Well-Scale Permeability Classification on the Indonesia Conventional Geothermal Reservoir

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ABSTRACT

Effective permeability characterisation in geothermal wells is paramount for optimising geothermal energy production. This study investigates the interpretation of permeability control using image log data and injection spinner logs to classify and capture the various permeable zones within geothermal reservoirs from a well-scale perspective. The classification delineates five primary types of permeable zones: high-intensity fracture zones, large aperture fracture sets, permeable fault cores, pores or microfracture-supported formations, and permeable unconformities or lithological contacts.

High-intensity fracture zones, typically occurring in brittle formations such as lava or welded tuff, are identified by closely spaced fractures with small apertures. These zones are well captured by image logs and exhibit a gradual response in spinner logs if they are permeable. Large aperture fracture sets, characterised by noticeable and continuous conductive fractures, show abrupt responses in spinner logs, indicating high permeability. However, the conductivity of these fractures can be biased by the presence of conductive minerals, impacting the actual permeability estimation. Permeable fault cores are marked by significant displacements or washouts in the borehole wall, often recorded as drilling breaks. These zones can pose challenges in logging due to caliper disorientation and image loss, making it difficult to determine the actual fault orientation. Porous formations and lithological contacts, which include interconnected pores and microfractures, enhance permeability and are well captured by image logs and under microscopic analysis. Lithological contact or unconformities, particularly angular unconformities or disconformities, can create permeable zones, but may sometimes be misinterpreted as faults.

Integrating multiple log analyses, including image, sonic, and density logs, is crucial for accurately identifying productive fractures and permeable zones. This approach addresses key challenges such as fracture continuity beyond the borehole, actual fracture permeability, and the geometry of fault planes in space. Additionally, understanding fracture kinematics through geomechanical analysis provides valuable insights into fracture characterisation. Non-fracture permeability, facilitated by porous formations and lithological contacts, also plays a significant role in well productivity. By comprehensively analysing these various permeable zones, this study enhances the understanding of reservoir hydrology and supports the effective planning and optimisation of geothermal wells, ultimately contributing to the successful exploitation of geothermal energy resources

1. INTRODUCTION

In the hydrothermal system, the common geothermal system in Indonesia, the circulation of high-temperature fluid within the reservoir is the most crucial component. In general, it will need sufficient heat or temperature, good caprock, and high-magnitude permeability. Permeability often becomes a factor that largely determines the success of a geothermal well, both for production and injection wells. That's because in a hydrothermal system also known as a conventional geothermal system, heat transfer occurs by convection through subsurface fluid circulation, rather than conduction heat transfer that occurs through rock bodies. Often the drilling activity of a hydrothermal system fails or does not get the expected electrical output because the permeability penetrated by the well has a small magnitude. Although it has a very high temperature, wells with a lower permeability magnitude do not have enough mass to flow, resulting in a small well output.

Some literature has discussed the types of permeability commonly encountered in geothermal reservoirs globally. Most of this literacy focuses on the study of matrix porosity and fracture. Wallis et al. (2015) discuss the role of matrix porosity and fracture zones in geothermal reservoirs, while Cant et al. (2018) focus on the study of the role of pores and microfractures in geothermal reservoir rock bodies. However, the geological setting dictates a unique geothermal system, which makes it relatively different from each other. Thus, this paper will focus on the frequent permeability control type description that usually occurs in Indonesia. The geological setting in Indonesia is relatively complex, both in tectonics and volcanic settings that influence the geothermal setting. Dynamic geology and frequent volcanic activity modify the old ones and increase the geological complexity. This setting is potentially penetrated by geothermal drilling activities with sufficient penetration 2-3 km deep, including the diversity of the types of permeability that control the flow of fluid in the well. Examples of cases discussed in this paper are taken from several cases encountered in geothermal field drilling campaigns in Indonesia, especially those done by Pertamina Geothermal Energy. This paper highlights how the permeability looks like in the well-scale from the image log data, as it is the most common and reliable data acquired in geothermal wells which provides excellent information about the formation in the borehole. Identification of permeability on a well scale is carried out by correlating drilling data such as geophysics logs, image logs and injection spinners. The image log data used is an electrical / resistivity image log so that it can provide an overview of complete geological conditions on the surface of the borehole wall, including lithology and structures such as faults and fractures. The spinner data will provide information regarding depth intervals that contribute to fluid flow or permeable zone intervals. The correlation of these data will give information on what geological features contribute to the permeable zone in the well-scale and their classification. This paper classifies permeability control into five types including the high-intensity fractures zone, large aperture fracture set, permeable fault core, pores and microfractures-supported formation and lithological contact. All of these types accommodate the

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primary and secondary permeability control in formation. To illustrate these permeability types in a fault structure and continuum, we adapt the illustration of fault anatomy of a normal fault in Figure 1 by Torabi et al. (2019).

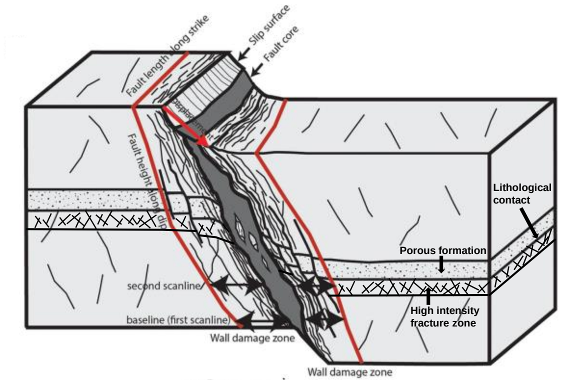

Figure 1: Fault anatomy concepts and fracture lateral distribution represent the schematic illustration of a normal fault including its fault core, damage zone, high-intensity fracture zone, porous formation and lithological contact (modified from Torabi et al. 2019).

2. DATA AND METHOD

Data used here is the image log and spinner log, with supported by geophysical logs, conducted from wells across geothermal fields in Indonesia. A spinner is a device for measuring in situ the velocity of fluid flow in a production or injection well based on the speed of rotation. The spinner can be helical, that is, longer than it is wide, or like a vane, which is similar to a fan blade. In both cases, the speed of rotation is measured and related to the effective velocity of the fluid. Generally, how the spinner works is similar to the tool that is used in the Gross Permeability Test (GPT) activity where the injection rate of water will be added if there is empty space for fluid to fill in the formation along the borehole.

A borehole image is an electronic picture of the rocks and fluids encountered by a wellbore. Such images are made by electrical, acoustic, or video devices which have been lowered into the well. Images are oriented, they have high vertical and lateral resolution and they provide critical information about fractures, faults, lithology, lithological contact and other geological features. Colour normalization is common in image log processing, including static and dynamic images. A static image is done by applying the normalization for the whole image interval logged, while the dynamic image is the result of certain interval normalization, usually for each 5 to 10 meters. Case studies have shown that borehole images are best used in conjunction with other available wellbore data, such as other logs, cuttings, cores and production or spinner data. In this study, we utilise high-resolution micro-resistivity borehole imagery to understand not only the distribution of structures in the subsurface but also to determine formation texture so lithology interpretation is doable.

The permeability control was identified by correlating the spinner or production interval with the geological features in the borehole wall, acquired from the image log and geophysics logs. The secondary permeability, including fractures and faults, is still the main suspect of permeability control in conventional geothermal systems. Nevertheless, if the occurrence of these features is absent or minor along with the production interval, then the possibility of primary permeability, matrix porosity or other features that control the fluid flow is rising.

3. SECONDARY PERMEABILITY

3.1 High-Intensity Fracture Zone

High-intensity fracture zones are defined by closely spaced fractures, up to 5 fractures per 1 meter, which often feature small apertures smaller than 1 cm but can create a highly permeable network that facilitates the movement of geothermal fluids (Figure 2). This permeability is significantly dependent on the fracture aperture, connectivity, and the infill material within the fractures.

One notable feature of these high-intensity zones is their occurrence in brittle formations such as lava flows, welded tuff, and volcanic breccia. These lithologies are more susceptible to fracturing due to their inherent brittleness, especially under the influence of local stress fields. We can use the gamma-ray log to help distinguish between different rock types, indicating zones of tuff, lava, and other volcanic deposits. These different lithologies contribute to the mechanical properties of the rock, with more brittle zones being more intensely fractured which is commonly distributed laterally. Therefore this type of permeability could be distributed laterally following the distribution of the rocks with the same mechanical properties.

The permeability of this zone is characterized by the gradual or smooth changes in the injection spinner response. The gradual change in the spinner log suggests a constant value of the permeability through depth if there is no significant fracture intensity increasing along the depth. This spinner response is similar to the spinner response in a zone that is controlled by porous formation.

However, there are several challenges associated with interpreting high-intensity fracture zones. The close spacing of fractures requires detailed and high-resolution imaging to accurately capture their distribution and orientation. The subjective nature of fracture-picking, where different interpreters may identify different sets of fractures, can lead to variations in the characterization of the reservoir. This variation can have significant implications for reservoir management, as over- or underestimating fracture density and permeability can impact the predicted productivity of the reservoir.

There is also a bias that the image log makes regarding the aperture of the fracture where it strongly depends on the correct fracture computation. The small fracture apertures captured in the image log, often less than 1 cm, add another layer of complexity. These small apertures may be difficult to detect and measure accurately, yet they play a crucial role in controlling fluid flow within the reservoir. High-resolution imaging and careful interpretation are essential to accurately characterize these features, but even with advanced techniques, there remains a degree of uncertainty.

The high-intensity fracture zones can be transformed into advanced fracture modelling such as the discrete fracture network model (DFN). The DFN modelling approach allows geoscientists to simulate the spatial distribution of fractures

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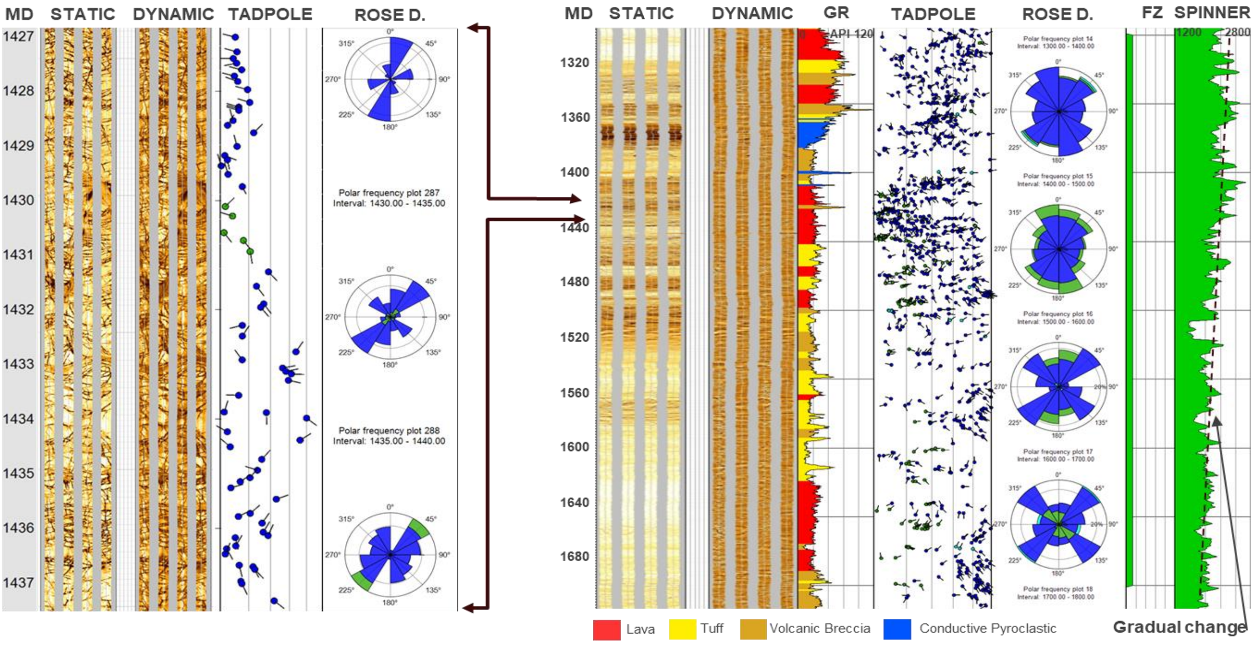

Figure 2: The image log appearance of the high-intensity fracture zone. This zone is strongly controlled by the lithology and its mechanical properties. Due to the bias and complexity in fractures picking, commonly the fracture orientation will have some variation.

within the reservoir. High-intensity fracture zones, characterized by closely spaced, intersecting fractures, are particularly suited to this method. The DFN model uses data from various sources, including image logs, which provide detailed information on fracture orientation, density, and aperture. However, before incorporating fracture data into the model, it's critical to apply a mechanical filter to select only the critically stressed fractures (Ikhwan et al., 2022). These fractures are the most likely to remain open under current stress conditions and therefore contribute most significantly to permeability. Moreover, the more intense the fracture intersections within a zone, the higher the resulting permeability. This is because intersecting fractures create a network of pathways that enhance fluid flow

One of the key challenges in fracture modelling is the high uncertainty between well areas. This uncertainty arises because data from wells provide only a limited view of the subsurface, and extrapolating between wells can lead to errors. The heterogeneity of fracture networks further complicates this extrapolation, as fractures can vary significantly over short distances. To address this uncertainty, it is essential to use multiple data sources and advanced modelling techniques like DFN (Ikhwan et al., 2022).

3.2 Large Aperture Fracture Set

In the case of this study, the large-aperture fracture set is a set of single fractures with apertures up to 20 cm that are separated consistently about 7 meters vertically in well and have the same fracture orientation (Figure 3). These separations could dictated by the geometry of the fault continuum. These fractures are well captured by image logs, which provide detailed visualizations of the fracture's size, orientation, and spatial distribution. The image logs reveal continuous conductive fractures that are likely to have significant permeability, allowing for efficient fluid transport within the reservoir. The large aperture fracture set significantly influences the overall permeability of the geothermal reservoir. Due to their size, these fractures can dominate the flow pathways, making them key targets for well placement and production strategies. The continuous nature of these fractures suggests that they can provide sustained flow rates, which is critical for the efficient extraction of geothermal energy.

This zone is usually high-permeable as the injection spinner responds abruptly on each fracture indicating a high injective index value. However, the permeability of these fractures can be influenced by the presence of conductive minerals such as clay or iron minerals like pyrite and magnetite. The image points out that these minerals, if present, can fill the fracture and reduce its permeability, leading to a potential overestimation of the fracture's actual contribution to fluid flow. This highlights the importance of integrating mineralogical data with fracture analysis to accurately assess the permeability.

Like the high-intensity fracture zone, the large aperture fracture set is associated with the damage zone in the fault structure. A damage zone is a volume of deformed wall rocks around a fault surface that results from the initiation, propagation, interaction and build-up of slip-along faults (Kim et al., 2004).). Fault growth commonly produces a fault core composed of slip surfaces and comminuted rock material, and also a broader volume of distributed deformation called the damage zone. In the geometry of a major fault axis, the damage zone is usually formed in the vicinity of the axis and its orientation could be relatively parallel or perpendicular to the master fault.

Due to the fracture orientation measurement being possible by using image log data, the interpreted fracture geometry in 3D space thus can be done, assuming there are no significant strike orientation and dip angle changes. This method is useful to predict the continuity of permeable pathways especially in the short distance from the source of data.

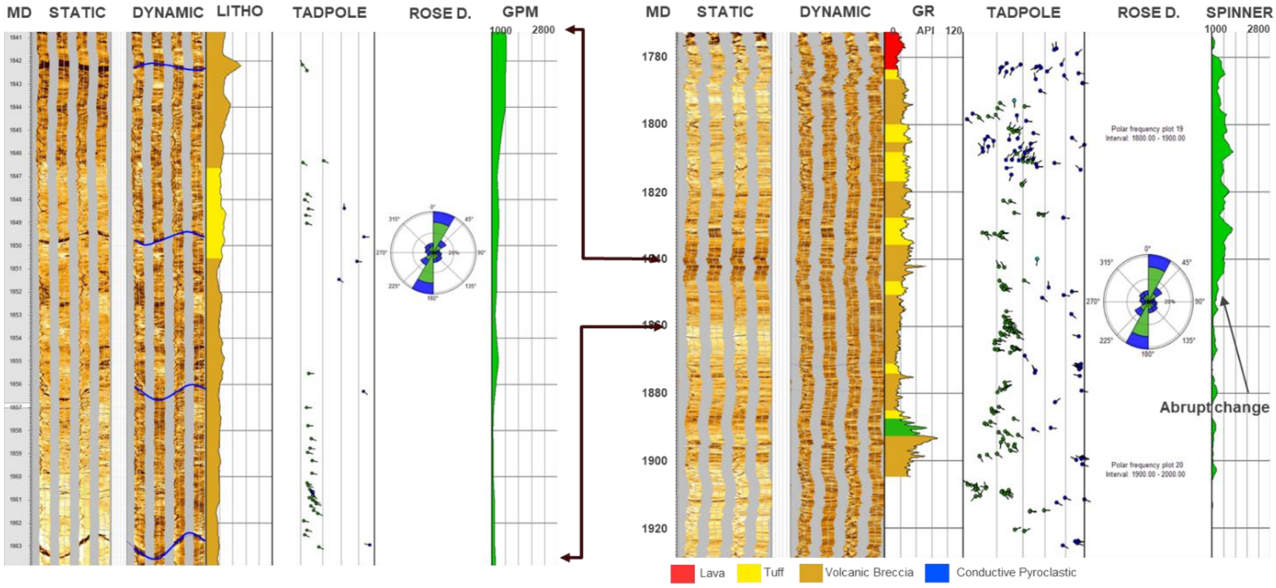

Figure 3: The image log appearance of the large-aperture fracture set. The 7 meter separation of each conductive large-aperture fractures is noticeable. Due to the greater overburden in depth, which gives more pressure and stress, leading to a more organized and well-oriented fractures orientation.

As the image log only provides confident borehole wall data, the continuity of the permeable fractures away from the borehole wall can also detected by using standard geophysics logs such as sonic. The permeable fractures can be predicted from the ratio of compressional wave to shear wave velocity (Vp/Vs), where a high Vp/Vs ratio usually correlates with high permeability.

3.3 Permeable Fault Core

Faults are believed to be one of the dominant permeability contributors in conventional geothermal systems where so many geothermal field development strategies make faults the main target in their drilling activities. A fault is a rock's physical discontinuity due to the stress implied on it, divide the rock into blocks where each block past the other. The fault core is a component in a fault geometry that is enveloped between the main slip surfaces, which accommodates intense deformation in the form of slip surfaces and fault rocks such as fault gouge, cataclasite, breccia, lenses, shale smear, and diagenetic features. The complexity and variation in fault core geometry and thickness affect fluid flow both along and across the fault. Thus, in the geothermal system widely, a fault core could be both a conduit and a barrier in a system.

The permeability of a fault core is largely controlled by the nature of the materials within it and the degree of fracturing. Highly fractured fault cores with open fractures and minimal cementation are likely to exhibit high permeability. In contrast, fault cores that are heavily cemented or filled with fine-grained fault gouge may act as barriers to fluid flow. The case in this paper illustrates where the fault core remains permeable, allowing for enhanced fluid movement, which is a favourable condition for geothermal energy production.

A permeable fault core can be detected on the image log data. An active and permeable fault plane usually has an aperture of more than 5 meters, causing a washout on the borehole wall. The washout was remarked by the disorientation of caliper logs due to the enlargement of borehole wall size, resulting in disturbed image log quality or no image data at all, like the case in this paper (Figure 4). Sometimes this zone is not able to be logged by using the caliper tool or often becomes a challenge in drilling operations and data acquisition. The permeability magnitude of this type is usually very high so most of the drilling operations will encounter continuous total loss circulation although the drilling fluid has been mixed with air. The drilling parameters can also be a sign of the fault core occurrence such as a drilling break where the rate of penetration (ROP), standpipe pressure (SPP), and weight on bit (WOB) exhibit abrupt changes due to the variation in rock strength and the presence of fractures.

4. PRIMARY PERMEABILITY

4.1 Pores or Microfractures-supported Formation

Two key properties that control reservoir behaviour are the porosity and permeability of the reservoir rocks (Jafari and Babadagli 2011). Porosity is the measure of void volume (space) and permeability indicates how easily a fluid can pass through a medium (Guéguen and Palciauskas 1994). Because porosity does not indicate the shape, size, and distribution of the voids, it provides limited information about the ability of a fluid to flow through the rock.

Porosity includes both connected porosity and unconnected porosity. Unconnected porosity refers to void spaces that are not interconnected with the rest of the void network and, therefore, cannot be accessed by fluids. Connected (or effective) porosity refers to void spaces that are interconnected and can, therefore, contribute to permeability. The connected pores are commonly found in sandstone or sedimentary formation, while the example of unconnected pores is often found in Indonesia's geothermal reservoir, which is often composed of pyroclastic rocks such as ignimbrite or volcanic breccia. The hydrothermal system in Indonesia is mostly associated with the Quaternary volcanoes, producing a large-scale pyroclastic deposit. Ignimbrite or volcanic breccia is a lithology that could contain abundant pores as the result of degassing during the lithification or cooling process. These pores, originally

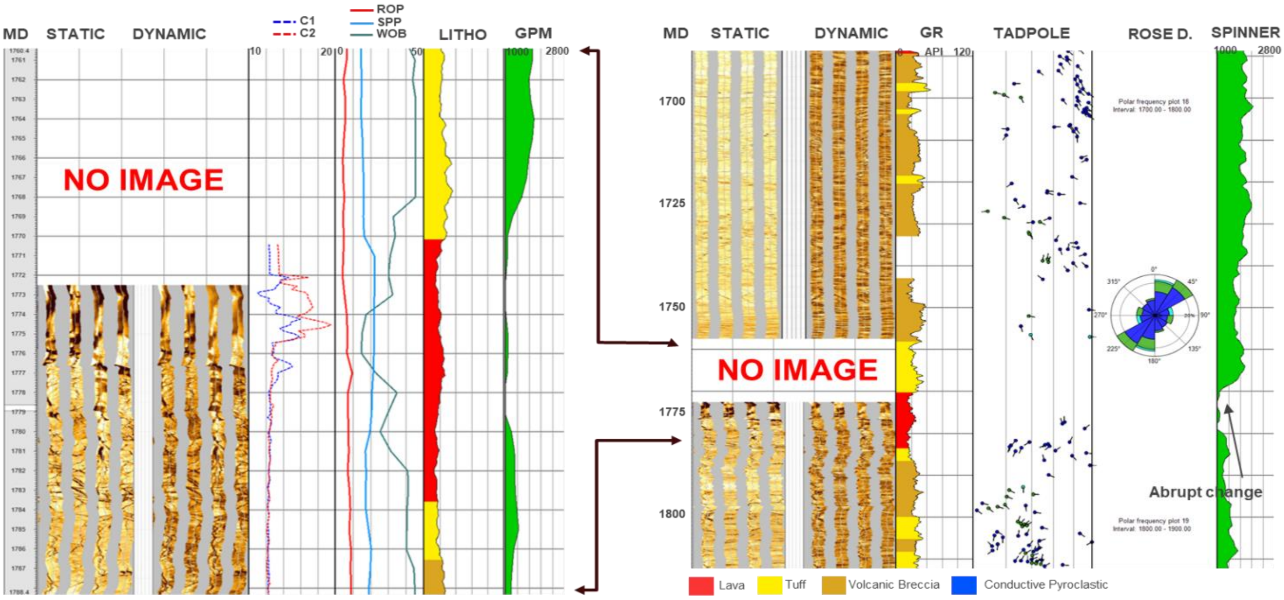

Figure 4: The image log appearance of the permeable fault core. The no image zone is the washout zone, indicated by the disorientation of caliper data, that disturbed the image log caliper tool and failed to acquire image data. This zone commonly align with the drilling break zone which indicated by abrupt changes of the drilling parameter

unconnected, might be connected during drilling activities due to pressure applied from the injected and circulated drilling fluid that resulting thermal distressing. This condition makes these voids permeable due to the permeability enhancement through the microfractures created from the local pressure, thermal distressing and also the quenching fractures due to the thermal stress during the mineral forming (McPhie et al., 1993). The thermal stress resulting from the sudden cooling of the hot material initiates polyhedric curvilinear fractures that typically propagate along mineral and fragment boundaries. The intra-matrix porosity in this type of rock can also enhanced by the deuteric alteration process or dissolution where fluids with low pH frequently dissolve metastable minerals, resulting in intracrystalline sieve and moldic texture that enhances the total rock porosity and permeability when the pore network is connected and free from new mineral precipitation (Sruoga and Rubinstein 2007).

The geophysics logs such as sonic, density or neutron logs can also determine the matrix porosity and permeability in the geothermal reservoir, especially on the less-fracture intensity interval (Figure 5). The image shows how a series of porous pyroclastic units such as ignimbrite and tuff contain a good porosity and permeability, determined from the sonic and density logs analysis. The spinner response in this zone is commonly gradual, indicating an interval of porous formation with a low to moderate injectivity index.

4.2 Lithological Contact

In Indonesia's stratovolcanic environment, the unconformities of lithological contact often appear due to the interlayer process between two different volcanic products. Usually the angular unconformity or disconformity are the most favorable unconformity for permeability. Some active tectonic events can also provide the vertical contrast between lithologies, for example, the eroded uplifted basement during orogenic events covered by the younger volcanic deposit.

The evidence of this permeability type is shown in Figure 5. This image was conducted through a well in the Karaha field, Java. There is a zone that contributes around 50% of the total fluid flow in the well, but no intensive fractures developed in this interval or beyond. Instead, a conductive zone with a thickness of about 0.3 - 0.5 meters which associated with a lithological contact zone between tuff and volcanic breccia. It is believed this lithological contact zone contributes to the injectivity index where the spinner response usually shows an abrupt changes.

5. DISCUSSION

This study has focused on characterizing the permeability control within conventional geothermal reservoirs in Indonesia, specifically at the well-scale, using image log data, injection spinner logs, and other geophysical logs. The complex geological setting of Indonesia, influenced by dynamic tectonics and volcanic activity, creates a diverse array of permeable zones that significantly impact geothermal well productivity.

The five primary types of permeable zones identified—high-intensity fracture zones, large aperture fracture sets, permeable fault cores, pores or microfracture-supported formations, and lithological contacts—each contribute uniquely to fluid flow within the reservoir. High-intensity fracture zones, typically found in brittle formations like lava flows and welded tuffs, are crucial for facilitating fluid movement due to their closely spaced fractures. However, the interpretation of these zones can be challenging due to the small aperture sizes and the subjective nature of fracture identification.

Large aperture fracture sets, play a significant role in geothermal reservoirs by providing high permeability pathways that dominate fluid flow. The integration of image logs with mineralogical data is critical for accurately assessing the permeability of these fractures, particularly in the presence of conductive minerals.

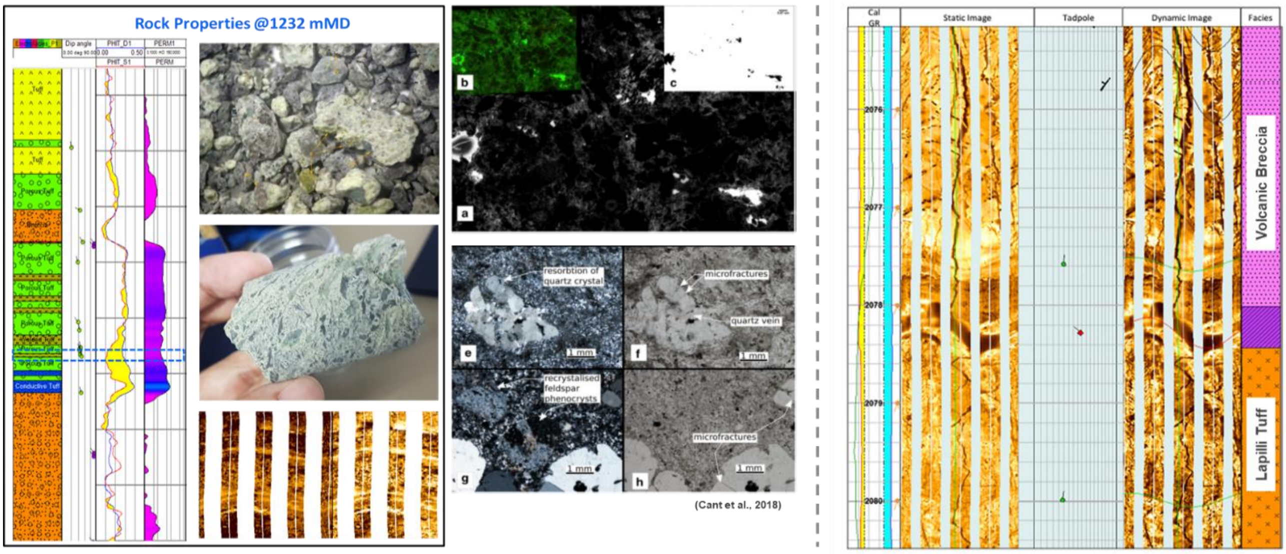

Figure 5: (Left) The image log appearance of the porous and permeable pyroclastic formation. The geophysics log analysis indicates high porosity and permeability in tuff and ignimbrite zone with no fractures existence. Cant et al. (2018) shows the example of pores and microfractures in the pyroclastic rock. (Right) The image log show the conductive zone bound a lithological contact.

Permeable fault cores present both opportunities and challenges in geothermal reservoir management. While these fault cores can enhance fluid flow, their complex geometry and the potential for cementation or gouge filling can also create barriers to flow. The study highlights the importance of careful logging and interpretation to distinguish between permeable and impermeable fault cores.

Primary permeability, associated with pores and microfractures within pyroclastic formations, also plays a vital role, particularly in Indonesian geothermal reservoirs dominated by volcanic lithologies. The study finds that porosity and permeability in these formations can be significantly enhanced by microfracturing and hydrothermal alteration, underscoring the importance of both pre-existing and induced porosity in reservoir performance.

Lithological contacts, though often overlooked, can be substantial contributors to well productivity, as seen in cases where these contacts create permeable zones that support significant fluid flow. This study's findings emphasize the need for comprehensive data integration, including geophysical logs and borehole imagery, to accurately identify and characterize these contacts.

Future work should focus on further refining fracture modelling techniques, such as discrete fracture network (DFN) models and subsurface fault geometry modelling, to improve predictions of fracture continuity and permeability between wells and precise the next well targeting plan. Additionally, the role of microfractures, pores and alterations in enhancing permeability should be more thoroughly investigated to optimize drilling and production strategies in complex geothermal settings like those in Indonesia.

REFERENCES

Cant, J. L., Siratovich, J. W., Cole, J. W., Villeneuve, M. C., and Kennedy, B. M., 2018 Matrix Permeability of Reservoir Rocks, Ngatamariki Geothermal Field, Taupo Volcanic Zone, New Zealand, Geothermal Energy 6:2.

Gueguen, Y., and Palciauskas, V., 1994, Introduction to the Physics of Rocks.

Ikhwan, M., Suryanto, S., and Tofan, R. M. S., 2022. Integration of Geoscience, Geomechanics, And Geostatistics Method To Model The Fracture Distribution And Permeability In Naturally Fractured Geothermal Reservoir, New Zealand Geothermal Workshop.

Jafari, A., Babadagli, T., 2012, Estimation of Equivalent Fracture Network Permeability using Fractal and Statistical Network Properties, Transp Porous Med 91, 339–362

Kim, Y. S., Peacock, D. C. P., and Sanderson, David, J., 2004, Fault Damage Zones, Journal of Structural Geology 26 503–517

McPhie, J., Doyle, M. and Allen, R. 1993. Volcanic Textures: a guide to the interpretation of texture in volcanic rocks. 209.

Sruoga, P. and Rubinstein, N. 2007. Processes Controlling Porosity and Permeability in Volcanic Reservoirs From the Austral And Neuquén Basins, Argentina. AAPG Bulletin, 91, 115–129, 836 https://doi.org/10.1306/08290605173

Torabi, A., Ellingsen, T., Johannessen, M., Alaei, B., Rotevatn, A., & Chiarella, D., 2019, Fault zone architecture and its scaling laws, Geological Society, London, Special Publications. 496. SP496-2018. 10.1144/SP496-2018-151.

Wallis, I., Moon H., Clearwater, J., Azwar, L., and Barnes., 2015, Perspective on Geothermal Permeability, New Zealand Geothermal Workshop