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Imaging Reservoir Structure of the Sibayak Geothermal Field (Indonesia) Based on Magnetotelluric Observations

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ABSTRACT

Sibayak geothermal field is located in the North Sumatra Province, Indonesia. Recently, a small-scale geothermal power plant (2 MWe) has been installed in this area. Since electricity demand increases in this area, Pertamina (Geothermal Division) plan to expand the capacity to 20 MWe in the year 2005. Accordingly, detailed knowledge of the reservoir structure and its extension must be determined. Magnetotellurics is thought to be one of the geophysical tools that is powerful for delineating reservoir structure. This paper describes the 2-D inversion of MT data and its correlation to the reservoir structure and extension in the Sibayak field. Borehole data and other previous geophysical work conducted by the first author are also used for constraining the MT data interpretation. It is revealed from this study that the reservoir structure in the Sibayak field is characterized by an up-domed shape of a resistive zone (resistivity = 50-200 ohm-m). The reservoir is mainly located in the central area between Mt Sibayak and Mt Pratektekan, where the highest subsurface temperature (300°C), the highest production (30 to >50 ton/hr steam) as well as the highest permeability (kh = 2-4 darcy-m) zone were recorded from the existing wells at depths of 1500 to 2000 meters. The reservoir is found within the sedimentary formation and also along the contact between the volcanic and sedimentary formations. This fact leads us to propose that future development of the Sibayak area should take place in the high temperature, high permeability and high well productivity region marked by the up-domed shape resisitive zone below the conductive cap rock.

Introduction

Sibayak geothermal field is the first geothermal field developed in Sumatra Island (Figure 1) under different stages of exploration. The exploration results confirmed that the Sibayak field has potential for further development. Accordingly, to date 10 wells have been drilled in this area for supplying a small-scale geothermal power plant (2 MWe). Since electricity demand is increasing in the North Sumatra Province, Pertamina will expand the installed capacity to 20 MWe in the year 2005. For this purpose, a detailed understanding of the reservoir structure and its extension in the Sibayak field is urgent to achieve. Accordingly, enhanced interpretation techniques of selected geophysical data have been carried out to confirm the reservoir structure, its extension and the most promising zone for further development. Borehole to surface resistivity (mise-a-la-masse) data have been used to image the permeability distribution in the Sibayak area (Daud, *et. al.*, 1999 and 2001a), while enhanced

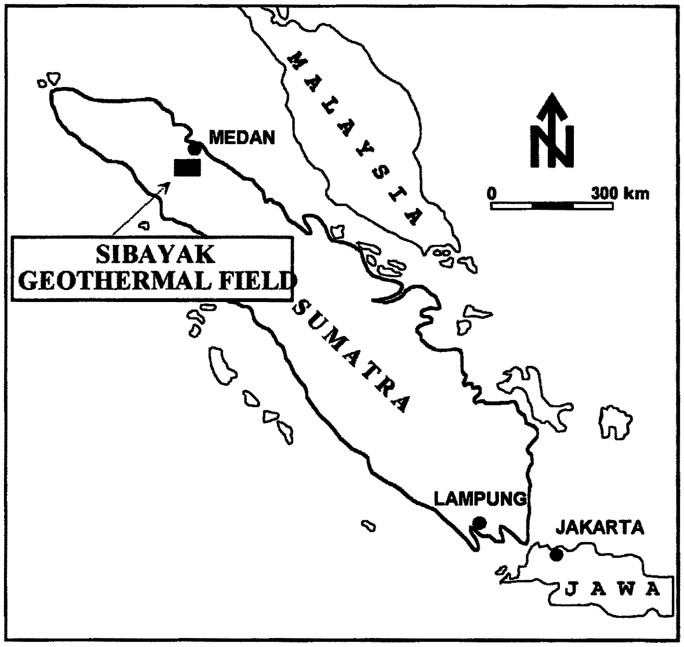

Figure 1. Loction map of the Sibayak geothermal field, North Sumatra Province, Indonesia.

interpretation technique for gravity data constrained by borehole data has delineated the subsurface structure associated with the reservoir distribution (Daud, *et. al.*, 2001b).

Recently, the Magnetotelluric (MT) method has been used in geothermal exploration as an effective tool for delineating subsurface resistivity structures. Furthermore, an enhanced interpretation technique needs to be applied to the MT data in order to get more realistic subsurface information. The object of the MT survey conducted in the Sibayak geothermal field was to confirm the deep information of resistivity structure associated with the geothermal system, undetected by the Schlumberger resistivity measurement. A 2-D inversion technique was used to confirm the reservoir structure and its extension in the Sibayak Field. This paper discusses the MT data interpretation results integrated with other geophysical and borehole data to image the reservoir structure, its extension and the most promising zone in the Sibayak Field.

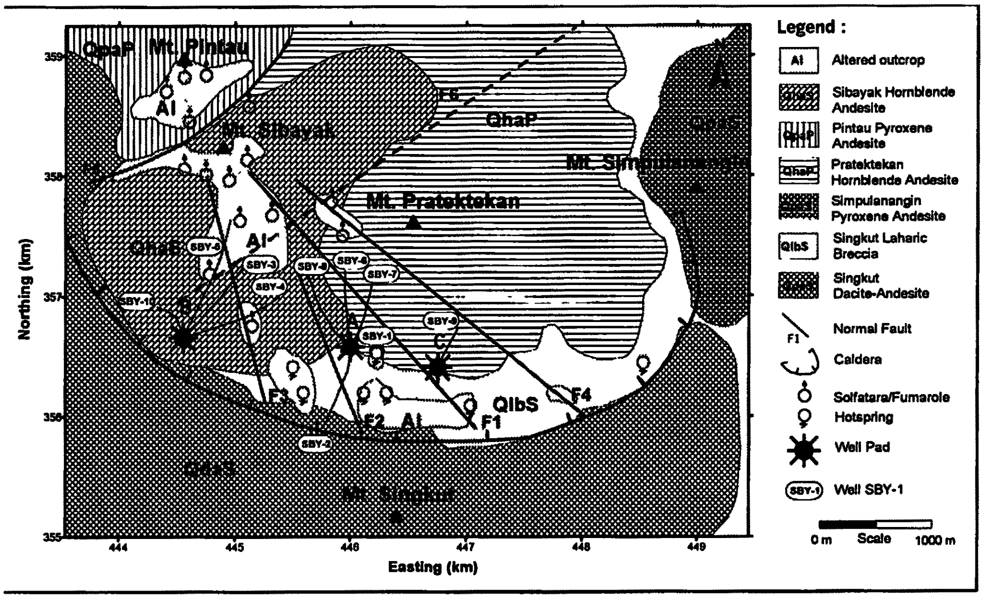

Figure 2. Simplified geology and surface manifestations of the Sibayak geothermal field, Indonesia.

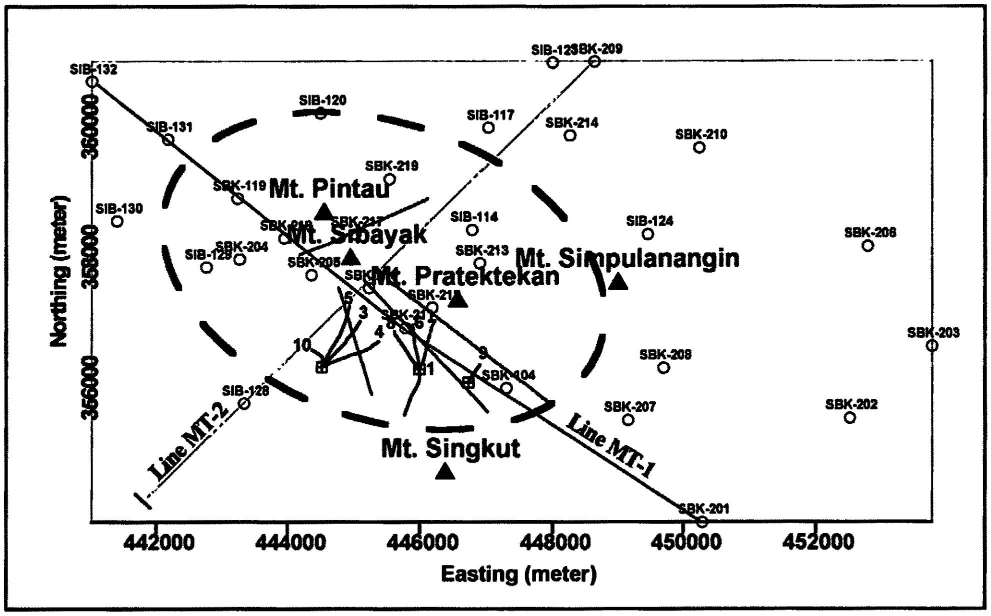

Figure 3. Map showing the locations of MT measurements in the Sibayak geothermal field and the orientations of the profiles Line MT-1 and Line MT-2..

Field Overview

The Sibayak geothermal field is situated in a high terrain area inside the Singkut caldera in the North Sumatra Province, Indonesia (Figure 2). The Sibayak area is composed of a Quaternary volcanic formation that is unconformably overlying a pre-Tertiary to Tertiary sedimentary formation, which is predominantly sandstone followed by shale and limestone. Drilling data shows that the sedimentary formation is generally found from 1150 meter depth.

The geological structures in the Sibayak area are mainly controlled by volcanic and tectonic processes. Intense fracture controlled permeability was inferred from shallow to deep circulation losses during drilling. In the area drilled to date most of the lost-circulation zones were found in the sedimentary formation as well as along the contact between the volcanic and sedimentary formations. Accordingly, it appears that the geothermal reservoir is confined to these sedimentary units.

Magnetotelluric Data

MT Database

In 1991, PT Alico conducted MT surveys at the Sibayak geothermal prospect, under contract from Pertamina. A total of 31 MT soundings, over a frequency range from 239.8 to 0.003 Hz, were made in a survey area of about 50 km^2, with a sounding spacing of 1 to 2 km. However, only 10 out of 31 sounding data were judged to be of sufficient quality to merit usefulness. Accordingly, in 1997, Geosystem srl in association with PT Qodharwan Wirasta Konsultan (QWK), conducted MT surveys at the Sibayak geothermal prospect, under contract from Pertamina. A total of 20 MT soundings were measured over an area of 85 km^2. These and the previous MT sounding locations (PT Alico, 1991) are shown in Figure 3. MT stations were recorded as a 5-channel single site in the frequency range 100 to 0.001 Hz, using two (and finally three) clocks synchronized EMI acquisition system, recording for 16-18 hours per site. Noise levels were relatively low, signal was good, and robust processing of all sites using local remote reference resulted in excellent data quality. No repeat soundings were necessary due to either noise or technical error. The full description of the acquisition and processing procedures, including static shift correction, is contained in Qodharwan (1997).

One-Dimensional Inversions

As first step of the quantitative interpretation, the MT data were then inverted using 1-D approach. Interpretation in terms of a layered earth can be carried out by assuming that a model consists of a minimum number of layers with sharp conductivity boundaries and by using M-estimator robust procedures (Sutarno, 1990) to resolve the layer thickness and resistivities from the data. The interpretation can also be carried out using a large number of layers, constraining the recovered model to 'minimum structure'. This technique is the so-called Occam 1-D inversion implemented by Constable et al. (1987). The former technique is preferred because it yields parameter resolution for the model, even with significant noises, and consequently identifies the structures that are supported by data. Discontinuous models from robust inversion are likely to be more representative of the vertical conductivity distribution within the volcanic formations than Occam models.

Most of the resulting models can be represented by an H-type three-layered sequence ($\rho 1 > \rho 2 < \rho 3$), characterized by a resistive layer (50-200 ohm-m), underlined by an approximately 300-900 m thick conductive (5-10 ohm-m) layer. These two layers rest on a resistive half-space with a resistivity of more than 500 ohm-m. However, the resistivity basement is poorly determined due to strong indication of 2-D or 3-D effects. Accordingly, the 1-D inversions are only used in the identification of the relatively shallow conductor. Further interpretation emphasizes two-dimensional inversion as will be described in the following section.

Two-Dimensional Inversions

The magnetotelluric data were further inverted using 2-D finite-difference based on the non-linear conjugate gradient algorithm following Rodi and Mackie (2001). Conjugate gradient relaxation is also used to solve the forward problems. The program inverts both TM and TE mode data, and solves for both resistivity and phase. However, TM mode was more emphasized as the TM mode is less distorted by 3-D effects (Wannamaker, *et. al.,* 1984). Input data can be arbitrary frequencies. Moreover, the program also allows for surface topography.

The subsurface resistivity distribution in any real situation is 3-D, and the interpretation in terms of 2-D models has inherent limitations. Nevertheless, these models are currently the best way to simulate seemingly complicated geological situations. Considering the number and spatial distribution of the collected data, it can be expected that the 2-D models obtained along several properly selected profiles should produce a useful picture of the geo-electrical structure in the studied area.

The MT survey at the Sibayak field was designed to provide information along the profiles parallel and perpendicular to the known structural system, especially the expected production zone. Six 2-D inversion models were run along profiles Line MT-1 to Line MT-6 (Daud, 2002). However, this paper only presents two of them (Line MT-1 and Line MT-2 as shown in Figure 3). The profiles were selected crossing the indicated up-flow zone in the central area between Mt Sibayak and Mt Pratektekan (Daud, *et al,,* 1999; 2001a and 2001b).

Given the deep 3-D nature, input data were restricted from 0.003 down to 30 seconds period. Though, the displayed part of the models are restricted to the zone of interest around the soundings, the models extend 90 km beyond the edges, both laterally and vertically. The fit between observed and calculated data was excellent and the relevant plots are included with each model.

Line MT-1

This profile has a NW-SE orientation (Figure 3) and it is selected crossing the northwestern outside caldera rim, the indicated production zone (up-flow zone), passing Mt Pratektekan, Mt Sibayak and Mt Pintau, continued to the indicated outflow zone in the southeastern caldera rim and ended in the southeast far from the caldera rim.

The main features in the Sibayak area are clearly defined along this profile (Figure 4). In the central portion of the model below SBK-205 and SBK-216 the electrical structure is characterized by an up-domed shape of resistive zone (20-200 ohm-m) down to 1500 to 2000 meters, covered by a strongly altered rock (5-10 ohm-m) along the profile with various thickness. The highest temperature recorded from well Sby-5 is about 300°C below the up-domed shape resistor down to 2200 m. Another interesting feature is the more resistive basement shape following the Singkut caldera boundaries in the northwest and southeast. Outflow zone is also clearly defined by this model

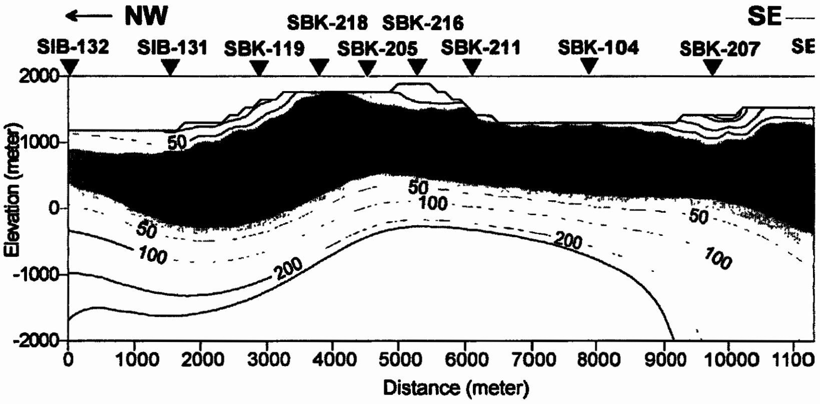

Figure 4. 2-D inversion result of the MT data along the profile Line MT-1. The values in the Figure represent true resistivities in ohm-m. The location of the profile can be seen in Figure 3.

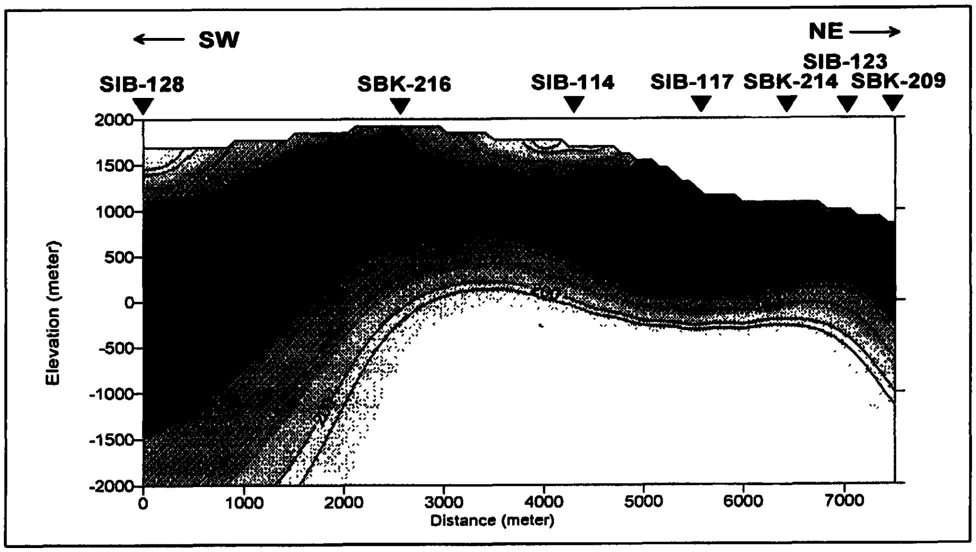

Figure 5. 2-D inversion result of the MT data along the profile Line MT-2. The values in the Figure represent true resistivities in ohm-m. The location of the profile can be seen in Figure 3.

northeastward following the decreasing topography toward the northeastern caldera margin.

Line MT-2

The profile is oriented SW-NE starting at the sounding station SIB-128 in the northwest outside the Singkut caldera (Figure 3). The profile crosses the central of up-flow zone, passes the area between Mt Sibayak and Mt Pratektekan, and ends at the sounding SBK-210 in the northeast.

It is shown in the Figure 5 that the up-domed shape resistor (50-200 ohm-m) underlying the strongly altered rock (5-10 ohm-m) is clearly defined below sounding station SBK-216 down to 1500-2000 meter. The indicated out-flow zone extends northeastward outside the caldera margin down to 1000 to 1500 m.

Reservoir Structure And the Promising Zone

The 2-D inversion of the MT data can be used as a useful guidance in delineating the Sibayak geothermal reservoir. Moreover, the subsurface structure interpreted from gravity data, permeability distribution, well productivity data and temperature data are incorporated to get better understanding of the reservoir structure of the Sibayak geothermal area.

Reservoir structure in the Sibayak geothermal field has an up-domed shape centered in the area between Mt Sibayak and Mt Pratektekan, covered by thick strongly altered rock (Figure 6). Vertical permeability in the reservoir zone is controlled by faults and intersection of fault structures as interpreted from gravity data (Daud, 2001b), while the horizontal permeability is probably controlled by lithological contact of volcanic and sedimentary formations or within the older sediments of sandstones and limestones as shown by borehole data. Drilling data in this area shows high temperature (> 280°C) and high productivity (30 to > 50 t/h steam). Furthermore, the highest subsurface temperature recorded in the existing wells (300°C in the well SBY-5) is encountered in the up-domed shape of the resistive zone at 1500 to 2000 meters in depth. Moreover, the most productive (30~50 t/hr steam) as well as the highest permeability zone (kh=2~4 darcy-m) is located in the up-domed shape reservoir zone (Daud, *et. al.*, 2001a).

In order to have better understanding of the spatial distribution of the interpreted up-domed shape of the resistive layer below the conductive alteration cap, we constructed a map by using the elevations of the top of the 50 ohm-m layer derived from the 2-D inversion of MT data. The 50 ohm-m layer was selected since the top of the layer has good correlations with temperature distribution of 200°C as recorded in the existing wells. Moreover, the permeability distribution data derived from Mise-a-la-masse data interpretation (Daud, *et. al.*, 2001a) as well as formation temperature data are also contoured in the map. It is clearly shown in

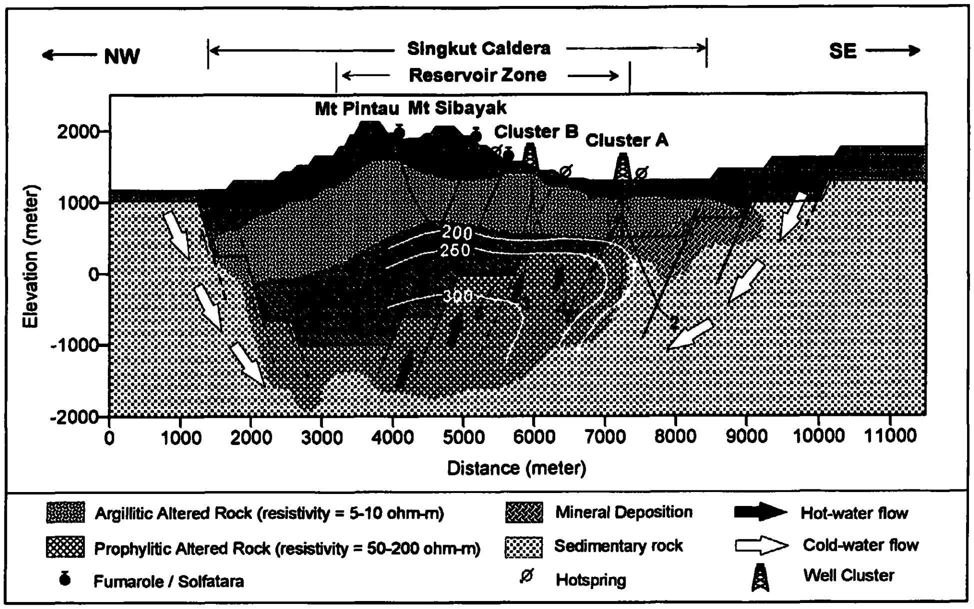

Figure 6. Reservoir structure and its extension of the Sibayak geothermal field. The geological structures are derived from gravity data (Daud, *et. al.*, 2001b). The location of the profile can be seen in Figure 7. White numbers in the profile denote temperature (in °C), while the black ones denote wells.

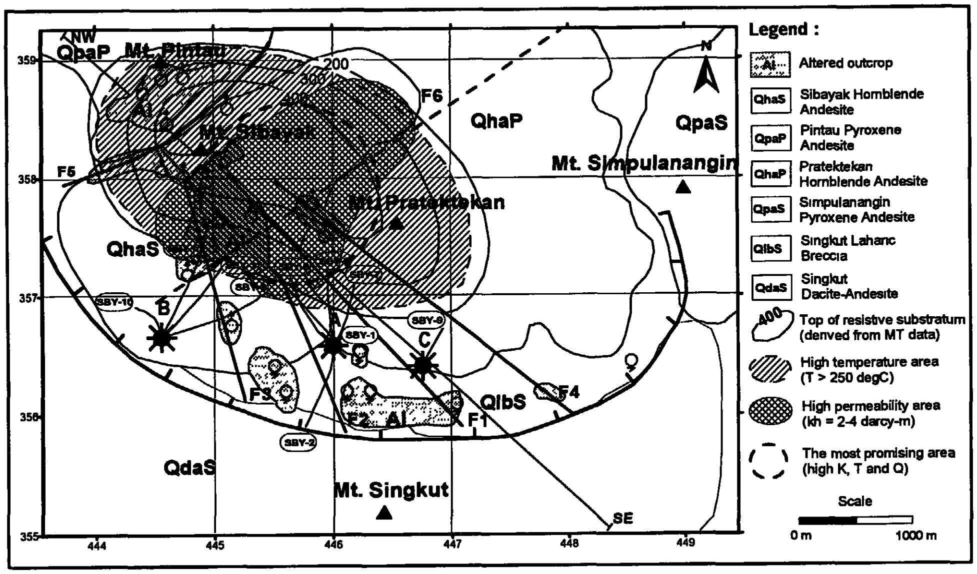

Figure 7. Compilation map of the elevation of the top of the up-domed shape resistive substratum, high temperature and high permeability area. More information about this Figure can be seen in Figure 2.

the Figure 7 that the top of the up-domed shape resistor (reservoir zone), represented by the contour line of 300 m, covers Mt Sibayak and Mt Pratektekan. The extension of the promising reservoir zone, represented by the contour line of 200 m, includes the higher temperature and more productive wells covering an area of about 7 km^2. This new insight has supported the previous hypothesis that the reservoir extension covers Mt Pratektekan, even though no surface manifestations are found around the mountain. This finding is similar to that found in Hatchobaru geothermal field, Japan (Ushijima, *et. al.,* 2000), that its reservoir extends to Mt Goto, even though no surface manifestation are seen around the mountain.

The area between Mt Sibayak and Mt Pratektekan is expected to be the most promising zone since the highest permeability (kh = 2-4 darcy-m), the highest temperature (300°C) and the most productive zone (Q > 50 t/hr steam) are located in this area. This fact leads us to propose a relationship of high temperature, high permeability and high well productivity with the up-domed shape resistive zone (reservoir zone) below the strongly altered zone (cap rock) for the Sibayak exploitation area. It is, therefore, recommended that further development should be directed to this area.

Conclusions

The reservoir structure of the Sibayak Geothermal Field has been delineated by using 2-D inversion of MT data. The reservoir structure is characterized by the up-domed shape of the resistive zone (resistivity = 50-200 ohm-m) underlying the conductive strongly altered rock (cap rock). The reservoir is mainly located in the central area between Mt Sibayak and Mt Pratektekan, where the highest subsurface temperature was recorded in the existing wells (300°C at Sby-5) at depths of 1500 to 2000 meters. In addition, well-bore data have recorded the biggest production (30 to >50 t/hr steam) as well as the highest permeability (2-4 darcy-m) in this area (Daud, *et. al.,* 2001a). Moreover, the area between Mt Sibayak and Mt Pratektekan is expected to be the most promising zone since the high permeability (kh = 2-4 darcy-m), high temperature (more than 250°C) and high production zone (Q > 50 t/hr steam) are located in this area.

This fact leads us to propose that future development of the Sibayak area should take place in the high temperature, high permeability and high well productivity region marked by the up-domed shape resisitive zone below the conductive cap rock.

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