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Investigation of Geothermal Structures of the Kadidia Area, Indonesia, using the Magnetotelluric Method

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ABSTRACT

During the year 2012, a magnetotelluric (MT) survey was carried out on the Kadidia geothermal area, Sulawesi Island, Indonesia with the aim of defining the electrical resistivity structures related to the geothermal system of the area. MT data were collected along S-N profiles and processed by using robust algorithms. Processed data were inverted and computed into two-dimensional models of resistivity and impedance phase. The interpretation of models revealed a good correlation between the features of the geothermal system and resistivity structures at depth. The models revealed a shallow low-resistivity region (at depth of about 0.5 km – 1.25 km), which may indicate the existence of the areal extension of the cap rocks for the geothermal system.

1. INTRODUCTION AND GEOLOGICAL SETTING

The Kadidia geothermal field is located on the Sigi regency, central Sulawesi province, Indonesia. The existence of a geothermal system was indicated by the appearance of hot springs with temperature values of 40^0C to 104 ^{0}C. An MT survey was carried out in 2012 on the Kadidia geothermal area. The aim of this project was to define the electrical resistivity structures related to the geothermal system. Regionally, the Kadidia geothermal area is located between two major faults in Central Sulawesi. Kadidia is bounded by the Palu Koro fault in the west and the Poso reverse fault in the east. A major fault with the northwest - southeast direction cuts diagonally across the investigation area. This is the fault structure that controls the appearance of hot springs in the village Ampera while the hot springs that appear in the Village Berdikari are controlled by fault structures trending southwest-northeast. The southwest-northeast structures coincide with the northeastern direction and appear on the boundary between the formation Napu and the formation Puna.

The Kadidia geothermal system formed in the non-volcanic environment of young and emerging zones in the depression zone. The distribution of geothermal prospect areas in Kadidia, based on the results of geological research method, is in the depression zone formed by a pull-apart structure. On the other hand, the Koala Rawa hot spring (southern part) is a geothermal system that is separate from the geothermal system of Kadidia. The reservoir in this area is thought to be granitic rocks composing the metamorphic breakthrough, which is rich in fractures and is permeable. As a result of the activities from the existing fault structures, the high permeability is caused by fractures that formed. The cap rock is composed of argillic alteration zone rocks that are rich in clay minerals and are impermeable. In addition, the Kadidia heat source area of the remaining magma heat is associated with young volcanic cones which could be the body of young plutonic rocks.

In the geology in the area (Figure 1), there are a few areas that allow inquiry into the source of heat. This includes the body of the granitic plutonic rocks created by the Plio-Pleistocene and plutonic body that are not exposed to the surface in the form of a depression that is located in the central part of the investigation area. The length of time of the formation of plutonic bodies are widespread in the area of investigation, which reinforces the notion that the parent body of granitic plutonic rocks can store enough heat in the geothermal system of Kadidia.

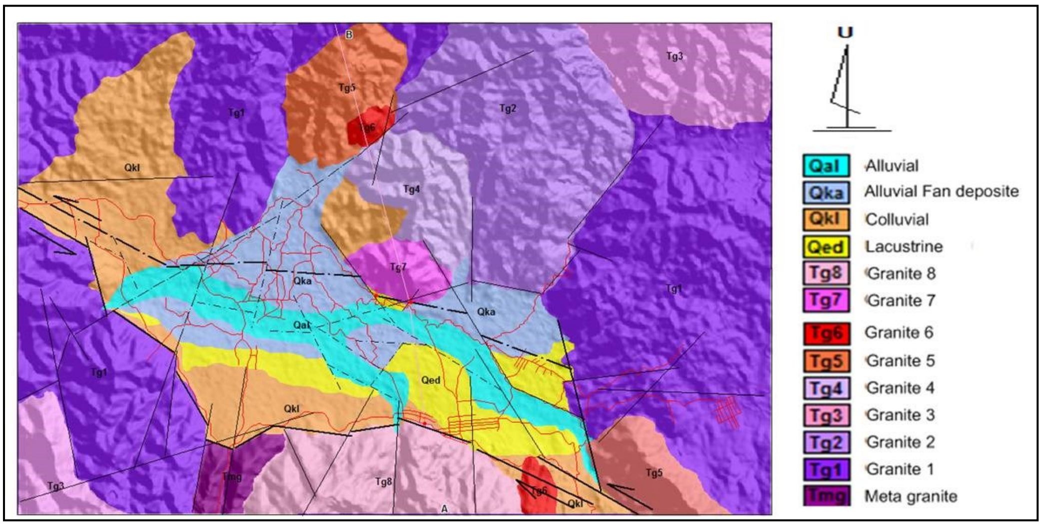

Figure 1. Geological Map

2. METHODOLOGY AND DATA ACQUISITION

The successful use of geophysical methods for geothermal exploration depends on the contrast of the physical properties of rocks. Geothermal resources require the presence of water and heat. Since the electrical resistivity is affected by changes in temperature and permeability, the electromagnetic and electrical methods can provide a model of the subsurface resistivity variation. The magnetotelluric (MT) method is a geophysical technique used to image the subsurface electrical resistivity (Cagniard, 1953; Vozoff, 1991). Using the Earth's naturally occurring electromagnetic fields as a source, it provides useful information about the lateral and vertical resistivity variation in the subsurface. The magnetotelluric method is one effective method for mapping the resistivity structures. This method measures the magnitude of response of the earth in electric (E) and magnetic (H) fields of the electromagnetic (EM) nature. The response includes the horizontal component of the magnetic field and the electric field of the earth is measured at the earth's surface. The investigation depth of MT can easily reach several km, being correlated to the different natural frequencies of the Earth (Bai et al., 2001; Gianni et al., 2003). This method is also able to detect conductors that are embedded in a resistive medium associated with the dimensions of the conductor. The resistivity contrast between the conductor and the host rock and the distribution of specific research areas are electrostratigraphic (Newman et al., 1985).

Forty-two MT sounding equipment with a site spacing of 1km to 1.5 km were carried out along six N–S trending profile lines (Line A-F) within Kadidia area (Figure 2). The data were collected from October-November 2012, using the wide band MT data acquisition units (GDP-32) of the Zonge system. The four horizontal components of the electric and magnetic fields were measured in N–S and E–W directions in a frequency range of 0.015625 Hz to 8 KHz. The vertical magnetic field component was also recorded at every site. The measurements were carried out for 12 to 20 hours at each site in four overlapping frequency bands.

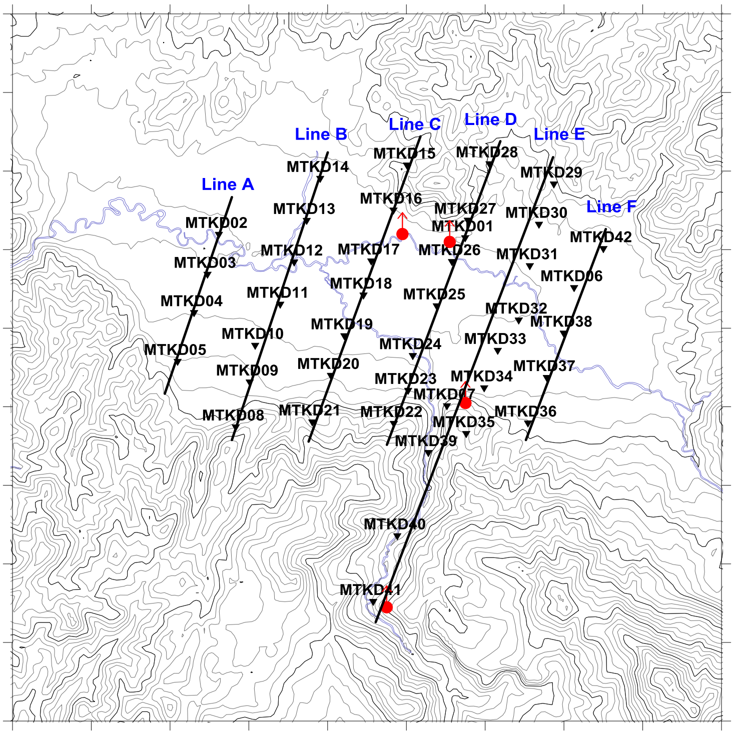

Figure 2. Topography of Kadidia and the locations of MT sites

3. ANALYSIS

All the data were processed using MTFT and Mtedit, which are utility programs for processing and reviewing magnetotelluric time-series data (Zonge software package). MTFT uses cascade decimation to Fourier transform the time-series and calculate the spectral data. On the other hand, the program MTEdit can be used to make robust impedance and apparent resistivity averages. Examination of MT responses at each site was attempted for a general qualitative assessment of the geoelectric character of the subsurface. The preliminary analysis indicated that the MT apparent resistivity curves could be classified into three groups indicating lateral changes in resistivity (Figure 3). The first group of curves was from the central part that are composed of sedimentary rocks, The second group of curves was from a similar environment to the first but with geothermal manifestations and the third group of sites was from the southern and northern parts that were composed of igneous rocks. The first and second groups showed conductive structures at higher frequencies and were resistive at lower frequencies. On the other hand, the third group of sites showed resistive structures that started from higher to lower frequencies. This pattern of curves indicated a good correlation between rock composition and resistivity values.

The static shift is a general problem on MT data . This problem arises from local resistivity perturbations that mainly affect the electric fields, causing a frequency independent shift of the apparent resistivity curves. To eliminate the problem of static shift, a statistical method and comparation with geoelectrical data available in the area were used. The statistical method was used to determine the median of apparent resistivity from a number of MT data around which the point was corrected. Apparent resistivity values were used to determine the median value which was the apparent resistivity in TE mode and TM mode.

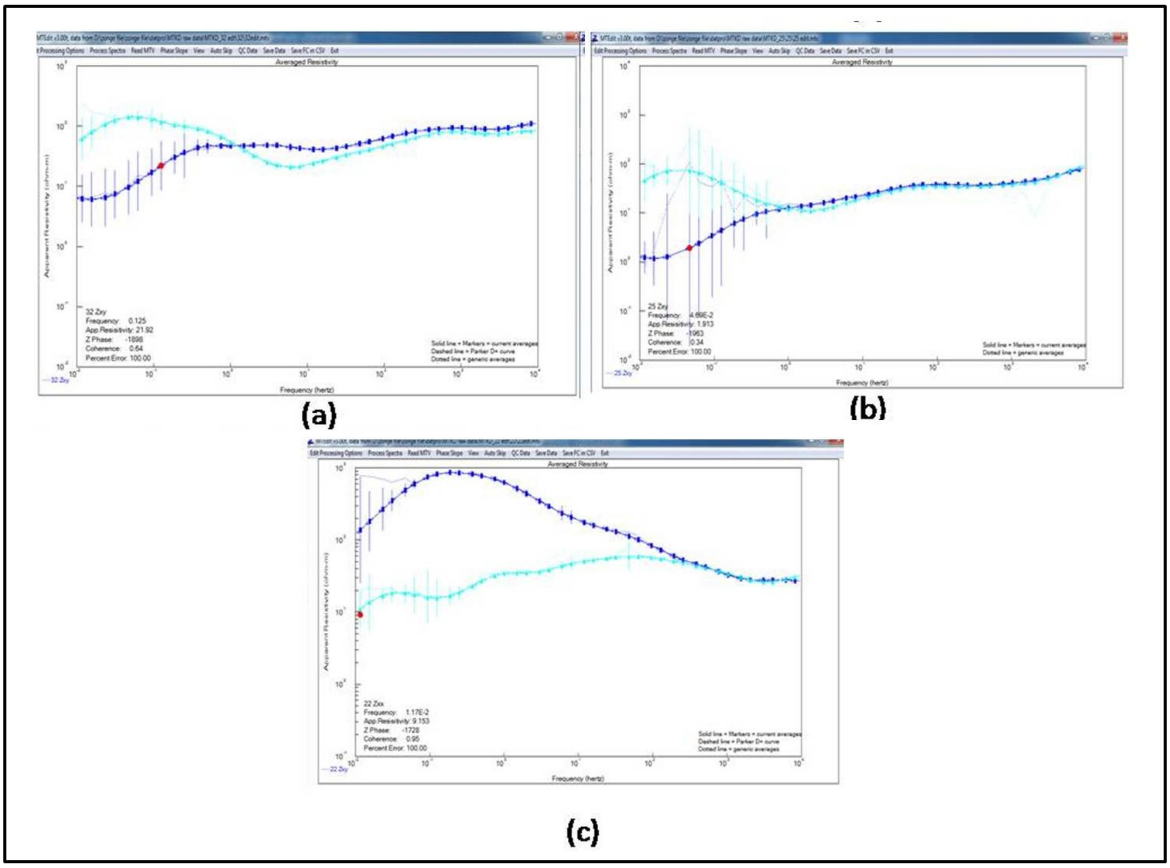

Figure 3. Common curves of adjacent sites along the acquisition profile

4. MODELING AND INTERPRETATION

As described in Section 1, the Kadidia area is characterised by a NW–SE geological strike (Palu Koro fault) that runs approximately orthogonal to the MT profile and is consistent with the indications derived from the analysis of the electric strike. Thus, 2D modelling should be appropriate for reconstructing the main electrostratigraphic features. The data were inverted for the 2D conductivity models using a regularised inversion algorithm (Rodi and Mackie, 2001).

All model parameters were allowed to vary freely during the inversion. A noise floor of 10% for the apparent resistivity and of 10% for the phase were used. Several inversions were performed for both the TM and TM–TE modes. Since the TM mode typically suffered less 3D distortion than TE (Wannamaker et al., 1984), some inversions took into account only the TM mode data. In order to verify the effect of finite strike on the data, the TM mode data was inverted starting from an a priori model obtained by the joint inversion of the TM and TE mode data. The resulting models were sensitive to structures up to depths of approximately 4 km to 5 km, whereas the data showed no detectable variations of resistivity at greater depth. Comparison of the many models obtained with 2D inversion allowed the definition of robust features which were the characteristics that did not depend on the a priori model but were required by the data.

Resistivity distribution patterns in the area Kadidia are generally similar to the rock lithology and its morphology (referring to the results of surface geological mapping, integrated surveying, and PSDG 2012). The morphology of the Kadidia area can be divided into these areas: the hills in the north and south which are both composed of igneous rocks and the morphology of the plain in the central part of the zone of depression as a result of normal faults on the north and south. These normal faults are composed of lacustrine and rock alluvial. The distribution of resistivity from low to medium (< 100 ohmm) occupy the center of the response of alluvium or lacustrine rocks while the high resistivity of > 100 ohmm is detected in the north and the south. This is expected because it mirrors the granite rock lithology filling the morphology hills. Gradation resistivity values occur in the middle of the meeting , which is expected in the area as a fault zone trending northwest- southeast, which indicates the presence of a graben in the center of the survey area

Zone boundary is a clearly visible depression on resistivity cross section (Figure 4) which were cut in the alluvial plain lithology and granite in the hills . Changes in the value of higher resistivity with increasing depth indicates that the more compact rocks and fresh at depth . The resistivity values that are less than 100 ohmm which fills the depression zone are interpreted as alluvial and lacustrine rocks that have diminishing extent with increasing depth. At a depth of 2000 m , the value of resistivity in the center of the uniform start with values greater than 100 ohmm. This shows that the depth of the rock lithology has reached the basement rock of granite. It is evident also in the resistivity cross section (Figure 5) where the resistivity began to rise at an elevation of approximately -1000 m above sea level (around 1750 m depth) on line 4 and an elevation of about -800 m above sea level , or about 1500 m depth .

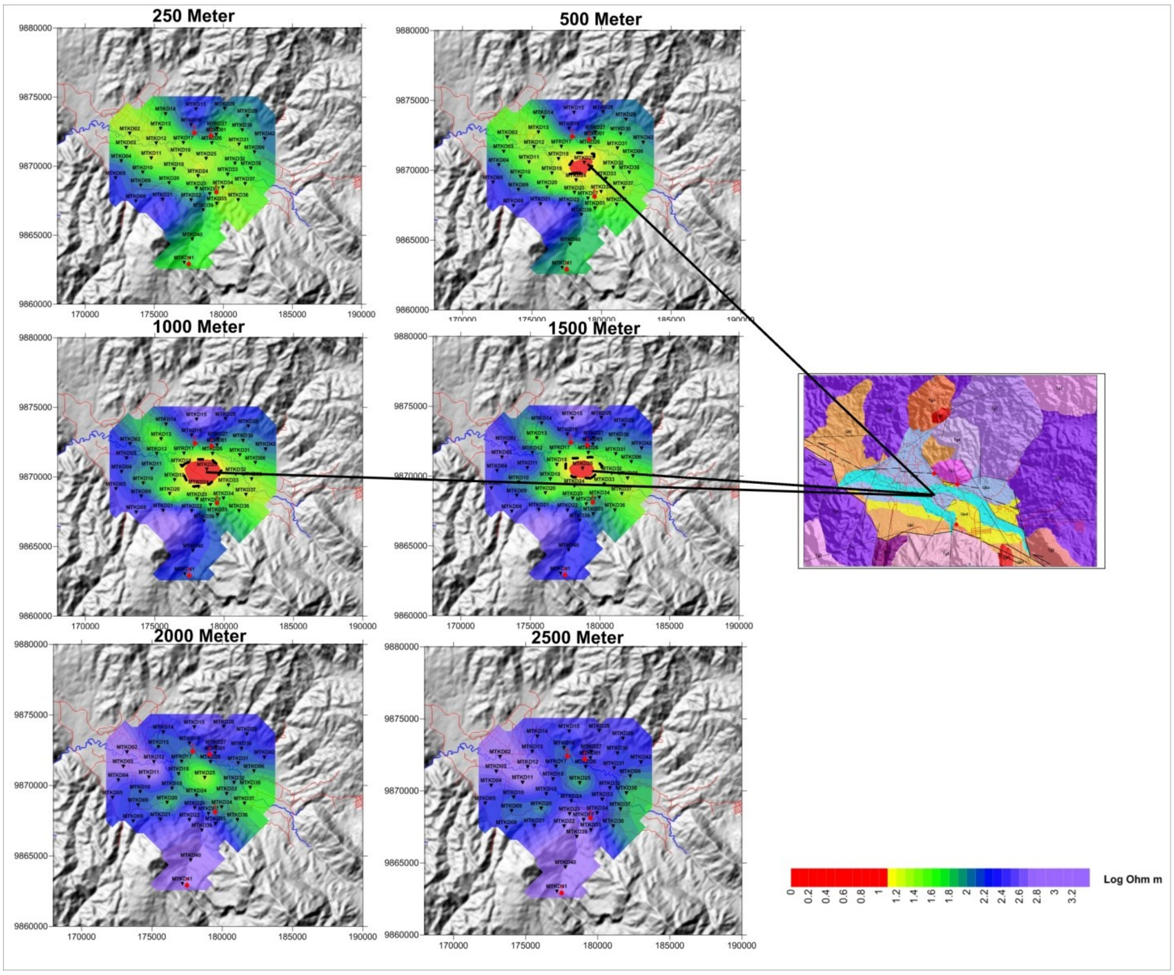

Figure 4. Resistivity model distribution

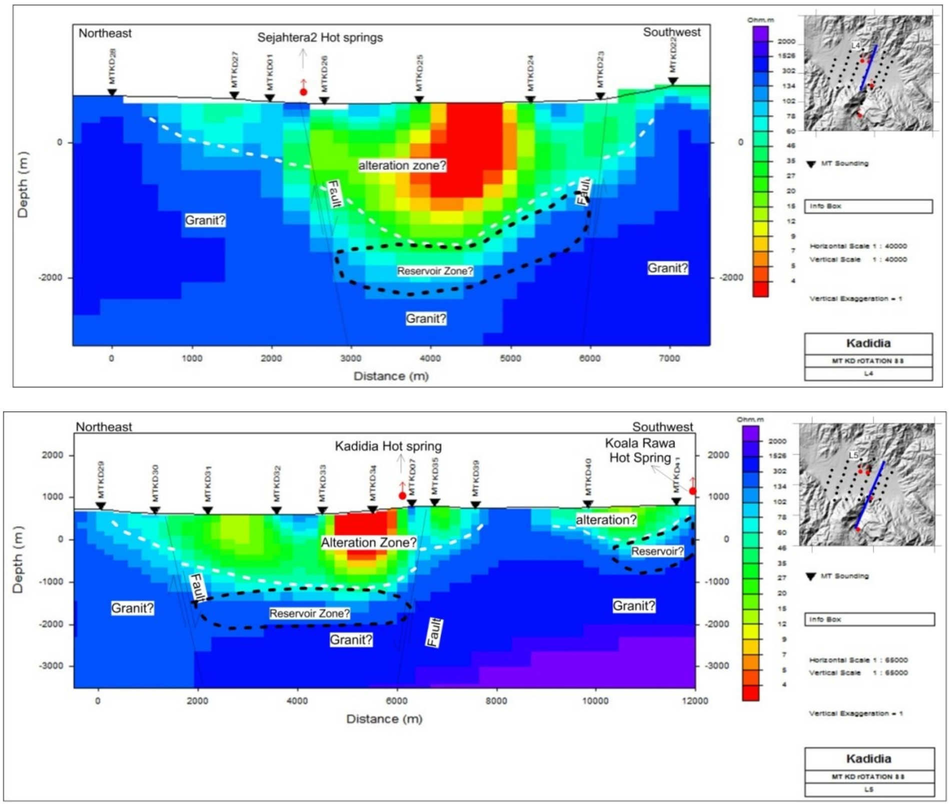

Figure 5. The resistivity models of Line D and E

Geothermal manifestations in Kadidia and Sejahtera are on the boundary zone with resistivity values of 25 to 100 ohms. Starting at a depth of 500 meters between the two geothermal manifestations (Sejahtera and Kadida), there is an anomalous low resistivity (< 10 ohmm) area which forms the contour. This low resistivity anomaly appears consistently and increases its width up to a depth of 1000 meters. Starting at a depth of 1250 meters, the resistivity anomaly becomes thinner and disappears at a depth of 1500 meters. This low resistivity anomaly is most likely an alteration zone by hot fluids that is partially surfaced as a hot springs in the Prosperous and Kadidia areas.

5. CONCLUSIONS

The magnetotelluric results from the Kadidia geothermal area are used to characterize the electrical structure of the area. The present study shows lateral as well as vertical and horizontal variations in electrical resistivity. Based on the MT results, the electrical resistivity structures related to geothermal system are defined. The geothermal prospect areas are in the depressed zone surrounding the area in Kadidia that had geothermal manifestations. Based on estimations, the cap rock layers are composed of alluvial, lacustrine, and granite that have undergone alteration with resistivity values less than 10 ohms. This layer is rich in clay minerals that are impermeable and are detected from depths of about 250 meters up to 1250 meters. Under the low resistivity layer, the detected resistivity values are above 100 ohms. This resistivity structure is predicted as reservoir layer that is composed of granitic rocks where the peak of the reservoir is at a depth of about 1250 to 1500 meters.

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