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Model Design for AMT Data Inversion*

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Abstract

By analyzing the characters of the mainstream commercial magnetotelluric inversion softwares in dealing with audio magnetotelluric data, a dynamic model-making method for inversion has been developed based on the observed AMT data. This method focusing on model domain can adjust mesh's scale and model's dimension depending on the field data just with a few parameters. By this, it is convenient to study the geo-electrical anomalies variations of different scale or dimensional models. Applying such model-making technique into the known hardrock geological setting, it is easy to obtain a new geo-electrical model which agrees with the resistivity curves of core samples better than before. It is demonstrated that this can increase the recognition of the resistivity contrast and deserves studying further.

Keywords

AMT Exploration, Making-Model Based on AMT Data, Geo-Electric Structure

1. Introduction

Audio magnetotelluric method (AMT), with simple logistics and no transmitter required, became a key geophysical method accompanying with more kinds of commercial AMT instruments produced in the markets since the 1990s (Yao, 2012) [1]. In the past several decades, one of the sparkles of geophysical exploration is the forward and inversion techniques applied into the field. In the induction electromagnetic exploration field, there were several practicably EM 2D inversion methods applied vastly, such as NLCG, RRI, OCCAM and so on [2] [3] [4]. The hardware and software progress made AMT method to be applied to many fields, such as base metals [5] [6], uranium exploration [7] and so on.

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*AMT, the natural-source audio-magnetotelluric method.

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As general geophysical exploration data process, there are mainly three steps to process AMT data. The first step is to convert each station's time serial data to the frequency domain before calculating the cross power spectrum. Then, the estimation of each station's impedance is followed by seeking a corresponding resistivity model which also satisfies a specified regularization function through inversion. However, many softwares to invert AMT data come from those focusing on MT data. Although the principle is identical for processing two types' data, the anomaly scale to be focused is much different because AMT exploration is about 2000 m depth underground and MT about the deeper and big scale anomalies. Moreover, some commercial software is bounded with several fixed models or will meet memory overflowing when inversing fine meshes. When studying the sand body anomaly among the weak resistivity contrast in uranium exploring by AMT data, an inversion process was outlined using different scale models with checking anomalies [8]. To meet such situations, a simple method of making different scale or dimensional model is required. The paper gives a way of making such models conveniently.

Here, a model-making method based on AMT field data is discussed specially and the main steps for programming are explained in detail. An example of AMT exploring in hardrock area using this model-making method showed that this method was conductive to detailed resistivity anomaly mining and these anomalies agreed with core sample resistivity curves. The paper aims at giving a method to make the model for detailed inversion based on field data, which makes it convenient to study resistivity anomalies variation of models.

2. Model Design

The paper here only focuses on the 2-D inversion problem of finding a 2-D electrical resistivity model that can fit the observed data in two mode's impedances (TE and TM). There are many papers on the fundamental equations for 2D modeling (e.g. Swift, *et al.*, 1971; Zhdanov, *et al.*, 1982; Wannamaker, *et al.*, 1985) [9] [10] [11] so that they will not be re-counted here. The inversion process minimizes a regularized function as the trade-off between a structure penalty function and the data residual norm weighted with data variances (Rodi & Mackie, 2001) [2]. The inversion codes based on these or similar modeling schemes are also widely used (e.g. Sasaki, 1989; deLugão, *et al.*, 1997; Rodi, W.L., *et al.*, 2001) [2] [3] [12]. The paper employed the NLCG inversion scheme of Rodi & Mackie (2001) [2], and electric and magnetic fields are computed using a finite-difference scheme by network analogs to Maxwell's equations (Charles M. Swift, 1971; Madden 1972) [9] [13]. The modelled domain (a user-defined 2D mesh of resistivity blocks incorporating topography) is much larger than the actual region of interest to ensure that the model boundaries are sufficiently far away from resistivity anomalies in order to satisfy the boundary conditions.

There is a coherence relationship between resistivity anomaly scale and that of the model's cell. If the cell grid is too coarse, it may integrate the anomaly and host rock into one cell so that the anomaly is not identified or attenuated. On the contrary, if cell grid is smaller than the scale of the anomaly, it may delineate the boundary between the anomaly and the host rock in detail. However, if the cells are too close, it may produce overburden calculating resource and causes memory overflow sometimes. The problem is that the scale of the resistivity anomaly is unknown before inversion procedure without the prior information.

In order to make the inversion model coherent with the AMT data characteristics, this making model method based on the real field data has the following three steps:

1) To calculate detecting depth of each frequency in all station data of the area or one profile.

2) To configure cells' height. In general, the height of the cells above the minimum detecting depth is set as a constant. The heights of the cells between the minimum and maximum detecting depths are set to a geometric progression, whose first term is that constant height and whose common ratio is based on how much the model dimension to be built. Below the maximum detecting depth, the height distribution is also a geometric progression, but its common ration is at least 0.1 more than that common ration above.

3) To configure horizontal column allocation. Setting two columns in the modeled domain, three columns or more are inserted between neighborly stations based on the AMT observing station space and the model's dimension to be designed. In two lateral zones out of the domain, the spacing between columns distributes also as a geometric progression, whose first term is the spacing between the first and the second column in the domain and whose common ratio is always set as 1.5.

This making model method has several advantages. First, the model made by this way can focus on the modeled domain zone much, especially using bigger common ration beyond the maximum detecting depth and in two lateral zones out of the domain. Second, this method is a solution to designing different scale model. There are two directional parameters to adjust model's dimension. In the vertical direction, one can use different common ratio or set different constant height of cells above minimum detecting depth. In the horizontal direction, one can set the number of the columns inserting between neighborly stations to adjust model's dimension.

For detecting depth is related to apparent resistivity of each frequency, this model-making method is different from that of only using hemi-sphere resistivity value as before and is corresponding to field data's detecting depth.

3. Hardrock Area Example

Due to the high resistivity value in the hardrock area and lack of significant resistivity contrast, it is more difficult to explore resistivity anomaly. However, in this situation, the weak resistivity contrast is related to some factors with many kinds of ore mineralization or safety so that it's significant to detect such anomalies. The following example is about exploring copper with AMT data in hardrock area, but the emphasis here is about how to mine detailed resistivity anomalies varying using the making model method above.

3.1. Geological Setting and AMT Data Acquiring

The AMT exploring profile (D profile) is in the copper ore distric of Chifuma, Kasempa, North-west province in Zambia. The survey area is mainly composed of Katanga group, which is composed of littoral clastic and carbonate rocks and comprises of Lower Roan formation, Upper Roan, Mwashya formation and Kundelungu formation from bottom to top (Figure 1). Lower Roan formation is the oldest stratum which is comprised of felds-quartz sandstone and dolomite rocks of the survey area and emerges at the southern part of the survey area. Upper Roan formation, whose outcrops are in south-west and south-east parts of the studying area, is sandy slate and dolomite rocks. Mwashya formation is the main ore stratum in central and northern parts and is composed of charry stand stone and dolomite rocks which contain much pyrite, chalcopyrite, pyrrhotite and magnetite. Kundelungu formation is mainly metamorphic sandstone and conglomerate in western and north-eastern parts (Gong, Y.S., *et al.*, 2015; Gong, Y.S., *et al.*, 2016) [14] [15].

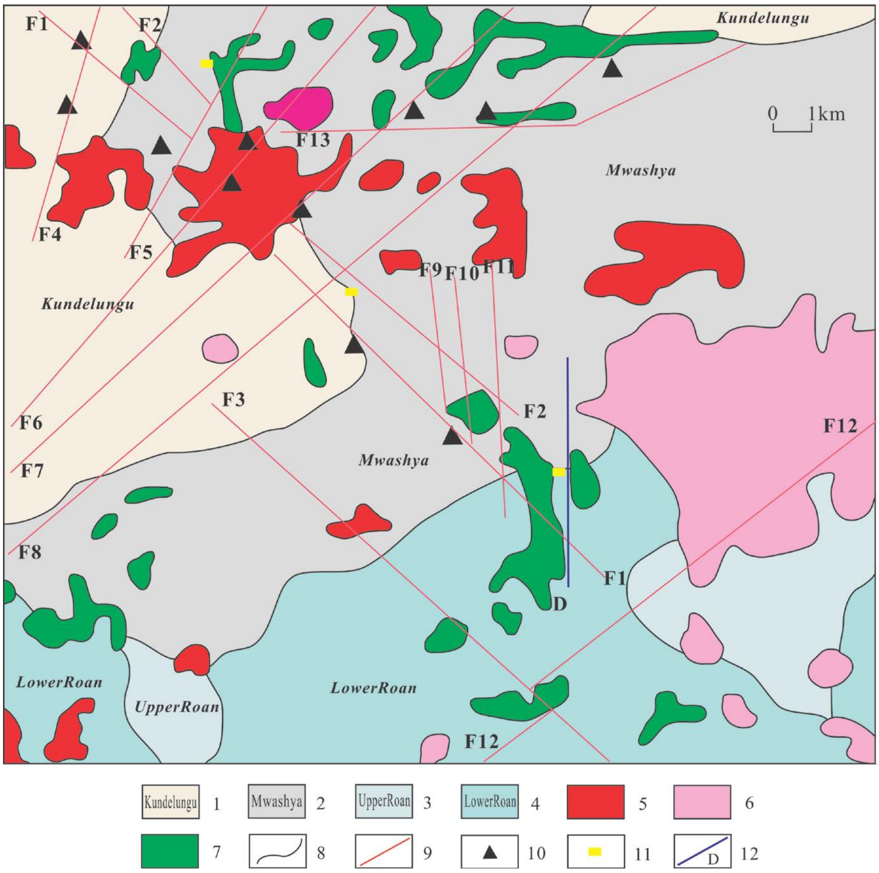

Figure 1. Geology map showing AMT profile and lithology of surveying area. (1, metamorphic sandstone; 2, charrystandstone and dolomite rocks; 3, sandy slate and dolomite rocks; 4, felds-quartz sandstone and dolomite rocks; 5, granite; 6, monzonite; 7, grabbo; 8, geological boundary; 9, fault; 10, Fe mine; 11, Cu mine; 12, AMT profile.) (after Gong, Y.S, *et al.*, 2016 [15]).

A 6 km long D profile in S-N direction was recorded with V8 multi-function receiver and AMTC-30 induction coils of Phoenix Geophysics Limited. The AMT station space is 50 meters and the electrode spacing is 50 meters with the tensor layout using non polarized electrodes. In order to further improve data quality, each station's data were recorded for over 25 minutes. There is little human interference to AMT data recording. The impedance frequencies range from 7 Hz to 8192 Hz.

In the D profile, there were two boreholes 1301 and 1391 at the distance 3100 m and 3600 m respectively. The depth of borehole 1301 is 847 m deep, and 1391 is 1300 m. Core samples at different depth of the two holes were machined into regular cube shape with 2 cm in length, 2 cm in width and 2 cm in high. For these cubes have three opposite faces, measuring resistivity of different opposite faces can be conducive to understanding whether these samples are electrical

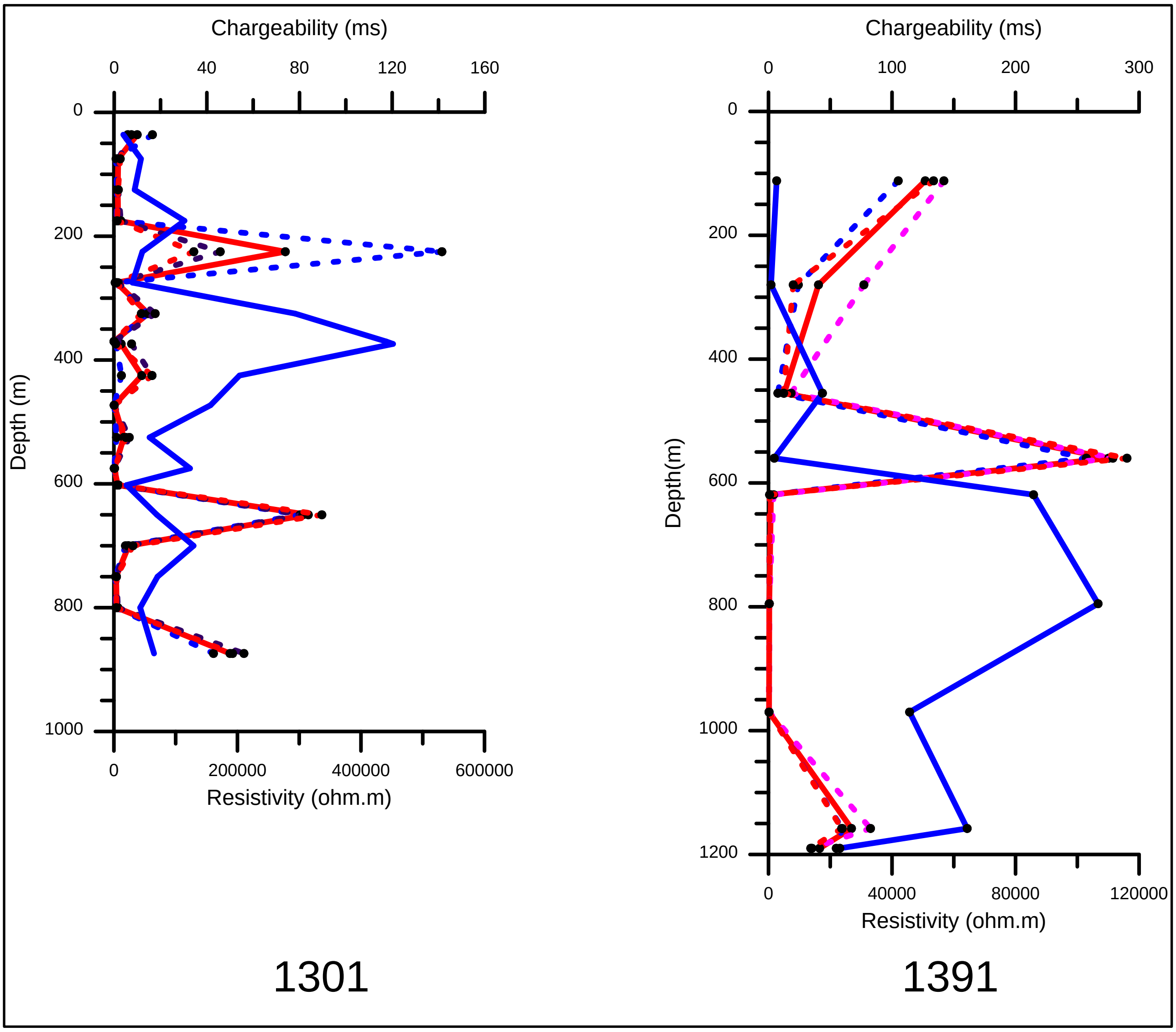

Figure 2. Resistivity and chargeability curves of core samples with depth. (dotted curves, resistivity of different opposite faces; red solid curve, mean of three opposite faces; blue solid curve, chargeability curve) (Data measured indoor).

anisotropy. The resistivity of different opposite faces with depth of the two boreholes shows as Figure 2. Obvious, there are different degrees of electrical anisotropy with depths. Not only the resistivity, but also the chargeability is measured and will be discussed later.

3.2. Inversion Results Comparing

The geo-electrical models inverted from AMT data of D profile represent in Figure 3 (model A and model B). Model A is inverted from general making model method, while model B is inverted from the model by the above mentioned method based on the profile's data with identical inversion program. These two inversion models present the similarity. The resistivity anomaly area and location in the both models are generally identical, for example, near the mark C and D the resistivity value is relatively low. The high resistivity area and conductive area in both models are identical, but also the left and right parts of the both models are high resistivity. The resistivity values in shallow parts of the both model are relatively low, while in deep are relatively high.

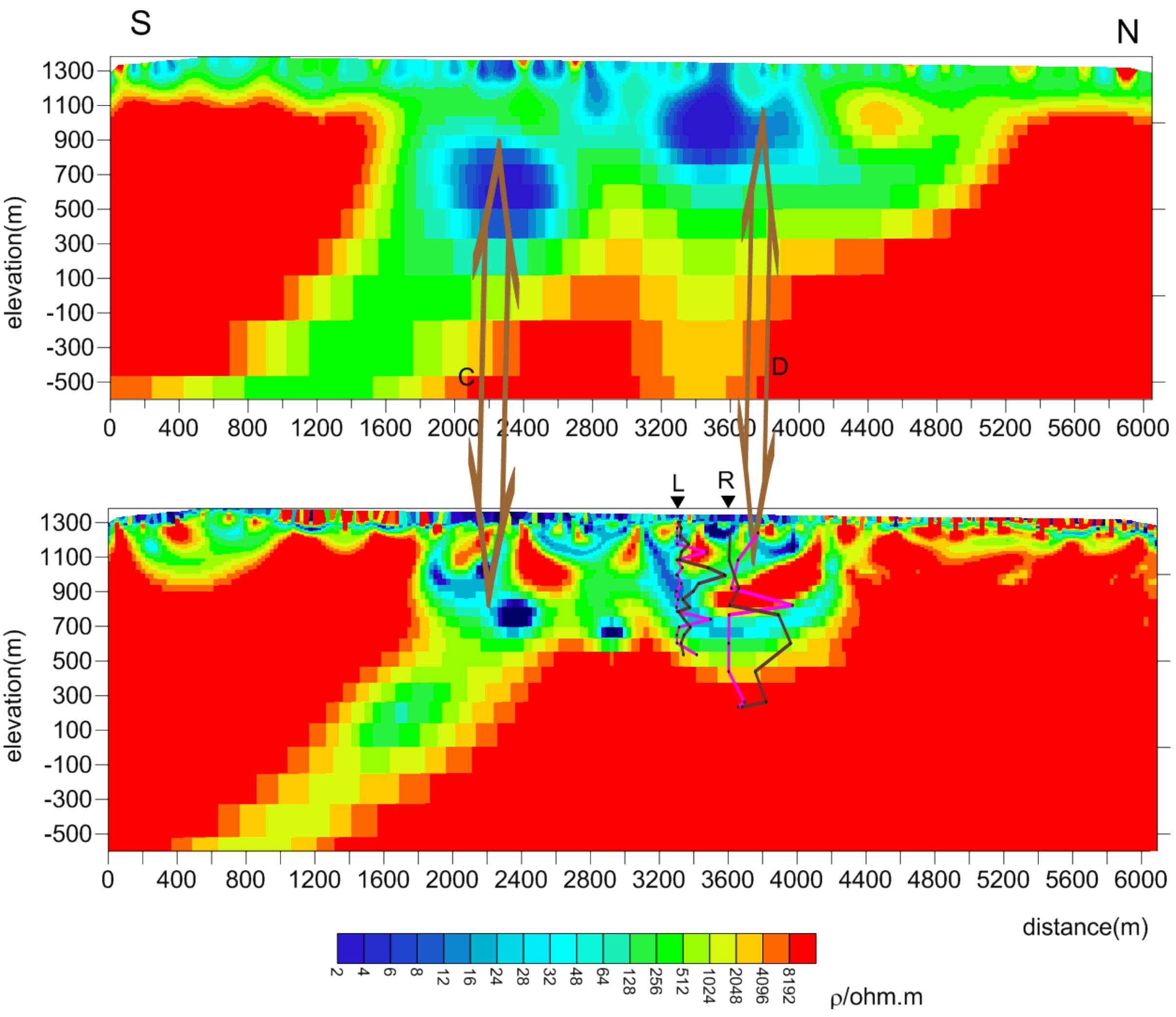

Figure 3. Geo-electrical models inverted from D profile. (model A, using general model; model B, using model based field data).

However, there are clear differences in Figure 3 where the model B gives new and more detailed information as following:

The parts, where the two bidirectional arrows (C and D in Figure 3) point to, are the relative low resistivity areas in both models. However, the parts in model B are mixed with relative high resistivity blocks instead of the only relative low resistivity area. Especially for D pointing at part in the model B, there are three relatively low different value anomalies composed while for the corresponding part in model A there is only a block of relative low resistivity.

The inversion geo-electrical model B (in Figure 3) did not change the general electrical anomaly distribution of the model A, but there appeared detailed information which the model A did not show. By applying dynamic model-making method to the inversion procedure, the relatively low or high resistivity blocks are decomposed into several different anomalies and more small scale resistivity variances are probed.

3.3. Reliability Discussion

In the above discussion, the inversion result's reliability was not mentioned. Here, the core sample resistivity curves will be used to discuss about the reliability. For geo-electrical model inverted from AMT data and the resistivity curves of the core samples are reflected the identical geo-electrical structure, both should be met each other. The resistivity curves from core samples are reliable so that it is one of key ways to check inversion reliability by comparing whether both are agreed with each other.

In order to comparing both conveniently, the core sample resistivity curves are pasted on the newly inverted geo-electrical profile as Figure 3 (L at the location of borehole 1301, R at that of 1391). The pink curves are resistivity varying with the depth and the resistivity value is the mean of three opposite face's resistivity values. The brown curves are chargeability curves.

The newly inverted model (model B) agrees with two borehole core sample resistivity better than model A. The borehole 1391 core sample resistivity curve present decreasing from the depth 550 m downward, then increasing at depth 950m and weakly decreasing at the bottom. At R of the profile in model B, it is clear that nearly at a depth of 500 m there is a high resistivity block whose top and bottom are lower resistivity anomalies. This geo-electrical structure varying agrees with core sample resistivity curve from depth 550 m to depth 1000 m. However, there is a big difference between mode A and core sample resistivity curve from depth 550 m to depth 1000 m. At depths below 600 m, there is a clear chargeability anomaly which is difficult to be explained from the geo-electrical model A; for the high resistivity blocks with high chargeability is unusual. But this is reasonable in the geo-electrical model B because the resistivity is significantly lower than its top and bottom at the corresponding depths.

In Figure 3, the resistivity curve shows higher near depths of 220 m, 650 m and 880 m under the borehole 1301. Near corresponding positions of both models, geo-electrical variation of model B shows such characteristics while that is vague in model A for there is no significantly high resistivity existing.

In this known geo-electrical variation covering the depth of 1200 m, the geo-electrical structure by inverting the model by the dynamic model-making method generally agrees with the core sample resistivity curves. Based on the above analysis and the comparison between geo-electrical models and resistivity curves, the newly inverted model improved the inverting reliability and was close to the real geo-electrical varying underground. There are newly emerging geo-electrical variations in the model B which gives the more detailed geo-electrical varying. Such variation only in some local parts in the model did not change the geo-electrical frame of model A.

4. Conclusions

In hardrock area, especially in granite rock environment, its resistivity is always much higher and the geo-electrical contrast is not prominent. These facts make it difficult to detect the geo-electrical variations. Mining such electrical resistivity anomalies is significant because this kind of geo-electrical variations is usually related to some key problems such as safety factors, some favorable factors for forming ores, and so on.

During the studying period, the reason why the model A did not agree with the core sample resistivity curves was considered as the decreasing resolution ability with the increase of depth based on the principle of electromagnetic field diffusion. But with further study, it was found that using different scale model to be inverted might mine new information that did not appear before. After checking the new anomaly with the known information such as core sample resistivity curves, the dynamic model-making method based on field data for inversion proved to be a valuable study direction. Besides, the ability of detecting the deep anomaly can be improved if the related methods are used appropriately.

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