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IMAGING RESERVOIR PERMEABILITY OF THE SIBAYAK GEOTHERMAL FIELD, INDONESIA USING GEOPHYSICAL MEASUREMENTS

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ABSTRACT

Sibayak geothermal field is located at about 65 km to the southwest of Medan in the North Sumatera Province, Indonesia. This field has been investigated by various geo-scientific methods since 1989, continued by drilling of 10 wells. The exploration results suggested that the Sibayak area is a high potential geothermal field. Recently, a 2 MW mono-block has been installed. However, considerable problems are still encountered in the Sibayak geothermal field: high acidic (corrosive) hot water in the vicinity of Mt Sibayak and scaling problem in several wells located around the southern Singkut caldera rim. To find the best target for further development, an attempt has been performed to image distribution of reservoir permeability in the Sibayak area, using surface and borehole geophysical data together with well productivity data. Surface geophysical data including magnetotelluric soundings were used to image distribution of subsurface conductivity, while gravity data were optimized to image subsurface structure related to permeability. Borehole geophysical data (mise-a-la-masse data) has been analyzed to image conductivity distribution related to permeability in the vicinity of production wells. The results were then integrated with production rates, permeability indication from lost circulation zones and temperature data to develop a map of reservoir permeability. It is concluded that good and moderate permeability extends to the area between Mt Sibayak and Mt Pratektekan where the NE-SW faults are intersected by the NW-SE ones, while low permeability zone is found to the southern part of the field just inside the southern caldera margin. The permeability distribution map can be used for planning drilling program at the Sibayak geothermal field. In particular, this results support exploratory drillings in the area between Mt Sibayak and Mt Pratektekan.

INTRODUCTION

Pertamina has conducted drillings of 10 wells in the Sibayak field, including exploration, production and re-injection boreholes. To date the Sibayak field has been producing for a mono-block of 2 MWe installed capacity. To expand the installed capacity to be 20 MWe (Sudarman et al, 2000a; Fauzi et al., 2000), the better understanding of its reservoir characteristics is required especially permeability distribution. Moreover, careful consideration to the high acidic hot water in the vicinity of the Mt Sibayak (Pertamina-Batan, 1998) and the scaling problem in the southern part of the field (Pertamina, 1994) should be taken into account in deciding the promising targets for future development.

To investigate the best target, the permeability distribution in the Sibayak field has been intensively studied by enhancing the interpretation of the existing geophysical data (magnetotelluric or MT and gravity) as well as borehole-to-surface geophysical data (i.e. mise-a-la-masse, MAM). The results are integrated with production test data in order to develop a fracture permeability map of the field and will be presented in the following sections.

The imaging of permeability has three main purposes: first, to provide permeability distribution that can be incorporated into the numerical modeling of reservoir, the second, to identify targets for future exploratory drillings which could expand sustainable production of the Sibayak geothermal resource, and the third, to contribute a useful information to the question of the reinjection of geothermal brines.

FIELD OVERVIEW

The Sibayak geothermal field is situated in a high terrain area inside the Singkut caldera (Figure 1).

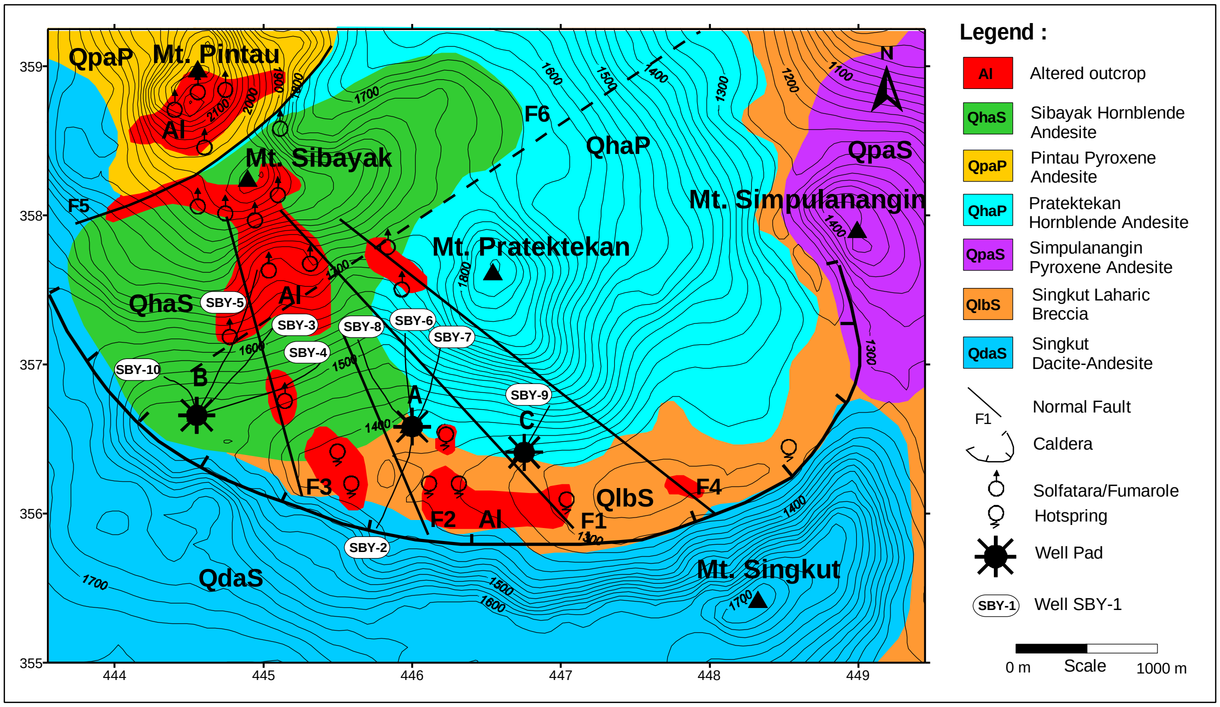

Figure 1. Geological structure of the Sibayak geothermal field

The thermal features consist of solfataras and fumaroles at high elevations and springs at lower elevations. There has been a complex volcanic history in the area with a number of centers of eruptions developing over a considerable period of time within the Quaternary.

The Sibayak area is composed of Quaternary volcanic formation in the upper part that is unconformably overlying pre-Tertiary to Tertiary sedimentary formations. The sedimentary formation, as outcropped to the west and east of Mt Sibayak and found in the deeper levels within the wells, is predominantly sandstone followed by shale and limestone. Drilling data shows that the sedimentary formation is generally found 1150 m below the surface. In the area drilled to date it appears as if the geothermal reservoir is confined to these sedimentary units.

The geological structures in the Sibayak area are mainly controlled by volcanic and tectonic processes. The caldera structure is elongated to NW-SE (F1 to F4), and it developed after the Mt Singkut volcanic eruption (0.1 Ma). Some fault structures within the caldera are oriented to NW-SE, which is parallel to the Great Sumatera Fault, and extend to the center of Mt Sibayak and Mt Pintau, where they are intersected by the NE-SW fault structure (F5). The NW-SE fault structures are also intersected by the NE-SW lineament (F6) encountered between Mt Sibayak and Mt Pratektekan. Intense fracture controlled permeability is inferred from shallow to deep circulation losses during drilling. Lost circulation while drilling is also encountered in wells Sby-1, Sby-6, and Sby-7 along the contact plane between volcanic and sedimentary formations.

The most permeable zones within the wells are encountered at deeper levels within the sediments associated with sandstone and limestone lithologies.

Six of the ten wells drilled in the Sibayak geothermal field are productive wells. The well outputs are divided into three categories: high (30~more than 50 ton/hr), moderate (20-30 ton/hr) and low (less than 20 ton/hr).

METHOD OVERVIEW

To image permeability distribution of the field, the MT and MAM data were used as a base. The resistivity anomalies obtained were then combined with the geological structures interpreted from gravity data to get permeability structures. The results were then compared to the productivity data of wells to produce more realistic permeability structures. The similar study was done in Kamojang geothermal field, Indonesia (Sudarman et al., 2000b), but with more emphasizing in CSAMT data.

MT data can be used for a guideline in delineating a deep reservoir boundary as well as a reservoir structure. Daud et al. (2000) discussed the resistivity and MT data measurements and their interpretations in the Sibayak geothermal field. Deep subsurface resistivity distribution was investigated by the MT measurements of 31 stations over a frequency range from 239.8 to 0.003 Hz. In this paper, only the resistivity boundary delineation is presented.

In a geothermal system, hydrothermal fluids flow through high permeability formation such as faults and fractures as well as in a horizontal contact between two formations. Therefore, the high permeability zone may have a high conductivity. In MAM measurement, electric currents flow easily through a high conductivity medium (Tagomori et al., 1984). As a result, the high permeability zone might be reflected by more conductive anomalous zone recorded by the MAM measurements.

Daud et al. (1999) discuss the basic principle and field measurements of the MAM method in the Sibayak geothermal field. Two production wells were used for line source of electrodes, SBY-1 in the east and SBY-4 in the west. The well SBY-1 is an almost vertical well with total depth of 1501 m (1495 m vertical depth), whereas the well SBY-4 is a directional well with total depth of 2181 m (or 1879 m vertical depth) and cased to the full 2172 m.

The MAM data can be presented as apparent resistivity distribution, which reflects distribution of gross resistivity in the survey area. In order to recognize a response of any subsurface anomalous body, the apparent resistivity value is subtracted by the theoretical resistivity value to get the residual resistivity. This residual resistivity distribution can be interpreted in a correlation with a permeability distribution in the surveyed area.

Geological structures in a geothermal field, such as caldera structure and its associated faults and fractures can be reconstructed by using an interpretation of gravity data (Alatorre-Zamora and Campos- Enriquez, 1991). Recognition of the faults and fractures in a geothermal field is very important to locate high permeability zones. Gravity data in the Sibayak field were obtained from 190 stations. The gravity data were then corrected as usual including terrain corrections to obtain Bouguer gravity values. In order to recognize local subsurface responses, the Bouguer data were then subtracted from regional effects using a least square method (Abdelrahman et al., 1985). The residual gravity values resulted was then displayed as a contour map for a further interpretation.

Lost circulation zones, which indicate subsurface permeability distribution can be provided by production test data of wells. Careful inspection to the production test data should then be taken for identifying whether the lost circulation zone is located along fracture planes and/or along horizontal contact between two formations (unconformity formations). Moreover, the formation temperature and pressure data are required to confirm the geothermal potential of the reservoir.

By combining the above tools, fracture permeability map of the geothermal system is then constructed.

RESULTS AND DISCUSSIONS

Figure 2 shows apparent resistivity contour map of MT data for the period T=0.33 s. It is clearly recognized in the map that the distribution of low resistivity zone (inside the caldera) to the depth of about 1000 m mainly coincides with the existing fault structures.

Figure 3 shows the residual resistivity map of MAM data. By careful inspection to the map, it is obviously recognized that the negative residual anomaly is located inside the Singkut caldera, except in the southern part of the area. The shape of the anomaly coincides with the structural features (faulting system) as strongly indicated by the residual gravity data (Figure 4). Almost all of the productive wells of the Sibayak power station (i.e., the wells SBY-3, 4, 5, 6, 7 and 8) are located within the negative residual resistivity zone. Furthermore, the most productive wells (i.e. the wells SBY-5 and SBY-8) are located inside the lowest residual resistivity zone (-5 Ohm-m). The negative residual resistivity zone in the Sibayak geothermal field has a good correlation with a zone of high formation temperature as well as large amount of lost circulations (Daud et al., 1999). The negative residual resistivity zone extends to the north-northeast direction.

To get better understanding in the correlation between the MAM residual resistivity and well production data, well output data are also presented in Figure 3. This map shows that the residual resistivity of less than –5 ohm-m corresponds to the high well output (30 to more than 50 ton/hr steam). The wells Sby-5, Sby-6 and SBY-8, which are located in the intersection of the NW-SE and NE-SW faults, are the most productive wells with the output of 57 ton/hr, 35 ton/hr and 33 ton/hr, respectively.

All of the surface and well information mentioned above are then integrated to construct a fracture permeability map of the Sibayak field (Figure 5).

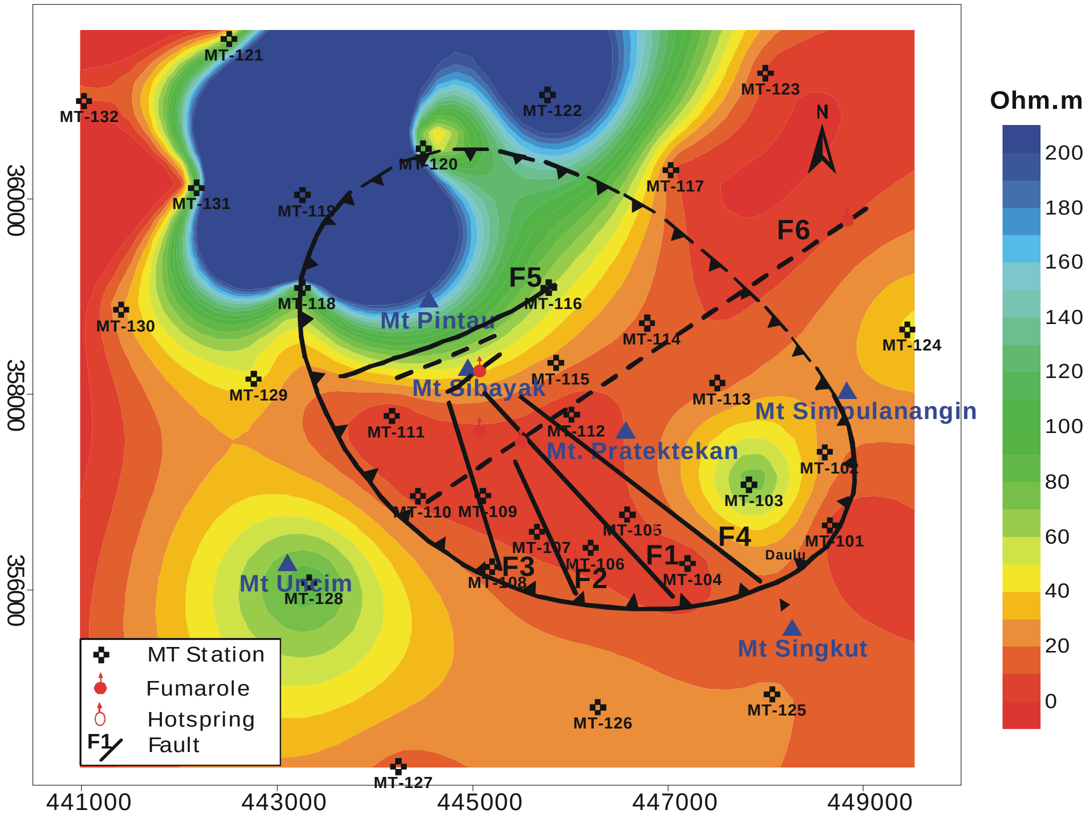

Figure 2. Distribution of apparent resistivity of MT data in the Sibayak geothermal field (T=0.33 s)

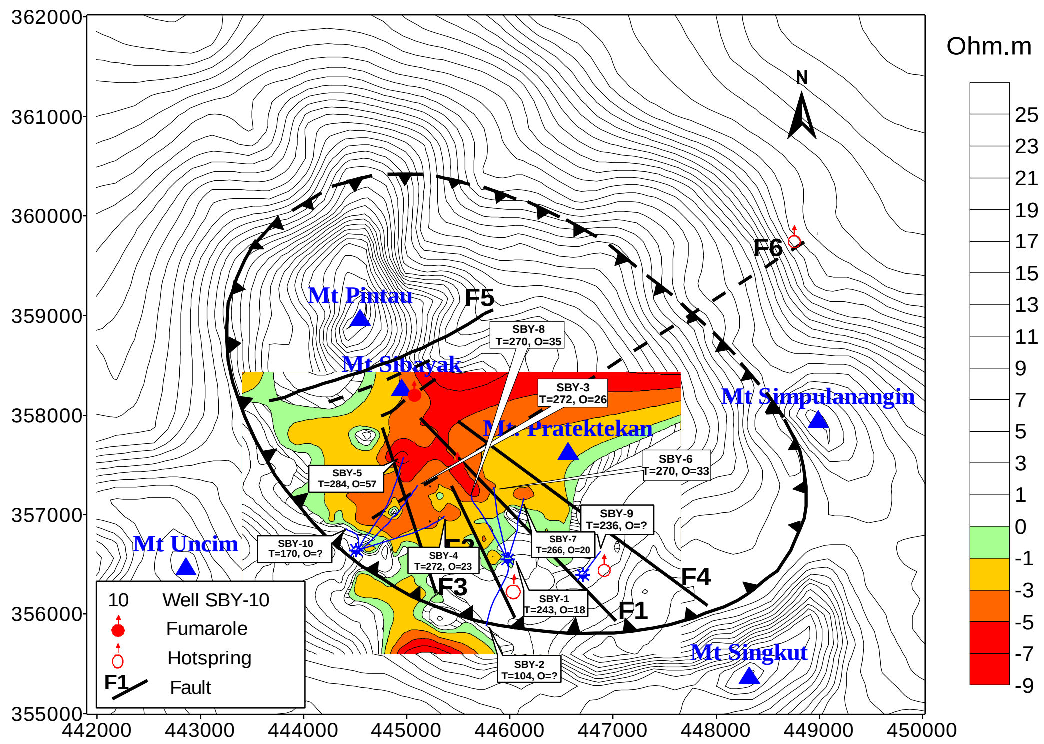

Figure 3. Distribution of negative residual apparent resistivity of MAM data and related well productivity data of the Sibayak geothermal field (T = down-hole temperature in ^{o}C and O = well output in ton/hr).

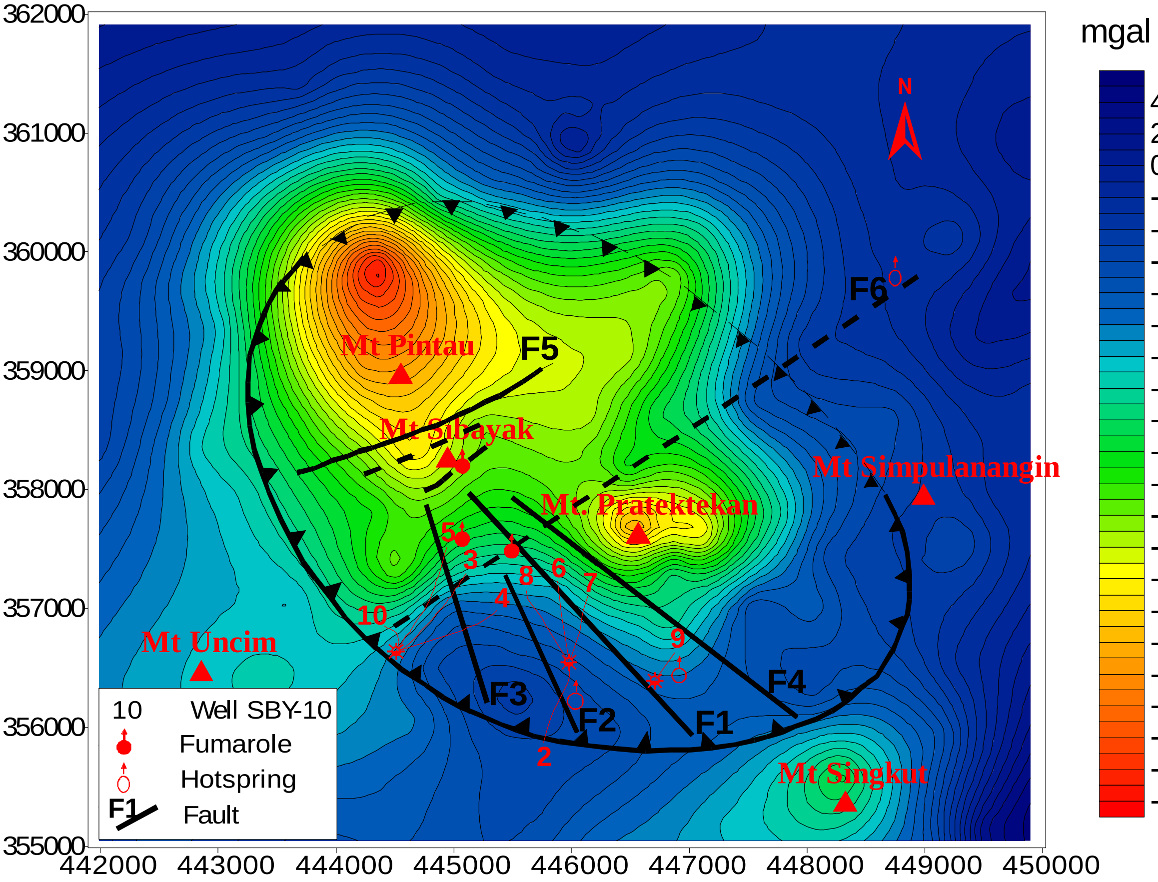

Figure 4. Residual Gravity Map of the Sibayak geothermal field

The permeability map in Figure 5 has a good correlation with the structural features as shown by Figure 1 as well as the residual gravity data interpretation (see Figure 4), specifically in the intersection of the NW-SE and NE-SW faults, where the highest permeability was found in this area. The geothermal field can thus be divided into three permeability zones: high, moderate and low. The high permeability zone (Kh = 2-4 D.m.), which has been encountered by well SBY-5, SBY-6 and SBY-8, is located in the center part of the field, where the NW-SE faults intersect the NE-SW ones covering an area about 2 km^2. The moderate permeability zone (Kh = 1 D.m.), as encountered by wells SBY-3 and SBY-4, surrounds the high permeability zone covering 3 km^2. The lowest permeability region (Kh = 0.5 D.m.) covers less than 5 km^2 in the southwestern and southeastern parts of the area. Based on the present study, further exploratory wells should therefore be directed to the high and moderate permeability zones.

The low permeability region in the southeastern part of the Sibayak area, which was not as expected before, is quite interesting to investigate. Since the fault structures extend to this area and many hot springs are also scattered around the same area. Moreover, the geochemical data shows the intensive scaling minerals found in this area (Pertamina, 1994).

Therefore, the low permeability might be caused by the scaling minerals occurred along the fractures. In other words, a densification of a formation was developed along the fracture zones. The densification is also indicated by the high value of the residual gravity data around this area. This phenomenon is similar to that found in the Broadlands-Ohaaki geothermal field in New Zealand (Hochstein and Henrys, 1989). This low permeability area should, therefore, be avoided for future drillings.

CONCLUSIONS

The permeability imaging in the Sibayak reservoir has been achieved by integrating the surface as well as borehole geophysical data and well productivity data. The permeability can be incorporated into a permeability map that characterizes the reservoir. It is concluded that the reservoir permeability is mainly controlled by intersection of faults as well as by bedding planes along the contacts of the volcanic and sedimentary formations in the study area.

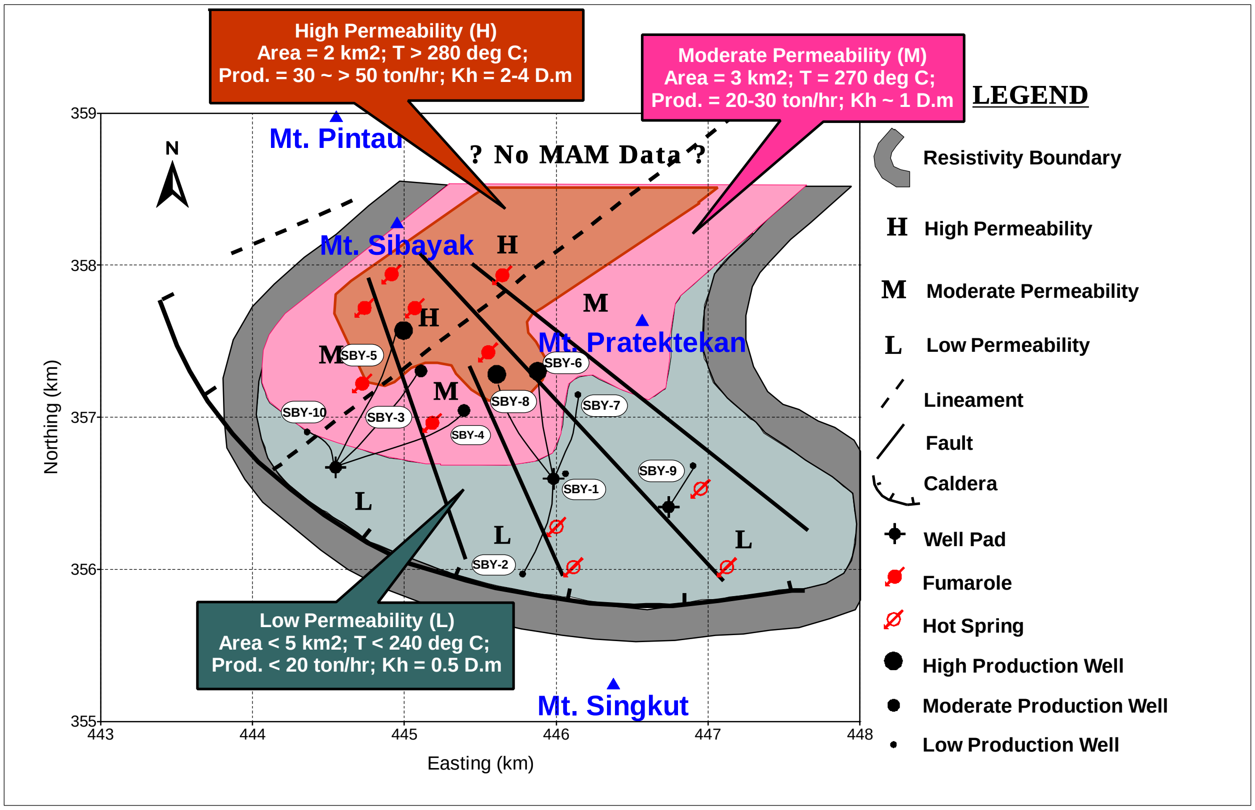

Figure 5. Permeability Map of the Sibayak geothermal field

The permeability image from this study can be used to categorize permeability distributions in the Sibayak Geothermal Field into the following zones:

- High permeability zone: Area = 2 km^2, T>280 ^{o}C, Kh = 2-4 D.m., with the average well production of 30 to more than 50 ton/hr of steam.
- Moderate permeability zone: Area = 3 km^2, T = 270 ^{o}C and Kh ~1 D.m., with the average well production of 20 to 30 ton/hr of steam.
- Low permeability zone: Area = 3 km^2, T<240 ^{o}C, and Kh = 0.5 D.m., with the average well production of less than 20 ton/hr of steam.

This study also supports future exploratory drillings in the high permeability zone located between Mt Sibayak and Mt Pratektekan. However, to confirm the proper location for the drilling site, it is suggested to cross check this permeability map with CSAMT data. It is, therefore, most recommended to conduct CSAMT survey in the Sibayak geothermal field.

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