# Sibayak Geothermal Field: New Insights from Updated MT Model

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**Keywords**

*Magnetotelluric, Inversion Model, Sibayak, Bottom of Clay Cap, Enhanced Conductivity, Pyrite, Saline Fluids*

**ABSTRACT**

Re-evaluating the Sibayak geothermal reservoir in North Sumatra, Indonesia, this study utilizes recent magnetotelluric (MT) data in 2023 to refine the existing 2D model into a 3D model. Compared to the 1996 model, a significant feature, an enhanced conductive body (0.1-1 Ω.m) was identified extending from outside the Singkut Caldera towards Mt. Pratektekan. Though past studies did not identify this conductive body, this discovery was confirmed by 1D and 2D MT inversions and intersects existing wells. The delineation of the base of the clay cap with the underlying enhanced conductive body presents a challenge due to the absence of a distinct boundary between the two in our 3D resistivity model. Meanwhile, 1D models could separate the bottom of clay cap and enhanced conductive body. While the exact cause remains under investigation, there are two possible causes of an enhanced conductive body which are saline fluids and sulfide minerals. This study emphasizes the value of updated geophysical data in understanding geothermal reservoirs and paves the way for further exploration and development in the Sibayak field.

## 1. Introduction

The Sibayak geothermal field, situated in North Sumatra, has been a contributing factor to Indonesia's geothermal energy production since 1996. Initially generating 2 MW, the field's capacity expanded to 12 MW in 2008 with the addition of two 5 MW units. However, an inactive steam sales contract with an Independent Power Producer (IPP) since 2012 prompted Pertamina Geothermal Energy (PGE) to re-evaluate Sibayak's potential to contribute to its ambitious 1 GW geothermal target.

Pertamina had conducted several geophysical data acquisitions. Initially, DC resistivity (Schlumberger) surveys were conducted to explore geothermal prospects with depth of investigation around 1000 meters, continued by an MT survey in 1992 and time domain electromagnetic (TDEM) for static shift correction in 1997 (Mulyadi, 2000). A gravity survey was also conducted by PT. Gondwana in 1989 – 1990 using a Lacoste Romberg gravity-meter (Daud, et al., 2001). In addition to the geophysical surveys, PGE undertook an update of the Sibayak reservoir model. The original model, developed in 2001, incorporated data from 10 wells drilled in the field (Atmojo, et al., 2001). Recognizing the potential impact of production history on reservoir characteristics, PGE created a new model in 2024 utilizing the available data since 2008 from the same 10 wells and incorporating post-production conditions. (Firanda, et al., 2024).

A team of geoscientists and reservoir engineers from PGE re-evaluated the Sibayak geothermal field's potential. This re-evaluation employed updated magnetotelluric (MT) data acquisition and resistivity inversion techniques to analyze the depth of the clay cap. Well cutting data from 10 wells provided information on clay content, which will be useful in evaluating the clay cap. The updated resistivity model revealed a previously unidentified, enhanced conductive anomaly (less than 5 ohm.m) extending from the surface to a depth of approximately 4,000 meters below sea level with a lateral extent of about 4,000 meters. This anomaly exhibits an oval shape and trends southwest-to-northeast beneath Mount Sibayak. Notably, this anomaly was absent in previous resistivity models, However, PGE's recent MT data acquisition and resistivity model was thoroughly evaluated, resulting in minor data masking for all decades above 160s (0.01 Hz) which PGE considered as satisfactory. It is also challenging to delineate the bottom of clay cap on our 3D resistivity model due to this high conductive body positions near the clay cap, resulting in a more smoothed and lower resolution view of the bottom of the clay cap (Cumming & Mackie, 2010). The nature of the high conductive anomaly remains an open question. This paper will study delineating the base of the clay cap including potential causes for enhanced conductivity based on well data.

### *1.1 Field Overview*

Sibayak field is a volcanic geothermal system inside Singkut caldera which formed at ~44 ka (Forni, et al., 2024) with two small conduit strato-volcano (Hochstein & Sudarman, 2015). Figure **1** shows two schematic conceptual models describing a volcanic hosted system and isotherms with alteration zone background derived from temperature log of the wells. The conceptual model was also used to update the numerical simulation of Sibayak Field (Firanda, et al., 2024) which consists of geothermal upflow beneath Mt. Sibayak outflowing towards southeast and northeast. Sibayak complex manifestations were found in the crater of Sibayak Mountain and flank of Sibayak inside the Singkut caldera (Fahmi, et al., 2021). Figure 2 is the geological map of Sibayak with structure orientation NW-SE. Although Sibayak is a volcanic hosted system, tertiary sediments play major roles for the permeability in Sibayak reservoir.

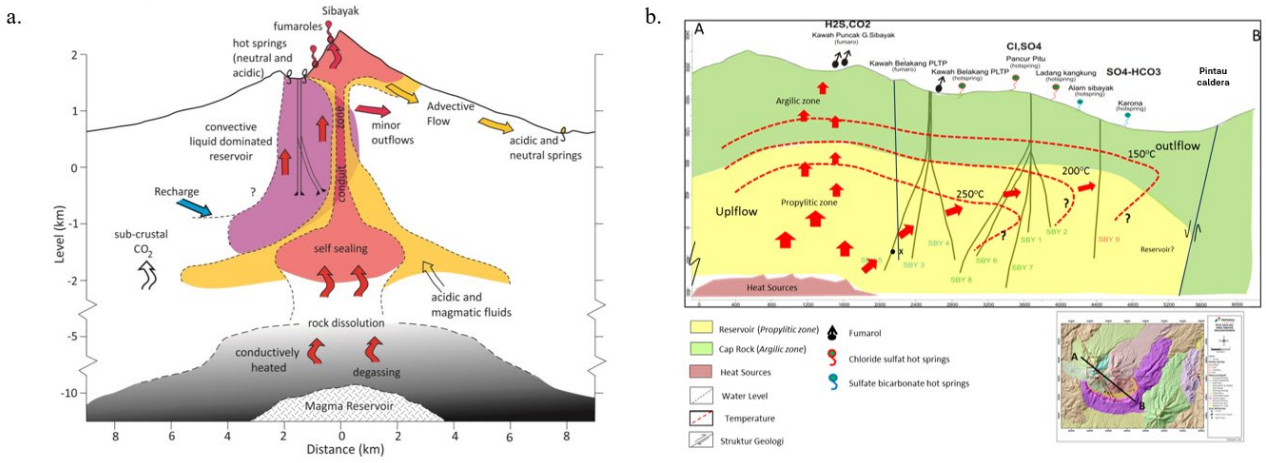



**Figure 1. a. Sketch of Sibayak volcanic hosted conceptual model (Hochstein & Sudarman, 2015) and b. Isotherm conceptual model with hydrological setting of Sibayak along the alteration zone background developed from well temperature log (PT. Pertamina Geothermal Energy Tbk, 2022)**

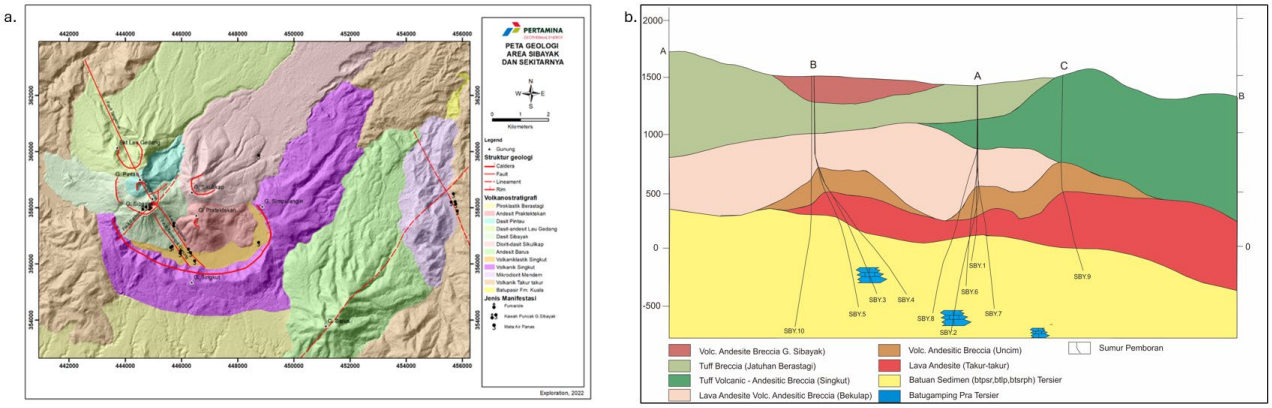



**Figure 2. a. Updated geological map with stratigraphy of Sibayak field (PT. Pertamina Geothermal Energy Tbk, 2022) and b. Geological cross section interpreted from well cuttings data (PT. Pertamina Geothermal Energy Tbk, 2016)**

## 2. Sibayak MT Surveys

Sibayak's MT data, acquired in 1991 by PT Alico and in 1997 by PT Qodharwan Wirasta Konsultan, with total 51 MT stations, were utilized for 2D inversion techniques to verify the reservoir structure and its extent (Daud, et al., 2002). To achieve a more comprehensive understanding of the Sibayak geothermal field using modern software and technology, a 3D inversion approach was carried out. This re-modeling process aimed to enhance the three-dimensional visualization of the Sibayak Field, improving the accuracy of the geothermal resource assessment. However, limitations were encountered due to the incomplete recovery of historical MT data. To address this challenge and refine the remodeling efforts, a new MT data acquisition campaign was conducted. PGE's in-house geophysics department acquired 54 MT stations using proprietary tools and standardized acquisition procedures.

A three-receiver magnetotelluric (MT) system, including two operational units and one backup, facilitated simultaneous data acquisition at two stations per day in Sibayak. Each station utilized

three MTC-80H coils with a frequency range of 1 kHz to 10,000 seconds and 4 electrode pots. Time series data processing was run in-house using SSMT software resulting in 4 excellent datasets, 48 good datasets and 2 fair datasets.

Figure 3 shows MT stations designed for characterizing the Sibayak reservoir. The station distribution was expected to be grid spaced or spread evenly with a target of 500 to 1000 m spacing in the inner core and 1500 m to 2000 m for the outer core with area of surveys around 100 $m^2$. Overall, the data acquisition met the target although in some areas such as in the northeast of Sibayak Mountain and south of Singkut Caldera MT data could not be acquired due to dense forest with minimum access and densely populated areas with high voltage power line.

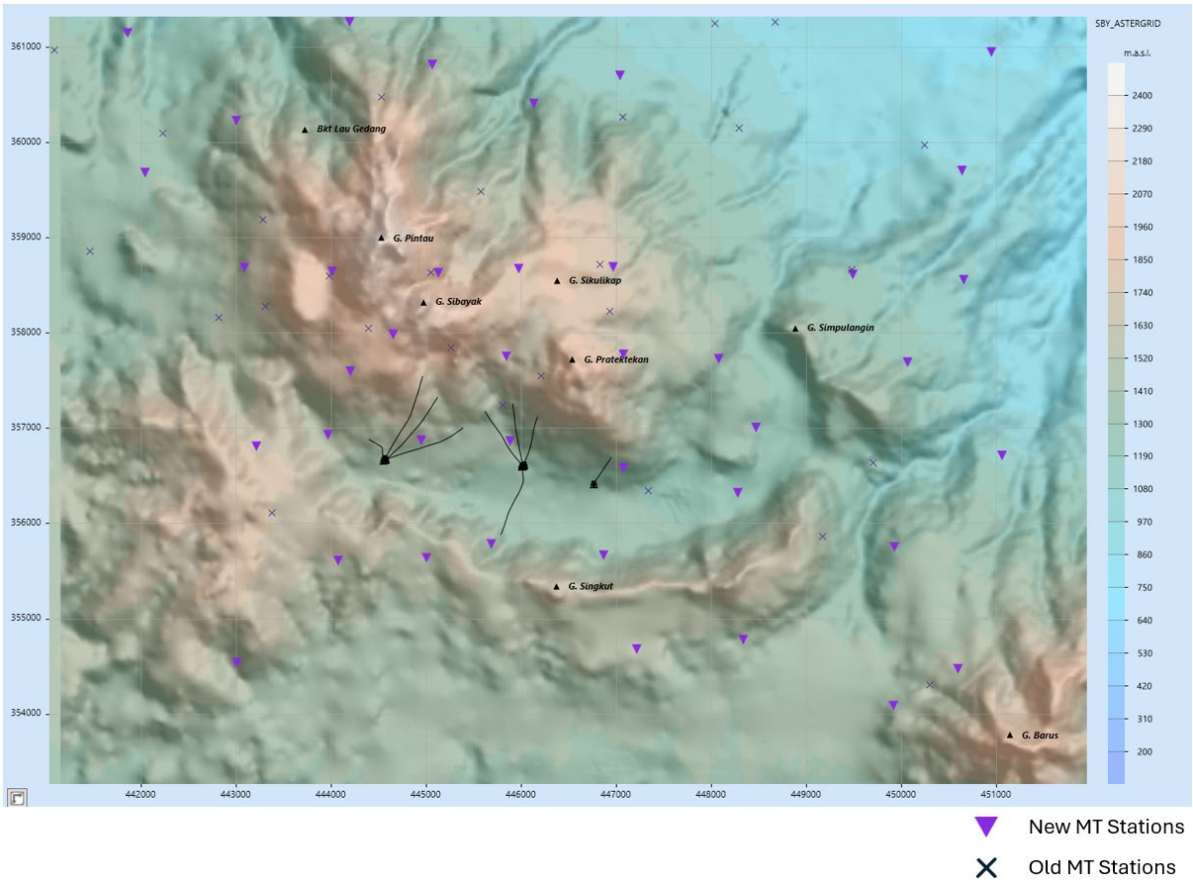



**Figure 3. Distribution of MT stations from data acquisition in 2023 (purple triangle) and 1991 & 1997 (cross).**

## 3. Sibayak MT Inversions

Prior to this study, previous MT datasets from the Sibayak geothermal field had undergone several analyses. The first study showed that 1D inversions could be used to delineate the clay cap, reservoir and subsurface structure (Mulyadi, 2000). Understanding the limitation of 1D inversion, 2D inversions were carried out to improve the interpretation of reservoir and basement from 1D inversions due to strong indication of 2D or 3D effects (Daud, et al., 2002). Advancements in technology have facilitated the routine application of 3D inversion techniques in recent years. Using a well-prepared MT dataset with recent technology, PGE conducted 3D inversion to create a better understanding of Sibayak reservoir.

Prior to 3D inversion, the data were rotated to 0 degrees (North) and edited to mask out noisy data, which was was only necessary for frequencies below 0.006 Hz due to anomalous behavior in the YX component at lower frequencies (Figure 4**)**. Both MT impedances and the vertical magnetic transfer function (tipper) were inverted. Additionally, we carried out in-house 1D and 2D inversions using Geotools software. The resulting 3D resistivity model revealed a previously unidentified, enhanced conductive anomaly extending from the outer Singkut Caldera towards Sibayak Mountain. The validity of this anomaly was investigated through further analyses such as comparing it to the previous model, conducting 1D and 2D inversions and lastly conducting a 3D sensitivity analysis.

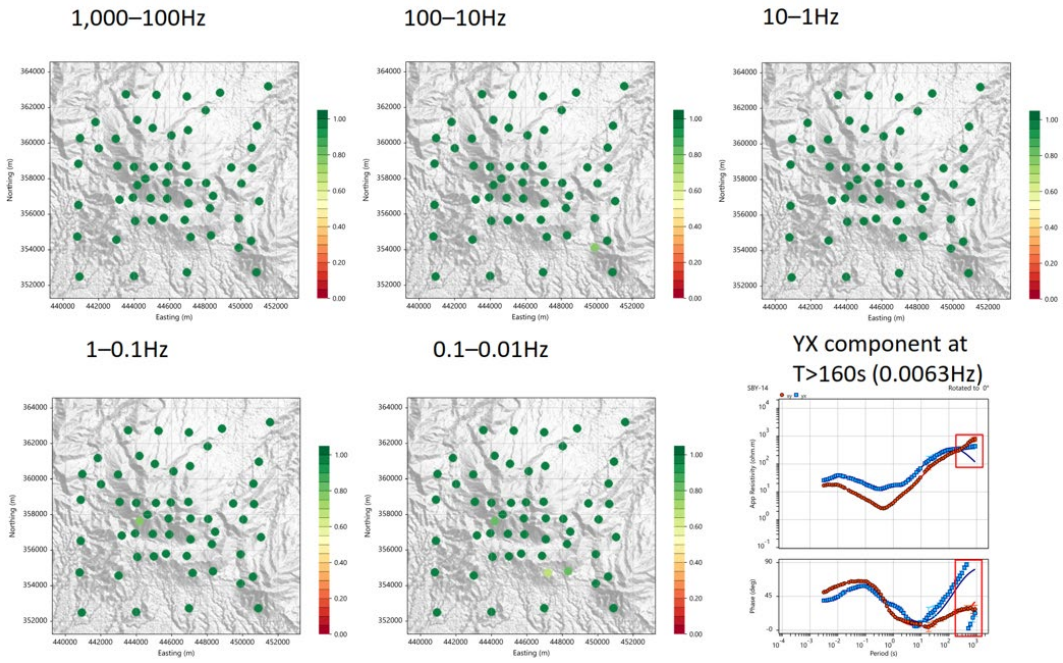



**Figure 4. Data masking of MT datasets in every frequency start from 1000 – 0.01 Hz. Color bar green-red describing the percentage of data masked, value 1 or green means no data masking performed.**

### *3.1 Comparisons of MT Inversion Models*

To verify the existence of the newly identified high conductive anomaly, several attempts were made to reconcile it with previous findings. As the original MT datasets used to generate the old 2D resistivity model were unavailable, the datasets of the old MT stations were plotted on the new 3D model, and the published image of the old 2D model was visually compared (Figure 5). Stations SBK-205, SBK-216, SBK-211, and SIB-128 are located within the footprint of the anomaly on the new 3D model. However, the old 2D model did not image a conductive body at these locations. This could be due to several reasons. First, the highly conductive anomaly might exhibit a 3D effect that could not be adequately captured by the older 2D inversion algorithms. Second, due to the deep 3D nature, input data for the 2D model were restricted from 0.003 down to 30 seconds period (Daud, et al., 2002).

An additional effort to reconcile the anomaly with previous findings involved comparing published old MT curves to new MT curves nearby. Around 200 meters from SBK-211 is SBY-20 station

with the same MT curve response (Figure 6). The most notable difference observed was a significantly higher initial resistivity (around 750 ohm.m) in the new SBK-211 curve compared to the old SBY-20 curve (around 40 ohm.m). This discrepancy could be attributed to the application of static shift correction using TDEM data in the processing of the old MT data, which was not employed for the new dataset. Both curves exhibited a deflection in the Rho-YX component at a period of 1 second, while the Rho-XY component deflection occurred before 1 second in both datasets.

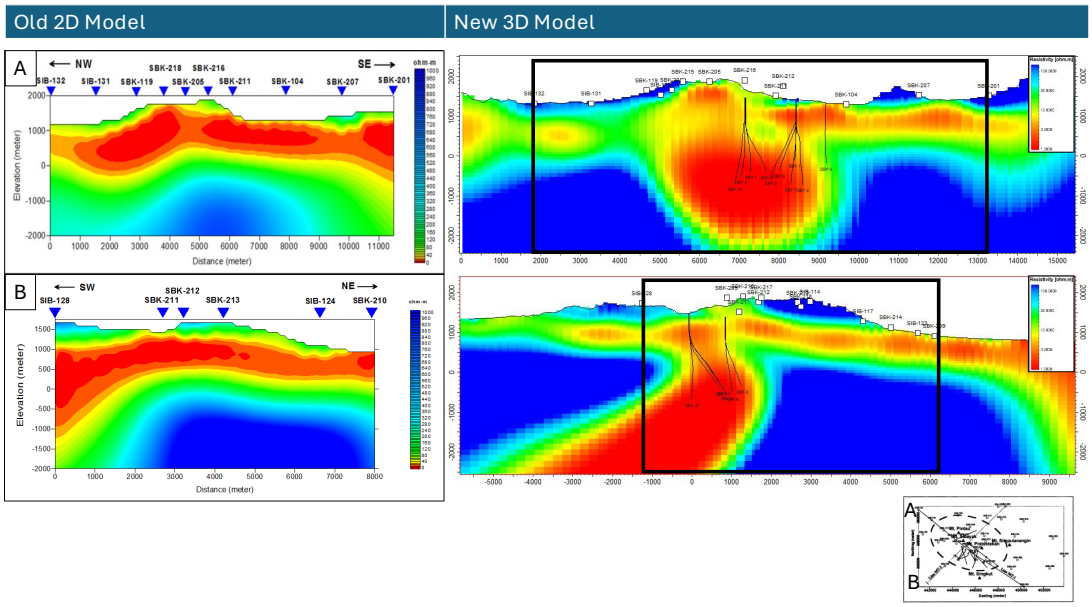



**Figure 5. Cross-section comparation between old 2D model (left) and new 3D model (right). The boundary of the old 2D model is visualized in a black box.**

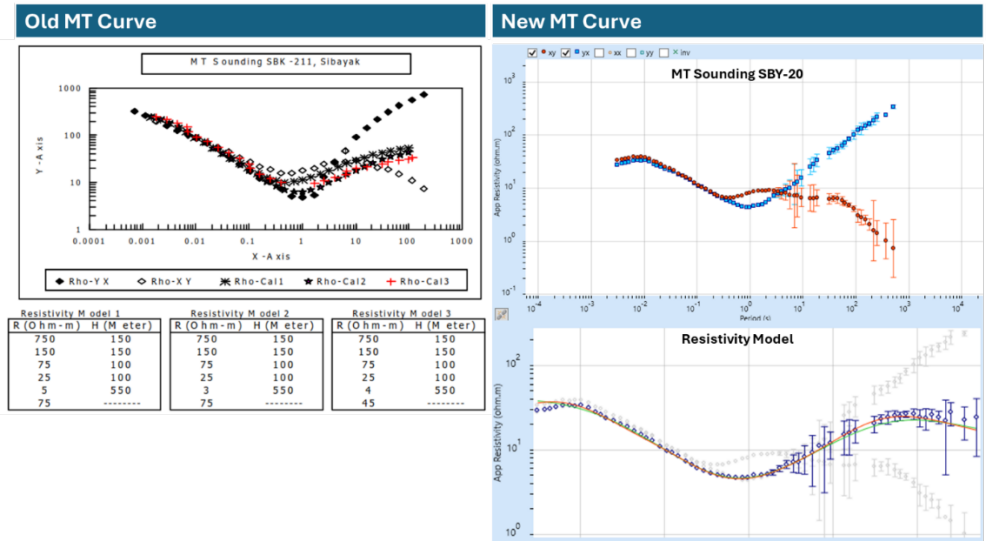



**Figure 6. Comparison of nearby station between SBK-211 (old MT dataset) and SBY-20 (new MT dataset) including each 1D inversion.**

### *3.2 New MT Inversions of 1D, 2D and 3D Models*

While 1D and 2D MT inversions using Geotools software offered a complementary approach, they presented limitations compared to 3D inversion. Unlike 3D models, which invert for distortion matrices, 1D and 2D inversions relied on static shift corrections obtained from TDEM surveys. This dependence on the type of static shift correction can potentially introduce distortions in the geometry of the geothermal clay cap as interpreted from the 1D and 2D models. However, the information derived from 1D and 2D models, when combined with alteration mineral data from wells, could still contribute to a comprehensive interpretation of the geothermal system.

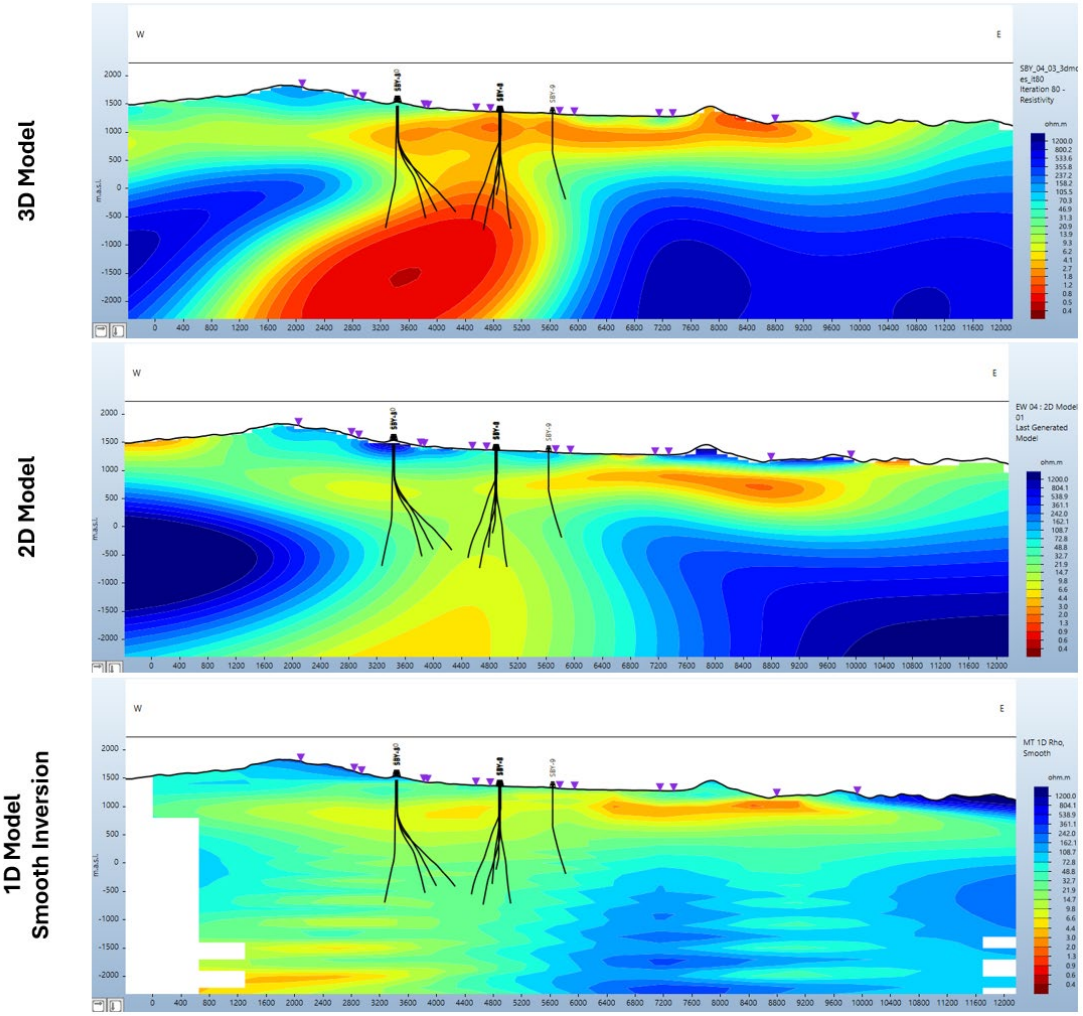



**Figure 7. Three West-East Cross-Sections, crossing wells trajectory from 3D, 2D and 1D model sequentially.**

To generate 1D models, a smooth inversion (Occam) method was performed as it was good enough to delineate the resistivity of the geothermal clay cap (Cumming & Mackie, 2010). These 1D models were generated for all data within a frequency range of 1000 Hz to 0.001 Hz, incorporating a 5% apparent resistivity noise floor. Subsequently, the 1D Occam models were horizontally interpolated to create a cross-sectional image (Figure 7**)**. The resulting 1D model provides a smooth representation of the resistivity down to a depth of approximately 1000 meters, with

increased scatter at greater depths. This scattering might be attributed to the influence of 2D and 3D effect.

A 2D inversion was conducted utilizing TE and TM mode curves within the frequency range of 1000 to 0.01 Hz, as determined by data masking. Typically, 2D inversions serve as a preliminary step to refine inversion parameters before progressing to 3D modeling.

The 3D inversion was initiated with a uniform 50 ohm-m initial model and a 5% error floor, converging after 80 iterations to a root mean square (RMS) value of 1.08. By incorporating data from 0.006 to 251 Hz, reliable depth resolution was achieved to a depth exceeding 5000 meters. This depth coverage adequately captured the high conductive anomaly extending from outside the Singkut Caldera towards Sibayak Mountain. Notably, nine of the ten wells are located within the outer core of this conductive anomaly. However, a cautious interpretation is warranted due to the age of the well reports, which precludes further detailed analyses such as X-ray diffraction (XRD).

### *3.3 Sensitivity Test*

To assess whether the deep conductive anomaly was an artifact of the inversion process or parameters, a sensitivity analysis was conducted (CGG Geoscience, Multiphysics, 2023). A modified 3D resistivity model (Figure 8.a) was created by replacing the enhanced conductive anomaly with a less conductive body (50 ohm.m). The impact of this modification on the forward response was evaluated by comparing the TE-TM mode curves of the original and modified models at stations within the southwestern study area (Figure 8.b). The apparent resistivity and phase curves from the original model (points) displayed significant deviations from those of the modified model (solid lines). This substantial difference in the forward responses demonstrates that the MT data possess sensitivity to the enhanced conductive body, suggesting its presence is required to accurately fit the observed data.

## 4. The Bottom of the Clay Cap from 1D and 3D MT

Delineating the bottom of the clay cap using 3D resistivity models is often straightforward and typical for geothermal field evaluations. However, in the Sibayak field, the presence of an enhanced conductive body positioned near the clay cap in the 3D model presented a significant challenge. This proximity resulted in a blurred interface between the conductive clay cap and the anomaly, hindering clear separation. To address this limitation, 1D MT inversions were employed to provide a higher-resolution characterization of the clay cap (Figure 7). Figure 7 illustrates a clear separation between the bottom of the clay cap (interpreted at 10 ohm.m) and the enhanced conductive body in the 1D model, in contrast to the ambiguity observed in the 3D model.

The absence of static shift correction in the 1D model presented a significant challenge. While the integration of well data, including alteration zones, enhanced the interpretation of the geothermal system, the direct correlation between the 1D and 3D model-derived clay cap depths and well data proved to be inconsistent (Figure 9). The lack of Methylene Blue tests (MBT) in the legacy well reports, an uncommon practice at the time, hindered a more precise correlation between the clay cap and the argillic alteration zone.

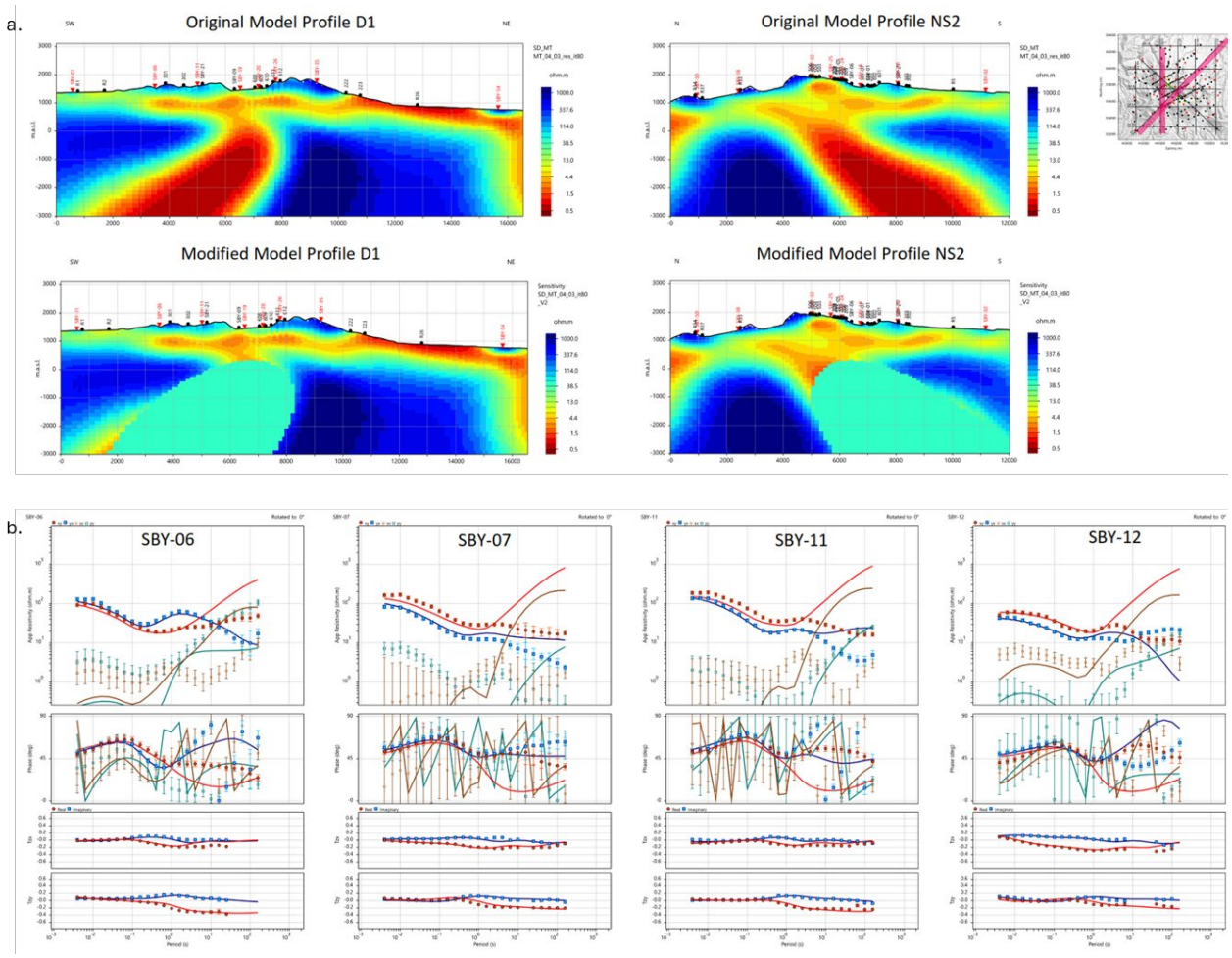



**Figure 8. a. Cross-sections of two profiles comparing between modified 3D model from high conductivity into 50 ohm.m body. b. MT-curves sampled from MT stations above the high conductive body with MT curve from forward modelling of the modified body (solid lines) and original data (dots).**

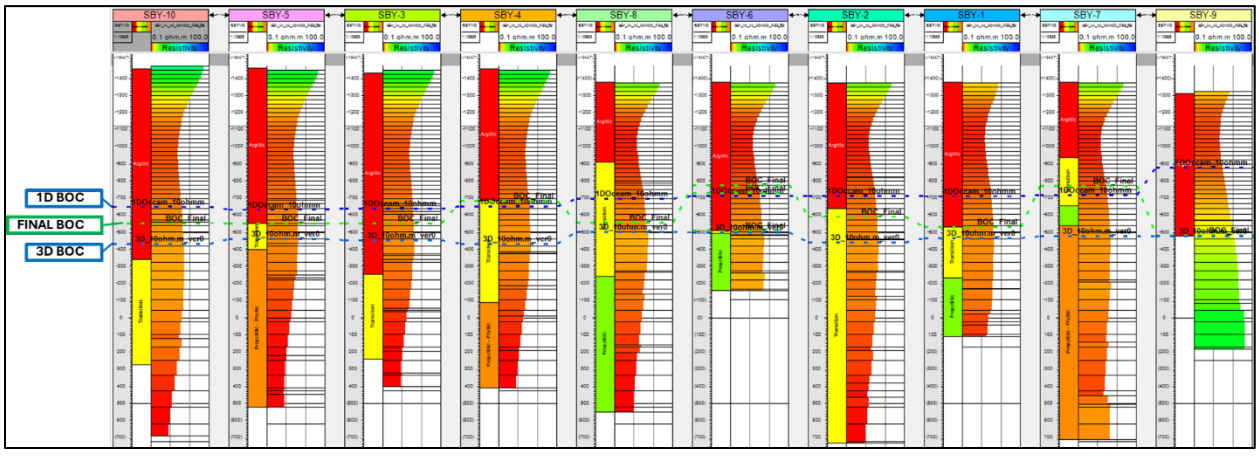



**Figure 9. 1D and 3D interpreted bottom of clay cap with alteration data from Sibayak wells.**

To address these limitations, a combined approach was adopted. The bottom of the argillic alteration zone was used as a primary constraint, and the general trend of the bottom of clay cap from the 1D model was incorporated into the 3D model using minimum curvature interpolation. This strategy aimed to mitigate the negative impacts of the low resolution associated with blurred resistivity value of the high conductive body and the clay cap on the 3D model Figure 10.

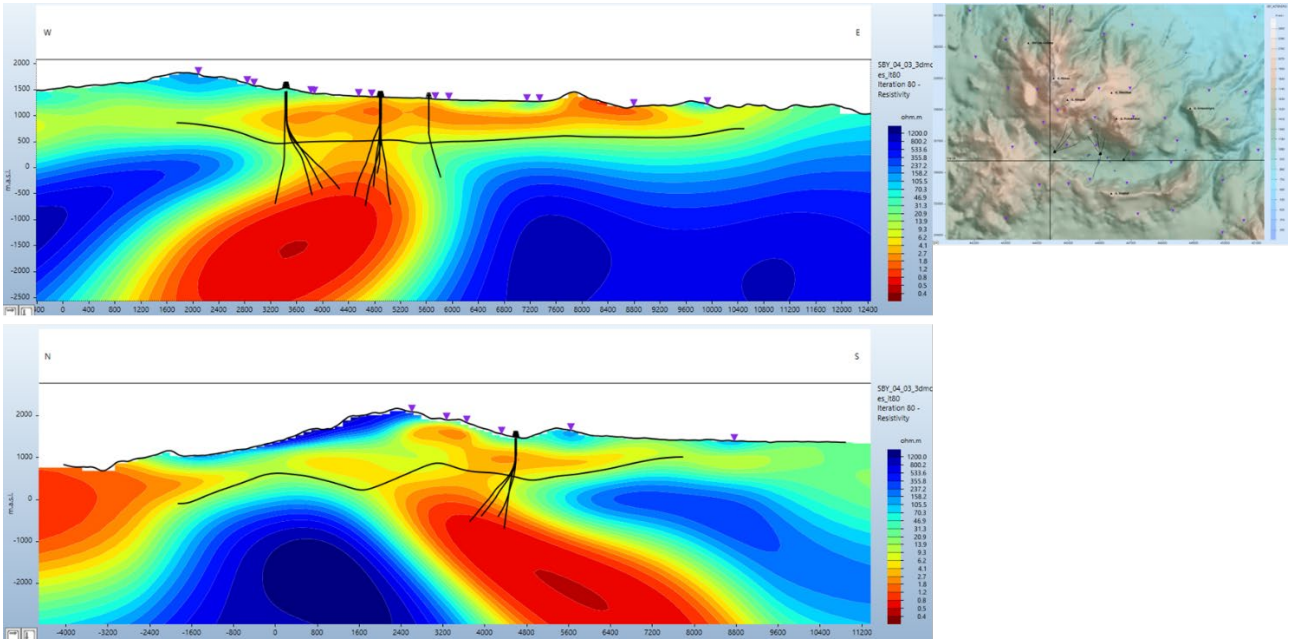


**Figure 10. Cross-sections of 3D model with the interpolated bottom of clay cap from 3D interpretation BOC bound with well data and 1D BOC trends.**

## 5. Possible Causes for Enhanced Conductivity

Potential causes for enhanced conductivity include graphite, ore minerals, saline fluids, and partial melting (Schilling, et al., 1997). However, given the likely presence of an impermeable barrier confining fluids, saline fluids are considered the most plausible explanations (Jones, 1992). A modeled electrical conductivity of sandstones saturated with NaCl solution (3.5wt% – 4wt%) as a function of porosity show electrical resistivity ranging from 1 to 5 ohm.m with 25% porosities (Jenkins, et al., 2023).

The other possible cause is that laboratory studies have established a correlation between high electrical conductivity and the presence of ore minerals, particularly sulfides. However, while this association is commonly observed, it is not universally applicable. Numerous case studies demonstrate that high conductivity can occur both with and without the presence of detectable sulfides (Lin, et al., 2023).

### *5.1 Saline fluid*

Deeper geothermal brines sampled from Sibayak wells contain average sodium ($Na^+$) and chloride ($Cl^-$) concentrations of 500 and 1300 ppm, respectively, equivalent to a salinity of 0.18 wt%. These salinity levels are typical for geothermal brines. Yet, Figure 2.b presents a simplified geological model of Sibayak based on well cuttings data. Upper tertiary sandstones were found on those wells

ranging from 800 to 0 masl. Although sandstones should have high permeability, permeability derived from well productivity in Sibayak were found to have small to intermediate permeability (< 30 milliDarcy) (PT. Pertamina Geothermal Energy Tbk, 2016) based on permeability category (Wheaton, 2016). This discrepancy is likely attributed to silica or calcite scaling within the sandstone formations. Such scaling may create impermeable barriers, potentially trapping saline fluids and consequently enhancing electrical conductivity as observed in the resistivity model.

### *5.2 Sulfide*

Pyrite is a sulfide mineral commonly appearing and reported during geothermal drilling. By utilizing this data, we can map the distribution of Pyrite within the Sibayak model. Figure 11a illustrates the distribution of Sibayak wells, incorporating alteration models, Pyrite content (ranging from 10 to 30 wt% as indicated by pink to red shading), and resistivity logs derived from 3D MT inversions. A horizon of Pyrite with 10wt% was mapped from the wells to know the distribution of Pyrite.

Figure 11b is a West to East cross-section presenting Sibayak wells with Pyrite content and a filtered <10 ohm.m 3D resistivity model as a background. An interpreted horizon of Pyrite > 10wt% was delineated with a dotted line and coinciding with the top of a conductive dome-shaped body. This correlation suggests a potential link between the enhanced conductivity and the presence of a sulfide body, warranting further investigation.

## 6. Discussions

In this study, 2D inversion was used to verify the presence of the highly conductive body identified in the 3D model, particularly its position relative to the production wells. The 2D inversion confirmed the existence of the conductive body, although its depth was estimated to be greater than that observed in the 3D model (Figure 7). This discrepancy underscores the importance of accurate static shift correction in both 1D and 2D inversions. Although static shift correction was not applied, the interpolated BOC is a success as shown in Figure 10 & Figure 11b.

To know more about the relationship between porosity, salinity, resistivity and temperature we could refer to a study by Ussher, et al., 2000. It is clear that the resistivity of Sibayak well brine sample data from Figure 12a could be ranging from 10 – 3 ohm.m, while an effective model in Figure 12b with temperature ranging from 250 – 300 $^{o}$C, Sibayak sandstone should have porosity more than 20%. Unfortunately, porosity data for Sibayak sandstones are currently unavailable.

The other possibilities are using a model generated by Clennell, et al., 2010 with 100% brine saturated sandstone with Pyrite bearing sandstones. By incorporating Pyrite contents ranging from 10 to 30%, as observed in Sibayak, resistivity values below 10 ohm.m can be simulated (Figure 13). This modeling approach can be further refined by incorporating detailed mineral composition data from the Sibayak wells.

If the high conductivity is attributed to trapped saline fluids, future development efforts should prioritize targeting the conductive body. This approach is supported by the observation that production wells are located within the conductive zone, while non-production wells (e.g., SBY-9) are situated outside this area.

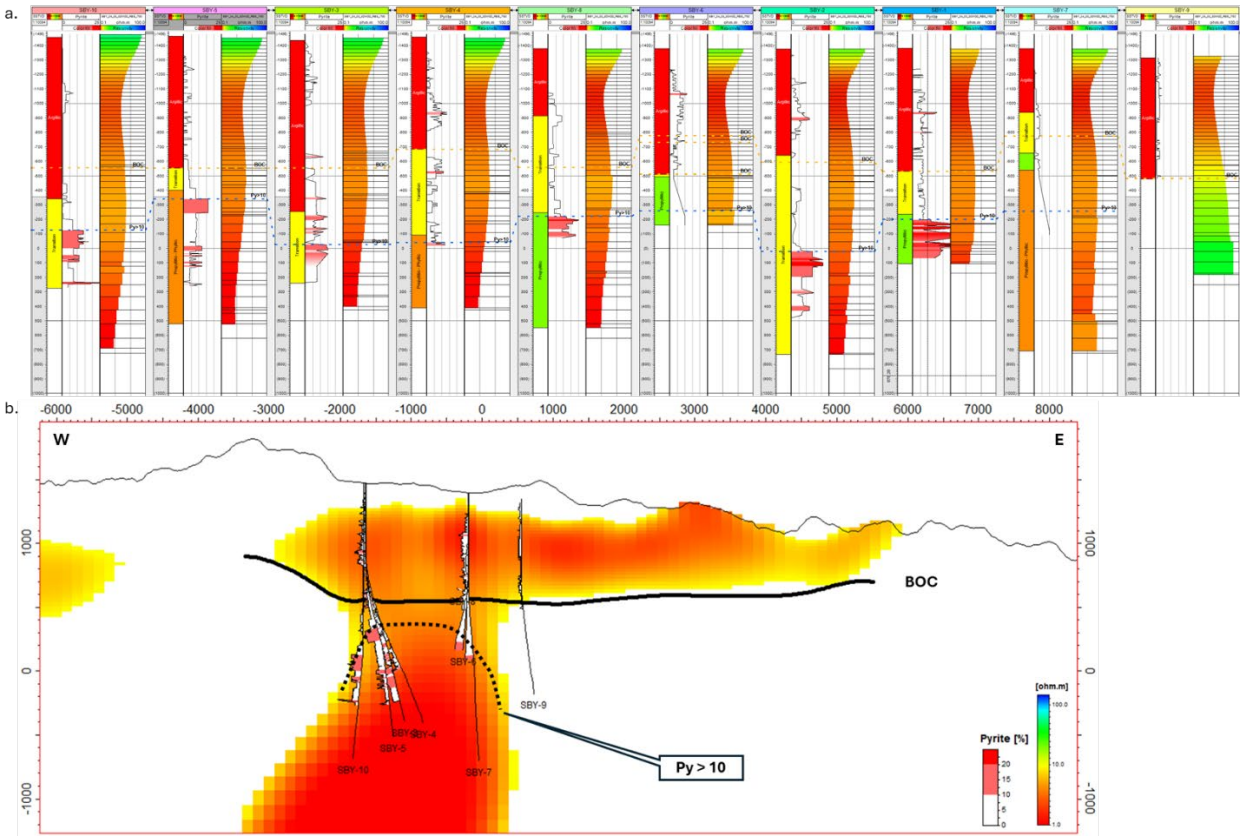



**Figure 11. a. Distribution of Pyrite content in percentage (%) : pink to red is more than 10% contents, b. W-E cross-section with a filtered less than 5 ohm.m resistivity model background and Sibayak wells with each Pyrite content, a dotted line is an interpreted line of Pyrite with more than 10% content.**

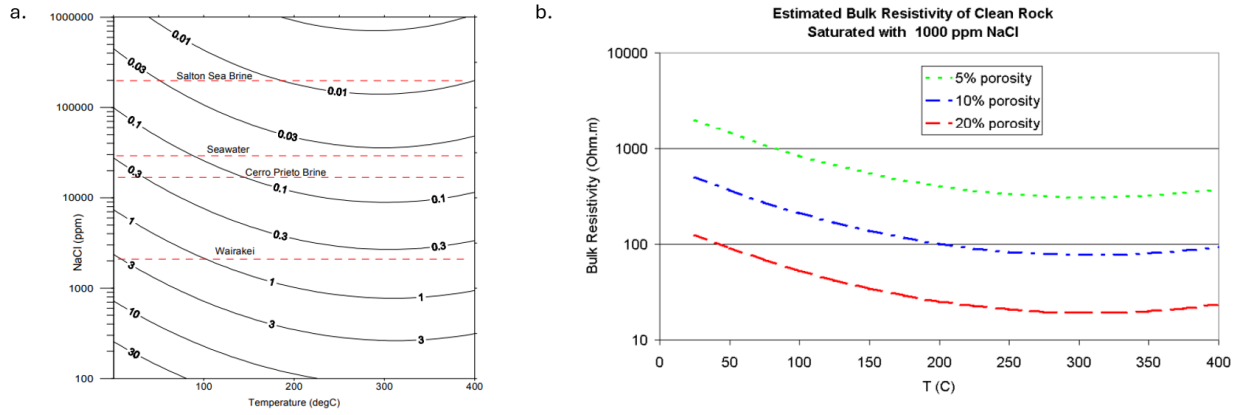



**Figure 12. Relationship of salinity, porosity, temperature and resistivity (Ussher, et al., 2000) a. Variation of resistivity in ohm.m of Nacl solutions from measurements (Ucok, et al., 1980) modified by (Ussher, et al., 2000). b. a modelled Archie's Law bulk resistivities for "clean" rocks containing saturated 1000 ppm NaCl.**

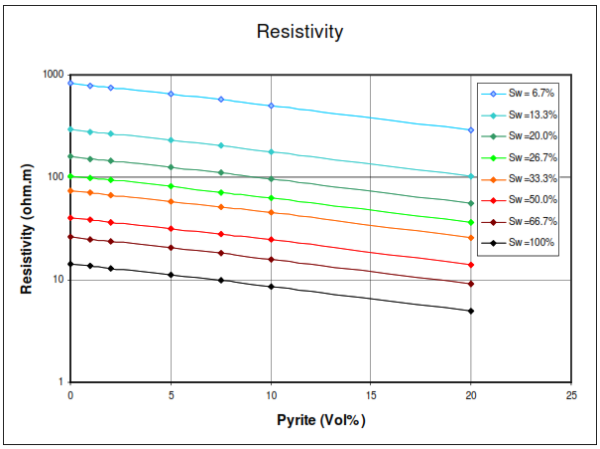



**Figure 13. Resistivity of brine-saturated Pyrite bearing sandstones model with variable gas saturation, using Hanai-Bruggeman method (Clennell, et al., 2010).**

Conversely, if sulfide mineralization is the primary cause of the enhanced conductivity, a comprehensive exploration program focused on identifying and evaluating rare mineral potential is warranted. Regardless of the underlying mechanism, drilling a new well into the core of the conductive body is essential to advance understanding of the system and assess its economic viability.

## 7. Conclusions

The integration of 1D and 3D inversion results with well data has significantly improved the delineation of the bottom of the clay cap (BOC), particularly in differentiating the clay cap from the underlying, highly conductive zone. Even though the causes of a deep enhanced conductivity in Sibayak are unclear, an enhanced conductive body is visible in all 1D, 2D and 3D MT inversions.

To explain the origin of enhanced conductivity, a combination of approaches is recommended. Drilling a new well targeting the conductive zone, coupled with resistivity logging, would provide direct evidence of the causative factors. Alternatively, rock physics modeling using methods like Hanai-Bruggeman or Archie's law could be employed to estimate formation factors for the Sibayak Tertiary sandstone. However, the lack of detailed rock property data limits the accuracy of such models.

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## REFERENCES


Atmojo, J. et al., 2001. *Numerical Modelling Study of Sibayak Geothermal Reservoir, North Sumatra, Indonesia.* Stanford, California, Twenty-Sixth Workshop on Geothermal Reservoir Engineering.

CGG Geoscience, Multiphysics, 2023. *Pertamina Geothermal Energy Internal Report of 3D MT Inversion Modeling - Sibayak,* s.l.: CGG Geoscience, Multiphysics.

Clennell, M. B. et al., 2010. *The influence of pyrite on rock electrical properties : a case study from NW Australian gas reservoirs.* s.l., SPWLA 51st Annaul Logging Symposium.

Cumming, W. & Mackie, R., 2010. *Resistivity Imaging of Geothermal Resources Using 1D, 2D and 3D MT Inversion and TDEM Static Shift Correction Illustrated by a Glass Mountain Case History.* Bali, Indonesia, World Geothermal Congress.

Daud, Y., Sudarman, S. & Ushijima, K., 2001. *Sibayak Geothermal Field (Indonesia): Structure Assessed From Gravity and Hydrogeological Considerations.* s.l., s.n.

Daud, Y., Sudarman, S. & Ushijima, K., 2002. *Imaging Reservoir Structure of the Sibayak Geothermal Field (Indonesia) Based on Magnetotelluric Observations.* s.l., s.n.

Fahmi, F. L. et al., 2021. *Geochemistry Monitoring of Surface Thermal Manifestation in Sibayak, North Sumatra, Indonesia.* Reykjavik, Iceland, World Geothermal Congress.

Firanda, E. et al., 2024. *Updating Numerical Simulation Model of Sibayak Field, Indonesia.* Standford, California, Forty-Ninth Workshop on Geothermal Reservoir Engineering.

Forni, F. et al., 2024. Remobilization and eruption of an upper crustal cumulate mush at the Singkut Caldera (North Sumatra, Indonesia). *Journal of Volcanology and Geothermal Research,* Volume 445.

Hochstein, M. P. & Sudarman, S., 2015. *Indonesian Volcanic Geothermal Systems.* Melbourne, Australia, World Geothermal Congress.

Jenkins, A. P., Rust, A. C., Blundy, J. & Biggs, J., 2023. Magnetotelluric investigations at Andean volcanoes: Partial melt or saline magmatic fluids?. *Journal of Volcanology and Geothermal Research.*

Jones, A. G., 1992. Electrical conductivity of the continental lower crust. In: D. M. Fountain, R. J. Arculus & R. W. Kay, eds. *Continental Lower Crust.* s.l.:Elsevier, pp. 81-143.

Lin, W., Yang, B., Han, B. & Hu, X., 2023. A Review of Subsurface Electrical Conductivity Anomalies in Magnetotelluric Imaging. *Sensors,* 23(1803).

Mulyadi, 2000. *Magnetic Telluric Method Applied For Geothermal Exploration in Sibayak, North Sumatra.* Kyushu - Tohoku, s.n.

PT. Pertamina Geothermal Energy Tbk, 2016. *Internal Report : Geological, Geochemistry, Geophysical and Reservoir Evaluation of Sibayak Geothermal Field, North Sumatra,* Jakarta, Indonesia: Resource Management Division of Planning and Development Directorate.

PT. Pertamina Geothermal Energy Tbk, 2022. *Internal Report : Geological Mapping Report of Sibayak Area,* Jakarta, Indonesia: Geoscience Region I Exploration Division of Exploration and Development Directorate.

Schilling, F. R., Partzsch, G. M., Brasse, H. & Schwarz, G., 1997. Partial melting below the magmatic arc in the Central Andes deduced from geoelectromagnetic field experiments and laboratory data. *Physics of the Earth and Planetary Interiors,* Volume 103, pp. 17-31.

Ucok, H., Ershaghi, I. & Olhoeft, G., 1980. Electrical resistivity of geothermal brines. *Journal of Petroleum Technology.*

Ussher, G., Harvey, C., Johnstone, R. & Anderson, E., 2000. Understanding the resistivities observed in geothermal systems. *World Geothermal Congress.*

Wheaton, R., 2016. *Fundamentals of Applied Reservoir Engineering.* s.l.:Gulf Professional Publishing.