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Application of Methylene Blue-dye Test and X-Ray Diffractometry to Guide Drilling Operation and Refine Subsurface Model in Hululais Geothermal System

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ABSTRACT

The Hululais Geothermal System contains two epidote zones that complicate reservoir identification: a shallow relict epidote zone and a deeper active reservoir zone. To support casing point decisions, the onsite Methylene Blue-dye Test (MeB) was applied as a rapid indicator of clay content, while X-ray Diffractometry (XRD) analysis was used to identify specific clay minerals and refine the hydrothermal alteration model. High MeB values are associated with smectite, smectite–chlorite, zeolite, and kaolinite, whereas chlorite, illite, and smectite–illite occur at lower values. Illite and smectite–illite are exclusively found at MeB values below 6%, making them reliable indicators of the active reservoir zone. A 12% MeB threshold effectively delineates the clay cap boundary. Spatial integration with the 3D MT-resistivity model shows strong agreement between the 12% MeB boundary and the 16 Ωm base of conductor surface, confirming a well-developed updoming clay cap over the production area. In contrast, the high-MeB smectite anomaly in the eastern peripheral area is interpreted as sedimentary basin-fill deposits rather than hydrothermal clay cap alteration.

1 INTRODUCTION

1.1 Field Overview

Situated in the Pacific Ring of Fire, geothermal resources in Indonesia are estimated to reach 23 GW. Sumatra Island conserves 40% of potential geothermal resources for utilization growth. One of them is known as the Hululais geothermal project, located in a segment of the Great Sumatra Fault, Bengkulu province, southern part of Sumatra, Indonesia. Twenty-four geothermal wells have been successfully drilled in the Hululais geothermal project, providing total 110 Mwe from producer wells and ensuring brine injection capacity (Figure 1).

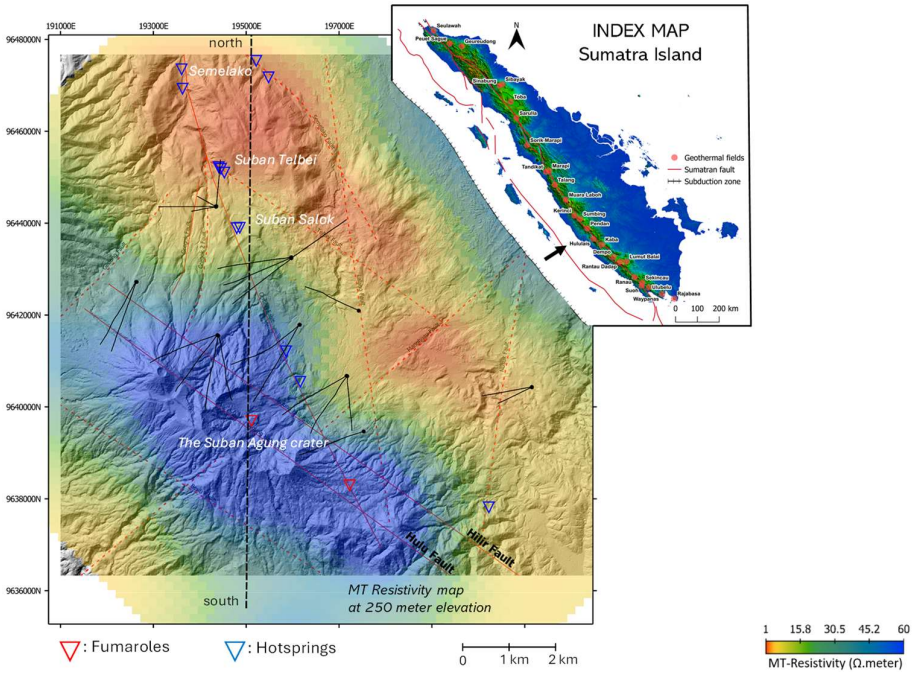


Figure 1. Location and lateral well trajectory map of the Hululais geothermal project, Indonesia

1.2 Dual Epidote Zones in The Hululais Geothermal System

In the Hululais Geothermal System, two epidote zones are encountered before reaching the reservoir system. Visual binocular observation of the cutting chips shows no distinguishable difference between relict epidote and active recent epidote in this field. However, relict epidote occurs discontinuously and is mainly located above the reservoir zone, whereas active recent epidote is present within the reservoir zone more extensively, and its abundance progressively increases with depth (Fig.2).

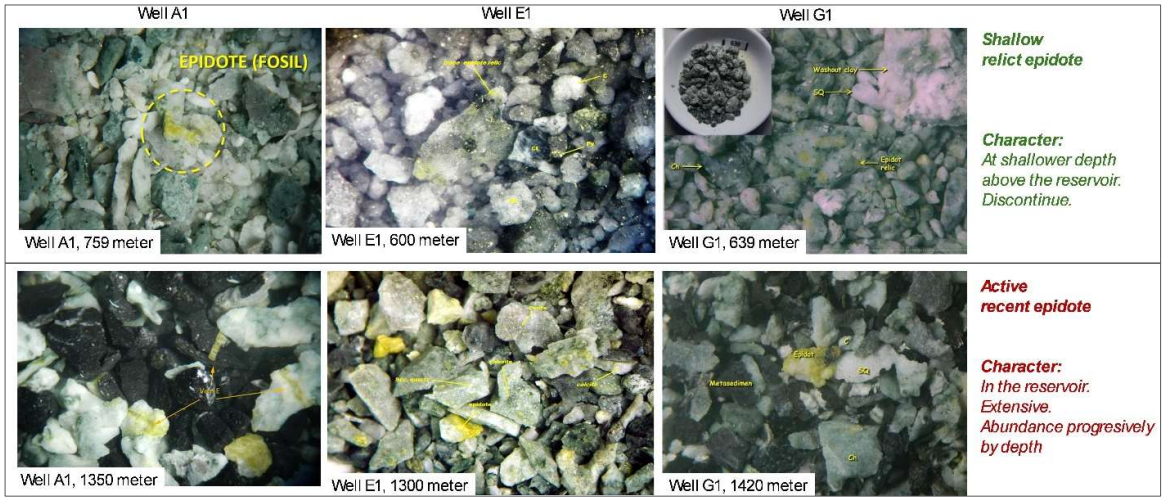


Figure 2. Binocular observation of the relict and active recent epidote from the cutting in production wells

Relict epidote is identified at relatively shallow elevations (800 to 400 masl) within the upflow zone and is spatially associated with mixed-layer clay and smectite. Corresponding MeB values fluctuate between 15–50%. In the other hand, recent epidote is detected at greater depths (+150 to –400 masl), defining ± 600 meter vertical offset between the shallow relict epidote and the deeper active epidote layer (Figure 3).

The recent epidote correlates with elevated borehole temperatures (≥200 °C) within the active reservoir system and exhibits stable low MeB values (≤12%), reflecting a hydrothermal assemblage dominated by chlorite, smectite-illite, and illite (Figure 4). The production casing points of the wells are strategically set near the recent epidote horizon, a practice that consistently enables successful entry into the reservoir zone and intersection with the productive faults in production wells at cluster A, C, E, and G. In contrast, the gaps between relict and active recent epidote exhibits variable behavior in the peripheral area. This epidote gap being significantly wider in cluster D, and absent in clusters P, H, and Q (Figure 3).

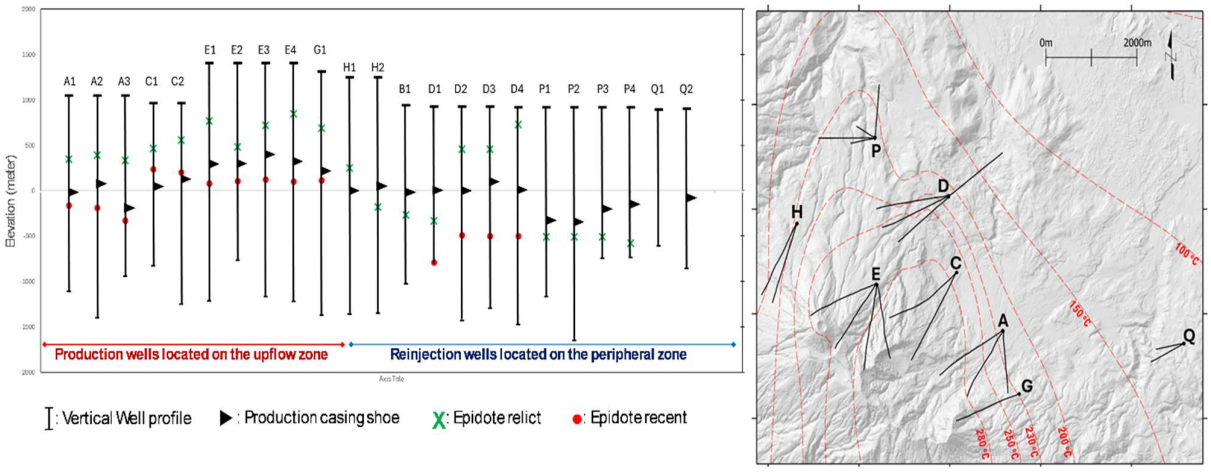


Figure 3. Vertical profile shows the gap between relict and active recent epidotes horizon in the reservoir of Hululais geothermal system

2 METHODOLOGY & DATASET

2.1 Application of Methylene Blue-Dye Test and X-Ray Diffractometry Analysis

During critical 13-3/8" casing point decision, onsite Methylene Blue-dye Test (MeB) was applied, as it resolves ambiguity in using epidote as a reservoir marker. Since MeB only measures bulk clay content, detailed X-Ray Diffractometry (XRD) analysis was performed on borehole samples from nine wells, to identify specific clay minerals, characterize, and build a hydrothermal alteration model.

2.2 Dataset

The dataset for this study comprises rock cutting samples collected from twenty-three boreholes within the Hululais geothermal field. The rock cuttings were obtained at 3-meter intervals throughout the borehole sections. Methylene Blue-dye Test (MeB) values were measured, plotted, and modelled from 2200 samples to quantify bulk clay content across the field. In addition, approximately 320 selected samples were examined in greater detail to determine their specific clay mineral assemblages using X-ray Diffractometry (XRD) machine.

3 RESULT

3.1 Correlation between Methylene Blue-Dye Test with Clay Mineral Species

The result shows distinct MeB ranges for different clay species: smectite (≤51%), zeolite and kaolinite (≤40%), and smectite-chlorite (≤35%). The lower MeB group belongs to chlorite (≤12%), furthermore, smectite-illite and illite are only identified at sample with MeB lower than 6% (Table 1).

Table 1. Clay mineral species determined by XRD and corresponding bulk MeB values

Identified clay species using X-ray Diffractometry	Methylene Blue-dye Test (%)
Smectite	
Zeolite	
Kaolinite	*Higher MeB* Group*
Smectite-Chlorite	
Chlorite	
Smectite-illite	*Lower MeB* Group*
Illite	

**MeB : Methylene Blue-dye Test (%)*

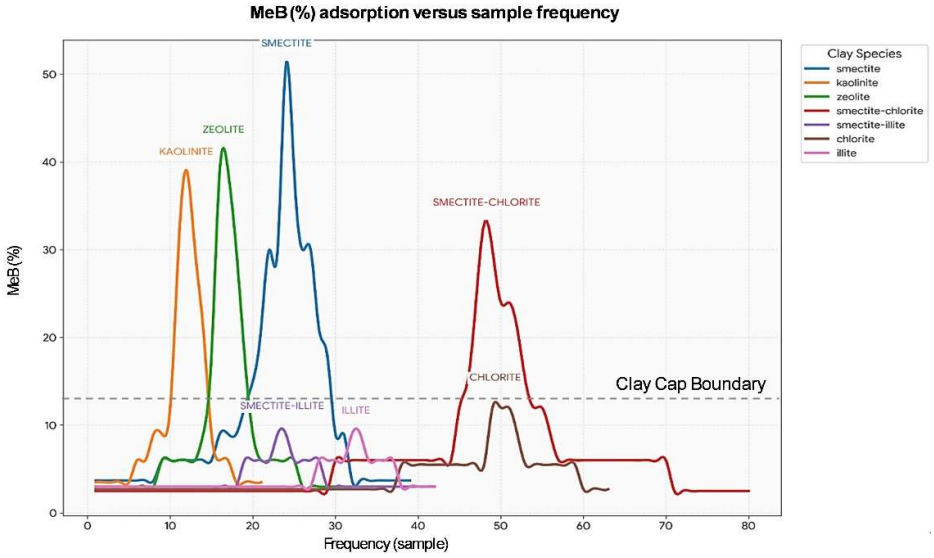


Figure 4. Frequency distribution of clay minerals show smectite–chlorite and chlorite are the most abundant clay assemblages and occur across a wide depth range, whereas kaolinite and zeolite show a more localized distribution.

3.2 Correlation between high smectite content and drilling hazard at peripheral zone

As noted by Grim (1953, cited in Gunderson et al., 2000), the MeB solution exhibits high selectivity for adsorption by smectite clay. This adsorption also occurs with the smectite component present in mixed-layer clay assemblages, including smectite-illite and smectite-chlorite. Consequently, elevated MeB values serve as an indication for higher smectite content within the analyzed cutting samples.

The depth versus MeB value correlation is presented in Figure 5, where two anomalous zones are identified: one in Well-D1 and another in Cluster-P. Additionally, a subsurface projection of MeB values along well trajectories reveal a distinctive distribution pattern within Cluster-Q (Figure 6).

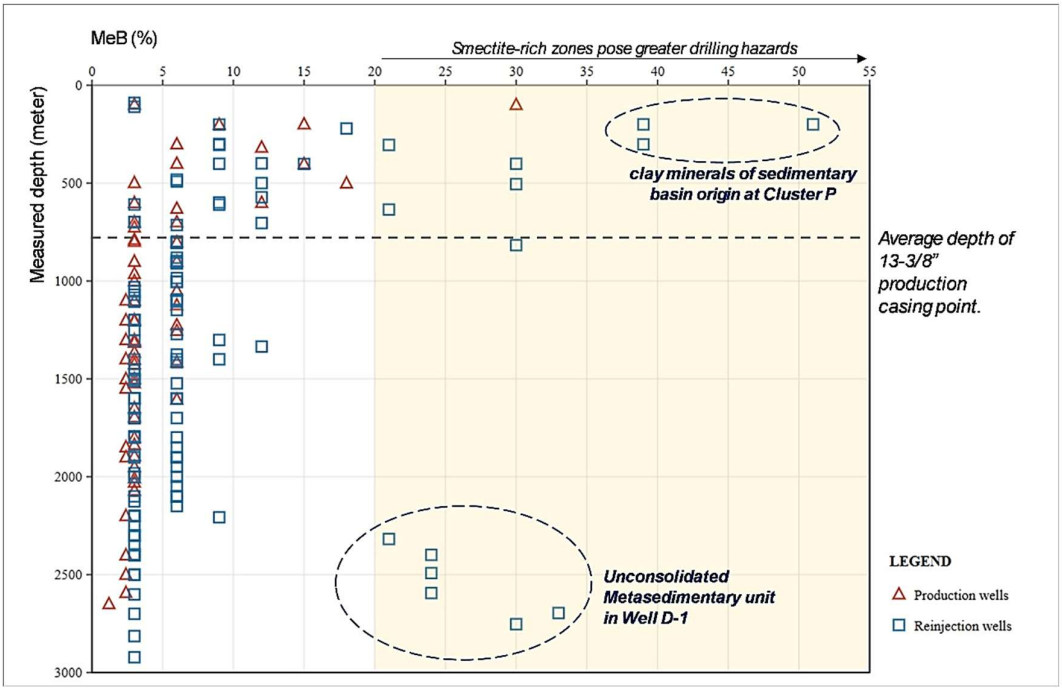


Figure 5. Higher MeB anomalies show a positive correlation with increased risk of drilling hazard in the peripheral zone of Hululais geothermal system

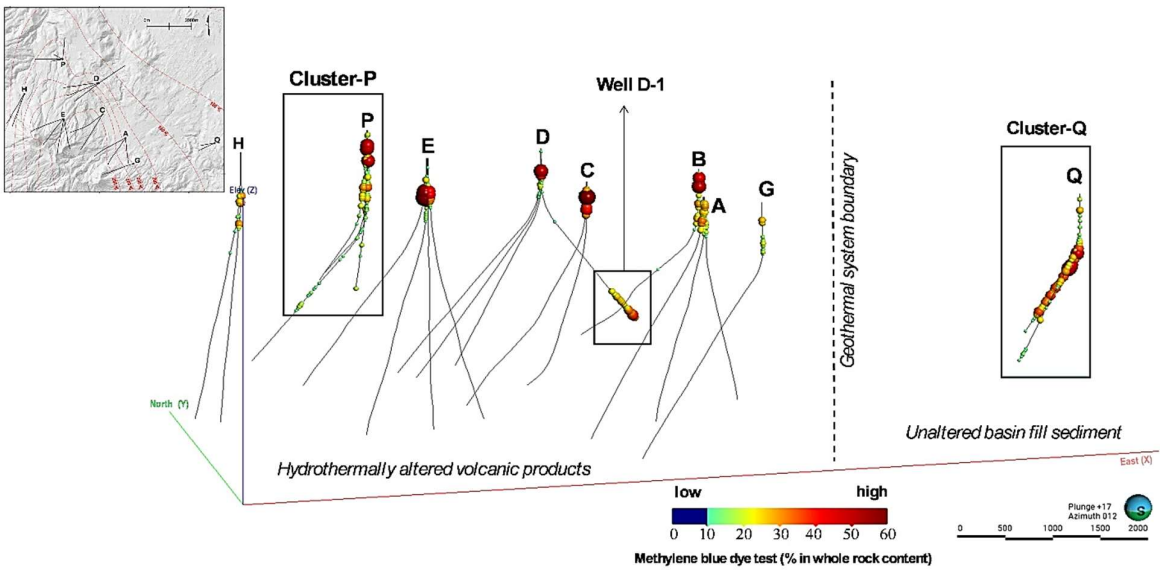


Figure 6. Subsurface projection of MeB values along well trajectories illustrate the anomalies in Cluster-P, Cluster-Q, and Well-D1 at peripheral zone of Hululais geothermal system

3.2.1 Outlier in Well D-1

Using borehole depth as the vertical axis and MeB values as the horizontal axis, the distribution pattern shows that high MeB samples which are typically indicative of low temperature smectite-rich, are rarely present in the deeper portions of most wells, except in Well-D1. Anomalous trend observed in Well-D1 exhibiting exceptionally high smectite content recovered from depths exceeding 2,000 meters (Figure 5 and 6).

3.2.2 Outlier in Cluster-P

A second outlier is identified in the injection wells of Cluster-P, located in the peripheral area of the Hululais geothermal system. Cutting samples recovered from near surface depths (200-350 m) show significantly high MeB values. It is attributed to clay minerals of sedimentary basin origin rather than hydrothermal alteration. Drilling operations in this zone were similarly affected by stuck pipe incidents (Figure 5 and 6).

3.2.3 Outlier in Cluster-Q

Although no XRD data is available for cuttings from Cluster-Q, continuous MeB measurements were obtained from both wells in the cluster throughout their entire drilled intervals. MeB values in this cluster are highly variable yet persistently elevated. Cluster-Q is similarly characterized by significant drilling hazards, including stuck pipe occurrences and bit-balling, with very low formation permeability during the drilling (Figure 6).

4 DISCUSSIONS

4.1 Comparison of Methylene Blue Dye Test and X-Ray Diffractometry

The characterization of clay minerals in geothermal drill cuttings can be approached through two principal analytical methods: the Methylene Blue dye test (MeB) and X-Ray Diffractometry (XRD). While both techniques target smectite-rich mineral assemblages, they differ substantially in terms of analytical resolution, operational practicality, and cost-effectiveness.

The MeB test offers a rapid, field-deployable approach suitable for high-frequency sampling during active drilling operations, whereas XRD provides a more comprehensive mineralogical characterization through laboratory-based analysis. A comparative assessment of these two methods is presented in Table 2, highlighting their respective capabilities, limitations, and recommended applications within the context of geothermal clay cap investigation.

Table 2. Comparative assessment of Methylene Blue Dye Test and X-Ray Diffractometry for clay mineral characterization in geothermal drill cuttings

Criteria	Methylene Blue Dye Test (MeB)	X-Ray Diffractometry (XRD)
Application Practice	Rapid, cost-effective, and suitable for onsite execution. Project cost is approximately 50 USD per well, accommodating 30–50 samples, averaging ~1 USD per sample. Field-deployable without laboratory infrastructure	Requires extended sample preparation involving four treatment stages (bulk, air-dried, glycolated, and heated), with analysis conducted in a laboratory setting. Total processing can exceed 24 hours. *Estimated cost: 25–40 USD/sample**
Analytical Capability	Quantifies bulk smectite content. Does not differentiate mixed-layer clay species (e.g., smectite-illite, smectite-chlorite) or non-smectite clay minerals.	Identifies individual clay species and provides detail proportional quantification of mixed-layer clay mineral assemblages.
Recommended Necessity	Recommended for high-frequency sampling at closely spaced intervals, particularly within shallow sections approaching the reservoir zone, given its operational versatility and ease of application.	Applied selectively based on interpretive requirements and available resources; particularly warranted where detailed mineralogical characterization is required.
Primary Purpose	Conducted by the wellsite geologist to inform real-time drilling decisions, guide production casing placement, and mitigate drilling hazards.	Serves as a best-practice analytical tool for detailed geological modelling, calibration of MeB data, and refinement of MT resistivity interpretations for conceptual model development and future well siting.

**Based on average price listing from Indonesian Universities and Government Research Centers*

4.2 Character of Clay Species in Hululais Geothermal System

4.2.1 Smectite-illite, illite, smectite-chlorite, and chlorite

Smectite–illite and illite occur at low MeB values. Toward the high frequency, smectite–chlorite represents a broad and consistently abundant population that overlaps with chlorite (Figure 4). The broad distribution of smectite-chlorite and chlorite suggesting they are not a good indicative marker in this field. On the other hand, illite and smectite-illite show good agreement with the occurrence of recent epidote and are considered suitable indicative minerals for the reservoir zone in the Hululais geothermal field.

4.2.2 Kaolinite and zeolite

Kaolinite and zeolite show narrow distribution frequency, indicating relatively localized occurrence (Figure 4). In this case, kaolinite is found in wells from Cluster A and G. The presence of kaolinite in these clusters suggests water–rock interaction under lower pH environment associated with magmatic fluid input beneath the Suban Agung crater (Figure 7).

4.2.3 Smectite

Smectite forms the most prominent peak in this field, with MeB values reaching up to 51% (Figure 4). Notably, these elevated MeB values are confined to samples from the peripheral zone of the system, recovered at relatively shallow depths (200–350 m) within Cluster-P (Figure 5 and 6). Further investigation reveals, the smectite in shallow part of Cluster-P originated from unconsolidated clay-sized sedimentary material with low influence of hydrothermal alteration.

An interpretation further supported by the repeated stuck pipe incidents encountered during drilling in this shallow zone, likely attributable to poor formation stability. Accordingly, the anomalously high MeB values in Cluster-P are interpreted as reflecting smectite of sedimentary origin, deposited through basin-filling processes governed by gravity and sedimentary transport mechanisms rather than hydrothermal alteration.

The deep high MeB anomaly evaluated in Well-D1 coincides with severe drilling problems, including stuck pipe events and formation collapses. These problems are consistent with the presence of highly unconsolidated and mechanically weak formations. Lithological examination indicates that this zone corresponds to metasedimentary rock units, another smectite-rich zone that is mainly controlled by the lithological factor.

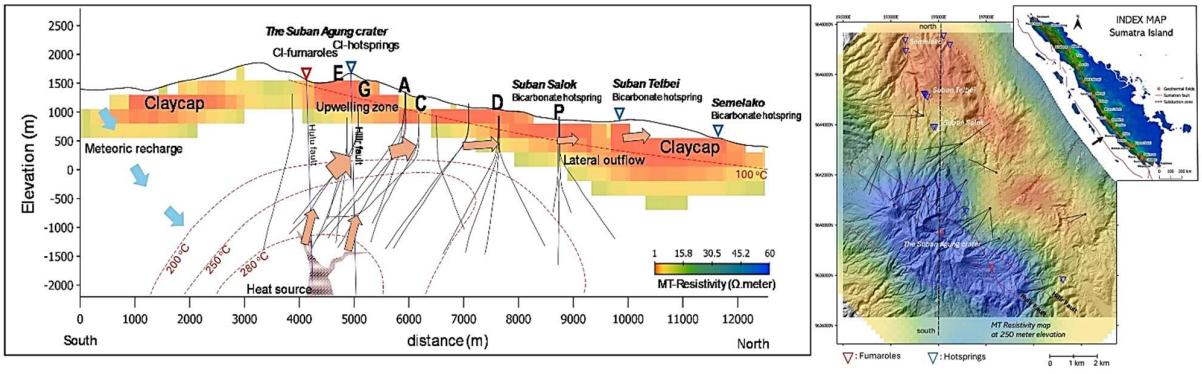


Figure 7. Conceptual model of Hululais geothermal system with the 16 Ωm base-of-conductor surface

4.3 Clay cap

The clay cap boundary identified from borehole data is approximated at values slightly below the 12% MeB threshold, effectively separates the smectite-rich clay cap from underlying mixed-layer, illite, and chlorite zones (Figure 4). In the production well zone (cluster A, C, E, and G) the MeB peaks up to 25% and gradually decreases to below 12% as the wells penetrate the reservoir zone and hit the permeable layer (Figure 6). This pattern indicates the presence of a well-developed clay cap in the production zone.

Nainggolan et al. (2025) identified the clay cap in the Hululais geothermal field using a 3D MT-resistivity model, defining the base of the conductive layer at approximately 16 Ωm. This conductive layer is interpreted to correspond to the smectite-rich clay cap. Spatial interpolation of the 12% MeB contour, overlaid on the MT-resistivity model and the 16 Ωm base of conductor surface, shows strong agreement between the MeB distribution and the geometry of the updoming clay cap (Figure 7).

5 CONCLUSIONS

The combined application of MeB and XRD on borehole samples from the Hululais Geothermal System successfully guided drilling operations and refined the subsurface hydrothermal alteration model. MeB values provide a reliable real-time proxy for bulk clay content, resolving the ambiguity of dual epidote zones encountered in this field. The 12% MeB threshold effectively delineates the clay cap boundary, with illite and smectite-illite confirmed as the most reliable mineralogical indicators of the active reservoir zone.

Anomalously high MeB values in Cluster-P, and Well-D1 are attributed to smectite of sedimentary and metasedimentary origin rather than hydrothermal alteration, explaining the drilling hazards encountered in these areas and redefining their role within the conceptual subsurface model.

Spatial integration of MeB data with MT-resistivity results confirms a well-developed updoming clay cap in the production zone. The 12% MeB boundary shows strong spatial correspondence with the base of conductor (BOC) identified from MT-resistivity, particularly the 16 Ωm resistivity surfaces, supporting their interpretation as the lower boundary of the smectite-rich clay cap. In contrast, the eastern peripheral smectite anomaly in Cluster-Q is interpreted as basin-fill deposits unrelated to the active hydrothermal system.

The combined MeB–XRD workflow is recommended as a practical and cost-effective approach for clay cap characterization, reservoir boundary identification, and real-time casing point decisions in geothermal drilling operations.

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