Subsurface Structure around Mas Crater of Papandayan Volcano based on Magnetotelluric and Geomagnetic Data

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Abstract: Papandayan is a hydrothermally active volcano in Indonesia. We revealed the subsurface structure around the Mas Crater area of Papandayan based on the magnetotelluric (MT) and geomagnetic (GM) method. For the MT method, 14 sounding stations were deployed and two of them are located close to the active fumaroles. We estimated the MT response functions using a remote reference and then modeled the data with the aid of a 1-D robust inversion. The resistivity structure can generally be divided into three layers, namely a thin resistive surface layer, a middle conductive layer, and a more resistive basement. We interpreted the middle layer to be the hydrothermal zone or clay mineral. For the GM method, we measured the total intensity at 19 data points. The IGRF and diurnal variation were subtracted from the raw data. We then obtained the 2-D magnetic susceptibility model of magnetic field anomaly using an Occam inversion. The model shows a significantly low susceptibility structure beneath the fumaroles which might correlate with thermally demagnetized rocks.

1. Introduction

Papandayan is one of the Indonesian active volcanoes located in Garut Regency, about 50 km to the southeast of Bandung. Its first major eruption in 1772 was a magmatic eruption with a volcanic explosivity index (VEI) of 3. More recent activity of the volcano occurred in November 2002 where moderate phreatic eruptions followed by debris avalanches and high-temperature lava flows were observed [1]. These eruptions resulted in the existence of 4 volcanic craters around the summit and some of them have been maintaining strong fumarolic activities for years e.g. Mas Crater. It is then interesting for researchers to study the structure underneath this area.

We have investigated the subsurface electrical resistivity and magnetic susceptibility around the Mas Crater area based on magnetotelluric (MT) and geomagnetic (GM) total intensity methods. In volcanic areas, electrical resistivity is sensitive to the fluids and clay alteration minerals whereas magnetic susceptibility possibly explains thermal demagnetization of the subsurface rock. The following sections cover the discussion of each method and its results.

2. MT Method

2.1. Brief Overview

MT is a passive geophysical exploration method for probing the Earth’s subsurface electrical resistivity based on the measurement of electromagnetic (EM) field on the surface [2]. Source field in the ionosphere and magnetosphere is naturally generated due to, e.g., solar activities, and provide a wide and continuous spectrum of EM waves. This source (primary) field induces a secondary field inside the Earth and the resultant field measured at the surface depends on the resistivity structure at depth.

MT impedance tensor $\mathbf{Z}$ is the response function in the frequency domain between the measured electric field $\mathbf{E}$ and magnetic field $\mathbf{H}$ at the Earth’s surface. It can be expressed mathematically as follows

$$\mathbf{E} = \mathbf{ZH} \quad \rightarrow \quad \begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix}$$  (1)
There are 14 MT sounding stations and 19 GM data points distributed around the Mas Crater area. The sites pd10 and pd11 are relatively closer to the fumaroles. The light-colored rocks that mostly cover this area are the debris avalanche deposits from the previous eruptions.

Each component of $\mathbf{Z}$ is a complex number and can be estimated by the cross-power spectral as

$$
\begin{pmatrix}
Z_{xx} & Z_{xy} \\
Z_{xy} & Z_{yy}
\end{pmatrix} = \left( \begin{pmatrix} R_x | H_x \\ R_y | H_y \end{pmatrix} \right)^{-1} \left( \begin{pmatrix} R_x | E_x \\ R_y | E_y \end{pmatrix} \right) \left( \begin{pmatrix} R_x | H_x \\ R_y | H_y \end{pmatrix} \right)^{-1} \left( \begin{pmatrix} R_x | E_x \\ R_y | E_y \end{pmatrix} \right)
$$

(2)

where $R_x$ and $R_y$ are the remote reference magnetic fields. The apparent resistivity ($\rho$) and impedance phase ($\phi$) of each component are then given by (i,j are x or y)

$$
\rho_{ij} = \frac{1}{\mu_0} \frac{|Z_{ij}|^2}{\omega}
$$

$$
\phi_{ij} = \tan^{-1} \frac{\text{Im}(Z_{ij})}{\text{Re}(Z_{ij})}
$$

(3)

2.2. Data Acquisition and Processing

MT data were collected in the Mas Crater area of Papandayan with a total of 14 stations. We used the remote reference technique where another measurement of the horizontal magnetic field in a noise-free area is utilized [3]. This technique has been widely implemented to reduce bias in the responses due to correlated noise in the local magnetic field ($H_x, H_y$). We recorded the data using a set of Phoenix MT instruments with high sampling frequency. Site pd10 and pd11 are close to two strong fumaroles as shown in Figure 1.

Raw MT data are time series of the horizontal components of electric field ($E_x, E_y$) and magnetic field ($H_x, H_y$) plus a vertical component of magnetic field ($H_z$). Time-to-frequency domain processing was done before this study, so we began with Electrical Data Interchange (EDI) files containing auto- and cross-spectra. The impedance, apparent resistivity, and phase are estimated using equations (2)-(3).
For modeling purposes, we designed two profile lines namely LINE1 and LINE2 that divide the sites into two groups. The azimuths of both profile lines are approximately NE-SW and LINE1 is nearly twice shorter than LINE2.

The apparent resistivity and phase curves of site pd8 can fairly represent those of the other sites (Figure 2). We obtained the responses from several hundreds of hertz to several tens of seconds. The apparent resistivity increases at periods longer than 1s and it is confirmed by the phase drops. Data at periods longer than 10s are severely contaminated by noise. According to the responses, we possibly resolve a relatively conductive layer near the surface and a more resistive layer at depth.

2.3. Result and Discussion

The apparent resistivity and phase were modeled with the aid of a robust 1-D inversion. The standard errors between the observed and calculated responses range from 5% to 15%. The comparison of apparent resistivity and phase pseudo-sections is shown in Figure 3. The observed responses have an acceptable quality that is indicated by the smooth and non-scattered pseudo-sections. Since the feature of apparent resistivity and phase are generally consistent, we could obtain resistivity models that satisfy both responses simultaneously.

The resistivity structures beneath the two MT profiles are shown in Figure 4. We observed a highly resistive layer underneath a conductive layer, which is consistent with our judgment based on the observed responses prior to the modelling. Toward the north-east, or further away from the volcano summit, the conductive layer is getting thinner, but the overall conductance is maintained. Considering the thickness and conductivity of the second (conductive) layer, the dimensionality of the structure beneath LINE2 is pretty much consistent with the 1-D assumption, while that of LINE1 slightly departs from the 1-D assumption.

The overall structure can be divided into three layers, namely a thin resistive surface layer, a conductive layer at a depth of about 0.1 to 1km, and a resistive layer at a depth of more than 1 km. The resistive surface layer is most likely to be the debris avalanche deposits or pyroclastic products from the previous eruptions. The underlying conductive layer might be interpreted as the presence of a hydrothermal zone or clay minerals that are commonly revealed in a volcanic area [4]. These could be related to the existence of several fumaroles located around sites pd10 and pd11. Some additional information or constraints, however, are required to confirm our simple interpretation of the structure.
Figure 3. Pseudo-sections comparison between the observed and calculated responses. Black lines indicate the data points and the color-filled region with no data is a spatial interpolation. The observed responses (data) have an acceptable quality that is indicated by the smooth and non-scattered pseudo-sections. Observed and calculated pseudo-sections are visually in good agreement.

3. Geomagnetic Method

3.1. Brief Overview

The Earth’s total intensity magnetic field is measured to probe the subsurface magnetic susceptibility distribution. Magnetic susceptibility is a stable physical parameter that depends on the rock types and environmental factors, and it plays an important role in controlling the rock’s magnetization. The temperature-dependent feature of magnetic susceptibility is usually the basis of interpretation in volcanic areas, that is, when rocks are placed at certain high temperatures, their magnetic moment gradually becomes disoriented and hence the resultant moment is decreased. Such a phenomenon is referred to as thermal demagnetization. In short, at some point, magnetic susceptibility decreases as temperature increases.
Figure 4. Resistivity models beneath the two MT profiles. The overall structure can be divided into three layers, namely a thin resistive surface layer, a more conductive layer at depth of 0.1 to 1km, and a resistive bottom layer. Toward the North-East, the conductive middle layer is getting thinner with higher conductivity.

Curie-Weiss's law mathematically formulates the inverse relationship between magnetic susceptibility $k$ to temperature $T$ and is given by

$$k = \frac{C}{T - T_c}$$

with $C$ and $T_c$ denote the Curie constant and Curie temperature of the material [5]. This equation quantitatively described the magnetic susceptibility drop with increasing temperature.

3.2. Data Acquisition and Processing
Geomagnetic data were acquired years later than the MT with a total of 19 measurement points. The survey was primarily done for the completion of undergraduate study of the first author. Unlike the MT stations, the geomagnetic sites are denser and closer to the fumarolic field. We used a set of G-856AX Memory Mag Proton Precession Magnetometer (PPM).

The data processing includes the IGRF correction and diurnal correction. The average IGRF value of the study area is 45,059nT. After subtracting the measured field with the IGRF and the corresponding diurnal variation, we obtained the local magnetic anomalies. Other commonly used processing steps such as upward continuation or reduction-to-pole were not performed because we seek shallow susceptibility heterogeneities. The anomalies along the magnetic profile (AB) (blue line in Figure 1) vary from 382nT to -75nT with the negative anomalies located in the middle of the profile.

3.3. Result and Discussion
We modeled the anomalies along the profile using an Occam inversion by ZondGM2D. The final model shown in the bottom panel of Figure 5 gives a misfit of 0.0026% of the data. That extremely small misfit implies that the model responses perfectly match the data as shown in the upper panel. The maximum depth resolution is about 150m and that is equivalent to the surface resistive layer of the MT model. Assuming that this layer is made up of uniform debris avalanche products, we then believed that the variation of susceptibility is generated by the temperature as described in equation (4).
Figure 5. Result of geomagnetic anomaly modeling. The top panel shows the match between the observed and calculated magnetic field whereas the bottom panel shows the magnetic susceptibility model. There is a surface moderate susceptibility layer that is thickened beneath the points having negative magnetic anomalies. Closer to A, there exists a low susceptibility structure underneath a small-high susceptibility body. The model has a surface moderate susceptibility layer that is thickened in the middle of the profile. Also, closer to A, there exists a low susceptibility structure underneath a small-high susceptibility body. This structure correctly reproduces the unusual magnetic anomaly kink. Considering the position of fumaroles, we interpreted this structure as the high-temperature demagnetized rocks.

4. Conclusion
The resistivity model obtained from the MT method consists of three horizontal layers. A middle conductive layer indicates the presence of a hydrothermal zone or clay mineral. The magnetic susceptibility model obtained from the GM method has two features; a surface moderate susceptibility layer that is thickened at points having negative anomalies, and a low susceptibility body that might correlate with the thermally demagnetized rocks.

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