Feasibility of multi-scale integrated modeling of potential field data in complex tectonic settings

Seyed-Hani Motavalli-Anbaran[1], Ali Jamasb[2]

1: Institute of Geophysics, University of Tehran, motavalli@ut.ac.ir

2: Institute of Geophysics, University of Tehran, ajamasb@ut.ac.ir

ABSTRACT

Gravity and magnetic data are the sum of the effects of all geological features in lateral and vertical extents. Accordingly, the differences between continental and oceanic settings are quite distinct in terms of their impact on the nature of the data and its processing workflow. Multi-scale integrated modeling is referred to the idea of breaking-down the model building procedure into several steps based on scale and different dataset. Through the use of various dataset with different depth sensitivities, the multi-scale integrated modeling approach is particularly feasible for complex tectonic settings where the signature of the regional structure is dominant in the data.

Keywords: depth-to-basement, gravity modelling, magnetic modelling, integrated modelling,

INTRODUCTION

The recent shift of exploration campaigns towards unexplored and complicated geological settings requires preliminary basin-scale studies which makes the use of gravity/magnetic methods quite reasonable. In the beginning, the information is limited and gravity/magnetic methods are employed within the context of standard processing/interpretation workflow which focuses on regional structural investigations (e.g., Trofimenko et al., 2015). The limits of gravity/magnetic arises from their lack of vertical resolution which makes it impossible to build a unique depth-model by solely using these two datasets. However, as other information layers become available, one can fix parts of the distribution based on reliable a priori information (i.e., seismic sections and/or well information) and try to reconstruct other parts in a way that the total gravity/magnetic response matches the observed values (e.g., Ali et al., 2008). To this end, the interpreter seeks to make sure that a given seismic structural interpretation can satisfy gravity/magnetic data and/or tries to add enough information to effectively remove the depth/density ambiguity (e.g., Azab et al., 2019). The inherent assumption is that the data are carefully conditioned and all unwanted effects are removed from the data beforehand. While this assumption can be achieved in many situations, it becomes harder to reach in complex tectonic settings. This paper discusses Multi-scale integrated modeling as an alternative for standard approximations used in usual gravity/magnetic interpretation.

Multi-scale modeling

The non-uniqueness of potential field data results in building several distinctly varying models all fully satisfying the data (Figures 1-3).

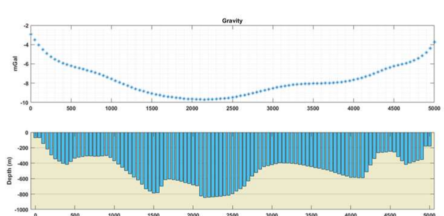

Figure 1: A synthetic model with both long and short-wavelength content (bottom panel). The gravity signature is calculated for a density contrast of -500 kg/m^3 at the surface and a vertical density gradient of 0.3 g/cm^3 (top panel). The model is composed of 100 prisms and the observation points are placed at the center of the prisms on the surface

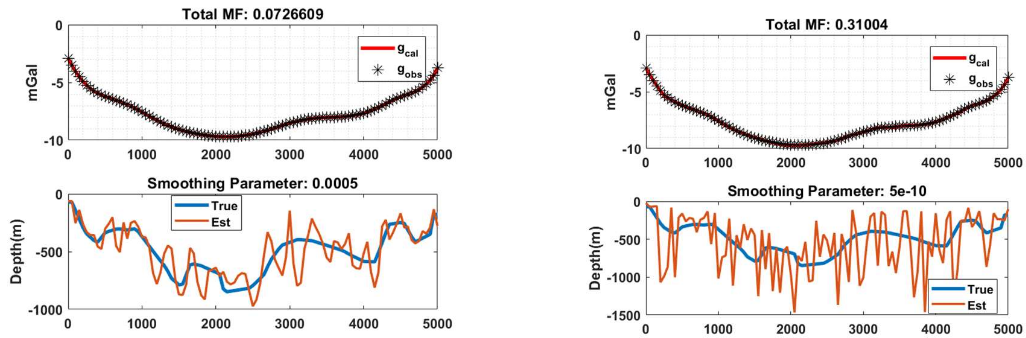

Figure 2 – Two solutions of inverting the synthetic data in Figure 1 (top) using fixed densities via the PSOES algorithm (Jamasb et al., 2019) and randomly chosen smoothing parameters. – MF: Total misfit defined as $\sqrt{\sum_{i=1}^{N}(g_i^{obs} - g_i^{cal})^2}$ with N being the number of observation points (N=100).

The non-uniqueness of the gravity method becomes severer in recovering of short-wavelength basement structural details due to attenuation of the gravity signal with depth. In this case, the recovery of short-wavelength structure can easily get disrupted by non-optimum smoothing weighting (Figure 3).

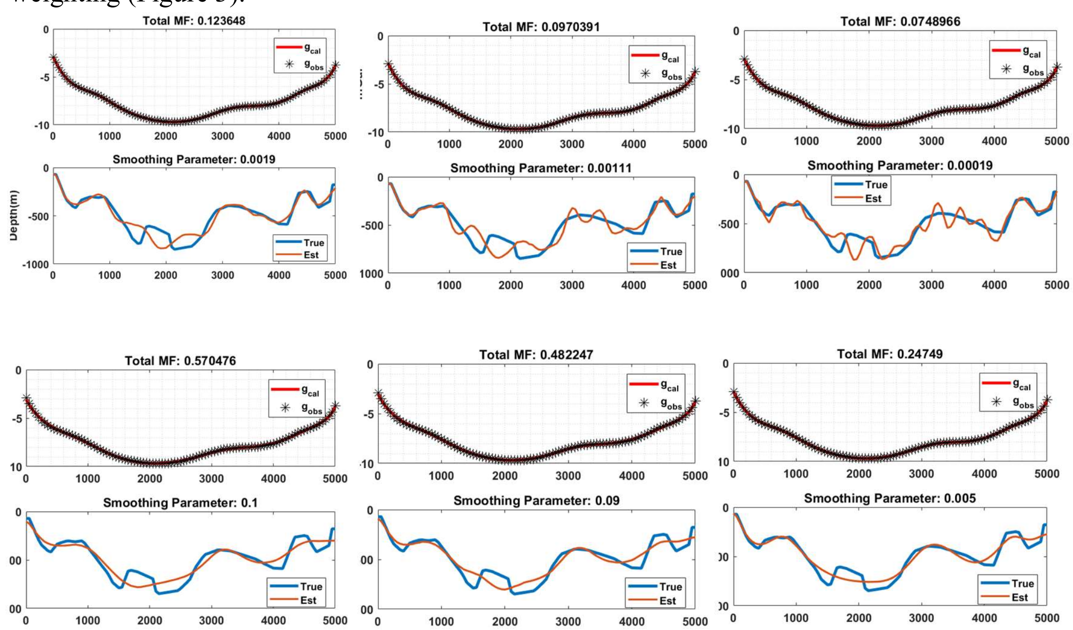

Figure 3: Six solutions of inverting the synthetic data in Figure 1 (top). All inversions are performed with 10 particles and for 2500 iterations of PSOES algorithm (Jamasb et al., 2019). Other than the smoothing parameter everything else is the same for all. The upper-panel shows recovered artificial short-wavelengths due to non-uniqueness of the gravity method and use of non-optimum smoothing parameter. The lower panel shows the distortion of short-wavelengths due to over-smoothing. – MF: Total misfit defined as $\sqrt{\sum_{i=1}^{N}(g_i^{obs} - g_i^{cal})^2}$ with N being the number of observation points (N=100)

This is particularly problematic since the zig-zag behavior of the recovered models in Figure 1 is not geologically interpretable and can easily be managed with the use of a smoothing operator. But non-optimum smoothing weighting can result in a model with arbitrary but fully interpretable short-wavelength features (Figure 3-upper panel). Figure 3 (lower panel) also shows that a too large smoothing weight can result in a long-wavelengths global solution. Multi-scale modeling is the idea of breaking-down the search for a model into several steps based on scale. At first, the scale is set relative to the long-wavelengths and the solution of each stage is then used as the starting point of modeling a finer scale.

Off-shore Studies

Gravity and magnetic data are the sum of the effects of all geological features in lateral and vertical extents. In this sense, the differences between continental and oceanic settings are quite distinct in terms their impact on the nature of the data and its processing workflow. In continents, the assumption of (partly) isostatic equilibrium is safe. Thus, at heights above the M.S.L, the gravity data can easily be corrected for geological noise (i.e., the signature of Moho and Lithosphere-Asthenosphere boundaries in Bouguer anomalies). It is then assumed that the isostatic anomaly only reflects features that either have not yet reached isostatic equilibrium such as sediment loads or short wavelength structures compensated regionally (faults, folding, ore bodies, etc.). However, in many cases, the thickness of an oceanic-like crust and the overlying sedimentary layer are of the same order. In these cases, joining several datasets with different depth sensitivities highly reduces the uncertainties due to any form of filtering/separation and can be considered as an important data conditioning step (Figure 4).

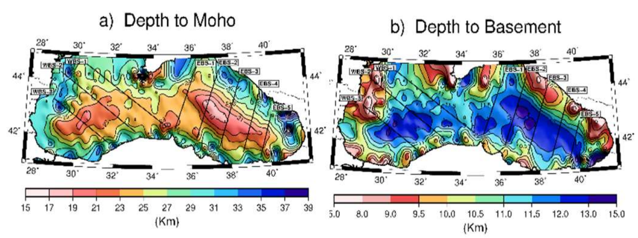

Figure 4 –Depth to Moho boundary and Depth to basement in Black Sea obtained from 3D joint inversion of Bouguer and the vertical gravity gradiometry component (Entezar-Saadat et al., 2020). Gravity and gradiometry data have different depth sensitivities as the gradiometry is a natural high-pass filter. It must be noted that the both gravity and gradiometry are affected by both interfaces (Moho and basement). However, the shallow structure is dominant in the gradiometry data while gravity data show mostly deeper effects. Combining the two datasets provides enough information for a unique tw0-interfaced solution.

Plate boundaries and transition zones

Figure 5 shows four potential field datasets in the southeast of Iran including geoid, gravity, gravity gradiometry vertical component and magnetic anomalies. The gravitational functionals are corrected for both topographic and isostatic effects and the magnetic dataset is reduced to pole shown at H=4 km. The active collision of Arabian and Eurasian plates and the subduction of the Arabian plate beneath Iran are dominantly reflected in all datasets in north-west and south-east of the map, respectively. The geoid data clearly show the extent of the continental collision and its separation from the subduction zone (the Minab fault system). The magnetic data show strong amplitudes over the volcanic rocks of on-shore Makran. The Gravity data show strong amplitudes over the Makran Continental shelf. The signatures of the Makran Subduction zone as well as the obduction of the Oman plane towards the Oman mountains are also quite apparent in magnetic data. The magnetic and gravity data correlate in on-shore Makran as well as in the continental collision zone. The on-going off-shore Makran subduction has resulted in the formation of the Makran Accretionary Prism (Grando and McClay, 2007). Active thrusting is taking place in the toe of the prism. However, since there has not been a collision, it is expected that thrusting is taking place in the sediments without much signature on the crystalline structure. That means the magnetic and gravity data may show different signatures over the prism.

CONCLUSION

The non-uniqueness of potential field data severely increases by geological noise. In this sense, any unwanted geological feature with a considerable signature in the data can be considered noise. The multi-scale integrated approach uses existing datasets and various modeling methods to effectively model this noise instead of using filtering and other standard means. This approach is particularly useful in complex tectonic settings where large-scale tectonic features have a dominant signature on the data.

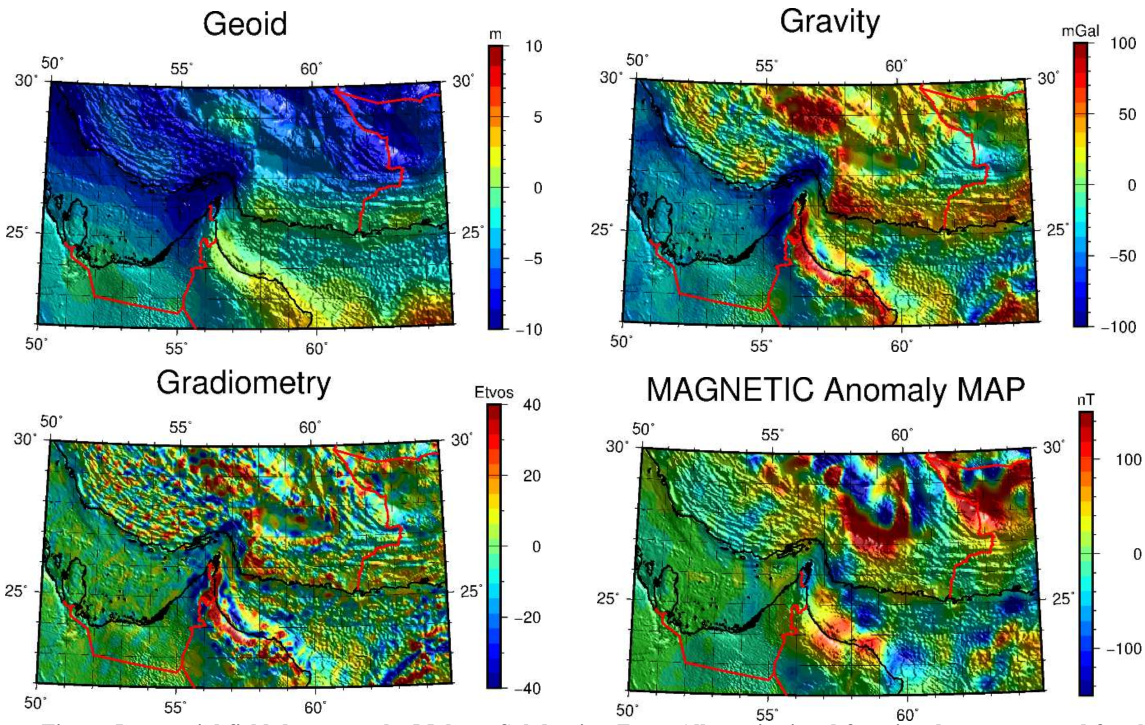

Figure 5–potential field data over the Makran Subduction Zone. All gravitational functionals are corrected for the topographic effect. The magnetic anomaly is reduced to pole. Different Sensitivities are apparent in data maps allowing for unique depth modeling. A topographic shading from the SRTM model is overlayed on all maps.

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