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# 3-D Joint Inversion of the Full Impedance Tensor and Magnetic Transfer Function in Atedai Geothermal Area Case

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**ABSTRACT**

Magnetotelluric (MT) sounding is a powerful geophysical method to explore the Earth's interior structure using its electrical conductivity. This method had been done in Atedai geothermal area, Province of East Nusa Tenggara, Indonesia. The existence of geothermal system is characterized by fumarole, hot springs, hot pools, mud pools, hot grounds, and alteration rocks by temperature 35 - 98°C. By using WSINV3DMT code of 3-D inversion. We did full impedance tensor and vertical magnetic transfer function or tipper to represent the 3-D Earth. The computation of WSINV3DMT depend on the size of data (N), not the size of model parameter (M). We use 30 MT stations, 12 number of frequencies, and 48 × 40 × 28 blocks in xyz component to recover this research area. In the end, we compare with or without using tipper in 3-D inversion. Joint 3-D inversion of full impedance tensor and vertical magnetic transfer function is more realistic than without using tipper.

## 1. INTRODUCTION

The magnetotelluric (MT) technique is a passive electromagnetic (EM) technique that involves measuring fluctuations in the natural electric (E), and magnetic (B) fields in orthogonal directions at the surface of the Earth as a means of determining the conductivity structure of the Earth at depths ranging from a few tens of meters to several hundreds of kilometers. The penetration depths of electromagnetic fields within the Earth depend on the electromagnetic sounding period, and on the Earth's conductivity structure.

Geological Agency had conducted MT survey in 2013 to execute 3G (Geology, Geochemistry, and Geophysics) result in 2000. Atedai geothermal area formed in post volcanic activity and controlled by both of structures trending northwest - southeast. Based on the DC method that low resistivity <10 Ωm is located at south, centre, and spread to the southeast part of area that covers hot ground, fumarole, alteration rock, and Watuwawer hot springs. MT measurement focused in that low resistivity which have 30 stations in order to get deeper subsurface information.

MT data processed by using WSINV3DMT code of 3-D Inversion. This algorithm has been developed based on a data-space variant of the Occam approach. Computational costs associated with construction and inversion of model-space matrices make a model-space Occam approach to 3D MT inversion impractical. These difficulties are overcome with a data-space approach, where matrix dimensions depend on the size of the data set, rather than the number of model parameters.

Here, we implement full impedance tensor and vertical magnetic transfer function in order to compare with or without using tipper function. In theory, tipper data can recover anomalous structure. In full impedance tensor, complex frequency dependent transfer function relating to parallel electric to magnetic fields,

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} = \begin{bmatrix} H_x \\ H_y \end{bmatrix} \tag{1}$$

However, modern MT field practice typically includes measurement of vertical magnetic fields (particularly at long periods, where a tri-axial magnetic is used), and thence computation of vertical field transfer functions,

$$\mathrm{H_z} = [\mathrm{T_{zx}} \quad \mathrm{T_{zy}}] \begin{bmatrix} \mathrm{H_x} \\ \mathrm{H_y} \end{bmatrix} \tag{2}$$

The vertical magnetic field is only produced when there are lateral or horizontal variations of conductivity. Researchers have often used a vertical magnetic transfer function in the form of induction vectors (Parkinson, 1959) to indicate or point to the source of conductivity anomalies and to establish or verify geoelectric strike directions (e.g., Bedrosian et al., 2004; Uyeshima et al., 2005 ; Tuncer et al., 2006).

## 2. MT DATA ACQUISITION

Atedai geothermal area lying in the southern part of Lembata Island, and administratively located in Lembata Regency, Province of East Nusa Tenggara. Geological Agency had conducted MT survey in 2013 concentrated in prospective area around Watuwawer manifestations based on 3G survey (geological, geochemical, and geophysical methods) in 2000. The site is underlain by quartenary volcanic formation and has 4 young volcanic cones along north - south, where Mt. Watulolo in north end and Mt. Kedang in south end of part area. The distribution of MT stations focuses to cover Watuwawer fumaroles have highest temperature 96°C and spread to Waiwejak hot springs have 37°C. Total MT measurements is 30 stations in parallel forming 4 lines and cut off main structure that have SW - NE direction.

### 3. MT INVERSION

The inversion algorithm is based on the classic Occam's inversion introduced by Constable et al. (1987) for the 1-D MT and DC resistivity sounding problems. The Occam inversion seeks a minimum structure model (as defined by some model norm which penalizes roughness) subject to an appropriate fit to the data. The minimization is accomplished with a modified Gauss-Newton algorithm, in which the regularization parameter (which controls the tradeoff between model roughness and data fit) is also used for step length control (Parker, 1994). The main advantages of Occam approach are its stability and robustness, and the fact that the scheme often converges to the desired misfit in a relatively small number of iterations (e.g., Siripunvaraporn and Egbert, 2000). The inverse problem transformed into the data space (e.g., Parker, 1994).

Because of non-linearity of the MT inverse problem, an iterative approach is required, based on linearizing $F[m]$ such that:

$$F[m_{k+1}] = F[m_k + \Delta m] = F[m_k] + J_k(m_{k+1} - m_k) \tag{3}$$

where the subscript $k$ denotes iteration number, and $J_k = (\partial F/\partial m)_k$ is the $N \times M$ sensitivity matrix calculated at $m_k$. The data space approach would work effectively if the number of data ($N$) is small compared to the number of model parameters ($M$). As shown by Parker (1994), the solution for iteration k can be expressed as linear combination of rows of the smoothed sensitivity matrix $C_m J^T$, i.e.

$$m_{k+1} - m_0 = C_m J_k^T \beta_{k+1} \tag{4}$$

where $\beta_{k+1} = [\lambda C_d + C_m J_k^T]^{-1} X_k$ is an unknown expansion coefficient vector, and $X_k = d - F[m_k] + J_k(m_k - m_0)$. By solving $\beta_{k+1}$, update the model, and then compute the misfit. All of these calculations are done with various values of λ just as in the model-space approach.

### 3. MT INVERSION RESULT

Initial model of 3-D MT Inversion uses 48 × 40 × 28 blocks in xyz to cover 30 station of MT data, and apply 12 number of frequencies (96 until 0.04 Hz). This MT data is rotated to $50^0$ NE (Figure 1).

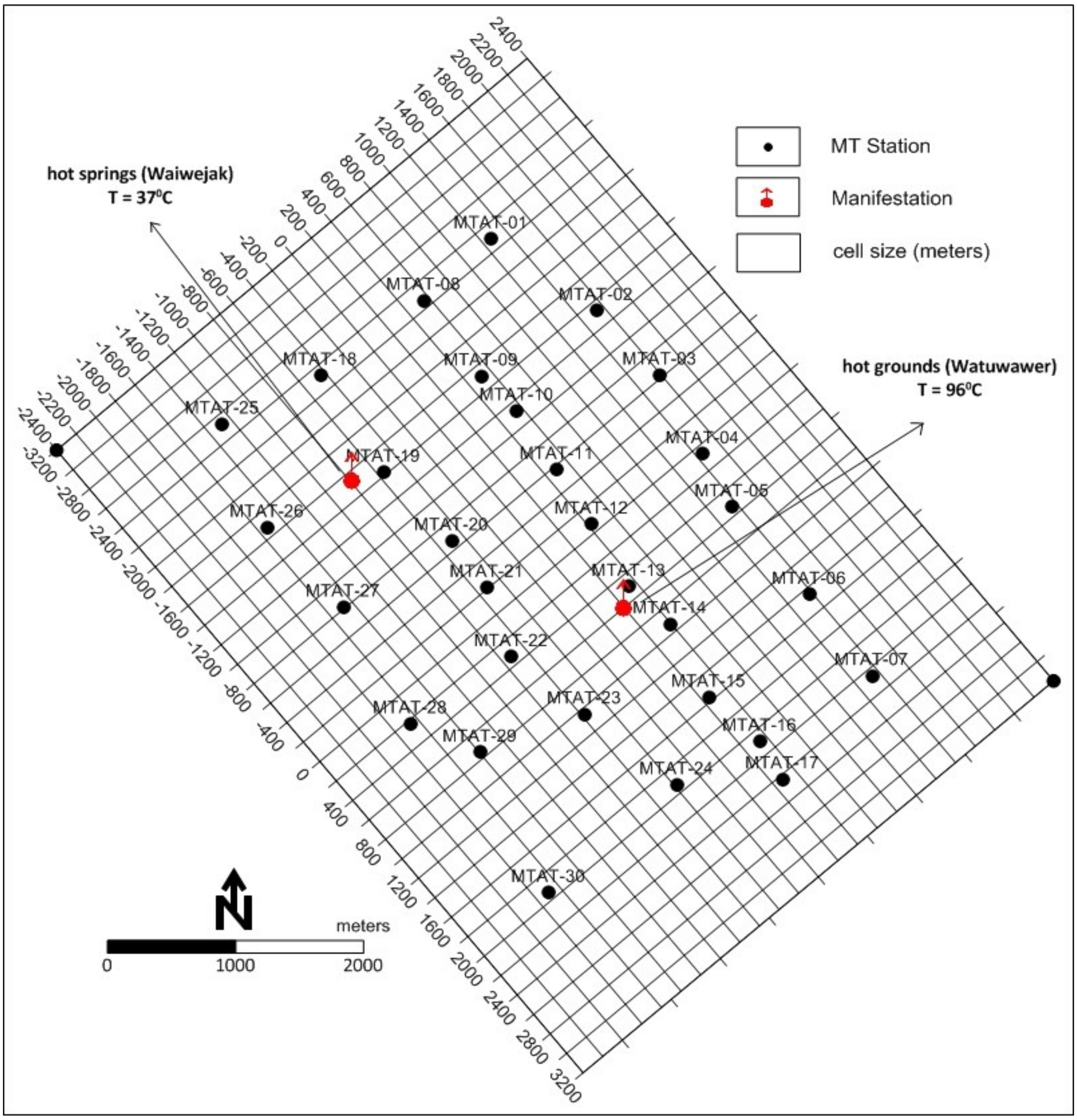


**Figure 1: Initial model of 3-D MT inversion.**

In Figure 2 show that model inversion result with and without using vertical magnetic transfer function (VTF) or tipper. We represent Line-2 and Line-3 because both lines across Watuwawer and Waiwejak manifestations. For both Line-2 and Line-3, model result with and without using VTF are consistent each other over the whole sections. However, the dimensional of low resistivity anomaly clearly with using VTF rather than using full component tensor only. This may be a false anomaly caused by the impedances $-Z_{yx}$ (the ratio $\mu_0 E_y/B_x$) and $Z_{yy}$ (the ratio $\mu_0 E_y/B_y$) associated with $E_y$. Therefore, $E_y$ tend to resolve lateral conductivity variations. However, vertical magnetic fields are generated by lateral conductivity gradients and boundaries, and spatial variations of the ratio $H_z/H_y$ can be used to diagnose lateral conductivity contrasts. Our results indicate that the combination of full impedance tensor using VTF can improve recovery of the true resistivity structure. Watuwawer fault acts as structures which control geothermal surface manifestation appear as Watuwawer fumarole.

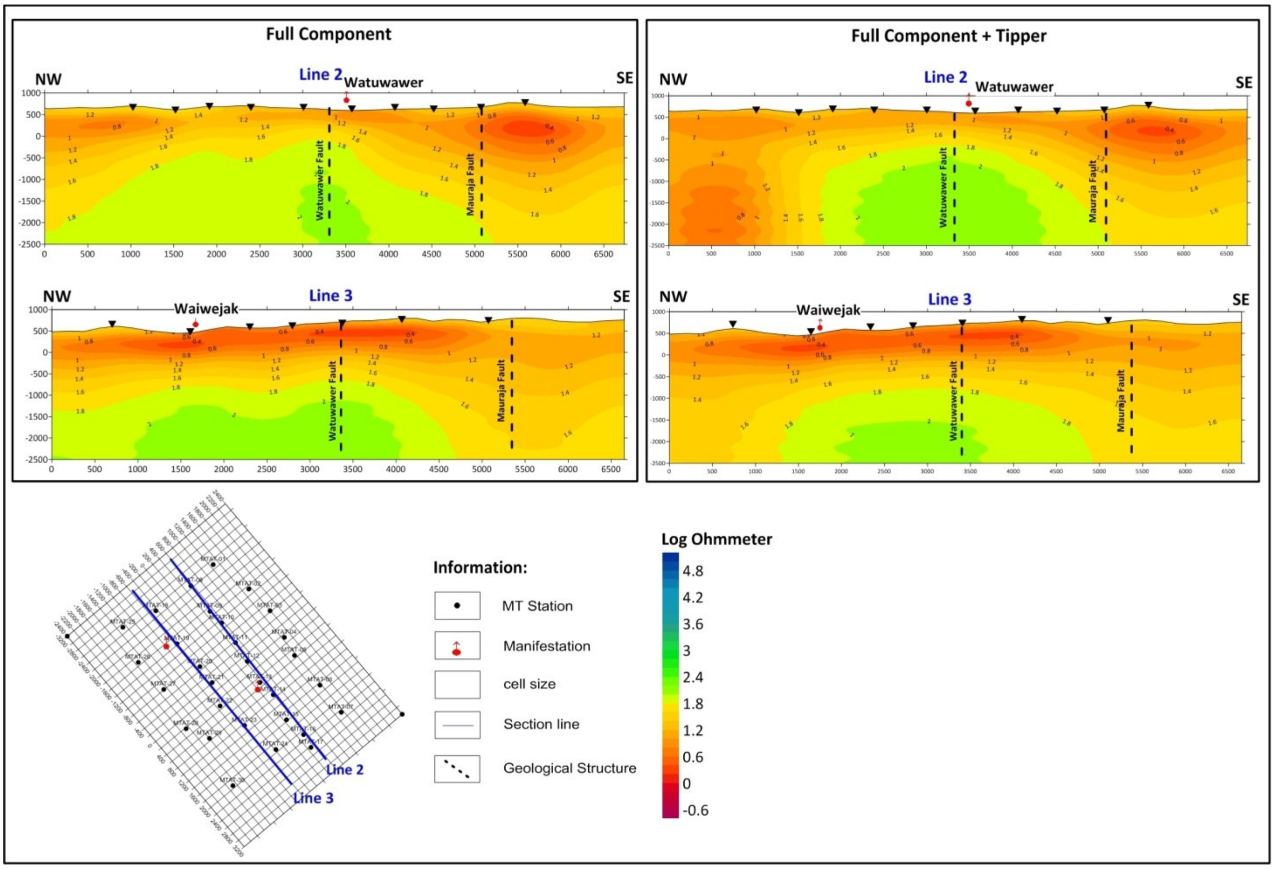


**Figure 2: Sections of Line-2 and Line-3 result.**

Figures 3 and 4 show the inverse solution at various depths by with/ without using VTF to the full impedance tensor. From 0.2 until 0.4 km depth mostly dominated by low resistivity zone for both Figure. However, by using full component tensor only (Figure 3), two closure medium resistivity appear along NS direction at 0.8 km depth. This two-closure medium resistivity become merge into elongated medium resistivity at 1.2 km depth, and open to the northern part of area at 2 km depth. Fortunately, by applying vertical magnetic transfer function (VTF) get better result because anomaly area changes are concentrated around manifestations. Small closure anomaly appeared around hot ground (Watuwawer) at 1 km depth, and this closure spread clearly to hot spring (Waiwejak) area at 2 km depth.

## 4. CONCLUSION

Applying full component tensors with or without using a tipper gave quite different result. Vertical magnetic were generated by lateral conductivity gradients and boundaries. The spatial variation of the ratio $H_z/H_y$ can be used to diagnose lateral conductivity contrasts. Thus, VTF are sensitive to horizontal structure, and to some extent to resistivity contrasts, but not to depths or absolute values of resistivity. Joint inversion of full component tensor and VTF can help constrain subsurface structures, as shown in section of Line-2 and Line-3, and also lateral conductivity contrast as shown in resistivity maps.

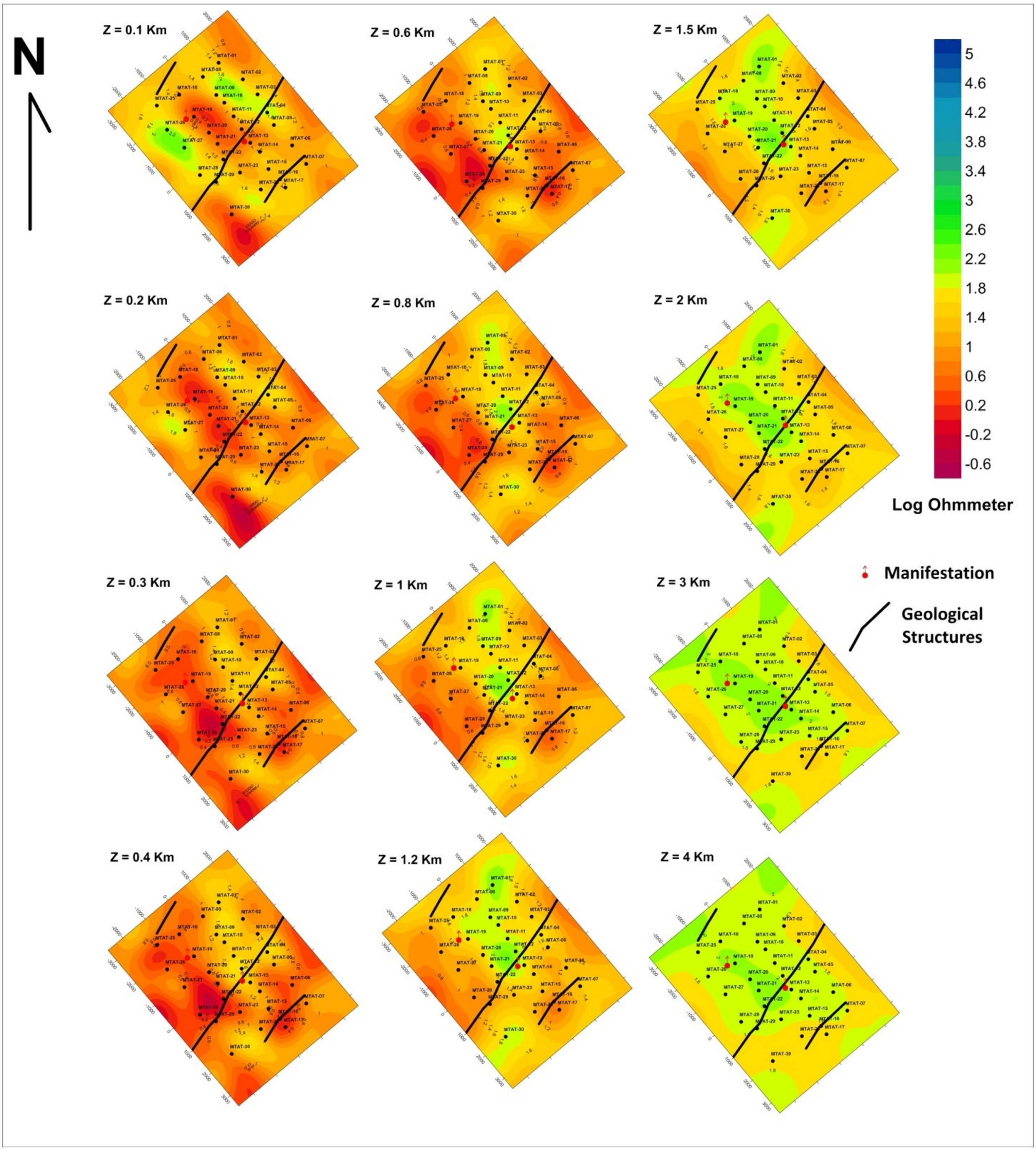


**Figure 3: Full impedance result.**

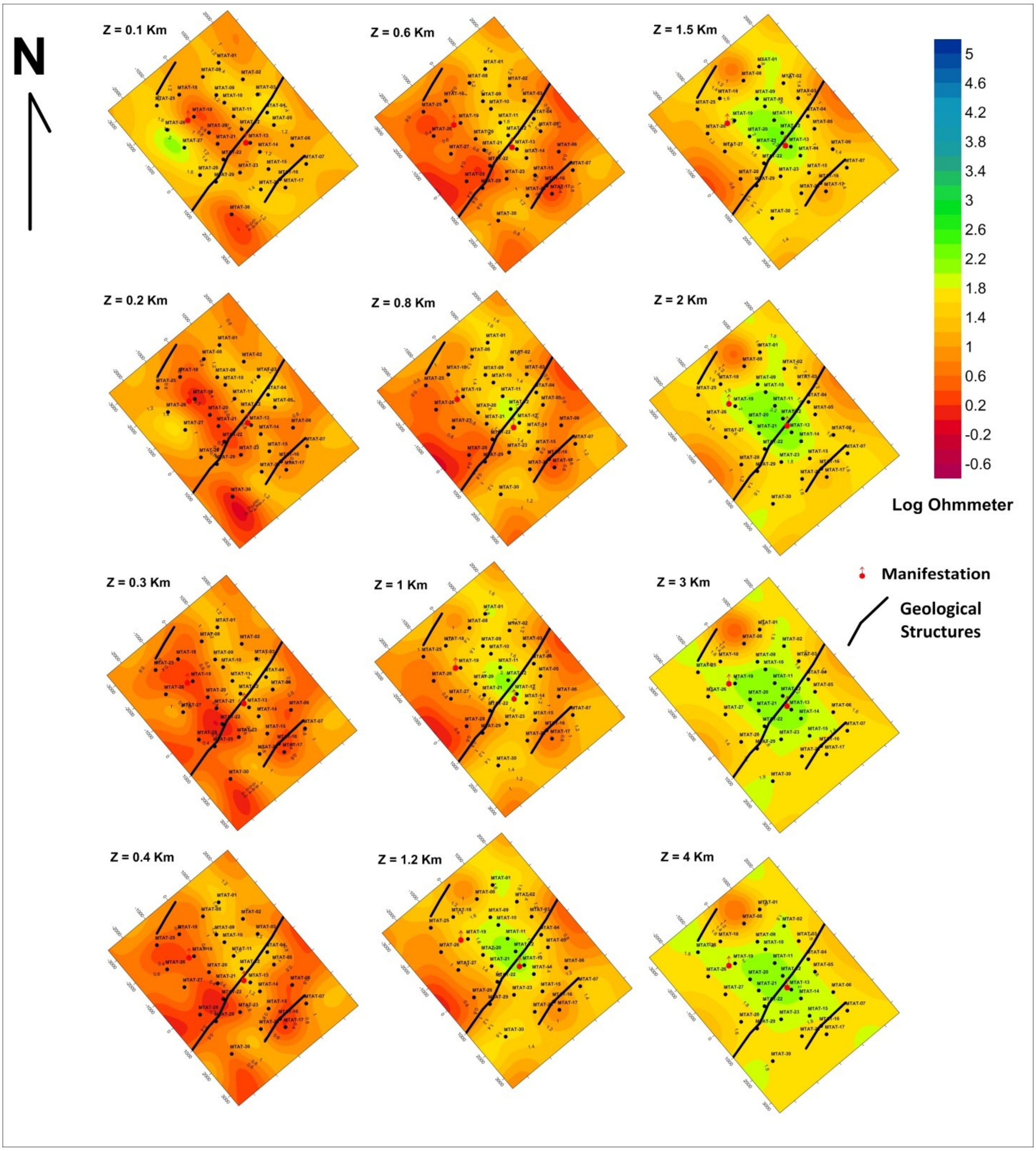


**Figure 4: Full impedance+tipper result.**

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