# Sibayak Geothermal Field (Indonesia): Structure Assessed From Gravity and Hydrogeological Considerations

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***Keywords***

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## ABSTRACT

Sibayak geothermal field (Indonesia) is associated with the Quaternary Singkut caldera. A gravity study was conducted to image the distribution of subsurface structure and its correlation to the distribution of the enhanced permeability area. Digital processing of the gravity data enabled delineation of the main features of the caldera's subsurface structure. A 2D structural model was established, which could be supported by 2-D gravity forward modeling. Accordingly, the caldera is featured by an asymmetric subsurface structure: a major depression in its northwestern and southeastern caldera collapse, and a gravity high reflecting densification (high density) of formation in the deeper level in the southern area. Lineaments reflecting the regional northwest-southeast as well as northeast-southwest structural fabric were observed, where they are intersected in the central area. Enhanced zones of fracturing favorable for entrapping hydrothermal fluids are located within this intersection, where the largest geothermal production zone (more than 50 ton/hr steam) was encountered by the well Sby-5. This area is expected as the best location for further exploration drilling. Correlation of the structures with hydrogeological and geochemical data enabled interpreting the geologic structures in the context of the hydrothermal system: an upflow zone is located at the intersection of perpendicular structures, while an outflow zone follows mainly the northwest-southeast structure toward the caldera margin in the south. Another outflow zone is also encountered following the northeast-southwest structure with an occurrence of hot springs outside the northeastern caldera margin. The structural image elaborated here constitutes a geologic frame for the prevailing hydrogeological conceptual model. This structural information is also useful for the task of selecting sites for the reinjection of geothermal brines.

## Introduction

Indonesia possesses, in different geologic environments, a large geothermal potential of up to 20,000 MWe (Fauzi, 2000). By January 2000, the installed capacity for generating electrical power from high enthalpy hydrothermal systems was 769.5 MWe (Sudarman *et al.*, 2000). It is expected that increasing the generation of electricity in the short term is possible by bringing into production geothermal fields located along the Indonesian volcanic region from Sumatera in the north to Sulawesi in the east. Concerning the Sumatra island, the most promising geothermal fields are distributed along the Great Sumatra Fault Zone (GSFZ) (Hochstein and Sudarman, 1993). This geothermal potential is directly related to the historic and present-day volcanic activity of this geologic province.

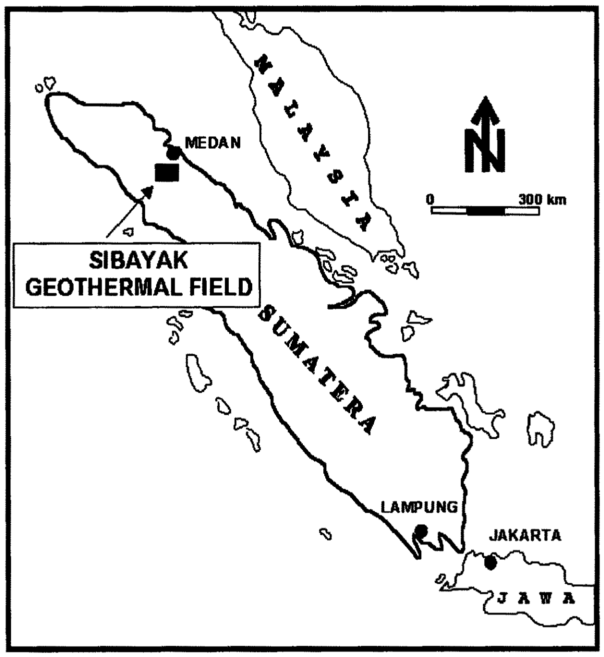


**Figure 1.** Location of Sibayak Geothermal field, North Sumatra Province, Indonesia.

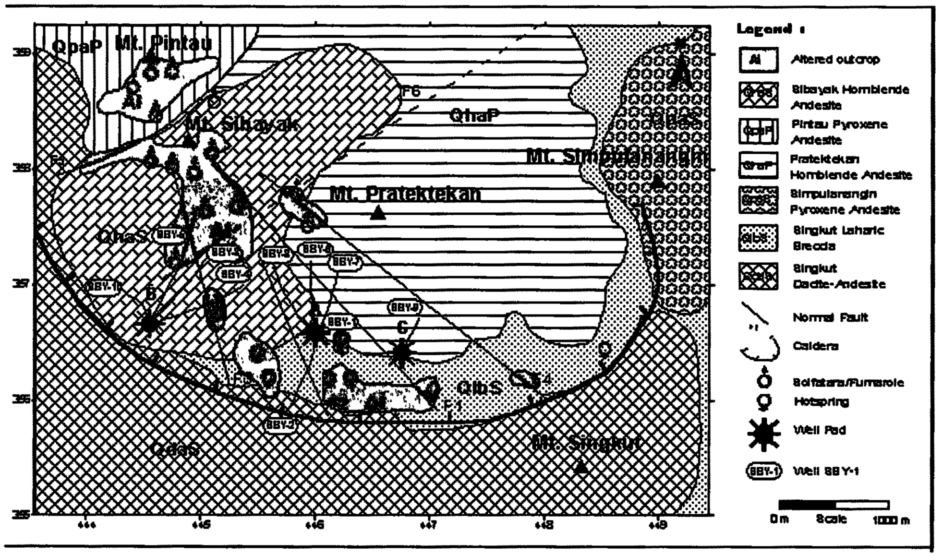


**Figure 2.** Simplified geology and surface manifestations of the Sibayak Geothermal Field, Indonesia.

The geothermal field of Sibayak is located (Figure 1) in the northern sector of the GSFZ, about 65 km to the southwest of Medan, the capital city of the North Sumatera Province. This field is associated with the Quaternary age Singkut caldera complex. Starting in 1989, Pertamina (State Oil and Gas Company) initiated a series of investigations to assess the potential of this area. Since then the feasibility for generating electric power from geothermal fluids has been well established through geologic, geochemical, and geophysical studies, as well as by an exploratory well (Mulyadi, 1997). Production began with a 2 MWe electricity generating unit (Monoblock) at the wellhead in 1996. To expand the installed capacity to 20 MWe (Sudarman *et. al.*, 2000; Fauzi *et al.*, 2000), a better understanding of its reservoir system and delineation of its extension are required especially the best locations for further production drilling.

In this context, knowledge of structures affecting the geologic units of this area plays an important role. This information, when correlated with geochemical and hydrogeological data, can also help to gain an understanding of the hydrogeological system. This information is also useful for the task of locating sites for the reinjection of geothermal brines.

The gravity survey conducted by Pertamina allowed delineation of the major structural features underlying the geothermal field (Pertamina-Gondwana, 1989). However, since no well data constrained the interpretation, this preliminary structural model did not account for detailed facts. Subsequently, as new well data were gathered in this field, we decided to pursue further interpretation of the gravity data to add detail to the preliminary structural model. We expected that a refined geologic picture could help us to better understand the hydrogeological system in the Sibayak area, to help us to identify places to which the production zone may extend, and to contribute useful information to the question of the reinjection of geothermal brines.

## Geologic Setting and Surface Manifestions

The Sibayak geothermal field is situated in an area of elevated terrain inside the Singkut caldera. Geology and structure in the area are shown in Figure 2. The thermal features consist of solfataras and fumaroles, which are scattered at high elevations around the summit of Mt Sibayak. Chloride springs with silica sinter are also found at the lower elevations in the southern and northeastern caldera margins. There has been a complex volcanic history in the area with a number of eruption centers developing over a considerable period of time within the Quaternary.

The Sibayak area is composed of a Quaternary volcanic formation in the upper part that is unconformably overlying pre-Tertiary to Tertiary sedimentary formations. The sedimentary formations, outcropping to the west and east of Mt Sibayak and found in the deeper levels within the wells, are predominantly sandstone followed by shale and limestone. Drilling data shows that the sedimentary formations are generally found 1150 m below the surface. The most permeable zones are encountered by the wells at deeper levels within the sediments and are generally associated with sandstone and limestone. 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 in the NW-SE direction, and it developed after the Mt Singkut volcanic eruption (0.1 Ma). Some fault structures within the caldera are oriented 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 in Figure 2). The NW-SE fault structures are also intersected by the NE-SW lineament (F6 in Figure 2) 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 was also encountered in wells Sby-1, Sby-6, and Sby-7 along the contact plane between volcanic and sedimentary formations. 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).

## Gravity Database

A gravity survey of the Sibayak field was conducted by P.T. Gondwana in 1989-1990 as a part of combined geophysical surveys. Gravity data in the Sibayak field were obtained for 190 stations. A Lacoste Romberg gravity-meter (type G-310) with an accuracy of 0.01 mgal was used. Tidal, latitude, free-air, Bouguer and terrain corrections were then applied to the gravity data. Details of the gravity survey and corresponding data reductions are reported in Pertamina- Gondwana (1989). Density was measured on samples from selected outcrops in the study area (Pertamina-Gondwana, 1989) and used as a control of average surface density calculated using Parasnis' as well as Nettleton's methods. The average density is 2.20 g/cm³ reflecting the average density in the near-surface, where the Quaternary volcanic units are scattered in the study area. This density is then used for calculation of the Bouguer anomaly data (Figure 3). The Tertiary sediment basement presents a mean density of 2.60 g/cm³.

## Processing and Interpretation

As a first step, regional-residual separations were carried out. This was accomplished by least-squares fitting of polynomial surfaces of the first and the second degree to the data (Abdelrahman *et al.*, 1985). The residual obtained by considering only the local detailed gravity survey is similar to that obtained when constraining the regional-residual separation process with the additional regional coverage. Accordingly, it was decided to work on the first local residual anomaly map (Figure 4). This residual map correlates fairly well with the Bouguer anomaly map (Figure 3).

A straightforward qualitative interpretation of this gravity pattern (Figure 4) is the following: gravity lows are associated to structural depressions, highs with structural highs or densified layers, whereas the gravity gradients indicate fault zones. As will be seen below, gravity modeling confirms this qualitative interpretation.

Sibayak caldera is mainly characterized by a negative gravity anomaly. Nevertheless, this negative gravity anomaly does not present a simple pattern. Distinct gravity lows are encountered in the northwestern as well as in the southeastern caldera. The gravity low that occupies the northern half of the collapse is characterized, at its northeastern and northwestern limits by northeast-southwest lineaments, but it also contains lineaments with a northwest-southeast orientation. Other northwest-southeast and north-south lineaments are found delimiting the gravity high in the southern caldera margin. Worthy of notice is the fact that most of the geothermal manifestations are located along the northwest-southeast structures, specifically in the intersection of the structures at about 1 km from the southern foothill of Mt Sibayak. Other manifestations are located along the northeast-southwest structures outside the northeastern caldera margin.

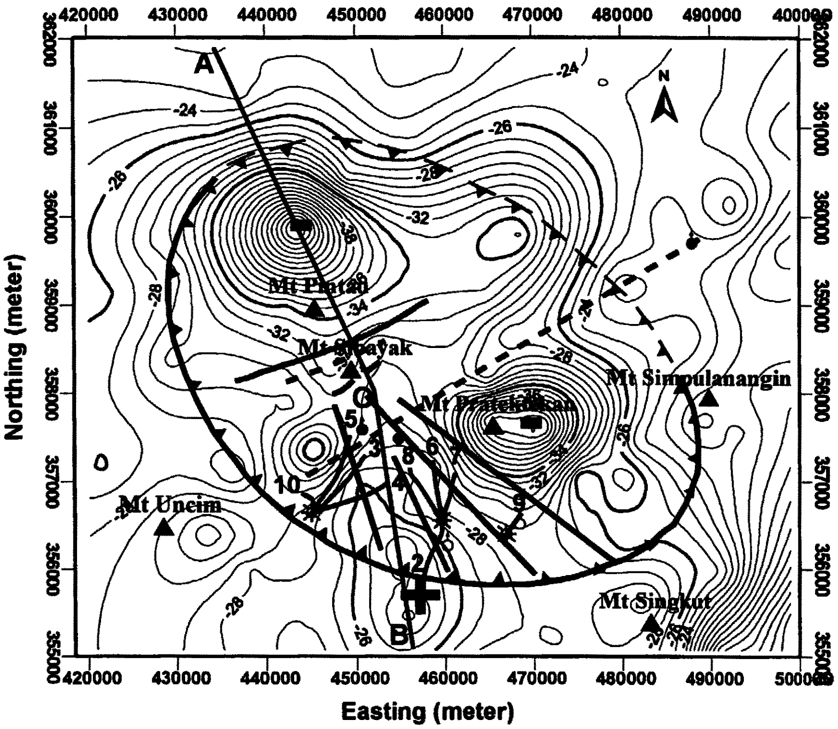


Figure 3. Bouguer gravity anomaly of the Sibayak geothermal field. Locations of profile AOB is indicated. Faults and lineaments are also indicated. The geothermal manifestations are represented by open and solid circles with arrows. Density of Bouguer correction is 2.20 g/cm³. Contour interval is 1 mgal.

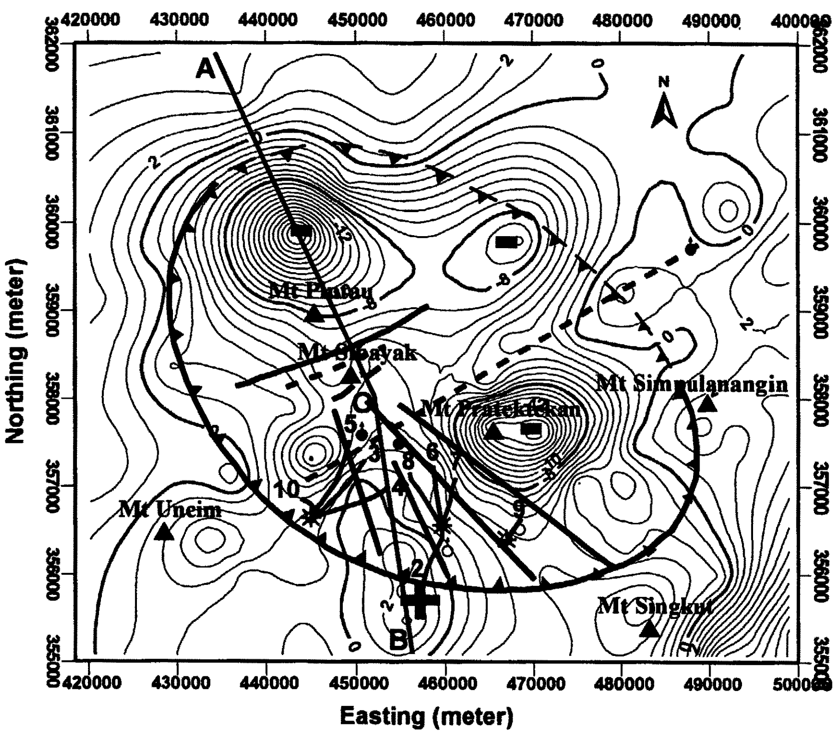


Figure 4. Residual gravity anomaly of the Sibayak geothermal field. Locations of profile AOB is indicated. Faults and lineaments are also indicated. The geothermal manifestations are represented by open and solid circles with arrows. Density of Bouguer corrections is 2.2 g/cm³. Contour interval is 1 mgal.

Furthermore, some steep gravity gradients are found following the caldera margin, specifically in the north, northwest and southwest. The southern and southeastern caldera margin is not well indicated by the residual gravity data. Instead of that, the gravity high is encountered just inside and outside the southern caldera margin. Moreover, since the surface as well as geochemical data show intensive hydrothermal mineralization in this area (Pertamina, 1994), this gravity high is interpreted as a densification of a formation by mineralization in fractures. This phenomenon is similar to that found in the Broadlands-Ohaaki geothermal field in New Zealand (Hochstein and Henrys, 1989).

Careful inspection of this residual gravity data and comparison to the geological data (Figure 2) shows a good agreement of the residual gravity data with the caldera boundary and fault structures in the Sibayak area.

## Computer Modeling

A 2-D interpretation was conducted in two steps. It was calculated that most of the residual anomaly could be accounted for by the interface between Quaternary volcanic and Tertiary sediment units. Acording to well data, this contact is about 1150 m deep in the area of production. A 2-D profile was modeled along profile AOB (see Figure 3 and Figure 4) to include the main structures inside the Singkut caldera. The 2-D modeling was constrained by the density measurements and well data as well as by other geophysical data (i.e. MT and DC resistivity). In this model, two main units were incorporated (Figure 5). The first unit is the lower part of the Tertiary sedimentary formation (density = 2.60 g/cm$^3$). The second unit is the Quaternary volcanic formations overlying the sedimentary units basement, as well as covering the upper part of this area. The reservoir as encountered by lost circulation zones during drilling is in the lower unit.

According to this model, the caldera is characterized by an asymmetric subsurface structure. In particular, distinct depressions are found in the northwestern portion as well as in the northeastern portion. The faults delimiting the caldera are quite clear, especially in the northwest. The high gravity value in the southern portion of this area is interpreted as a densification of the formation (density up to 2.75 g/cm$^3$) as a result of the development of hydrothemal mineralization (Pertamina, 1994).

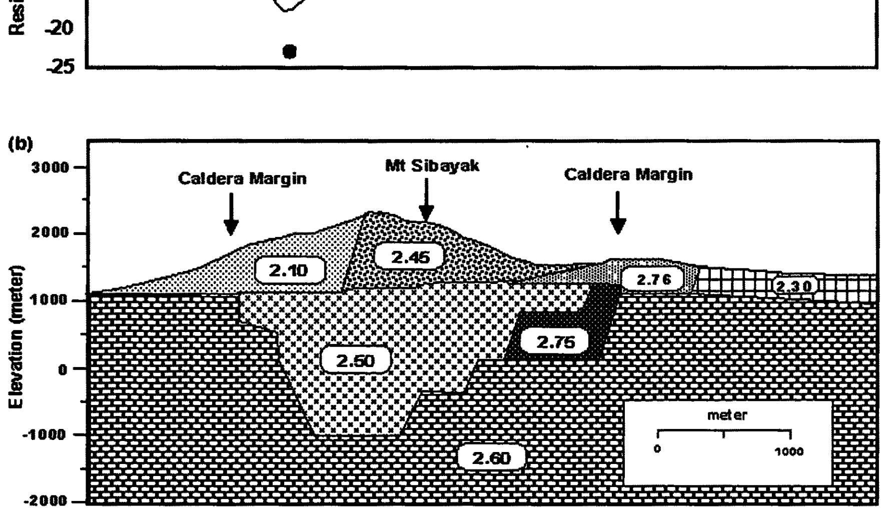


**Figure 5.** (a). Residual and computed gravity anomaly of Sibayak field along profile AOB. (b). 2-D gravity model along profile AOB. Location of profile AOB is shown in Figure 3 and Figure 4. Density is indicated in g/cm$^3$.

## Hydrogeological Considerations

According to the conceptual hydrogeological model (Pertamina-Batan, 1998) the upflow zone of the Sibayak field is located below the southern vicinity of Mt Sibayak as indicated by the highest chloride concentration within that area (800-1300 ppm). Formation temperature data (Daud *et al.*, 1999) also indicate the highest temperature in this area (more than 280°C). The outflow hydrothermal water then moves toward the southern caldera rim through fracture zones. On the contrary, $^{18}O$ isotope data shows that recharge water moves from Mt Singkut in the southern caldera rim towards the Sibayak crater. Furthermore, the mise-a-la-masse data shows a negative residual apparent resistivity anomaly found in the southern part of the study area just inside and outside the southern caldera rim. This anomaly has a good correlation with a high lost-circulation zone encountered by drilling. Nevertheless, the formation temperature is quite low as encountered by the well SBY-2. This anomaly is interpreted as a permeable formation zone in the deeper level filled by a cold water inflow (natural recharge) moving toward the main reservoir in the central part of the study area (Daud *et al.*, 1999).

Resistivity and MT data interpretation (Daud *et al.*, 2000) support the existence of the upflow zone around Mt Sibayak. However, another outflow zone is also indicated by this resistivity data northeastward of the occurrence of hotsprings in the northeastern part of the study area outside the caldera rim.

The structural picture furnished by the gravity data clearly reflects the northwest-southeast faults (F1 to F5) and northeast-southwest regional structural system (F6) (Figure 2). In particular, it can be noticed that the intersection of the two perpendicular faults gives rise to a zone of vertical permeability that enables the geothermal fluids to rise to the surface.

Imaging permeability in the Sibayak field by geophysical and wellbore data, Daud *et al.* (1999) and Daud *et al.* (2001) noted that the high permeability zone (kh = 2~4 darcy m) is found at the intersection of the faults. This high permeability zone has been encountered by the wells SBY-5, SBY-6 and SBY-8 within the sandstone and limestone lithologies of the sedimentary formation, covering an area of about 2 $km^2$. The average well production of the three wells is from 30 to more than 50 tons/hr steam with reservoir temperature of more than 280°C.

Accordingly, the intersection of the faults is the best site for further exploratory drilling. The southern area inside the caldera margin, where the intense scaling development occurs as indicated by geochemical data (Pertamina, 1994) and confirmed by the gravity modeling, should be avoided for the further exploratory drilling. The high permeability zone in the deeper level of southern caldera rim might be used for a reinjection site, where the natural recharge water flows to the main reservoir through it.

## Conclusions

A gravity study has delineated the major structural features of the Singkut caldera and Sibayak geothermal field. It is characterized by an asymmetric subsurface structure: a major depression in its northwestern and southeastern caldera collapse, and a gravity high reflecting densification (high density) of formation in the deeper level in the southern area. Lineaments reflecting the regional northwest-southeast structural fabric were observed. Other lineaments with northeast-southwest orientation were also encountered. The most productive geothermal production zone (30 to more than 50 tons/hr steam) is located within the intersection of faults as proved by drillings. This area is expected as the best site for further exploration drilling. Correlation of hydrogeological and geochemical data enabled interpreting the different geologic structures in the context of the hydrothermal system: an upflow zone is encountered at the intersection of perpendicular structures, while an outflow zone follows mainly the northwest-southeast structure toward the caldera margin in the south. Another outflow zone is also encountered following the northeast-southwest structure with an occurrence of hotspring outside the northeastern caldera margin. The structural image elaborated here constitutes a geologic frame for the prevailing hydrogeological conceptual model. This structural information is also useful for the task of selecting sites for the reinjection of geothermal brines.

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