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MAGNETIC TELLURIC METHOD APPLIED FOR GEOTHERMAL EXPLORATION IN SIBAYAK, NORTH SUMATRA

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ABSTRACT

Pertamina has conducted geothermal exploration in Sibayak, showing that the depths to the top of most geothermal reservoir area about 1000-2000m. Previous geophysical exploration work by Pertamina emphasized the use of DC-resistivity (Schlumberger) methods. However, these techniques can typically only penetrate to a depth of less than 1000m and are too shallow to map the geothermal system in this area. The area covered by very low resistivity of 10Ωm gave a false geothermal prospect at the southwestern part of the area. This anomaly indicates the area of outflow of geothermal fluids from the nearby Mt. Sibayak. By using the magnetotelluric (MT) method to investigate to a depth of greater than 1000m (e.g. f=0.33Hz for resistivity > 3Ωm), it may help the explorationist get a better picture of the deep resistivity structure. The pattern of the resistivity contours may depict the flow of geothermal fluids; the tongue-like structures show the area where the outflow of geothermal fluids is.

Pertamina has been tapping the hot fluids by drilling into the selected prospect area. Eight wells have penetrated a region of high temperatures (250-275°C). The highest temperatures were found in SBY-5, in the area near the Mt. Sibayak. The sub-surface temperature then decreased southward to 200°C.

An important part of the interpretation process is to integrate the results with other available data. This is necessary because low resistivity anomalies are not always suitable as geothermal targets. For this reason, integration with other geologic and drilling data can help to eliminate undesirable low-resistivity targets from consideration.

INTODUCTION

The geothermal area of Sibayak is located near Medan; it is about 3-4 hour by car from Medan (Fig. 1.). Pertamina has used DC-resistivity (Schlumberger) surveys to explore geothermal prospects for a number of years. This method has the advantage in that it is relatively low-cost and easy to run, but it has a maximum depth of investigation of about 1000m. To probe deeper, Pertamina has applied the MT method to complement the DC-resistivity method. In addition to MT data, the Time Domain Electro-Magnetic (TDEM) is also normally measured at locations coincident to the MT stations to correct for the static effects in the MT data (Pellerin and Hohmann, 1990, and Capuano et al, 1988). Pertamina conducted the first MT survey in 1992 and then continued its survey by adding TDEM in 1997.

For this paper, we will discuss how MT has correlated with the drilling results in the prospect area of Sibayak.

APPLICATION

A geoelectric structure can show the presence of a geothermal system. The main part of its system is simply divided into three layers of resistivity. It is commonly composed of an overburden, a layer of low resistivity, and a sub-stratum of relatively resistive rock. The low resistivity layer may act as cap rock and the resistive sub-stratum may act as reservoir rock. The low resistivity of the cap rock could be due to an altered rock that consists mainly of clay minerals (Anderson et. al., and David et. al., 1999). By mapping this layer of low resistivity, the geothermal prospect may be delineated. In Indonesia, the depth to the top of most of the geothermal reservoirs is between 250m below and above sea level. The low resistivity of the clay cap above the reservoir is typically at depths of about 500 to 1000m. The DC-resistivity methods have been found effective in detecting the top of the clay cap, but can not resolve deeper (Fig. 2A). With the MT technique one can image the clay cap and estimate thickness and the resistivity structure below the cap (Fig. 2B).

One may construct a plan view map at various depths and resistivities. For example the Ulubelu prospect, these were at f=3Hz and 0.3Hz, (Mulyadi, 1998). One may also invert all the MT soundings into 1-D resistivity layers. A few cross sections were then constructed by splicing the resistivity layers together, starting with one-dimensional (1-D) models. Three of the sections were across the most interesting area, shown on Fig. 4A and 4B.

Two-dimensional (2-D) resistivity modeling could also be applied. Finally, all the MT results were correlated with the drilling results (e.g. temperature, clay-silica contents, and lithology).

DISCUSSION

Sibayak Geothermal Area

Both the DC resistivity and the MT methods have shown the low resistivity area to be in the same place. There was an extensive area of low resistivity of about 12 km^2 (Fig. 3A). However, the high temperature and permeable area from drilling was only 5-6km^2 out of 12 km^2. To confirm the boundary of prospect area, Pertamina then conducted MT-TDEM, but the shape of the low resistivity area did not change much. This area of low resistivity, less than 16Ωm (f=0.3 Hz), was most likely to indicate a geothermal prospect area (Fig. 3B). The area that is covered by resistivity contours of 20Ωm and of 25Ωm shows a tongue-like structure. The tongue-like structure may indicate an outflow of geothermal fluids to the southeast and northeast. A source of hot fluids as indicated by the resistivity contour of 10Ωm is Mt. Sibayak (Fig. 3B). This conductive area, at a depth of about 2km, where the skin depth (km) = 0.35 x √(10Ωm x three seconds), could be due to acid fluids. The high temperature of hot fluids, found in the nearest well to Mt. Sibayak (SBY-5), could have created an intensively altered rock that caused the very conductive zone. The conductive layers of the MT soundings around Mt. Sibayak, (e.g. SBK-205, SBK-216, and SBK-217), were lower than the other MT soundings. Since then, no drilling has occurred in the area near Mt. Sibayak due to the zone of acid fluids.

Layers with a true resistivity of 1 to 5Ωm represent most of the 12 km^2 of low resistivity area (both DC-resistivity and MT). Part of the area was underlain by a sub-stratum of about 50Ωm. Therefore, the essential area of interest is defined within the area of low resistivity that is underlain by the sub-stratum of 50Ωm. The essential area of interest is only about 5-6km^2 out of the total conductive area of 12 km^2.

The first well SBY-1 was drilled successfully in the zone of 75Ωm and tapped geothermal fluids with temperature of 225°C at a depth of 1500m. The well SBY-2 was then drilled to obtain the boundary of the geothermal area by directional drilling to the south; the drilling target was the sub-stratum of 20Ωm. The temperatures at the bottom hole (2088 meters) were relatively low (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 NW to SE, 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 from the middle to the edge of the area follow the increasing resistivity contour at f=0.33Hz. This phenomenon may indicate that temperature decrease correlates with the sub-stratum resistivity increase. The tongue-like structure may also indicate that the geothermal fluids may flow upward to the southern caldera rim then turn to the east to follow the edge of the caldera. The other possible outflow of geothermal fluids, toward the northeast, could not be proved.

Resistivity Section

Production from the wells does not directly correlate with the structure of the layered resistivity model. There is evidence that the wells SBY-5, SBY-3, and SBY-4, which produce energy equivalent to about 5MWe, 3MWe, and 2Mwe, tap the same resistivity sub-stratum, i.e. 50Ωm. In contrast, the wells SBY-6, SBY-7, SBY-8, and SBY-9 tap the sub-stratum of 75Ωm. It means that the permeability of the reservoir is not indicated by the resistivity of the layers. The purpose of most drillings in Sibayak is to tap geothermal energy from the resistive 50-75Ωm sub-stratum. Well SBY-10 was drilled into the more resistive sub-stratum (100Ωm). This sub-stratum could be interpreted as a zone of low temperature or as an impermeable zone. The drilling targets of SBY-9 and SBY-10 were, successively, the 75Ωm zone underneath Mt. Praktektekan and the 100Ωm zone on the eastern edge of the geothermal area. The observed temperatures within SBY-9 and SBY-10 were, successively, 225°C at a depth of 1300m and 134°C at a depth of about 2000 meters. The well SBY-9 reached temperature of 225°C but its boiling point is 283°C. The lost circulation of drilling fluids that occurred in both wells SBY-9 and SBY-10 occurred at the resistivity boundary, implying that they could be geological structures (Fig. 3A and 4A). Two geothermal wells, SBY-2 and SBY-10, have low temperatures that are interpreted as the boundary of the geothermal prospect area.

The following is a comparison between resistivity layers inverted from the MT-sounding SBK-216 and the logged lithology of well SBY-3 (Fig. 5). The top of the resistive sub-stratum is well correlated to the level where there is decreasing clay content and increasing silica content. The resistive sub-stratum may correlate with the depth of lost circulation of drilling fluid, the sedimentary rocks, and the geothermal reservoir. However, the top of the sedimentary rocks did not correlate well with the specific resistivity layers. It seems that the sedimentary rocks were only part of the geothermal reservoir within the resistive sub-stratum.

The 2-D resistivity model created after TDEM-MT, which was carried out intensively during 1996-1997, showed a similarity to the resistivity pattern of the former 1-D model.

The Model of Resistivity Layer

The model of resistivity layers may give a better picture of the sub-surface conditions (Fig. 6). The two resistivity models show the flow of the geothermal fluids in the reservoir. Therefore, one may use them to help with the next drilling targets. By using these models, one may not make more mistakes locating drilling locations, for example SBY-2, SBY-9, and SBY-10, unless drilling for an injection well. The drilling target is the zone of 45-75Ωm; nevertheless, the first priorities are the geological structures, for example faults, to find good permeability.

CONCLUSION

The MT method has helped to locate a geothermal prospect in Sibayak. It also gives good guidance for the definition of a drilling target. The drilling target is usually a resistive sub-stratum overlain by the conductive zone, which consists of altered minerals. Another resistive sub-stratum greater than 100Ωm may indicate impermeable or cold rocks.

Two geothermal wells, SBY-2 and SBY-10, clearly penetrated low temperatures that are interpreted as the boundary of the geothermal prospect area. The reservoir of the geothermal fluids is the area covered by the 16 Ωm, f=0.33 Hertz resistivity contour.

The top of the resistive sub-stratum may correlate with the depth where clay contents decrease and silica contents increase. It also corresponds to the geothermal reservoir, but sometimes it does not correlate with the zone of lost circulation of drilling fluids. There is evidence that decreasing resistivity is strongly correlated with increasing clay content, but resistivity changes do not correlate well with lithology changes as observed in the drilling logs. The decrease in resistivity could also be caused by changes in acidity.

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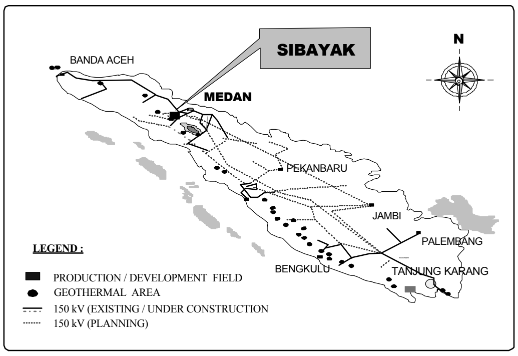
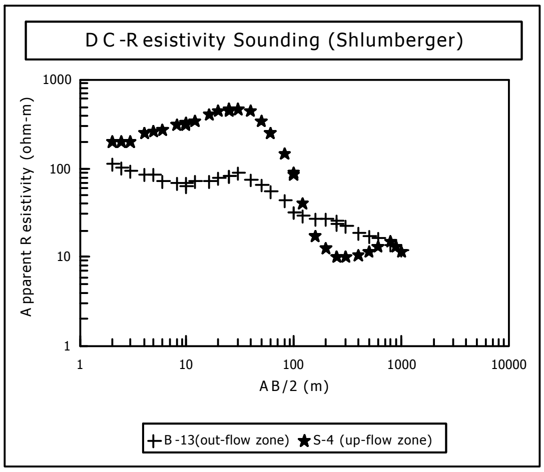
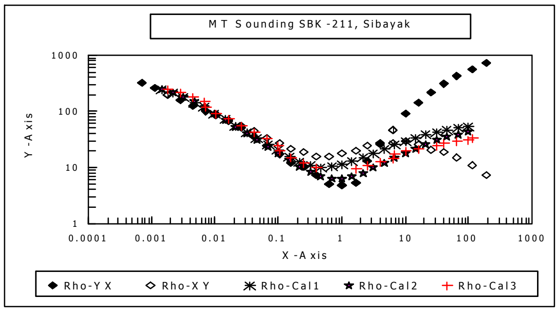


Fig. 1. The location of the Sibayak geothermal area.



Res. Model (B-13) R(ohm-m)	H (m)	Res. Model (S-04) R(ohm-m)	H (m)
116	1.8	161	2
57	6	646	23
112	18	10	273
23	100	15	99999
24	125		
10	99999		

Fig. 2A. The depth penetration of a representative DC-Resistivity Sounding (<1000m), after pt. Cakrabuana Perkasa, 1991.



Resistivity Model 1 R(Ohm-m)	H (Meter)	Resistivity Model 2 R(Ohm-m)	H (Meter)	Resistivity Model 3 R(Ohm-m)	H (Meter)
750	150	750	150	750	150
150	150	150	150	150	150
75	100	75	100	75	100
25	100	25	100	25	100
5	550	3	550	4	550
75	--------	75	--------	45	--------

Well	Total Loss	Top sed.
SBY-06	1233m	1253m
SBY-08	1270-1390	1215m

Fig. 2B. The depth penetration of MT sounding (1000m).

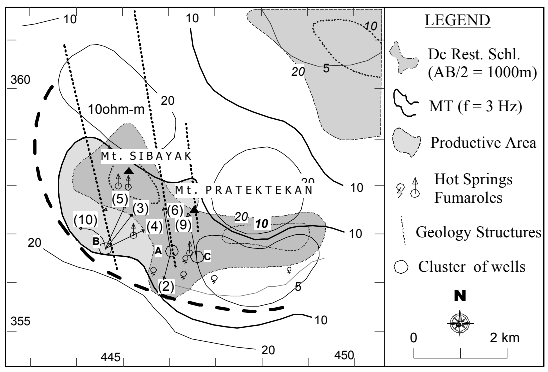


Fig. 3A. Apparent resistivity map of Sibayak (1992).

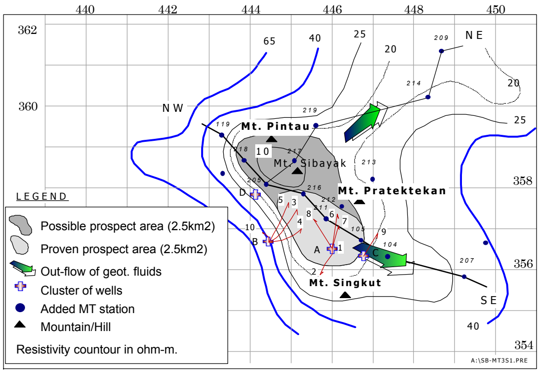


Fig. 3B. Apparent resistivity map at f=0.33Hz, (1997).

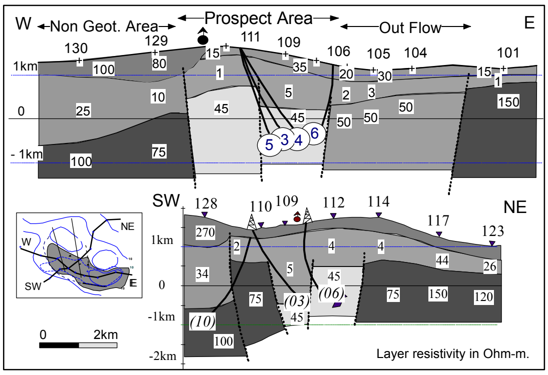


Fig. 4A. Resistivity sections, (1996).

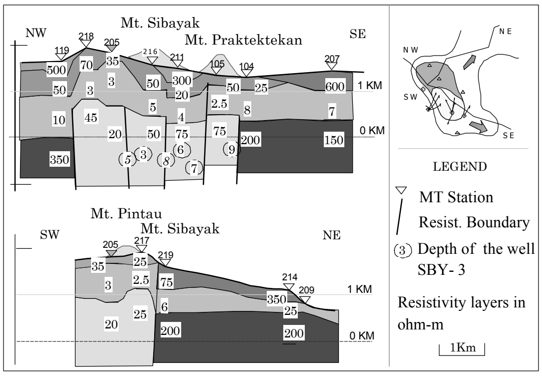


Fig. 4B. Resistivity sections, (1997-98).

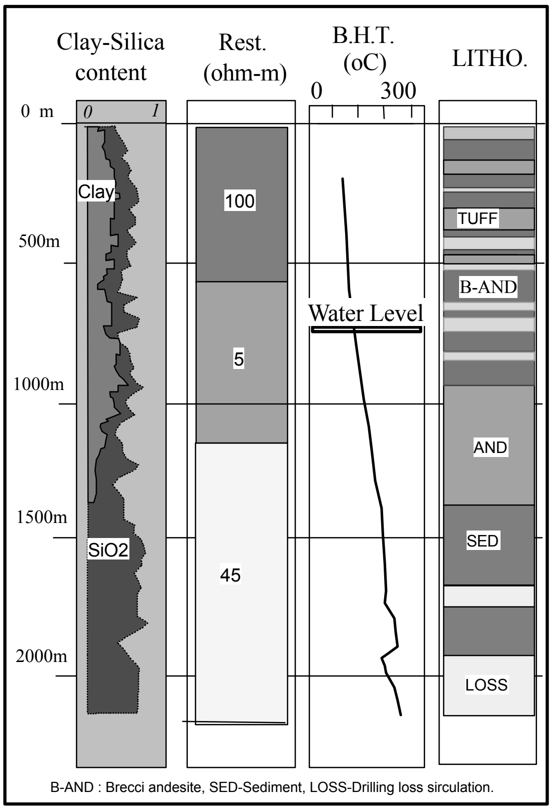


Fig.5. Sibayak geothermal area, North Sumatra, correlation of MT-TDEM with well of SBY-03.

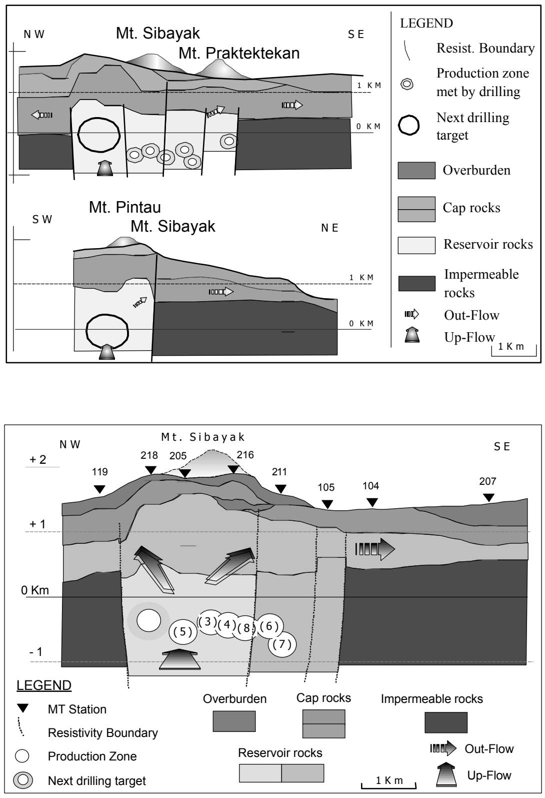


Fig. 6. The model of resistivity layers of Sibayak.