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# MAGNETOTELLURIC METHOD APPLIED FOR EXPLORATION OF GEOTHERMAL RESOURCES IN SUMATRA

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ABSTRACT

Pertamina has conducted geothermal exploration in Sumatra showing that the depths to the top of most of the geothermal reservoirs are about 1000-2000 meters. Previous geophysical exploration work by Pertamina emphasized the use of DC-resistivity methods such as the Schlumberger method. However, these techniques can typically only penetrate to a depth of less than 1000 meters and are too shallow to map the geothermal system in most areas. With the magnetotelluric (MT) method, investigation to depths of greater than 1000 meters are routine, which gives the explorationist a better picture of the deep resistivity structure. Pertamina now applies MT methods to explore for geothermal resources in most area. In conjunction with the MT data. time-domain electromagnetic (TDEM) data are usually measured to correct for static effects in the MT data.

The first step in interpreting MT data, it is common to use maps of apparent resistivity at a certain period typically 1 second to delineate an anomaly of low resistivity area. Resistivity cross-sections are then constructed through the most interesting areas starting with one-dimensional (l-D) models, which are spliced together along the cross-section. Two-dimensional (2-D) resistivity modeling could also be applied if the data showed to warrant a 2-D interpretation. In general it is found that the resistivity layers can not be clearly correlated with lithologi of the altered rocks and hydrology of the system. *An* important part of the interpretation process is to integrate the evaluations with other available data. This is necessary due to low resistivity anomalies are not always prospective as geothermal targets. For this reason, integration with other geologic and drilling data, if available, can help to eliminate low resistivity anomalies from consideration that are not prospective.

The MT method that has been Conducted in the area of Sibayak appear to detect the reservoir rocks coincide with resistivity substratum of about 45 Ωm. The very resistive (greater than 100 Ωm) sub-stratums show formations with high temperature but low permeability. In the Ulubelu geothermal project area, a 1200 meters drills hole in the conductive area confirmed that the top of the resistive sub-stratum correlated well with the top of loss circulation of dnlling fluids and water level. To date there is no dnlling information for deeper resistivity structure. The top of the resistive sub-stratum was correspond to the top of the intrusive body met by temperature gradient well in Sumurup, Jambi-West Sumatra.

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Time Domain Electro magnetic (TDEM) are also normally measured at coincident locations to the MT stations to correct for static effects in the MT data (Pellerin and Hochmann, 1990, and Capueno et. al., 1988). For this paper, we will discuss may then apply. After that, applying a mount of MT stations to bound the geothermal prospect area is very common. During conduct the MT survey, the other shallow probed method such as the TDEM (Time Domain Electro-magnetic) was also measured at the same station of MT that was used for static corrections.

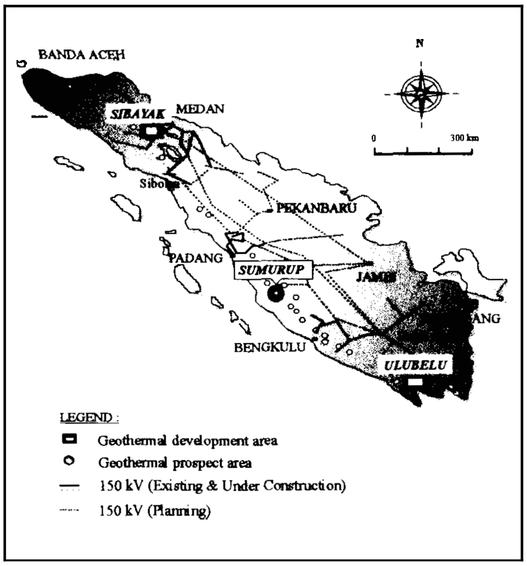


**Fig. 1. Location of the studied area, Sumatra, Indonesia.**

APPLICATION

The geoelectric structure of a geothermal field can usually be characterized by low resistivity layer that overlies a high resistivity reservoir. The low resistivity of the cap could be due to an altered rock that consist mainly of clay minerals (Pellerin et. Al., 1996; Browne, 1989).

In Indonesia, the depths to the top of most of geothermal reservoirs are located at about 1500 to 2000 meters below the surface. The low resistivity of the clay cap above the reservoir is typically at depths of from about 500 to 1000 meters. The DC-resistivity methods have been found to be effective in detecting the top of the clay cap, but can not resolve deeper. With the MT technique we can image the clay cap and estimate thickness and the resistivity structure below the cap.

In the three prospect areas we review below, the DC resistivity surveys were run early in the evaluation process. In each case these surveys delineated areas of interest based on the Qstribution of low resistivities. This help to focus the survey planning for the follow up MT-TDEM surveys.

In addition the MT data are inverted into I-D resistivity models. A plan view map at various apparent resistivities, commonly 1Hz and 0.5Hz, and resistivity sections across an area of particular interest are constructed to interpret the MT data. Occasionally, 2-D resistivity models are also constructed to try to better quantity resistivity trends.

DISCUSSION

Sibayak Geothermal Area

There is an extensive area of low resistivities of about $12 km^2$. The area of low resistivity is characterized by a low resistivity layer of generally 1 to $5 \Omega m$ that overlies a high resistivity sub-stratum of about $45 \Omega m$. The key area of interest is defined within the area that underlies by the $45 \Omega m$ sub-stratum (Figure 2).

Pertamina has been developing a geothermal energy by tapping the hot fluids through the selective conductive prospect area of 6 $km^2$ that is out of 12 $km^2$. Amounts of 8 wells had indlcated high temperatures, that area from 250 to 275°C. The highest temperature of 275°C met by drilling was in the area nearby the mountain of Sibayak. The sub-surface temperature may then decrease down to 220°C into the South dlrection.

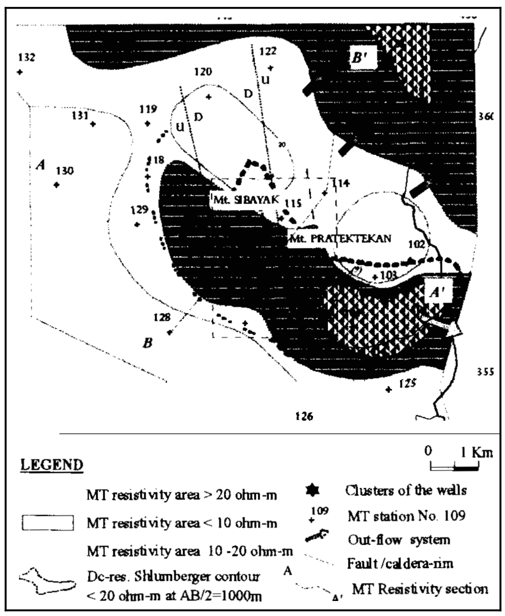


**Fig. 2. MT apparent resistivity at 0.33 seconds of Sibayak geothermal area, North Sumatra.**

The first well SBY-1 was dnlled successfully to tap geothermal fluids with temperature of 225°C at the depth of 1450 meters. Drilling the well SBY-2 was then to obtain the boundary of the geothermal area by direction dnlling to the South to the edge of the conductive area. The temperatures at the bottom hole (2088 meters) were relatively low that were 83°C. The measured temperatures of the other seven wells that are in the middle of the conductive area were relatively **high.** For example, from North to South. the reservoir temperatures of the well SBY-5, SBY-3 and SBY-4 were successively 275°C. 240°C and 244°C. The decreasing temperatures appear from the middle to edge of the area does follow the increasing resistivity contours. This phenomenon may indicate that the decreasing of fluid's temperature is in accord with the increasing of resistivities. This may also indicate that the geothermal fluids may flow out toward the South up to the caldera rim then turning to the East to follow the edge of the caldera.

The productions of the well do not commonly correlate with the resistivity layered model. There was evidence that the wells SBY-5. SBY-3 and SBY-4 have produced energy equivalent to about 5MWe, 3MWe and 2MWe that were tapped from the same resistivity layer, i.e. 45Ωm. It means that the permeability of the reservoir is not well indlcated **by** the change of the layer resistivity.

The purpose of the most drillings in Sibayak is to tap geothermal energy from the resistive substratum. That is 45Ωm. Unless SBY-10 was dnlled into the more resistive sub-stratum, that is 50-100Ωm, where it is underneath Mt. Praktektekan. The sub-stratum with resistivities greater 50Ωm were interpreted to be as a low temperature zone or an impermeable zone. The observed temperature was 142°C at the depth of about 2100 meters below surface. The loss of circulation of dnlling fluids at the depth of 1800m may be due to the dnlling met the resistivity boundary (Figure 3). The pressure fall of test conducted a week after drilling finished indlcated **kh** of about 0.6 Darcy-meters.

In the following is the accordance between resistivity layers inverted from the MT-sounding SBY-109 and log lithology of the well SBY-3 (Figure 4). The top of resistive substratum was well correlate to level where the decreasing for clay content and the increasing for silica content. The resistive sub-stratum may still indicate the depth where the loss circulation of drilling fluid occurred and the water level in the wells and the top of the geothermal reservoir. However, the top of the resistive sub-stratum did not correlate well with the top of the sedimentary rocks met **by** drilling. It seems that the part of the sedimentary rocks formed the geothermal reservoir; that is a part of the resistive substratum.

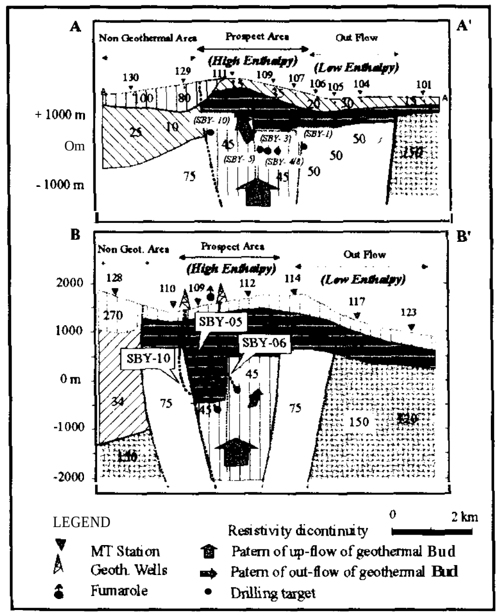


**Fig. 3. Resistivity sections of Sibayak geothermal area, North Sumatra.**

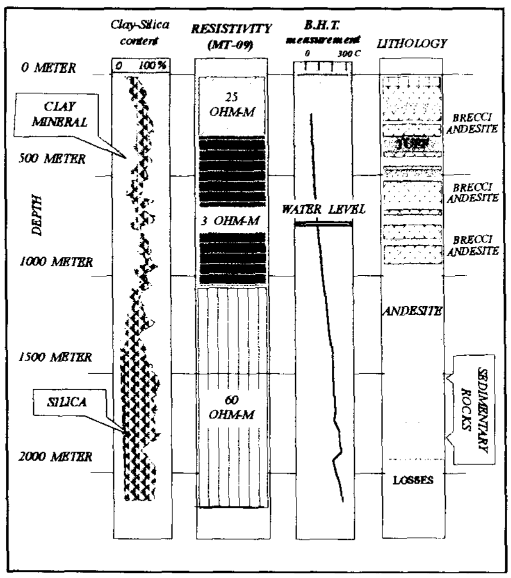


**Fig. 4. Sibayak geothermal area, North Sumatra, correlation of MT with SBY-3 well.**

The 2-D resistivity model created after TDEM-MT that carried out intensively during 1996-1997, showing similarity in resistivity pattern of the former 1-D model. Therefore, no advanced evaluation may conduct due to its similarity.

Ulubelu Geothermal Propsect Area

There is a wide conductive area at least 12 $km^2$ at the Ulubelu geothermal prospect area. It seems that the recent conductive areas obtained by MT survey did not coincide with the one obtained by DC-resistivity (Schlumberger). It was understood due to different penetration of each method. Although, all the locations of three slime-holes were in the conductive area of DC-Resistivity, the slim-hole UBL-2 was mislead according to the MT-resistivity map. The UBL-2 was in the resistive area of the apparent resistivity map that obtained from MT survey (Figure 5). The resistive area seems to act as an impermeable bamer rock that separates the Ulubelu geothermal prospect into two parts, that are in the North and South. It is very common to locate an exploration drilling relatively in the middle of the conductive area. However, most of the locations of slime-holes, are not in the center of the conductive area due to time consuming of the land-use permit. There was plan to drill these three locations UBL-1, UBL-2 and UBL-3, to depth of about 1200m. Unfortunately, two of them that area UBL-2 and UBL-3 only reached to depth of about 800 to 900 meters.

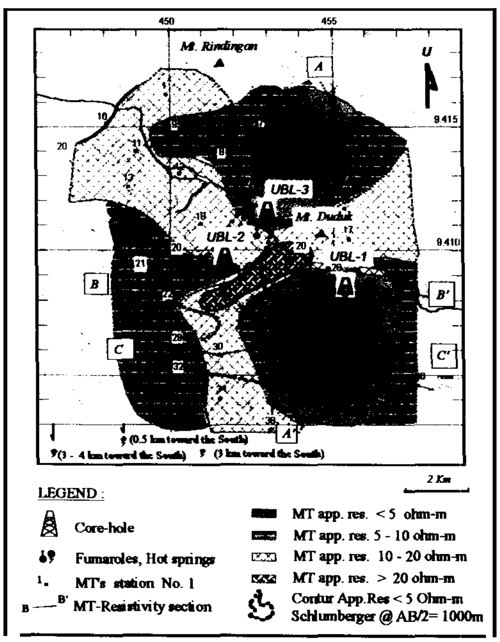


**Fig. 5. MT apparent resistivity at 1 second of Ulubelu, Lampung-South Sumatra.**

The slim-hole of UBL-1 and of UBL-3 may lead for geothermal prospecting where they may penetrate the 75 and of 45 Ωm resistive sub-stratums of the resistivity sections (Figure 6). While the slime-hole of UBL-2 may penetrate the very resistive sub-stratum of 200Ωm, where an impermeable zone has met by drilling after the depth of 600 meters below surface.

Drilling to the first location, UBL-1, indicated the high temperature and pressure at the depth of 1160 meters. They were 210°C and 47Ksc. Lost circulation of drilling fluids occurred at the depth of 500 to 800 meters. Similar discoveries were also to the UBL-3. Inversely, the sub-surface conditions of the UBL-2 were high temperature but low permeability at the depth over 600 meters below surface. The low permeability could be due to a weakly altered rock that was basalt-andesitic rock has met by drilling at the depth of 600 to 800 meters. The weakly altered rock also corresponds to the very resistive sub-stratum. It was picturing clearly within the section A-A and B-B' underneath the UBL-2 (Figure 6). There is no more information below the depth of 900 meters obtained due to drilling problem.

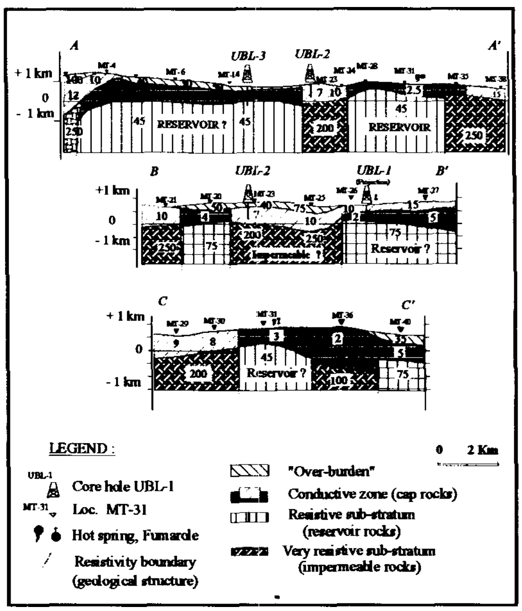


**Fig. 6. Ulubelu area, Lampung - South Sumatra MT - resistivity sections.**

There is no clear indication that of the volcanic lithology variations are due to strong layer resistivity changes. This occurs as is the case with the relatively no changing in layer resistivity of the different lithology met by the slim-holes UBL-1 and UBL-2. By dnlling, the andesite-basaltic rocks and the basaltic rocks occur, successively, at depth of 100-250 meters in the UBL-1 and at depth of 200-600 meters in the UBL-2. It seemed like that they are in the similar range of resistivities. Their values are in between 7 to 10 Rm (Figure 6).

The correlation between the MT-resistivity layers and slim-hole of the UBL-1 is in Figure 7. The resistive substratum of 75Ωm was part of the zone where the total loss of the circulation of drilling fluids occurred. This zone was well depicted by a shape of inverse temperatures, after heating the well up to 5 hours, meaning that it was permeable. The similar phenomenon also occurred within the slim-hole UBL-3, indicating the top of resistive sub stratum of 45Ωm coincides with the depth where the circulation of drilling fluids starts loosing.

Drilling the UBL-1 showed that there were strong altered andesite rocks to depth down to 600 meters containing mainly clay minerals. They classified as smectite, mixed layer clay and chlorite zones (Figure 7). The altered zones look accord to the layer resistivities. They decreased from 10Ωm down to 1.2Ωm with depth. If this the case, the intensities of alterations of the rocks increase, so the values of rocks' resistivities become decreasing.

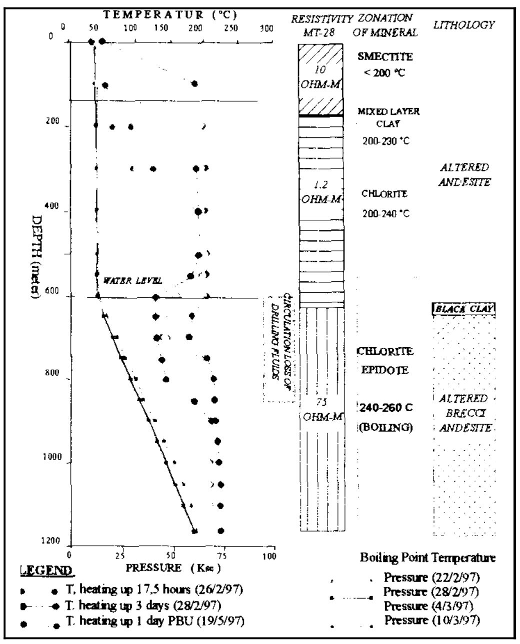


**Fig. 7. Ulubelu geothermal prospect, South Sumatra, correlation of MT with UBL-1 slime-hole.**

The underlying chlorite-epidote zone corresponded to the 75Ωm substratum. An increased in resistivity may be due to less intensity of alteration, for example: less clay content and much silica content, and a vapor may dominate in the zone such as indlcated when the well discharged showing steam. The resistive substratum may correspond to the altered brecci andesite rocks.

Sumurup Geothermal Prospect Area

Pertamina recently has conducted an MT survey in the year of 1966. The MT apparent resistivity map at the periods of 0.3 seconds showed a conductive area lies in between resistive area forming a graben likes structures (Figure 8). The other geophysical method, for example gravity, also showed a negative anomaly that may reflect a presence of less dense body in a basin. If this is the case, this kind of structure with less dense body may be act as well as geothermal reservoir.

A location of temperature gradients well was then plan to be inside and as accord to both the conductive areas of the DC-resistivity (Schlumberger) and the MT surveys. A hot spring with surface temperature of about 80-90°C occurs not far from the location of the well

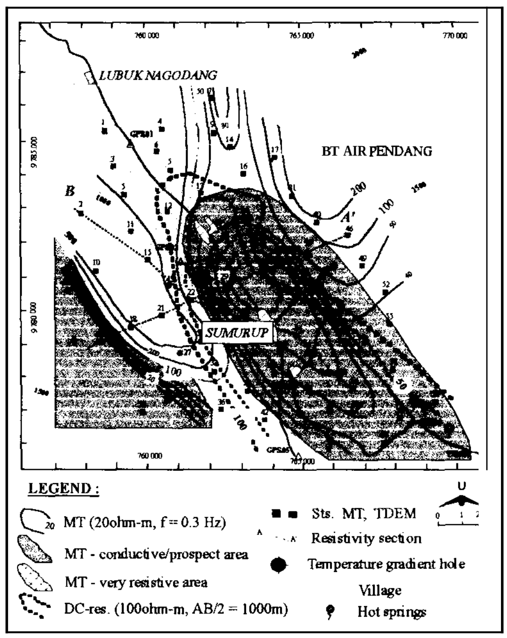


**Fig. 8. Resistivity map showing the area of geo thermal prospect, Jambi - West Sumatra**

The temperature gradient well has dnlled down to 300 meters depth at the area between the MT-sounding UBL-22 and UBL-29. The results were a gradtent temperature of about 1.4°C/10m and the formation temperature at the depth of 290 meters was about 88°C. The well also has met with an intrusive rock of cborite that overlaid by sand stones and andesitic rocks. The diorite rock has also outcropped at the area not for from the well and it spreads over the area.

Drilling the temperature gradient well indicated that brecci-andesites correlated well with the 10-25Rm layers obtained from MT-22 and MT-29 (Figure 9). These layers (cited as alluvial rock at the geological map of Sumurup) could form a conductive cap layer. The conductive cap layer tends to thicken to the SE (Figure 9 and 10). The last lithology met by drilling, that was diorite, corresponded well to the resistive layer of 150Ωm of MT-22, but it did not correspond to the 4Rm layer obtained from MT-29. Therefore, it seems that there is a fault locates in between the station of MT-22 and of MT-29.

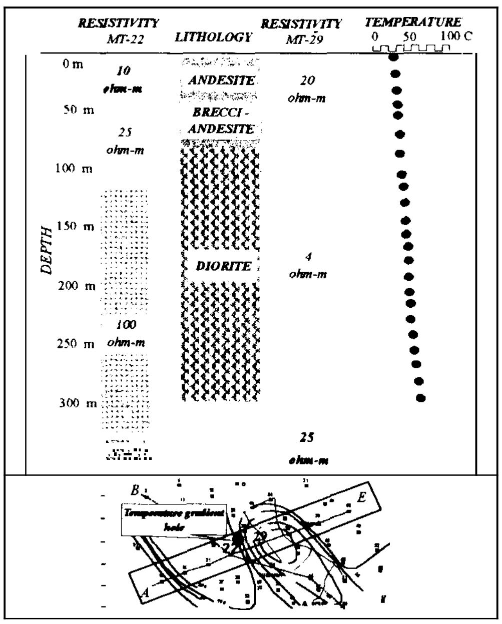


**Fig. 9. Sumurup geothermal area, West Sumatra, correlation of MT with temperature gradient hole.**

Plotting the data of temperature gradtent showed a type of conductive heat transfer along the hole of the temperature gradient well (Figure 9). Considering the conductive heat transfer, the geothermometer temperature obtained from Na-K-Mg diagram, that was 250°C. may be at the depth of 1500 meters by extrapolating the curve of temperature gradient. Concerning to the other considerations, that are the 1500 meters depth and the less dense body presented in the area where the conductive anomaly occurred: a 45-75Ωm layer may act as geothermal reservoir (Figure 10). The 45-75Rm layer may consist of andesitic rocks and it contains hot geothermal fluids. The presence of hot fluids in the rocks was indicated by the temperature of 87°C at the depth of 290 meters in the temperature gradtent well (Figure 9 and 10).

Overlying conductive area of 3-20Rm may act as a cap rock that consists of altered andesite and altered brecci andesite rocks met by dnlling. The cap rock tends to thicken into the directions of South-East (Figure 10). Underneath this cap rocks where the 45-75Rm is present may be interpreted as a part of drilling target for geothermal exploration.

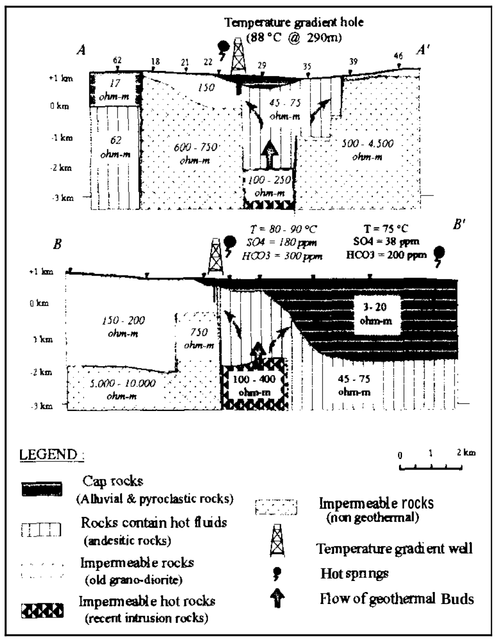


**Fig. 10. Sumurup geothermal area, Jambi -West Sumatra, 1-D MT-Resistivity models.**

There was resistive substratum of 100-400Ωm below this layer. It could be tentatively modeled as a heat source. The other very resistive substratum in the Sumurup geothermal prospect area, tend to be able to correspond to the older pyroclastic rocks that covered most of the area (Mulyadi, 1997). The formations seemed like to bound the geothermal prospect at the East and West side of the area.

The temperature gradient well that drilled down to 300 meters was not deep enough to probe the resistivity distribution within the prospect area. Therefore no information obtained from the well to correlate the very resistive sub-stratum at deep level. Considering very resistive sub-stratums that covered most of the area and there is only small area covered by less resistive sub-stratum; the Sumurup area seems to have low potential energy.

## CONCLUSION

The MT method has helped to locate a geothermal prospect in Sumatra. It also gives a good guidance for defining a drilling target. The drilling target is usually a resistive sub-stratum that overlies by the conductive zone due to altered minerals. Another resistive sub-stratum greater 100Ωm may indicate impermeable rocks.

Top of resistive sub-stratum may correlate well with depth where clay contents decrease, while silica contents increase. It also corresponds to the zone of geothermal reservoir, but it is sometimes not able to detect a top of the loss circulation of drilling fluids, lithology changes.

There is evidence that decreasing in resistivity is strongly due to increasing in clay content, but resistivity changes do not correlate well with lithology changes that observed by drilling.

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