Three-dimensional imaging of volcanic systems with magnetotellurics

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Summary

Imaging the subsurface of volcanic systems with geophysics has been dominated by more conventional techniques like seismic tomography. However, with the advent of three-dimensional (3-D) electromagnetic inverse modeling, magnetotellurics (MT) has become a powerful tool for imaging volcanic systems due to its direct sensitivity to fluids. Here, several case studies utilizing MT to characterize volcanic systems in 3-D using ModEM are summarized, including several Washington Cascade volcanoes, Long Valley Caldera, Montserrat, and Hararat Rahat, Saudi Arabia. Lessons learned from these studies include: insuring that the inversion grid is of sufficient size to allow for anomalies outside the survey area, arriving at an acceptable model in terms of data fit and geologically realistic is an iterative process, interpretation of anomalies requires other independent geological and geophysical information, and estimating subsurface physical properties from the resistivity model must be done with care. Additional research needs to be done on accounting for topography and anisotropy, relating resistivity to physical properties, and joint interpretation/inversion of multiple geophysical data sets.

Keywords: ModEM, volcano, magma, geothermal, hydrothermal

Introduction

The advantage of measuring electrical resistivity over other subsurface physical properties is the direct sensitivity to fluids, including magmatic fluids and hydrothermal fluids. Moreover, changes observed in resistivity when fluids are present can change by orders of magnitude, whereas other geophysical methods will observe changes on the order of a few percent. With the addition of laboratory measurements on melt resistivity (e.g. Pommier & Le-Trong (2011)), better constraints can be placed on melt fraction, petrology, viscosity, and temperature. Faster and more efficient 3D inversion algorithms available to the MT community (e.g. Siripunvaraporn et al. (2005), Kelbert et al. (2014)) have expanded the usefulness of imaging subsurface resistivity structures, particularly volcanic systems. Over the last decade there have been many examples of using MT to image volcanic areas in 3D (e.g. Hill et al. (2009); Peacock et al. (2015)).

Here we briefly describe several case studies on imaging volcanic terrains with MT in 3-D using ModEM developed by Egbert & Kelbert (2012); Kelbert et al. (2014) and some practical lessons learned. In these studies the preferred model was found through an iterative process of averaging starting models, reduction of error floors and covariance, then testing of anomalous structures through forward modeling and constrained inversion. Input files were created using MTpy (Krieger & Peacock, 2014) and input data was edited and interpolated using the EDI-Editor in MTpy. Depth layers increase exponentially from the first layer. Topography was not included in any of the models because of the crude representation in the finite-difference mesh. All inversions were run on the Pleiades supercomputer at the high-end computing center (HECC) located at NASA Ames. See Table 1 for inversion parameters.

Long Valley Magmatic System, California

The Long Valley volcanic system in Eastern California is an active and dynamic magmatic system. Although many geologic studies have interpreted the volcanic history of the area and multiple geophysical studies have characterized the subsurface, no single model for the Long Valley volcanic system exists. The key remaining research questions include: is there a magma source under the resurgent dome? What is the heat source for the near surface hydrothermal system? And what is causing earthquake swarms in the south moat?

A grid of around 170 MT stations spaced at 2 km were
collected during multiple field trips between 2012-2016, where an additional 20 stations from Wannamaker et al. (1991) were included in the input data. All components of the impedance tensors and induction vectors were inverted. The starting model was a combination of the preferred models from Peacock et al. (2015) and Peacock et al. (2016). The first run had error floors set to 0.10√Z_{xy}·Z_{yx} and 0.05 for induction vectors, with a covariance of 0.5 in all directions. After 95 iterations a global RMS of 1.9 was found. Error floors were reduced to 0.05√Z_{xy}·Z_{yx} and 0.02 for induction vectors, and the covariance was set to 0.3 in all directions. After 126 iterations an RMS of 1.85 was found.

![Figure 1](image1.png)

**Figure 1:** A close up view of the electrical resistivity model under Mammoth Mountain. Purple spheres are earthquake locations (Lin, 2013) and magenta spheres are from the 2014 swarm (Shelly et al., 2015). Left: a 2-D cross section of the resistivity model outlining the conductive anomalies. White line is the possible fault trace of the caldera ring fracture that allows fluids to migrate. Right: 3-D view of the conductive anomalies with an iso-surface at 30 Ωm. The top conductor is a zone of hydrothermal fluids related to the deeper zone of 5-10% basaltic melt.

Electrically conductive zones correlate with seismic anomalies, potential field data, earthquake locations, and estimated inflation sources from GPS data. These conductive regions include two zones of partial melt below the Mono Craters at 10 km depth, a zone of partial melt below Mammoth Mountain at 8 km (Figure 1), and potential zones of partial melt 10 km below the south moat and Deer Mountain. A magmatic zone also is imaged at 30 km depth below the northern edge of the caldera and could be the source feeding the volcanic system. If there is a zone of partial melt beneath the resurgent dome, it must be less than 3%, suggesting a cooling magma mush. The interesting part about the Mammoth Mountain anomaly is that there are no stations directly above the anomaly, however the 3-D inversion has been able to successfully characterize the zone of partial melt and the isolated hydrothermal system.

**Mount Baker, Washington**

As part of a Play Fairway geothermal assessment on the eastern flank of Mt. Baker, 26 MT stations were collected in 2016 on a grid with 2 km station spacing. The input model and data were rotated to N40W to align with regional features. The starting model was 100 Ωm half-space where just impedance was inverted with error floors of 0.10√Z_{xy}·Z_{yx} and a covariance of 0.4. Iteration 105 (RMS = 2.8) was used as a starting model to invert for just the induction vectors with an error floor of 0.05 and a covariance of 0.4. Iteration 43 (RMS = 2.3) was used as a starting model to invert both impedance and induction vectors, with error floors of 0.03√Z_{xy}·Z_{yx} and 0.02 for induction vectors, and the covariance was set to 0.3 in all directions. An RMS of 2.3 was found after 132 iterations.

The resistivity model images a small hydrothermal system and deep north trending fault zones. However, the most interesting observation from the model is that the resistivity model images conductive zones underneath Mt. Baker where the magma source is assumed to be, even though the survey is 10 km from fumaroles on Mt. Baker (Figure 2). Though the resistivity model can provide little constraints on shape and size, the model can estimate location and depth.

![Figure 2](image2.png)

**Figure 2:** Left: looking east at Mt. Baker with an iso-surface of 30 Ωm. Right: Bird’s eye view of Mt. Baker at resistivity model below 15 km. Orange box is survey area.

**Mount St. Helens, Mount Adams & Mount Rainier, Washington**

The MT portion of the iMUSH (imaging under Mount St. Helens) project is to investigate the contested origin of the Southwest Washington Crustal Conductor and to constrain potential connections between Mt. Adams and Mount St. Helens that were imaged by Hill et al. (2009). A total of 297 stations were used including 134 stations from iMUSH, 37 MT stations
Peacock, J.R. et al., 2017, 3-D Imaging of Volcanoes with MT

Table 1: Inversion Parameters

<table>
<thead>
<tr>
<th>Location</th>
<th>Grid Size (cells) (km)</th>
<th>Cell Size (m²)</th>
<th>Layer 1 (m)</th>
<th>Period Range (s)</th>
<th>Num. Per.</th>
<th>Num. Sta.</th>
<th>Iter. Time (min)</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long Valley</td>
<td>126 x 125 x 50 360 x 400 x 400</td>
<td>500</td>
<td>10</td>
<td>0.013 – 682.0</td>
<td>23</td>
<td>190</td>
<td>65</td>
<td>1.8</td>
</tr>
<tr>
<td>Mt. Baker</td>
<td>110 x 77 x 40 140 x 120 x 280</td>
<td>200</td>
<td>10</td>
<td>0.005 – 1,000</td>
<td>23</td>
<td>23</td>
<td>20</td>
<td>2.3</td>
</tr>
<tr>
<td>iMUSH</td>
<td>190 x 158 x 40 600 x 600 x 500</td>
<td>1,000</td>
<td>20</td>
<td>0.003 – 10,000</td>
<td>23</td>
<td>295</td>
<td>70</td>
<td>2.3</td>
</tr>
<tr>
<td>Harrat Ra-</td>
<td>60 x 110 x 60 600 x 600 x 600</td>
<td>2,000</td>
<td>25</td>
<td>0.003 – 3,160</td>
<td>25</td>
<td>119</td>
<td>40</td>
<td>2.5</td>
</tr>
</tbody>
</table>

from a Play Fairway geothermal assessment on the north and south flank of Mount St. Helens in 2016, 23 sites from the CAFE line (Wannamaker et al., 2014; McGary et al., 2014), 3 from the MOCHA survey (Key et al., 2015) and 3 from the EarthScope transportable array. The ocean and Puget Sound were included in the 100 Ω half-space starting model. Input data for the first run included all components of the impedance tensor and induction vectors with error ors of 0.10√Zxy·Zyx and 0.15 for induction vectors, and the covariance was set to 0.5 in all directions. After 54 iterations an RMS of 4.8 was found, where most of the misfit was in the induction vectors.

The preliminary model suggests that there may not be a coherent connection between Mount St. Helens and Mt. Adams (Figure 3). Rather, the resistivity model suggests that conductivity is focused within a series of narrow discrete bodies striking north-northwest. This could be related to the smoothness of the model and requires further testing. The elongated anomaly under Mount St. Helens is related to the shear zone and may be attributed to fluids within in a highly fracture sedimentary formation. A conductive body underlies the north side of Mount Rainier similar to McGary et al. (2014), which could be a zone of 5-10% partial melt. With large data sets, initially applying large error ors and large smoothing constraints proved helpful in identifying problematic stations.

Harrat Rahat, Saudi Arabia

In 1256 CE, a lava flow that lasted 90 days erupted from Harrat Rahat. The flow came within kilometers of the holy city of Medinah, and in part motivates an ongoing volcanic hazard assessment of the region. One aspect of this assessment is using MT to image the magmatic system of the Rahat and assess volcanic hazards within the area. In 2016, 119 broadband and 18 long-period MT stations were collected in a grid with 5-10 km station spacing. The Red Sea was included in the 100 Ω half-space starting model. Error ors were set to 0.05√Zxy·Zyx and 0.01 for induction vectors, and the covariance was set to 0.3 in all directions. After 91 iterations an RMS of 2.5 was found.

Interestingly, no conductive body exists beneath the most recent eruption, rather a large resistive body, which is in many ways indistinct from the surrounding Precambrian crust. However, there is a subtle less resistive zone under the northern and youngest part of the Harrat that has a connection to the surface on the eastern side of Medinah. This feature has not been tested yet. The most striking observation from the model is a series of northeast-trending elongated conductive bodies below 15 km that are nearly equally spaced between similarly shaped resis-
tors. These bodies are nearly perpendicular to the direction of Red Sea extension, they may be related to inherited structure rather than modern tectonics. The pattern is also indicative of anisotropy, which still needs to be tested. The elevated conductivity at these depths may indicate a small degree of partial melt focused along pre-existing structures.

Figure 4: Looking northeast on the Harrat Ra-
hat showing conductive anomalies with an iso-
surface at 30 Ωm. The depth slice is at 15 km. The purple line is the outline of the Hyoung volcanic rocks at the surface. Black dots are station locations. Notice the northeast trending bodies.

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References


