

Cubic Spline Regularization Applied to 1D Magnetotelluric Inverse Modeling in Geothermal Areas

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ABSTRACT

Electrical resistivity interpretations in geothermal areas typically show a three domain geoelectric structure consisting in an upper resistive horizon, an intermediate and highly-conductive layer (the cap-rock) and a fairly resistive zone, potentially hosting the geothermal reservoir. The clay cap usually give rise to low resistivity anomalies that represent attractive targets for magnetotelluric exploration. Different algorithms are available to get 1D realistic pictures of the geoelectric structure from magnetotelluric soundings, such as blocky/sharp boundaries or smoothed, Occam-type approaches. Here we introduce a new method to model 1D resistivity profiles. In our approach, a cubic spline is assumed to be a realistic approximation of the true resistivity-depth distribution. The advantages of the method are twofold. First, cubic splines need a much smaller number of model parameters to be defined than the layered models used in smoothed inversion algorithms; this can be particularly useful in pseudo 2D/3D inversions or Monte Carlo approaches, where a large number of 1D models must be solved. Second, being the spline intrinsically a smooth 1D resistivity depth profile, there is no need of solution regularization. An example of application of this approach to MT single site data from a geothermal field is presented, and a comparison with blocky and smoothed models and data from a deep exploratory well is made.

1. INTRODUCTION

Underground electrical resistivity distribution is a crucial parameter for the characterization of geothermal settings (e.g. Wright et al., 1985; Muñoz, 2014). Brines and clays that cap a geothermal system derive from prolonged reactions of the rocks with the thermal fluids (Fig. 1), which produce a clay alteration layer over a wide temperature range from less than 100°C to over 200°C (Caldwell et al. 1986). At lower temperatures (70–150°C), the clay cap is mainly characterized by smectite. Rocks containing smectite clays are likely to have resistivities 6 to 10 times lower than rocks with a similar proportion of illite (in acidic rocks) and/or chlorite (more abundant in basaltic rocks) and 12 times lower than rocks with kaolinitic alteration (Ussher et al., 2000). The clay cap usually yields low electrical resistivity anomalies that represent attractive targets for geophysical exploration (Cumming, 2009), especially for magnetotelluric (MT) and/or time domain electromagnetic (TDEM) surveys (Spichak and Manzella, 2009).

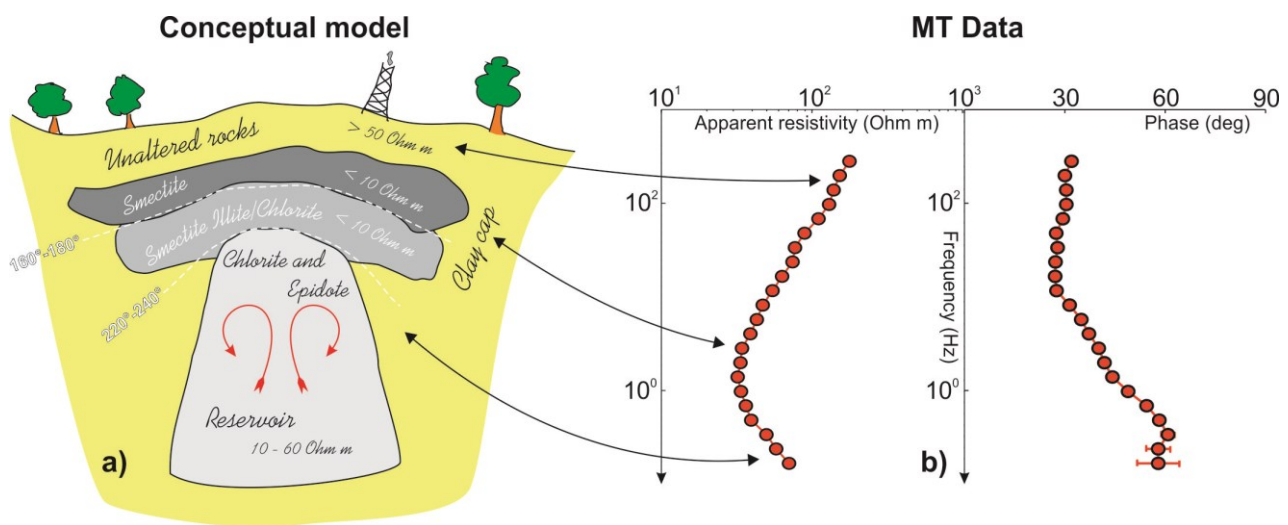


Figure 1: a) Simple conceptual model of a geothermal system (after Pellerin et al. 1996, Ussher et al., 2000; Anderson et al., 2000). b) Example of typical MT sounding (apparent resistivity and phase response) recorded at the Menengai (Kenya) geothermal system (see text).

At higher temperatures, above 180°C, illite and/or chlorite form a mixed layer with smectite and therefore resistivities gradually increase. At temperatures over 220–240°C, alteration mainly yields chlorite and epidote that show a higher resistivity pattern than their lower temperature counterparts (Ussher et al., 2000). Thus, an increase in resistivity beneath a highly conductive shallower

layer (the clay cap), reflecting an increase of temperature with depth, is considered a common signature of high-temperature geothermal systems (Muñoz, 2014).

From a simple conceptual model of geothermal system, as a first approximation, three resistivity 'domains' are expected to characterize 1D MT soundings from geothermal areas. An example of typical resistivity structure is also shown in Fig. 1. The effective apparent resistivity from a MT sounding decreases from the values of the order of 100 Ohm m to about 30 Ohm m and then increases again up to 100 Ohm m. A similar trend can also be seen in the phase curve. The corresponding depth vs true resistivity curve (to be estimated from the data) is therefore expected to be easily approximated by a simple function like a piecewise cubic polynomial spline.

Different algorithms are available in the literature to get realistic pictures of the geoelectric structure from 1D magnetotelluric soundings. Blocky/sharp boundaries models restrict the solution to the class of models consisting of a small number of layers. However such models may introduce large unrealistic discontinuities and therefore smooth models are usually preferred in geothermal exploration because they better match the effective pattern of clay alteration, temperature and porosity. In order to reduce the possibility of data misinterpretation and to eliminate arbitrary discontinuities in simple layered models, the classical approach by Constable et al. (1987) is applied. This approach uses a large number of layers and searches for the smoothest model which fits the data to within an expected tolerance. The major drawback of the method is the large number of free parameters (the resistivity of each layer) that must be estimated. This makes the use of this approach difficult when a large number of 1D models must be solved simultaneously as in pseudo-3D or Montecarlo inversions. Here we propose a new 1D inversion algorithm based on a piecewise cubic polynomial spline approximation of the true resistivity vs depth curve that produces smooth models and allows for few free parameters.

2. INVERSION ALGORITHM

A cubic spline is assumed to be a realistic approximation of the true resistivity-depth distribution. Referring to the simple conceptual model (Fig. 1a) we assumed, two cubic polynomials are usually enough to accurately reproduce the 'high-low-high' pattern of the resistivity-depth distribution. These two cubic polynomials can be described by five free parameters assuming null derivative at the surface, at the connection point between the two polynomial and at depth. By densely sampling the spline at different depth, a multi layered model is obtained and then used to compute the apparent resistivity and phase response of the model to be compared to the experimental data. The five free parameters are then iteratively modified to reduce the error fitting between the calculated and effective apparent resistivity and phase data below a given value. Since the spline is intrinsically a smooth 1D resistivity profile, there is no need of solution regularization. This avoids the subjective choice of the dumping regularization factor.

3. EXAMPLE OF APPLICATION

We show an example of application of the cubic spline regularization to data from the geothermal field of Menengai, Kenya. Figure 2 shows the location of the geothermal site together with the position of the MT station and the exploration borehole analyzed in this section.

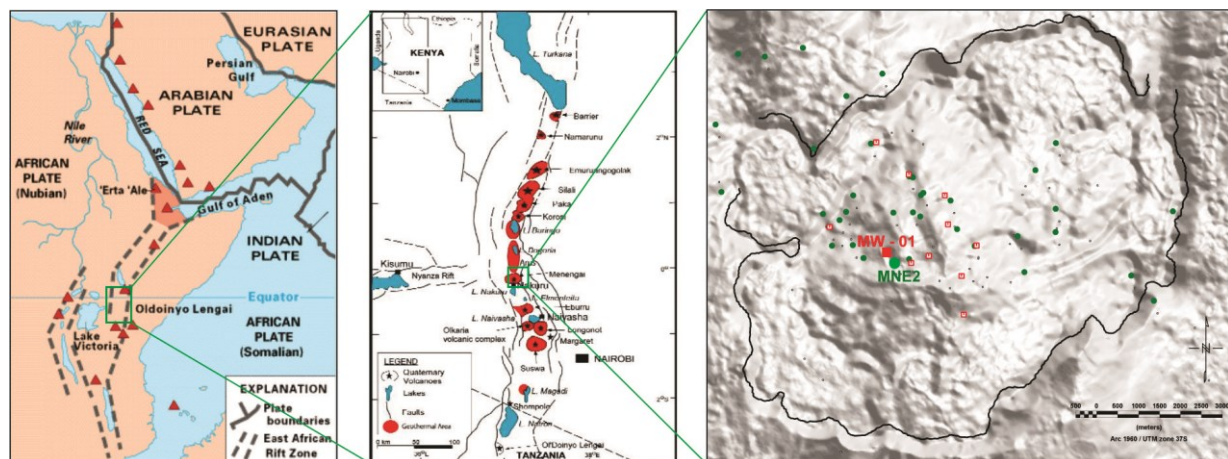


Figure 2: The Menengai geothermal field and location of the main caldera within the Kenya Rift system (left). Position of the MW-01 well (red square) and the MNE2 MT station (green dot) discussed in the text is also shown (right).

Regional exploration for geothermal resources in Kenya indicates that Quaternary volcanic complexes within the Kenya rift provide the most promising prospects for geothermal exploration. Consequently, detailed surface exploration for geothermal resources have been concentrated in these volcanic complexes. The massive Menengai shield volcano is an example of the geothermal fields occurring along the Kenya Rift Valley. The formation of the shield volcano began about 200 000 years ago and was followed by the eruption of two voluminous ash-flow tuffs, each preceded by major pumice falls. The first took place about 29 000 years ago and produced a large caldera. The second major eruption produced a huge amount of compositionally zoned peralkaline trachytic magma about 8 000 years ago and was associated with formation of the present-day summit caldera. More than 70 post-caldera lava flows cover the caldera floor, the youngest of which may be only a few hundred years old. There is fumarolic activity inside the caldera and also at the North Eastern external rim. According to Gislason (1989) the geothermal system is active from about 0.4 - 0.3 Ma. The post-caldera lavas date back to 1 400 yrs BP, but some of them could be even more recent.

The apparent signatures of geothermal potential include the young volcanism represented by the numerous recent eruptions both inside and outside the caldera, the large caldera collapse and intense tectonic activity resulting in intense faults marking the area. The occurrence of active fumaroles, steaming ground and hot/warm water boreholes indicate hydrothermal activity and the possible existence of geothermal reservoirs in the prospect. A recent review of the geophysical, geological and well bores data set acquired over the Menengai geothermal area in the past decades was carried out by ELC (2012). In this frame we focus on the comparison between the electrical 1D MT resistivity model of the MNE2 MT station (Fig. 2) and the data from the MW-01 well, less than 200 m apart.

After static shift correction by means of TDEM records, we have processed the data of MNE2 MT station and found three different possible models that all reproduce the measured effective apparent resistivity and phase of MT data (Fig. 1b) at the same confidence level. Figure 3 shows a comparison between the blocky model (red curve) consisting of five layers, the smooth Occam-type model (green curve) with 35 layers and the spline model (blue curve) made by two cubic polynomials (five free parameters), together with the temperature log recorded in the borehole MW-01.

Both the Occam and the cubic spline models show a similar trend in the vertical distribution of resistivity. The minimum value of resistivity that both curves indicate at about 500 m depth, is well correlated with the sudden change of the temperature gradient. At larger depth, all models show very smooth increase in resistivity that suggests a resolution decrease with depth of the MT sounding. The blocky model has a similar pattern, although the resistivity jumps at 1500 and 3300 m are probably unrealistic, since the Occam and cubic spline smoother models explain the measured data with the same misfit.

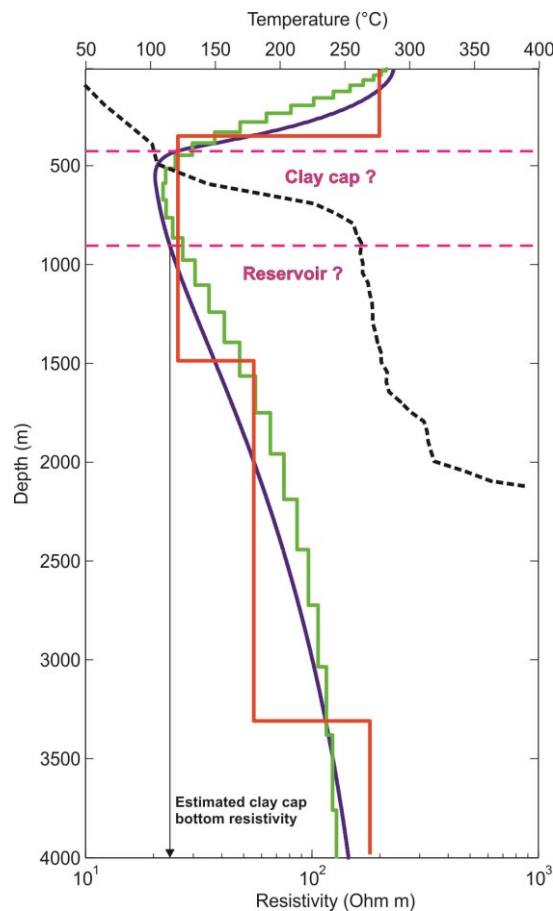


Figure 3: Electrical 1D resistivity models at the MNE2 MT station (see Fig. 2 for location). The blocky (red curve), the smooth Occam (green curve) and the spline (blue curve) models that reproduce the measured data with the same confidence level are shown and compared with the temperature log (black dashed line) recorded 44 days after drilling completion in the nearby well MW-01

The 1D electrical resistivity models can be compared to the stratigraphic records from the MW-01 well (Fig. 4). MW-01 well was the first exploration well drilled in the Menengai caldera. Trachyte with lenses of tuff and occasional syenitic intrusives were found. The shallower rocks exhibit little or no hydrothermal alteration with mainly low temperature minerals (hematite and zeolites). At depth, hydrothermal alteration ranges from moderate to high with calcite, quartz, epidote and illite clays. The first occurrence of epidote has been found at a depth of 824 m indicating formation temperature greater than 250°C. Permeability is good, with the aquifers mainly confined to fractures and faults. Comparison between alteration mineralogy temperatures and fluid inclusions indicate that the system is partially in equilibrium.

The alteration minerals of the Menengai area reflect to a fair extent the temperature measured in the wells, suggesting that the system is relatively young, although some pieces of evidence of recent cooling can be inferred from the appearance of epidote at a

depth of 700-800 m even in wells where the temperature is well below 200°C. The most conspicuous element derived from the analysis of the secondary minerals refers to the configuration of the horizon with epidote, which may be in principle associated with the propylitic zone. Disregarding the irregularities registered in some of the wells, it can be observed that the top of the reservoir exhibits a very well defined dome-like shape, and it occurs at depth > 1000 m a.s.l. in the wells drilled in the central part of the caldera and dropping to <500 m a.s.l. in the peripheral wells (ELC, 2012).

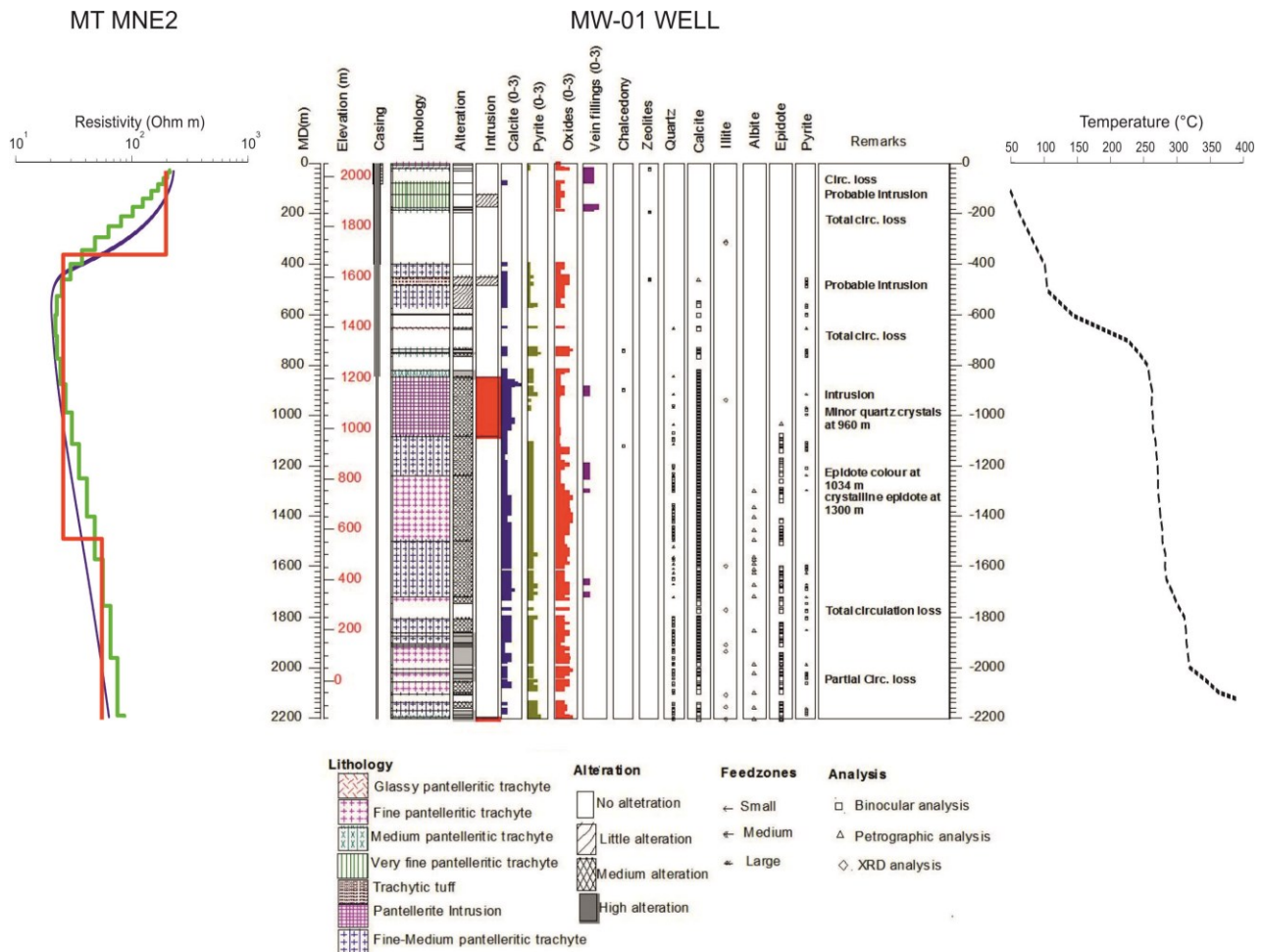


Figure 4: Electrical 1D resistivity profiles obtained at the MNE2 MT station compared to stratigraphic data and temperature log from the exploration well MW-01.

The vertical temperature profile in the hole MW-01 suggests three main domains: a shallow layer up to 500 with a relatively low temperature gradient, an intermediate layer up to 750 m depth with high gradient and a deeper layer with low gradient. Both the Occam and the cubic spline models indicate a minimum of the resistivity that correspond with the top of the intermediate high gradient layer. The intermediate high temperature gradient layer therefore can be associated with a low-permeability and low-resistivity clay cap while the underlying low temperature gradient (higher permeability) and higher resistivity domain may identify the reservoir. The lower temperature gradient and high resistivity at shallow depth layer can be associated with the uppermost rocks showing little alteration.

4. CONCLUSIONS

The cubic spline inversion proposed in this study yielded a smooth model which is consistent with the other two widely applied inversion approaches, especially with the Occam-type one. It can provide fast and reasonable results when a relatively simple, three-layerd geological structure has to be imaged from magnetotelluric data. However, caution should be exercised in the case of complex geothermal environments, where a three-layerstructure may be too simple to properly describe the true resistivity distribution. Therefore the cubic spline method can be applied to geothermal exploration in order to have a general insight of the resistivity pattern. However, the low number of free parameters might permit rapid pseudo-2D-3D laterally-constrained inversions to be used as preliminary models for subsequent more accurate 2D or 3D inversions.

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