Modeling of Reservoir Structure by Using Magnetotelluric Method in the Area of Mt. Argopuro, East Java, Indonesia

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Abstract. The purpose of this study was to review a regional geothermal system by applying the magnetotelluric method, which is one of the geophysical methods that can be used to map subsurface resistivity structures. This method uses electromagnetic waves of natural resources, namely the interaction of the sun (solar wind) and lightning activity on earth. This study used an inverse modeling method, i.e. the non-linear conjugate gradient method, to estimate the resistivity value as a function of depth at points of sounding, while 2-dimensional modeling was used to describe the distribution of the resistivity values laterally or vertically on a trajectory of measurements. Data were collected from the area of Mt. Argopuro, East Java, where the magnetotelluric method has not been applied before. A geothermal system was found under Mt. Argopuro consisting of altered rock, reservoirs and hot rock with sources of heat associated with high resistivity values (1024 ohm.m). The area has potential for geothermal energy exploration in the future.

Keywords: *altered rock; magnetotelluric; Mt. Argopuro; reservoir; resistivity.*

1 Introduction

The use of geothermal energy can reduce the use of petroleum or other fossil fuels by millions of barrels annually [1]. Many countries today are cautiously starting to look for other sources of energy for the years to come because of the depletion of available fossil energy. Especially in Indonesia, the reserve of fossil fuels is diminishing rapidly, while their use will cease to be economical in the near future. Considering estimates of the world's energy needs in the future, we clearly need alternative energy sources. Renewable alternatives such as geothermal energy are the answer. In general, geothermal energy is developed in post-volcanic areas. The Indonesian geothermal prospect area amounts to 265 locations with potential power reaching 28,000 MWe [2].

Geophysical methods can be applied to study the structure of the earth's crust in terms of investigation and exploration [3]. The magnetotelluric method is a

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geophysical method that utilizes the natural electromagnetic field, which is an association of electric-magnetic phenomena in the nature of the electrical conductivity of a medium, especially under the earth's surface. The structure of the earth's subsurface conductivity can be estimated from simultaneous measurement of the electrical field and the magnetic field on the surface [4].

In geothermal exploration, the MT method is often used because of its excellence in detecting earth layers with different resistivity or conductivity of various rock materials and fluids below the earth's surface. In addition, the penetration depth, the range of EM waves propagating into the ground, the work pace when covering large areas, and the simplicity of data acquisition in the field are major advantages of this method [5]. It is effective in detecting the depth of heat sources in a geothermal system. This method has been validated often by other methods such as the gravity method, the magnetic method, and so on.

Cagniard [6] made the formulation of the relationship between the electric field (E) and the magnetic field (H). The relationship between amplitude, phase and propagation direction of the electric field and the magnetic field on the surface depends on the subsurface resistivity distribution. Tikhonov [7] showed that at low frequency the derivative of the magnetic field (H) is proportional to the orthogonal components of the electric field (E). Hence, if the variations of the electric field and the magnetic field are measured simultaneously then the ratio of the complex (impedance) can be used to describe the penetration of the electromagnetic field into the earth [8].

Magnetotelluric signals have a frequency range of 0.001-104 Hz. Components with higher frequency (1-104 Hz) are caused by thunderstorms. Meanwhile, the external field arises due to solar storms when the sun emits electrically charged particles [9] producing variations in the terrain, which is a low frequency source (~ 0.001-1 Hz).

2 Survey and Research Location

EM data collection was done in the area of Mt. Argopuro, a volcanic complex in East Java, Indonesia. This volcano has an altitude of 3088 m and currently is no longer active [10]. The Mt. Argopuro complex is a product of the subduction of the Indo-Australian Plate under the Eurasian Plate, which formed the Sunda Magmatic Arc. Tectonically this area belongs to the transition zone. The activity of the volcanic began in the Late Miocene and lasted until the Quaternary or Resen. Mt. Argopuro lithology can be grouped into two types: Old Argopuro depositions and Young Argopuro depositions. The Old Argopuro depositions can be grouped into seven rock units, from old to young: Lava and

Pyroclastic Unit Mt. Gilap, Lava and Pyroclastic Unit Cemorokandang, Lava and Pyroclastic Unit Mt. Gendeng, Lava and Pyroclastic Unit Mount Patrol, Lava and pyroclastic Unit Mt. Malang, Lava and Pyroclastic Unit Mt. Siluman and Lava and Pyroclastic Unit Mt. Berhala [11]. Figure 1 shows a map of the study area made using Google Earth.

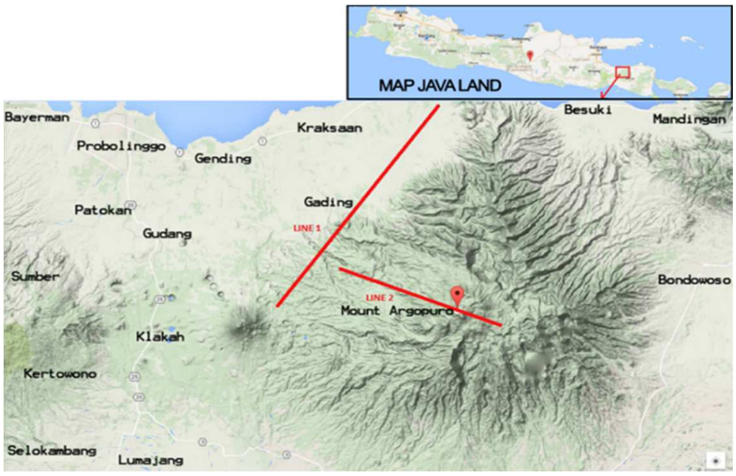

Figure 1 Data measurements location on Mt. Argopuro [10].

3 Methodology

In general, the basic concept of MT method consists of using the following Maxwell equations [12]:

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{1}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2}$$

$$\nabla \cdot B = 0 \tag{3}$$

$$\nabla \cdot D = q \tag{4}$$

In Eqs. (1) to (4), H is the magnetic intensity, J is the current density, E is the electric field, B is the magnetic field induction, D is the shift of electricity, and q is the electric charge.

By using the curl operation on the Maxwell equations, we get the following equations in Eq. (5) and (6) [13]:

$$(\nabla^2 + \mathrm{k}^2)E = 0 \tag{5}$$

$$(\nabla^2 + \mathrm{k}^2)H = 0 \quad (6)$$

where

$$\mathrm{k}^2 = i\omega\mu\sigma - \omega^2\mu\varepsilon \quad (7)$$

In Eq. (7), k is the wave number, ε is the dielectric permitivity, ω is the angular frequency, μ is the magnetic permeability and σ is the electrical conductivity. By using the approach of the values of ε and μ on the interval ω in the MT wave frequency area, the value *iωμσ » ω2με*, so it can be written in Eq. (8) that:

$$k = \sqrt{-i\omega\mu\sigma} \quad (8)$$

And by the fundamental equation (Helmholtz) for the components of the electric field the following equation can be obtained from Eq. (9) as follows:

$$\nabla^2\mathrm{E} = \mu\sigma\frac{\partial E}{\partial t} + \mu\varepsilon\,\frac{\partial^2 E}{\partial t^2} \quad (9)$$

and for the components of the magnetic field shown in Eq.(10):

$$\nabla^2\mathrm{H} = \mu\sigma\frac{\partial H}{\partial t} + \mu\varepsilon\,\frac{\partial^2 H}{\partial t^2} \quad (10)$$

The EM wave penetration depth is expressed by the factor of skin depth (δ), defined as the depth at which the electric field strength attenuation is equal to 1/e of the original electric field strength [14]. The EM wave penetration depth depends on the magnitude and frequency of the electrical conductivity of the medium through which it passes [15]. Skin depth can be written in Eq. (11) as follows:

$$\delta = \frac{1}{\beta} = 503\sqrt{\rho T} \quad (11)$$

where T is the EM wave period.

In the case of 1-D modeling, variation depends only on depth, so there is no different E in the x direction or the y direction and the same goes for H, so the following applies:

$$Z_{xy} = -Z_{yx}; Z_{xx} = Z_{yy} = 0 \quad (12)$$

The impedance can also be expressed as the amplitude and phase. In practice, these quantities are more often expressed in the form of apparent resistivity in the 1-D model in Eq. (13) as follows [16]:

$$\rho_a = \frac{1}{\omega\,\mu_0}\,|Z(\omega)|^2 \quad (13)$$

In the case of a 2-D modeling, E and H are influenced by the direction of the measurements made on the direction strike. Therefore, the EM wave can be decomposed into two types, namely transverse electric (TE) polarization mode, where the electric field is in the direction of the strike, and transverse magnetic (TM) polarization mode, where the electric field is perpendicular to the strike, as shown in Figure 2.

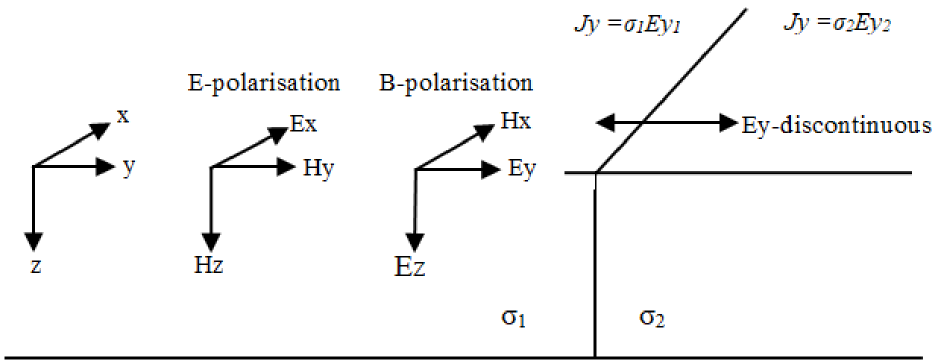

Figure 2 TE and TM polarization in the case of 2-D modeling (modified [8]).

Thus in the case of a 2-D resistivity structure, the following in Eq. (14) can be determined [8]:

$$Z_{xy} \neq -Z_{yx}; Z_{xx} = Z_{yy} = 0 \quad (14)$$

Hence, the apparent resistivity and phase in the case of 2-D modeling with reference to the TE and TM polarization images above are explained by Eqs. (15) and (16):

TE Mode:

$$\rho_{xy} = \frac{1}{\omega\mu_0}\left|\frac{E_x}{H_y}\right|^2; \ \emptyset_{xy} = tan^{-1}\left|\frac{E_x}{H_y}\right| \quad (15)$$

TM Mode:

$$\rho_{yx} = \frac{1}{\omega\mu_0}\left|\frac{E_y}{H_x}\right|^2; \ \emptyset_{yx} = tan^{-1}\left|\frac{E_y}{H_x}\right| \quad (16)$$

MT data retrieval is done through simultaneous measurement of the orthogonal components of *E* and *H*, which consist of components x and y. The positive x direction is usually used as a reference point in the north, while the positive y direction is used as a reference point in the east.

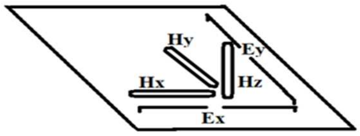

Figure 3 *E* and *H* measurement configuration for the MT method.

The methodology used to process the research data is an inverse modeling method. In the inversion process, an analysis of field data is conducted by curve fitting between the mathematical models and the field data. One of the goals of the inversion process is to estimate the physical parameters of previously unknown rocks [17-18].

Assuming m is the model and F is the state function, and d' are the prediction data obtained, then for forward modeling can be written in Eq. (17) as follows:

$$d' = Fm \tag{17}$$

If the measurement data is d, then the model that fits the data could be obtained from comparing d and d'.

Field studies are usually started by getting the measurement data d (observed) and then choosing a method to get the model, m. Inversion is a way to get the model from the measurement data. Inverse modeling can be written in Eq. (18) as follows:

$$m = dF^{-1} \tag{18}$$

Solving problems using a Newton algorithm is done by minimizing the objective function ψ, defined by Eq. (19) as follows:

$$\psi(m) = (d - F(m)^T V^{-1}(d - F(m)) \tag{19}$$

where V is the weighting matrix. The application of Newton's method for minimizing Eq.(14) gives the following solution in Eq. (20):

$$m_{n+1} = m_n - [\,J_n^T J_n + H_n^T(F(m) - d)\,]^{-1} J_n^T (F(m) - d) \tag{20}$$

where $m_{(n+1)}$ is the model at iteration n, J is the Jacobian matrix that is the first derivative of ψ against m. H is the second derivative of ψ against m.

For 2-D models, apparent resistivity values have lateral dimensions (x) and vertical dimensions (z). In general, the relationship of data and model parameters can also be expressed by Equation (17). Solving problems using the algorithms non-linear conjugate gradient (NLCG) is done by minimizing the objective function, ψ, defined by Eq. (21) as follows:

$$\psi(m) = (d - F(m)^T V^{-1}\big(d - F(m)\big) + \varepsilon^2 m^T W_m m \tag{21}$$

where ε is a positive number as the relative weights of the two factors are minimized, and W is the smoothness factor that is a continuous function model that can be expressed by the first derivative or second derivative. Application of the NLCG method to minimize Equation (14) gives the following solution in Eq. (22):

$$m_{n+1} = m_n - [J_n^T J_n + H_n^T (F(m) - d) + \varepsilon W_m]^{-1} J_n^T (F(m) - d) \quad (22)$$

The inversion modeling algorithm as described by Rodi & Mackie [19] was applied in the NLCG WinGlink program. Compared to other inversion methods, NLCG is more efficient pertaining to computation time.

In the process of inversion, smoothing of the resistivity and phase curves is carried out. The resistivity (ρ^{data}) and phase (φ^{data}) values are smoothed but the resulting model will still refer to the data. Variances due to differences between the values of the model and the actual data are calculated as the root mean square (*rms*) misfit. If the apparent resistivity and phase data are available for N sites and M frequencies, then the *rms* misfit is defined by the formula in Eq. (23) as follows:

$$rms = \sqrt{\frac{1}{2NM}\sum_{j=1}^{M}\sum_{i=1}^{N}\frac{(\rho_{ij}^{data} - \rho_{ij}^{smooth})^2}{e_{ij}^{r2}} + \frac{1}{2NM}\sum_{j=1}^{M}\sum_{i=1}^{N}\frac{(\varphi_{ij}^{data} - \varphi_{ij}^{smooth})^2}{e_{ij}^{p2}}} \quad (23)$$

where e^r and e^p are the standard errors associated with the resistivity data and the existing phases.

An *rms* misfit significantly more than 1 indicates that the noise in the data is greater than the error. A misfit less than 1 indicates that the error is too large, or the data are overfitted. Also, resistivity becomes very rough in the model. Generally, the optimal value of *rms* misfit is between 1 and 2 [20].

The correspondence between the model responses and observational data is commonly expressed by an objective function to be minimized. The process of searching the minimum objective function is associated with the process of finding the optimum models. The minimum characteristics of a function are used to search the model parameters. More generally, the model is modified such that the response makes the model fit to the data. In the process of modeling inversion can only be done if the relationship between the data and the model parameters are known.

The field data obtained from the magnetotelluric method in the form of time series data are transformed into the frequency domain. Smoothing is performed for the results of the modeling for a better fit with the real situation. Furthermore, 1-D and 2-D modeling is conducted and both are then interpreted.

4 Data Processing and Results

MT response measurements were carried out at 11 points on line 1 and 9 points on line 2. In accordance with the working steps, MT data processing is carried out in several stages, from the collection of field data in the form of time series data to data processing in the frequency domain. Data selection is done for each point of data collection to fit the trend of the geothermal areas. Data smoothing is done bedore phase inversion. Data processing is performed using the software tools SSMT2000, MTEditor, and then WinGLink. The data obtained from the acquisition results are time series data. Data processing is done with the SSMT2000 software application by transforming the time series data into the frequency domain. Then follows the process of noise reduction by robust processing. Robust processing is based on statistical-data processing techniques that utilize re-weighting of the rest of the residuals (iterative residual weighting) that identify and remove the outer outliers if the data are biased by non-Gaussian noise.

MTEditor is used for selecting points from each cross power point for the data to better fit to the trend graphs appropriate to the circumstances. Nice graphs of data obtained in the field can usually be seen from the Rho-xy and Rho-yx. In MTEditor, the data can also be smoothened. Usually, the data saturation of the data, either at the time of acquisition or retrieval, is less than 1 percent. If the data have too much saturation, MTEditor can be used to set the scale of the value of resistivity and frequency. Figure 4 is an example of the data after the selection process and smoothing is carried out.

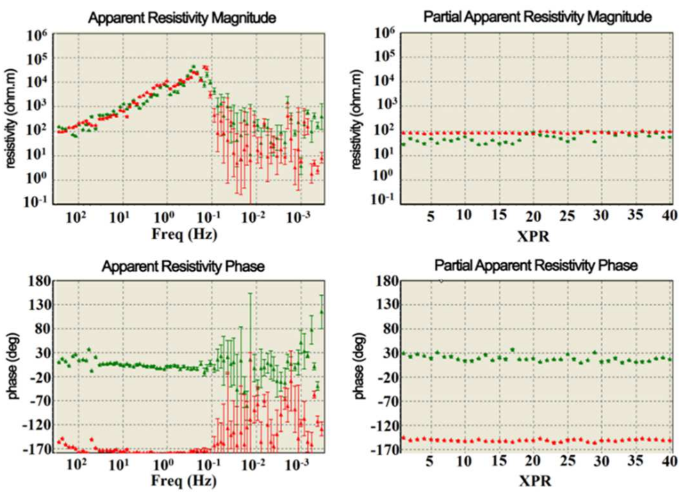

Figure 4 Editing window in MTEditor software (red: TE curve, green: TM curve).

The data are presented in four windows, representing apparent resistivity magnitude, partial apparent resistivity magnitude, apparent resistivity phase, and partial apparent resistivity phase respectively. All the windows are interrelated to each other. If any point is clicked in the window of the apparent resistivity magnitude, a point in the partial apparent resistivity magnitude window appears. Smoothing is conducted so that points located far from the average line will be adjusted to the trend line. After that, the data in this point can be used for the next stage.

In the WinGLink software application, several steps are done to convert some of the data obtained, such as WGS 1984 datum, MT magnetotelluric data type, etc. Then all .edi files are entered that have been obtained prior to the determination of the elevation of the data in the Maps tab. After determining the elevation of each point is done, static phase shift correction or smoothing and 1D modeling are done simultaneously with the Sounding tab.

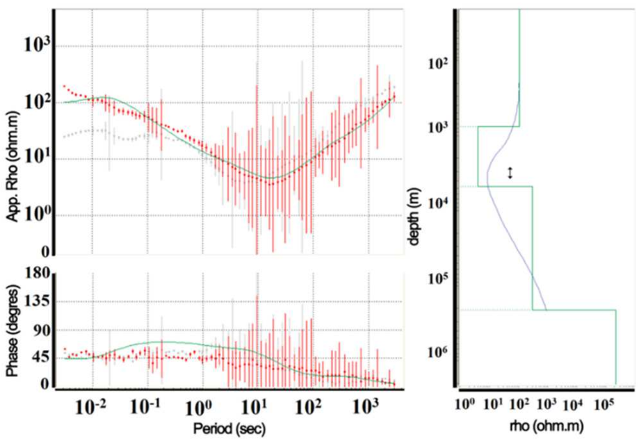

Figure 5 Smoothing window and 1-D modeling in WinGLink.

Then MT static shift correction is conducted. This correction is needed partly because of inhomogeneities near the surface (shallow depth) and uneven topography. This can be done in several ways, either by TDEM data or by a mathematical formula. The proposed method uses an averaging technique, where the point to be corrected is averaged by dots in the vicinity. This method gives results close to those of TDEM [21].

After all points in the folder have been treated the same way, we get the 1-D model. Then the 2D inversion modeling results will be acquired. 2D inversion and iteration must be done to get the appropriate conceptual model and make it easier to interpret. For line 1, the iteration process is carried out as much as 100 times and for line 2 as much as 90 times. See Figures 6 and 7 for images of the 2D models for line 1 and line 2.

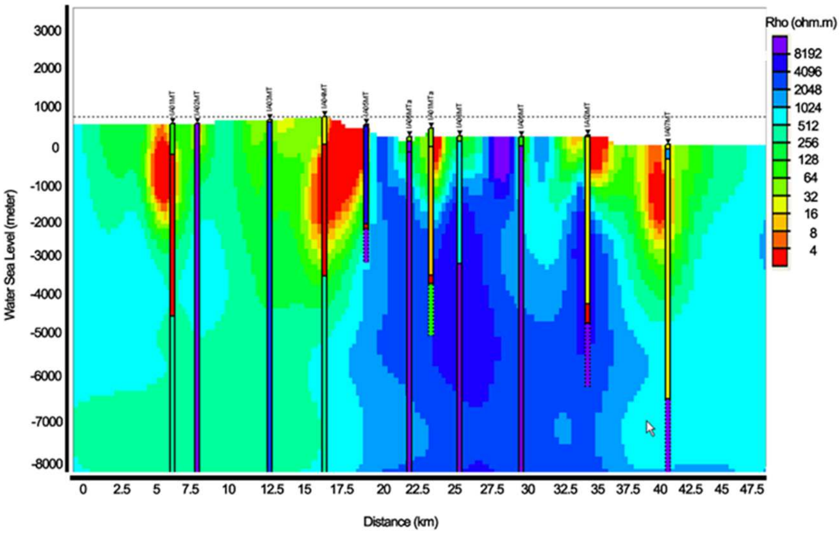

Figure 6 2-D Inversion results for line 1.

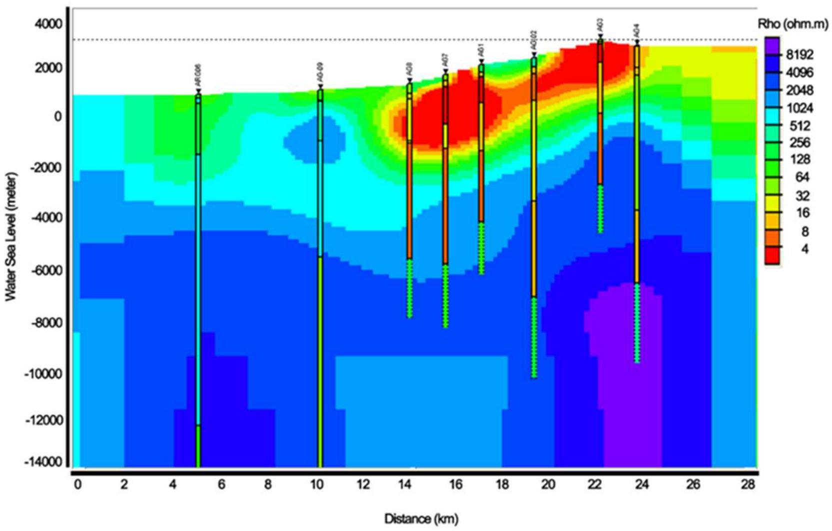

Figure 7 2-D Inversion results for line 2.

From the results an image of the thermal structural below the surface of Mt. Argopuro can be created in order to establish the geothermal potential of the area.

5 Discussion

It was found that on line 1 multiple components had different resistivity values and together form/indicate a conceptual geothermal system. Firstly, altered rock or cap rock that is characterized by very low resistivity (less than 8 ohm-m), has a depth of up to 2000 m, which is colored red. Secondly, structure/faults and a very dilute subsurface fluid flow up to the surface, with high resistivity of up to 2048 ohm-m. Thirdly, reservoir zones that are middle-middle alteration zones (< 8 ohm-m) and have high resistivity (> 1024 ohm-m) and a depth of 2000-5000 m, which are colored green-blue. Fourthly, hot rocks as a source of heat from the earth. This heat source zone is characterized by very high resistivity (> 1024 ohm-m), has a depth of over 8000 m and is colored blue-violet.

The obtained results show that Mt. Argopuro has a geothermal system that includes cap rock, reservoirs, rock and base fluid as heat sources (Figure 8).

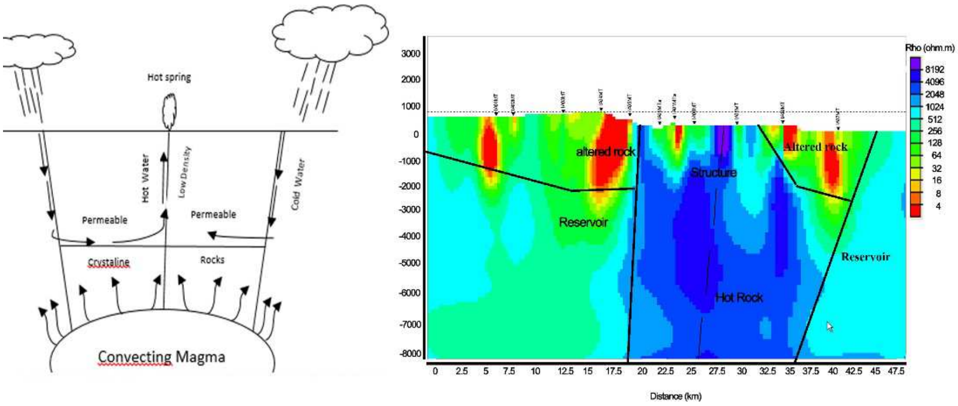

Figure 8 Hydrothermal circulation and conceptual geothermal system model for line 1 (modified from White, 1967) [22].

Line 2 with images showing alleged conceptual model components. Firstly, altered rock or cap rock characterized by very low resistivity (less than 8 ohm-m) with a depth of up to 2000 m, which is colored red. Secondly, reservoir zones that are middle-middle alteration zones (< 8 ohm-m) and have high resistivity (> 1024 ohm-m), with a depth of 1000-4000 m, which are marked with a light green color. This reservoir was investigated further to estimate the reserve potential. Thirdly, hot rocks as a source of heat from the earth. This heat source zone is characterized by very high resistivity (> 1024 ohm-m), with a depth of over 8000 m, which is colored blue-violet. Visible zone of high resistivity as an energy source. Hot rock has high heat. The distribution resistivity structure of 3 layers is strongly associated with differences in distribution/temperature [23]. In addition there is a correlation between the resistivity value between each component on line 1 and line 2.

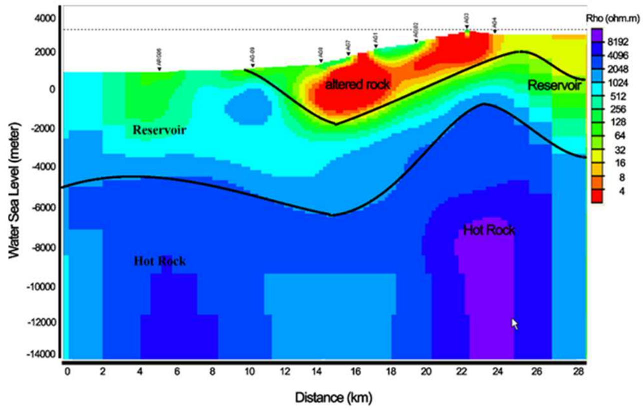

Figure 9 Conceptual geothermal system model for line 2.

6 Conclusion

The subsurface structure of Mt. Argopuro was studied using the magnetotelluric method. The NLCG inversion used in this study was found to be computationally more efficient compared to using the OCCAM and REBOCC techniques in similar settings [24-25]. For the two smaller data sets that were inverted, the NLCG inversion was two to four times faster than the other inversion methods. For the larger data set, the NLCG inversion converged more than one order of magnitude faster than the other methods [26].

Based on the electrical conductivity values (measurements), a model of the subsurface structure under Mt. Argopuro was proposed. The structure forms a conceptual geothermal system indicated by the four characteristic components of the geothermal system, namely altered rock on line 1 and line 2 with a resistivity of less than 8 ohm.m at a depth of about 2000 m. The difference in resistivity values lateral to the subsurface indicates a fault. The resistivity value of more than 8 ohm.m of the reservoir fluid at a depth of between 2000-5000 m is thought to indicate a source of heat energy from below. And then there is hot rock with resistivity values of more than 1024 ohm.m at a depth of about 8000 m.

It can be concluded that Mt. Argopuro has geothermal potential as indicated by the constituent components of the subsurface structure, i.e. altered rock, reservoirs, fractures, and hot rock. The subsurface structure also contains heat sources with high resistivity values (> 1024 ohm.m) indicating considerable potential.

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