1D and 2D Inversions of Magnetotelluric Data from Butajira Geothermal Field, Southern Ethiopia

Outline

- Introduction
- The Magnetotelluric Method
- 1D and 2D Inversions
- Results and Discussions
- Conclusions and Recommendations
Erupted well 2014

Current situation
Introduction

Butajira - located in the western escarpment of CMER & characterized by:

- Pyroclastic flow deposits and Basaltic out crop
- Geothermal manifestation
- Rich in ground water
- Lacustrine sediment

Figure 1. 3D DEM map showing physiography of the study area
Figure 2. Crater Lake (Har Shetan), active mud pool and occasional geyser ejected and warm spring which indicate thermal activity in sub surface
Figure 3. Geological map of study area (modified after Zelalem Abebe and Yared Sinetibeb, 2017).
Objectives of the study

- Obtain a model of the subsurface resistivity structure of the Butajira geothermal field
- Estimate the probability of occurrence, extension and depth of the geothermal reservoir and possible recharge zones for the system
- Advance the state of knowledge of the prospect to one level
- Increase rate of survey coverage
A passive EM geophysical method which measures the natural electromagnetic signals

The natural source of energy of Magnetotelluric signals:

High frequency signal, >1 Hz  Low frequency signal, <1 Hz
MT survey layout, data processing, data quality and inversion

Figure 4. Schematic set up of MT survey layout (JICA 2015) and data processing and inversion flow.
The Magnetotelluric Method Cont.

The MT impedance tensor and dimensionality

\[
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix} =
\begin{bmatrix}
Z_{xx} & Z_{xy} \\
Z_{yx} & Z_{yy}
\end{bmatrix}
\begin{bmatrix}
H_x \\
H_y
\end{bmatrix}
\]

- **1D** case, it is enough to calculate \( E \) and \( H \) independently on their orientation.
- **2D** and **3D** cases, we need to measure in different spatial components of EM-fields.

<table>
<thead>
<tr>
<th></th>
<th>1D</th>
<th>2D</th>
<th>3D</th>
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<tbody>
<tr>
<td>( Z_{xx} )</td>
<td>( Z_{yy} = 0 )</td>
<td>( Z_{xy} \neq -Z_{yx} )</td>
<td></td>
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<tr>
<td>( Z_{yx} )</td>
<td>( Z_{xy} = -Z_{yx} )</td>
<td>( Z_{xx} \neq Z_{yy} )</td>
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<tr>
<td>( Z_{xy} )</td>
<td>( Z_{xy} \neq -Z_{yx} )</td>
<td>( Z_{xy} \neq -Z_{yx} )</td>
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\( \rho_{xy} \approx 0.2T \left( \frac{E_x}{H_y} \right)^2 \), \( \rho_{yx} \approx 0.2T \left( \frac{E_y}{H_x} \right)^2 \), \( \delta \approx 0.5 \sqrt{\frac{\rho}{f}} \)  
\( \delta \) = Skin depth (km)
The Magnetotelluric Survey in Butajira

- 32 MT stations were surveyed
- Remote reference technique was applied

Figure 5. MT observation points and remote reference station
The Magnetotelluric Data Quality

Data quality

- Most of the sounding data is a medium quality and can be interpreted up to 100 second period length

Figure 6. Example of raw and processed MT data of station number of BTJ074.
MT Sounding Curves plotted at different frequencies

Figure 6. Trend of sounding curves at different frequencies.

\[
\rho_{xy} = \frac{1}{\omega \mu_0} \left| \frac{E_y}{H_y} \right|^2 = \frac{1}{\omega \mu_0} |Z_{xy}|^2 \quad \text{TE mode}
\]

\[
\rho_{yx} = \frac{1}{\omega \mu_0} \left| \frac{E_x}{H_x} \right|^2 = \frac{1}{\omega \mu_0} |Z_{yx}|^2 \quad \text{TM mode}
\]
Dimensionality Analysis
Inversion and Modelling

1D MT Inversion

- Levenberg-Marquardt, a non-linear least square method and can be done by minimizing the objective function $F$.

$$F = (d - g (m_0 + \Delta m)) + \lambda ||\Delta m||^2$$

Where $F$ = objective function

- $d$ = data (apparent resistivity and phase)
- $g$ = forward operator
- $m$ = solution models
- $\Delta m$ = model parameter updates
- $m_0$ = initial model
- $\lambda$ = parameter that shows effect of model perturbation or damping factor
1D Marquardt Inversion and Modelling of Station B58 along P4

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<th>Parameter</th>
<th>Initial</th>
<th>Final</th>
<th>Fix</th>
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<td>10</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>rho 2</td>
<td>17</td>
<td>51.3</td>
<td>0</td>
</tr>
<tr>
<td>rho 3</td>
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<td>3.86</td>
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<td>rho 4</td>
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<tr>
<td>rho 5</td>
<td>6</td>
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<tr>
<td>thic 1</td>
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</tr>
<tr>
<td>thic 2</td>
<td>250</td>
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<td>0</td>
</tr>
<tr>
<td>thic 3</td>
<td>500</td>
<td>1654</td>
<td>0</td>
</tr>
<tr>
<td>thic 4</td>
<td>250</td>
<td>10140</td>
<td>0</td>
</tr>
<tr>
<td>Iteration</td>
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<tr>
<td>RMS</td>
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2D MT Inversion

- 2D Occam inversion
- At k-th iteration, the estimated model parameters are obtained by solving the following equation:

\[ m_{k+1} = \left[ \mu (\partial_y^T \partial_y + \partial_z^T \partial_z) + (WJ_k)^T WJ_k \right]^{-1} (WJ_k)^T W \]

where \( m \) = matrix of model parameters
\( k \) = number of iteration, \( \mu \) = Lagrange multiplier
\( \partial_y \) = roughness matrix to describe different model parameter laterally
\( \partial_z \) = roughness matrix to describe model parameter vertically
\( T \) = transpose of matrix
\( W \) = weighted diagonal matrix
\( J \) = Jacobian matrix
Parameters used for 2D inversion

- Strike angle rotation = 75 °
- TE + TM
- Maximum number of iteration = 20
- Target RMS = 0.5
- Half space resistivity = 20 Ωm
2D MT Inversion Cont.

**Strike Direction**

Strike direction is taken between period of 100-1000 seconds
2D Data and Response of TE Mode along Profile 3

Figure 7. Pseudo Section of TE Mode along P3
2D Data and Response of TM Mode along Profile 3

Figure 8. Pseudo Section of TM Mode along P3
1D Results and Discussions

Results of 1D Resistivity sections along profiles P1, P2, P3
Results of 2D Resistivity models along profiles P1, P2, P3 and P4
Conclusions and Recommendations

- The MT method detected a low resistive surface layer (< 10 Ωm) of up to about 1.5 km thickness, can be correlated as alteration zones caused by geothermal activity or lacustrine sediments or hydrothermally altered clay cap.

- Below this low resistive layer resistivity is increasing up to (10-60 Ωm). This indicates the advancement to a possible reservoir at depth below 1500 m with a thickness of about 1 Km.

- The faults have been detected on the profiles 1 and 2, so it is strongly recommended to have addition profiles on this portion in order to understand the extension of the fault and reservoir.

- Additional MT/TEM stations and 3D MT survey are recommended.

- Gravity survey is also recommended to delineate the geological structure.
Thank you