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3D Play Fairway Analysis for Delineating Exploration Targets in the Tulehu Geothermal Field, Indonesia

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Play Fairway Analysis of Tulehu Geothermal Favourability Index for Mitigation of Exploration Risks in the Banda Fault Zone

ABSTRACT

The Tulehu geothermal field in Maluku, Indonesia, is a strategic asset whose development faces challenges related to exploration risks. Previous drilling of four exploration wells has not consistently yielded adequate permeability and/or temperature results for commercial-scale development. This failure highlights the need for a more systematic approach to reduce drilling risk. This study aims to determine the optimal subsurface target using the Play Fairway Analysis (PFA) method within a 3D framework. This method quantitatively evaluates and integrates key geothermal system parameters, namely heat, permeability, cap rock, and drilling economic viability, based on existing geological, geophysical, and well data. Each parameter is transformed into a spatial index model and combined through a weighting scheme to produce a Favourability Index Model. The modeling results indicate that the area with the highest favorability (index > 0.91) is located south to southeast of the Banda Fault, at elevations between -784 m and -2,068 m. These prospective locations align with evidence from the productive feed zone in well TLU-B-02, indicating that previous interpretations of fault geometry need to be revised. These modeling results provide a strong scientific basis for identifying and prioritizing subsurface drilling targets, thereby reducing exploration risk in subsequent development phases.

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INTRODUCTION

The Tulehu Geothermal Field, located on Ambon Island, Maluku, is one of the Geothermal Working Areas (*GWAs*) developed by PT PLN (*Persero*) with an estimated potential of 60 MWe and an initial development plan of 2 × 10 MW (Daud et al., 2022; Wibowo et al., 2020). However, like many geothermal fields in complex volcanic–tectonic environments, exploration in Tulehu faces a high level of uncertainty (Purba et al., 2018; Hadi et al., 2015). The drilling history at this field reflects these challenges. Four main exploration wells—TLU-D-01, TLU-B-01, TLU-C-01, and TLU-B-02—have been drilled targeting the Banda Fault and the Banda Hatuasa Fault (Daud et al., 2022). Although some wells have shown evidence of one element of a geothermal system (e.g., high temperatures >200°C in TLU-B-01 or indications of permeability in TLU-C-01), none have consistently found the ideal combination of heat and permeability for commercial production, except for the TLU-B-02 well, which has shown the most promising results (D. Adityatama et al., 2021; D. W. Adityatama et al., 2020; Do et al., 2019; Soerjadji, 2018; Sumardi et al., 2022).

Post-drilling analysis of the TLU-B-02 well provides important insights: a productive feed zone has been identified on the southeastern side of the Banda Fault (Daud et al., 2017,

2022; Qahhar et al., 2015; Sulistyo et al., 2020; Tveit & Mannseth, 2018). This finding fundamentally challenges previous conceptual models that assumed a northwest-trending fault dip (Gunnarsson & Aradóttir, 2015; Deon et al., 2015). This disparity underscores that the main risk in Tulehu exploration lies in the incomplete understanding of structural control over permeability (Faulds et al., 2019; Brehme et al., 2016). Given the extremely high drilling costs for geothermal wells, failure to target the right location could result in significant financial losses and delays in project development (Purba et al., 2018; Hadi et al., 2015).

In a study conducted by Suwarto et al. (2017), significant focus was placed on the complexities of geothermal exploration in volcanic–tectonic environments, with particular emphasis on fault-controlled permeability and the challenges of pinpointing productive zones. The study explored geothermal fields in various regions and highlighted the unpredictability of geological conditions, especially in complex fault systems like the Tulehu Geothermal Field. However, this research mainly focused on regional fault mapping and did not delve deep into specific case studies or well performance in areas like Tulehu, where the fault dynamics are not yet fully understood. Additionally, the study did not address the financial implications of such uncertainties, particularly in geothermal drilling, which is a high-cost endeavor.

A second study by Fathoni et al. (2019) focused on the exploration history and drilling data of geothermal wells in the Ambon region, emphasizing the challenges of drilling in high-risk areas. The findings indicated that while certain wells showed promise in terms of temperature and permeability, no study comprehensively analyzed the impact of drilling uncertainties on financial and operational aspects, such as well success rates and the costs associated with failed exploration efforts. Furthermore, this study did not integrate structural understanding, such as fault dynamics, into the decision-making process for well placement, which is crucial for optimizing geothermal resource development.

The objective of this study is to analyze the structural control of permeability in the Tulehu Geothermal Field and assess how drilling decisions based on fault structures impact the success and cost-efficiency of geothermal exploration. The study aims to refine conceptual models of geothermal resource mapping, offering more accurate guidance for future drilling activities. The findings of this research are expected to provide valuable insights into improving geothermal exploration strategies, particularly in high-risk regions, and can help reduce exploration costs and project delays, ultimately contributing to the sustainable development of geothermal energy in Indonesia.

METHOD

This method quantitatively evaluates and integrates key geothermal system parameters, namely heat, permeability, *cap rock*, and drilling economic viability, based on existing geological, geophysical, and well data. The research chronology includes an explanation of the research design and procedures (in the form of algorithms, pseudocode, or other approaches), as well as methods for testing and data acquisition. To ensure scientific validity, the description of the course of research is supported by references so that the explanations can be accepted scientifically. The effects of electrical discharges on the acidity of *HVNE* and *NELV* are illustrated in Figure 2(a), and the effects of breakdown voltage of *NE* and *NELV* are illustrated in Figure 2(b).

RESULTS AND DISCUSSION

Individual Parameter Modeling

3D modeling of each key parameter produces evidence-based models that serve as the foundation for integration.

- **Heat Model:** The subsurface temperature distribution model (Figure 1) shows clear thermal anomalies, where high-temperature isotherms (>200°C) form a dome-like structure (*updoming*) strongly associated with the surface trace of the Banda Fault. This confirms the fault's role as the primary conduit for convective heat transport from the deep heat source.

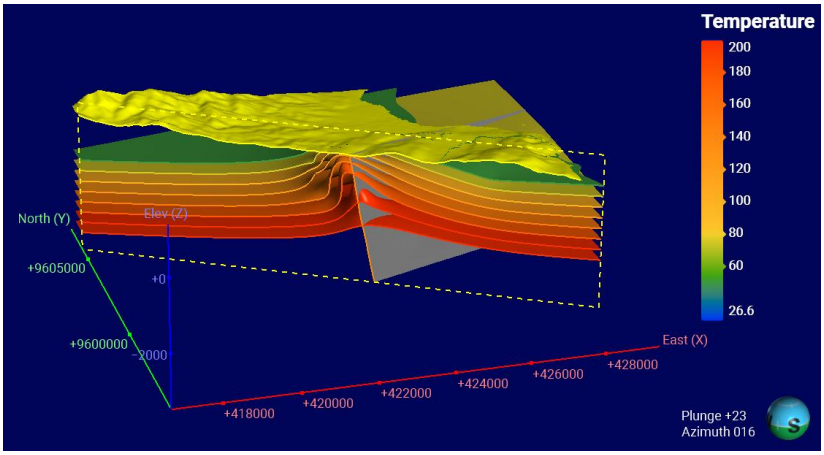

Figure 1. 3D subsurface temperature distribution model. Red indicates temperatures >200°C, forming an *updoming* pattern along the Banda Fault.

- **Permeability Model:** The distance-to-fault model (Figure 2) effectively maps the proximal zone (<100 m) around the revised fault plane (dipping to the southeast). This zone is considered the location with the highest probability of finding sufficient fracture permeability for fluid production.

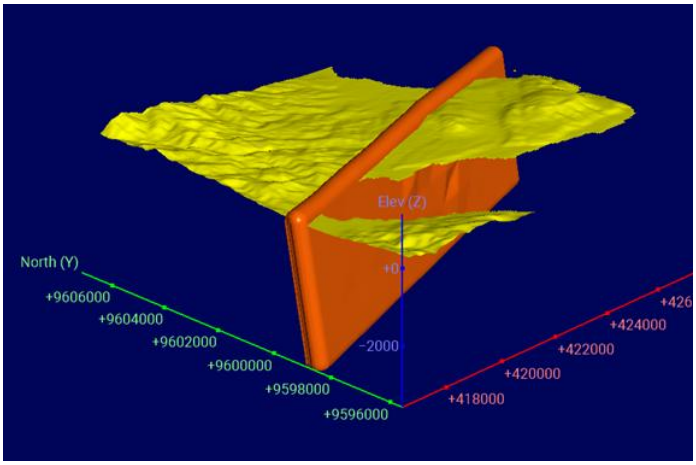

Figure 2. 3D proximity model to the Banda Fault plane.

- **Cap Rock Model:** The MT resistivity model and alteration model (Figure 3) consistently identify a broad conductive layer (argillic alteration zone) at shallow to

intermediate depths. This layer is interpreted as an effective *cap rock*, overlying the more resistive core below, which is the reservoir target.

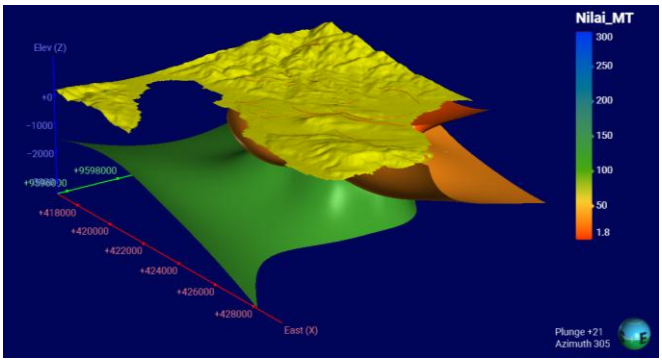

Figure 3. 3D resistivity model slice from MT data. The orange layer (resistivity <10 Ωm) is interpreted as cap rock.

- **Drilling Economics:** The drilling economic model in this study is assessed based on drilling depth (Figure 4). Shallow drilling depths are more economical.

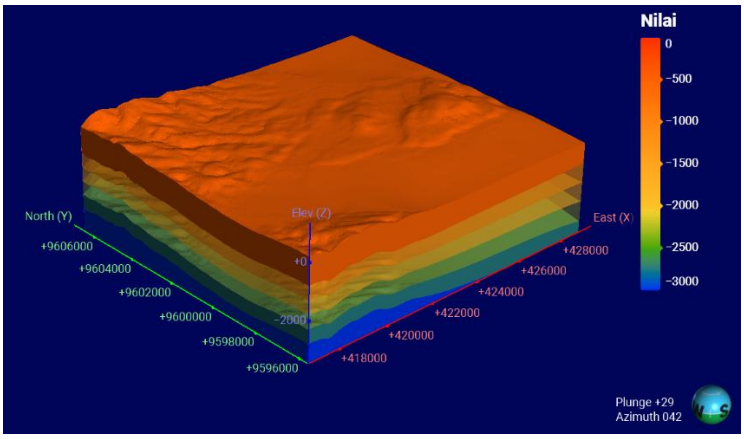

Figure 4. Drilling depth model

Integrated *Favourability Index Model*

Integration of the four weighted index models produces *the* 3D *Favourability Index Model*. This model represents the spatial probability of exploration success, where higher values indicate optimal coincidence of all geothermal system elements.

Visually, zones with the highest favorability (index values > 0.8, orange to red colors) are clearly concentrated along the southern-southeastern side of the Banda Fault. This distribution differs significantly from the targets aimed at by the initial wells drilled on the northwest side of the fault, indicating a paradigm shift in the understanding of the field's prospectivity.

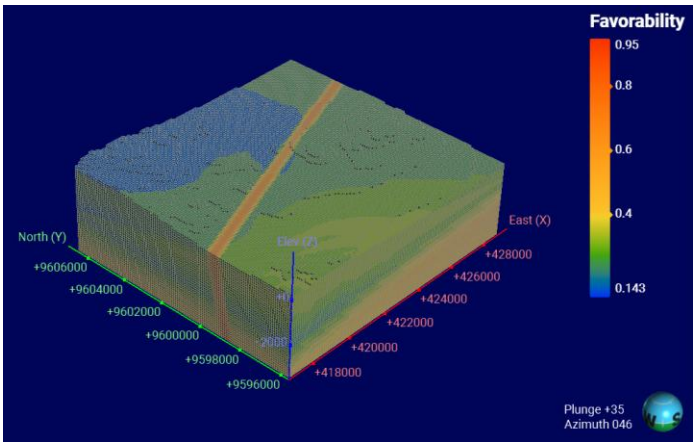

Figure 5. 3D Favorability Index Model

Implications of Modeling Results

The main result of this study is the identification of a geothermal *sweet spot* in Tulehu located on the southeastern side of the Banda Fault. This finding has significant implications. First, it confirms the hypothesis that the initial conceptual model, which assumed a northwest dip of the fault, needs to be revised. Data from well TLU-B-02 and the PFA modeling results consistently support a model where the Banda Fault is a normal fault dipping to the southeast, with its main permeable zone located in the lower block (*footwall)* or within the fault zone itself on that side.

Second, the concentration of high favorability zones in this location indicates that the failure of previous wells was most likely not due to the absence of an active geothermal system, but rather to inaccurate location targeting. These wells were most likely drilled outside the optimal permeability zone.

Drilling Target Delineation

To translate the favorability model into concrete drilling targets, a cut-off value of 0.91 was applied. This value was chosen because it is an index value calibrated with the proven productive *feed zone* location in well TLU-B-02. The results of this screening (Figure 9) delineate a spatially limited rock volume, which becomes the primary drilling target. This target is located within the elevation range of -784 m to -2,068 m and represents a volume where:

1. Temperatures are estimated to be sufficiently high for electricity generation (>200°C).
2. The distance to the Banda Fault fracture zone is very close, maximizing permeability potential.
3. It is directly below an effective *cap rock* layer.
4. It is at a depth that is still economically viable for drilling.

CONCLUSION

This study has successfully applied the 3D *Play Fairway Analysis* (*PFA*) method to quantitatively map geothermal potential in the Tulehu Field. The main conclusion that can be drawn is that the *PFA* method is capable of integrating diverse geoscience data sets, such as geology, geophysics, and well data, into a single coherent probability model to reduce

exploration risk. The modeling results clearly indicate that the most favorable subsurface area (*sweet spot*) in the Tulehu Field is located on the south–southeast side of the Banda Fault, challenging previous conceptual models. The most prospective drilling targets, with a *favourability index* value exceeding 0.91, are located at depths between –784 m and –2,068 m. The resulting *Favourability Index Model* provides a strong and objective scientific basis for guiding further exploration strategies, thereby increasing the probability of technical success and reducing financial risk in future drilling activities.

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