity model by the very low resistivity, a common problem in MT modelling where low resistivity layers tend to mask more resistive features underneath.

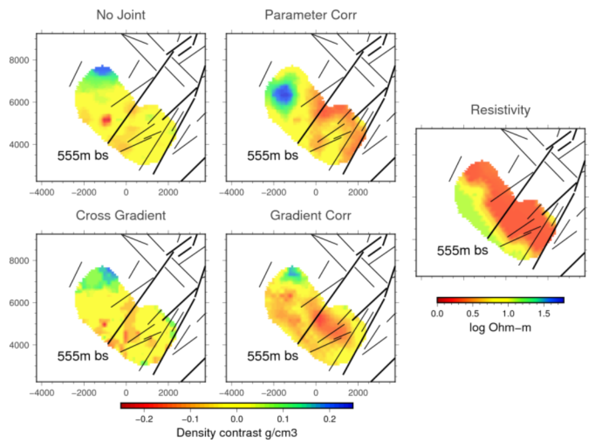

Figure 7: Density models (four left panels) at 555 m below surface (bs) compared to the resistivity model (right panel). Note that the resistivity color scale is in log10 unit.

The rather featureless density models (Figures 7,8) obtained with the gradient technique (cross gradient and gradient correlation) may be understood in the context of volcanic geothermal system. We do not expect large variation of density in such geological context and gradients are therefore small. It is not clear though why the contrast between the low density layer and the background is not more apparent than what we observe. In contrast, the parameter correlation seems to add clear and interesting information on the clay cap. The gravity inversion constrained by the resistivity model seems to add valuable information about the geometry and the base of the clay cap, potentially highlighting more clearly the central part of the interpreted up flow in a zone of widespread low resistivity. Furthermore, it seems to help to better image structures below it that are not well identified in the resistivity model (section s3, Figure 8). The structure beneath the clay cap might be in relation with the fault network linking the deep hot source with the surface.

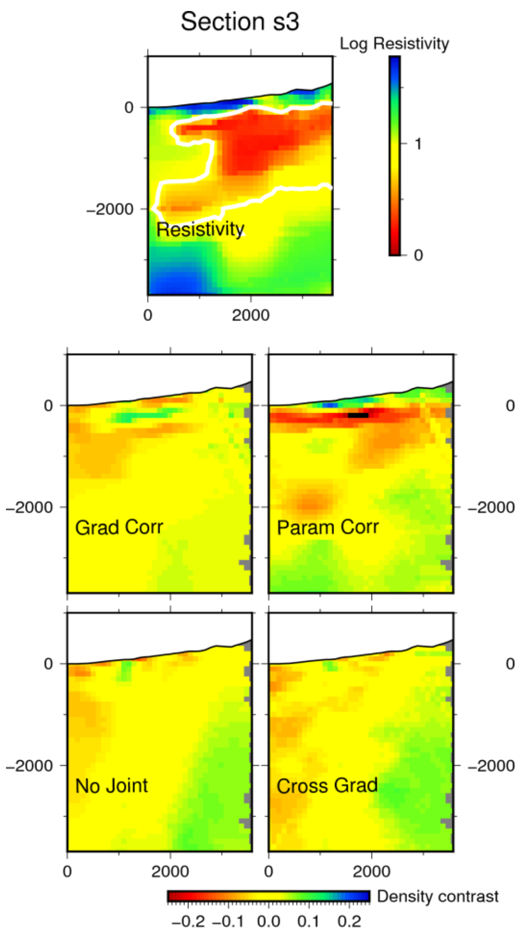

Figure 8: Vertical cross section along two profiles (Figure 4). Comparison between the resistivity model (top panels) and the four density models obtained from the coupled inversion. The No joint correspond to no coupling. Note that the resistivity color scale is in log10 unit. The white contour in the resistivity sections corresponds to 7 Ohm-m. Cross grad from Eq.1, grad corr from Eq.2 and para corr from Eq.3.

5. CONCLUSION

We investigated the capacity of joint inversion of MT and gravity to help the interpretation of the geologic units imaged by MT. The gravity inversion constrained by the MT results using the formalism of joint inversion provides 3-D density models in relation with the resistivity distribution. We are able to image salient features such as the clay cap that forms in volcanic geothermal environment above a geothermal reservoir. In this study, we presented a joint inversion with several coupling techniques between resistivity and density. The couplings are based on both gradients and parameter correlations. We tested the approach on real data in different geological context, sub basalt imaging of masked sedimentary basins in Afar and geothermal exploration in a Caribbean volcanic island. It appears that gradient couplings are efficient if there are strong parameter contrasts. In contrast, the correlation coupling between density and resistivity seems to highlight the clay cap geometry well, with a resulting anomaly more clearly focused on an area otherwise interpreted as hosting a potential geothermal up flow. It also helps visualize structural features beneath it partly hidden to MT.

ACKNOWLEDGEMENTS

We thank Oyster Oil&Gas Ltd and Teranov SAS for their permission to show the geophysical data.

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