# Integration of Geoscience, Geomechanics, And Geostatistics Method To Model The Fracture Distribution And Permeability In Naturally Fractured Geothermal Reservoir



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## ABSTRACT

It is well-known that geothermal reservoirs are mostly controlled by secondary permeability, for instance, natural fractures zone and fault, as the natural conduit for geothermal fluid flow. However, not all natural fractures contribute to the fluid flow. In this paper, we attempt to identify the contributed-natural fractures to hydrothermal flow by using the geoscience data, geomechanics and geostatistics method in the naturally-fractured reservoir characterization through the discrete fracture network (DFN) model.

A geomechanics method is used to filter the fractures along the borehole so the fractures input in the modelling only uses the critically-stressed fractures as the possible permeable fractures. This driver is converted into an intensity log and mainly controls the vertical spacing fracture distribution in the 3D model. In the horizontal dimension, we utilize the deterministic surface fault model and microearthquake (MEQ) events distribution, which is interpreted as an indication of fluid flow through fault or fracture to give us geologically reasonable spatial control in modelling the DFN. To confirm the modelled flowing natural fractures distribution, we upscale the DFN model into the permeable zone model. The permeability calculation parameter is derived from the assumption that we generate from image log data such as aperture and modelled fracture length. This permeability model will compare with the actual feedzone or depth of sweet spots in the well which has been proved to contribute to the fluid flow. The discrete fracture network model derived from this method gives a fit permeability model with the actual flow condition in the well-scale. The reason is that the permeability control, in this case, is mostly associated with fracture intensity. In other words, a high-intensity fracture zone with a certain orientation penetrated by the well will give high permeability magnitude, thus characterizing the reservoir through the DFN model will be a benefit.

## 1. INTRODUCTION

### 1.1 Geothermal Systems at Glance

In the need for world decarbonization, geothermal energy appears as one of the promising green energy sources that will contribute significantly to the energy transition era. The heat energy storage all over the world with various heat scales and forms depends on their geological setting. It provides sustainable energy that can be utilized in many ways including for power generation or direct use such as heating or farming. A geothermal system, generally, can be divided into two types based on its heat transfer process. The conventional geothermal system, or called the hydrothermal system, transfers the heat through convection, involving the natural hot fluid in the geothermal reservoir (Renner et al., 1975). The unconventional geothermal system or enhanced geothermal system (EGS) is the system that transfers the heat through the conduction process using rocks instead of fluid. Thus in the EGS system, the permeability is man-created so they can drain the surface fluid into the hot rock, heat the fluid and flow to the surface due to the buoyancy.

This paper is focused on modelling the conventional geothermal system or natural hydrothermal system. The hydrothermal system is already proven to produce a huge power generation and can be found globally such as in Indonesia, the Philippines, Iceland, the United States, and New Zealand, which is mostly a volcanic-hosted geothermal area. Three main components that dictate the energy capacity in a hydrothermal reservoir are fluid, heat, and permeability (Sebastiano et al., 2019). Permeability is needed in developing the geothermal field, either natural or enhanced (like the one in the EGS), to transport the fluid which stores the heat energy (Wallis et al., 2015). Permeability is, in essence, the capacity for fluid to flow through the rock. The permeability in a hydrothermal system is mostly controlled by fault and fractures, although matrix porosity from formation sometimes also has a critical contribution either. So it is critical to know the geometry and distribution of the fractures in the reservoir to better understand the reservoir's hydrology and improve our well placement and well-targeting strategy to intersect the permeable zone to have a sufficient well output.

### 1.2 Discrete Fracture Network (DFN)

The discrete fracture network or DFN modelling is already considered one of the prominent methods to characterize the naturally fractured reservoir and is widely used in oil and gas and also mining industries. The DFN refers to a computational model that explicitly represents the geometrical properties of each individual fracture (e.g. orientation, size, position, shape and aperture), and the topological relationships between individual fractures and fracture sets (Lei et al., 2017). The DFN model is derived from several methods and data input. For example, modelling the DFN in oil and gas reservoirs can utilize the fractures information from the image log and fault geometry from the seismic data, so the scope of the modelling processing can be well-estimated. Bauer & Toth (2017) model the DFN in the karst reservoir formation by using the integration of image log, seismic, core and thins section data to predict the porosity and permeability in production interval. Le Goc et al. (2017) build a DFN model to support and construct underground facilities such as tunnels by using multiple data such as outcrop traces, borehole logs, and tunnel mapping. Globally, fracture modelling attempts to characterize the geothermal reservoir has been done by Juliusson & Horne (2010), Mafucci et al. (2013) and Joonnekindt & Levannier (2021). However, these publications lack the fault mechanics property concept application as one of the important aspects that need to be addressed when discussing the natural fracture permeability. More detailed and intense publication regarding

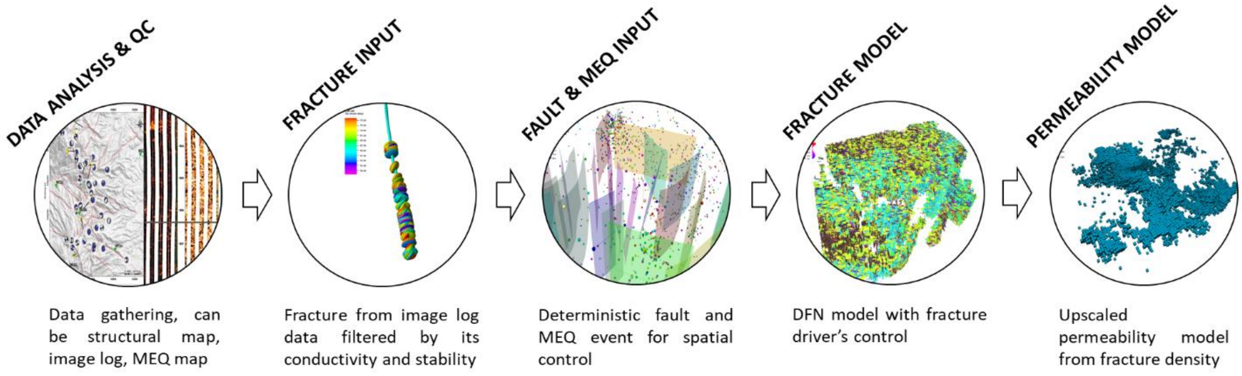


**Figure 1: The general workflow of how the DFN model build to predict the fracture distribution and geometry**

the DFN modelling in the geothermal field is related to the EGS system, such as those published by Finilla et al. (2019) and Forbes et al. (2019), which less relevant and applicable in the natural hydrothermal reservoir.

Moreover, there are some challenges to doing fracture modelling in a geothermal reservoir. First, although fractures are abundant, not all of them are permeable and contribute to fluid flow. Many cases indicate where fractures are intense and recorded in the image log but in reality, there is no flow in this interval. The reason might be that among the abundant fractures, the fluid flow only flows through a certain orientation due to a certain fracture mechanism. Second, unlike in the oil and gas industry, fracture modelling in geothermal faces difficulties regarding the availability of rigid subsurface data such as a seismic image. Seismic imaging is rarely done in a complex-volcanic geothermal environment, so estimating the fault and fracture distribution in spatial or between wells is difficult

To solve this, we try to optimize the available geoscience data such as geology and geophysics to cover the "blind spot" left due to the unavailable seismic data so the fracture modelling is still possible to do. They include all the data available on the surface and subsurface to act as the fracture control in DFN modelling, such as geology and geophysics data and also geomechanics method to have a geologically-make sense fracture distribution model. The fracture control is the data-driven parameter that we used to control the distribution and orientation of the fractures. The purpose of this fracture modelling is not straightforward to calculate the permeability magnitude in a reservoir numerical simulation or to match the actual configuration and distribution of the fracture in the subsurface. It is more to estimate the favourable area to drill which might have a higher success ratio in terms of fracture permeability, so we have a better next-well targeting strategy

Figure 1 is an overview of how the DFN modelling is done and is briefly explained. First, all the data that will be used gathered and filter for QC, for example, the structural map and borehole image. The subsurface fracture data mainly comes from wells' borehole image log data. This data was analyzed by using the geomechanics method and will mainly control the fracture distribution in the vertical orientation. Then the geological and geophysics data will contribute to the fracture control for horizontal orientation. By combining these data, we can do the fracture modelling and then upscale the fracture model into a permeability model by inputting the fracture attribute such as fracture length and fracture aperture. Then we match the model with the actual feedzone identified from the existing well-test data such as the spinner test. The permeability model magnitude will be filtered until getting a confident match between the model and the actual feedzone interval from spinner data. All the modelling process using Petrel software from Schlumberger.

## 2. METHOD

### 2.1 Fracture Stability Analysis

After data gathering and quality control, the first data analysis was performed on each image log data from wells. The analysis includes the permeable fracture identification, for example, the conductive fractures, and also the mechanical properties of the fractures such as the fracture stability analysis. The conductive fracture identification is simply done by looking for the dark fracture sinusoid in the image log. The mechanics and kinematics of fractures and faults are closely related to geomechanical studies. In the context of identifying the dominant permeability in the geothermal reservoir, several references and previous studies of geomechanics can be used that include the characterization of mechanical properties and fracture stability or commonly called critically stressed fracture analysis. Critically stressed fracture or unstable fracture is a fracture that has a high potential to slip due to the influence of the current stress field. Figure 2 shows the workflow of the 1D geomechanics model. The data used here is the basic data needed in geomechanics modelling, such as geophysics logs, core, and image logs and many more. The workflow is representing how to estimate the stress in the subsurface including the vertical stress and horizontal stresses. The information about these principal stresses can be used to analyse the mechanical property of each fracture plane recorded in the image log, so we can identify the fracture stability to estimate its permeability capability potential.

Critically stressed fracture analysis was first performed by Zoback (2010), who argued that fractures or faults that are permeable or capable to drain the fluid are active or critically stressed. In a fracture dataset that has different strike and dip orientations, unstable fractures will be affected by the direction of the local principal stress. The strike dip orientation of this fracture can be objectified and converted into geographic coordinates, making it possible to calculate the shear and normal stress applied on the fracture plane. Shear stress is a pressure that works in the direction of the fracture plane, while normal stress is a pressure that is perpendicular to the direction of the fracture plane. Barton et al. (1995) proposed a way to project the data orientation of such fracture sets into geographic coordinates using Euler's

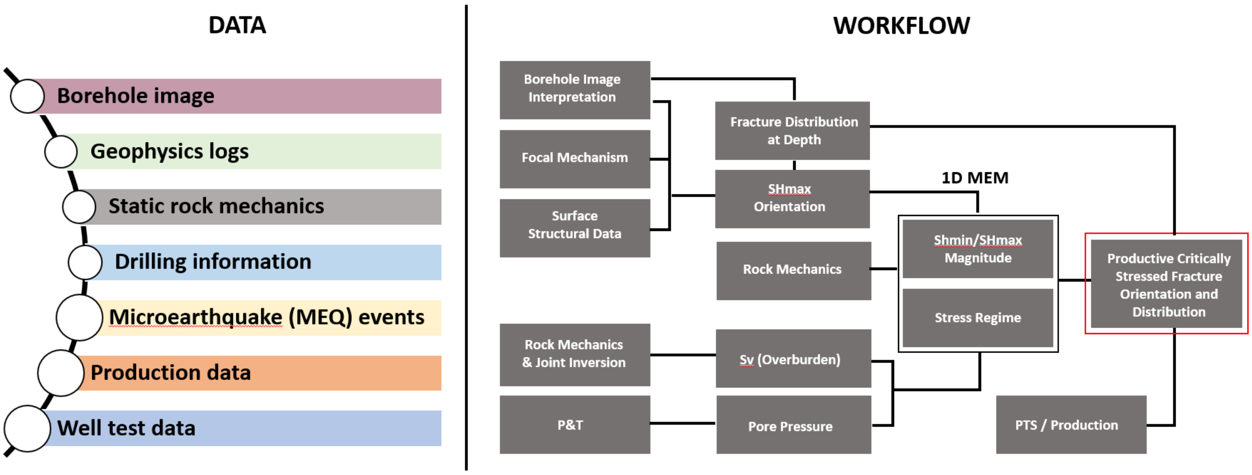


**Figure 2: The 1D geomechanics model workflow to identify the critically-stressed fracture from the image log data**

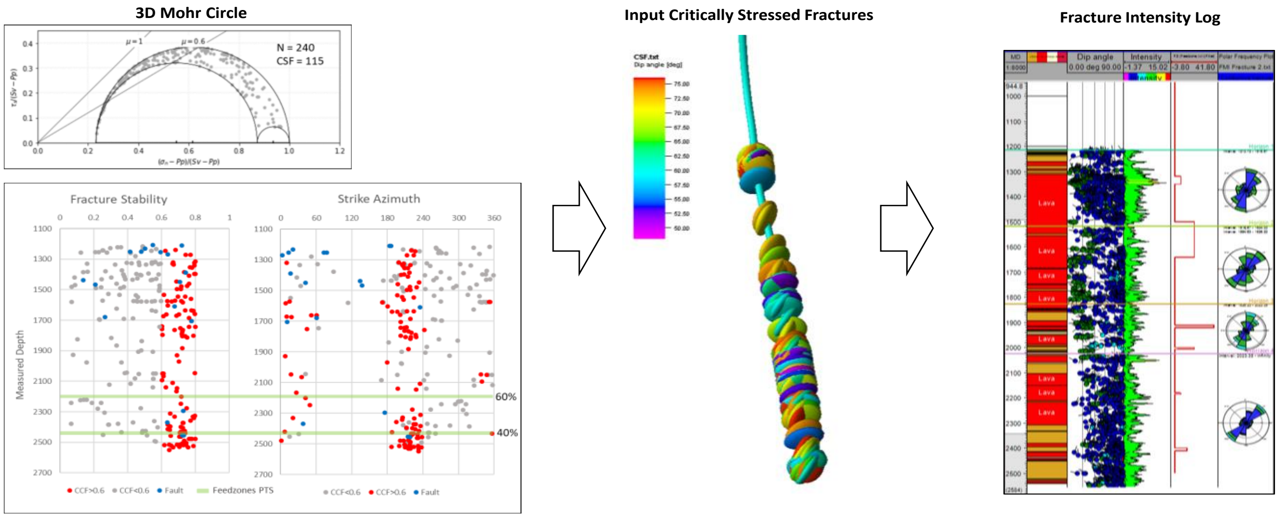


**Figure 3: Fracture stability analysis performed on each image log data to so only the possible permeable fractures that upscaled into a fracture intensity log**

rotation matrix calculations. The unstable and potentially open fractures are fractures that have a ratio of shear to normal stress between 0.6 and 1 (Figure 3). This stress projection can be plotted in a diagram called 3D Mohr Circle. This 3D Mohr Circle is a graphical representation of the stress tensor and all its projections, or the possible value of the normal effective stress and the shear stress, on a given plane. These active fractures are necessary for their relationship to permeability because active fractures can maintain the opening or aperture of the fracture itself and also prevent deposition from alteration minerals that can lower permeability magnitude. Here the fracture stability analysis is performed to identify the critically stressed fracture, which is interpreted as the possible permeable fracture. By using this method we can filter the fractures in the image log so only the critically stressed fracture is included as the input in the fracture modelling. This also solves the first question that we mentioned earlier about the uncertainty of which fractures contribute to the fluid flow. The critically-stressed fracture input on each well will be upscaled into an intensity log and will influence the vertical distribution of fractures between wells.

## 2.2 Distance to Faults and Microseismics Events

The second step is using the geological and geophysics data as another fracture control to populate the fracture distribution into spatial or horizontal space. The data used here is the prominent major fault framework seen on the surface and the microseismic events data. The deterministic fault model is mostly derived from remote sensing analysis and supported by the fieldwork. Their distribution in the subsurface is mostly supported by an enhanced geophysical method such as the second vertical derivative and Euler deconvolution method from the gravity data (Cooper, 2008). They are assumed as the fault core in a fault geometry, which should be surrounded by a developed fracture zone and expected extensional fractures. Faults are commonly associated with fault zones in various scales and developed extension fractures. The extension fractures are often found formed closely with slip on fault surface, which is mostly shaped perpendicular with the slip vector. However, in reality, the fracture geometry, orientation, and distribution are mostly not necessarily uniformed in a certain orientation

The idea of using the deterministic fault model as the fracture control is fractures will be more developed and localized around the fault core, so the deterministic fault core model here can be used in a distance function. So the closer an area to a fault, the more fractures they get, which means there will be more fracture intersections that will enhance the potential natural secondary permeability. The fault core in this stage is assumed as a relatively planar fault plane without significant geometry and orientation changes. This method will also generate more fractures in a fault intersection area, as it is believed to be a favourable zone for well targeting in a tectonic-controlled geothermal setting because it will be interconnected in the vicinity of the intersection fault plane.

The microearthquake or microseismic data also can be used to populate the fracture distribution in space. Microseismic is the energy coming from low magnitude Earthquakes and small-scale movements. They occur due to the volume change within the rock mass or change in the shear-stress components (Zhang et al., 2015). However, they can also be caused by man-made sources (i.e. drilling, mining and hydrocarbon production). Microseismic events are detected through geophones planted on the survey surface area or down a borehole. The method is also known as passive seismicity, which focuses on low frequency (between 0 to 10 Hz). Passive seismicity is a real-time microseismic record of the body and provides continuous footage of what is happening in the earth as industrial activities engage In this study, the microseismic event is interpreted as triggered by the movement of fluid flow through the fractures that cause the fracture. Therefore, we can interpret that the more dense a microseismic cluster occurred so the more fractures will be formed around the microseismic events. However, sometimes the microseismic events are not clustered or well correlated with the fault model. The density of the microseismic events also could be influenced by the water injection from the injection well. In many cases, a microseismic event is not only triggered by fluid movement but also a pure tectonic event without involving fluid. Besides looking for the data density, the microseismic data is also possible to show the spatial pattern, which can be interpreted as a lineament related to a fault or fluid conduit. Nevertheless, events clustering is easier to determine from the available data instead of the spatial events pattern. Therefore, using microseismic data needs further quality control and data analysis.

### 2.2 Integration and Upscaled Model

These three data inputs above will combine into a single 3D intensity model (Figure 4). The model is populated by using the geostatistical method such as the Kriging or Gaussian method. Kriging is a deterministic interpolation griding one “best” local and smooth estimate. This method uses variogram to search, collect and distribute data. Gaussian simulation is a stochastic method based on kriging, but capable of capturing extreme values in a heterogeneous reservoir. In reservoir modelling, several modelling approaches can be performed. Some of deterministic, providing one result, while others are stochastic, providing several equally probable results based on the same input data (only varied by a seed number used in a Monte Carlo simulation). The kriging is used to calculate the best estimate (by minimizing the error variance) of rock properties, interpolating well data. The limitation of such a method is that in a large model, low values tend to be overestimated and high values underestimated. Stochastic simulation methods are better at capturing the heterogeneities (extreme value variation) of the subsurface by assessing its (expected) spatial variability. So in this study, the Gaussian method was used to distribute the input data in building the intensity model due to the availability and limitation of the well data.

This intensity model will be the generator in fracture modelling in the reservoir. There are three main components in generating the fracture model from the intensity model: fracture distribution, fracture geometry and fracture orientation. The fracture distribution was modelled by using the method published by Berg (2019) related to estimating fracture density or P32. He published methods for calculating fracture density (P32) and size from image logs. This equation calculates fracture density (P32) using fracture orientation and size, and borehole diameter. The fracture geometry is the second parameter that influences fracture modelling. In this work, fractures are considered to be rectangular and planar. The fracture geometry is generated by using an equation by calculating a correction factor for each fracture and then dividing the sum of the correction factors by the interval length. There are two methods for determining size: 1) In the enclosed-length method, the borehole-enclosed fracture-edge lengths and borehole-enclosed fracture areas are used to estimate average fracture size. 2) In the density-compare method, P32 is first calculated directly by dividing the total borehole-enclosed fracture area by the borehole volume. The equation is then applied repeatedly to the fractures within the interval, varying fracture size until the equation-calculated P32 matches the directly calculated P32. Both methods have been verified using the DFN model. The fracture connectivity index is calculated using the number of fracture intersections divided by the number of whole fractures. The number of whole fractures is calculated by dividing the borehole-enclosed fracture area by the product of fracture height and length. In the fracture orientation parameter stage, the strike and dip angle of the modelled fractures is derived from the actual image log data.

Because the purpose of the DFN modelling is to be upscaled into the permeability model later, the fracture attribute in the permeability calculation property such as fracture aperture is calculated from the image log data and the fracture length is modelled from the software. The fracture geometry assumed in this study is an elongated fracture so the fracture length is

*Fracture length = sqrt (area x elongation ratio)*

Fracture aperture is computed as a hydraulic aperture which is the cubic mean of the fracture width. The term hydraulic is used since this method is proportional to fluid flow through the fracture and this aids in the comparison of flow capacities of different fractures. Theoretical and modelling work to relate the response of imaging tools to the aperture of the fractures was carried out in the late 1980s at the Schlumberger Doll Research centre (Luthi and Souhaité, 1990). This work demonstrated that the borehole imaging tools of the time respond to fractures by a predictable amount of excess current compared to the background response as the tool crosses the fracture. Further, it was shown that the integration of the excess current could be directly related to the width of the fracture through an equation

*Fracture Aperture = W = c x A x Rmb x Rxo1-b*

Where W = fracture aperture, b,c = constant from tool modelling, A = excess current divided by voltage and integrated along a line perpendicular to the fracture trace, Rm = mud resistivity, Rxo = flushed zone resistivity. Aperture is the most widely relied on measure for fracture ’openness’ which again is related to fluid flow/permeability. However, it is a very uncertain parameter and must be investigated for each case and each reservoir. There are many factors affecting the aperture even though we use these general laws: mineral fill, asperities, fracture angles and interconnections. The aperture may also be affected by effective stress (Total Stress = Pore Pressure + Effective Stress).

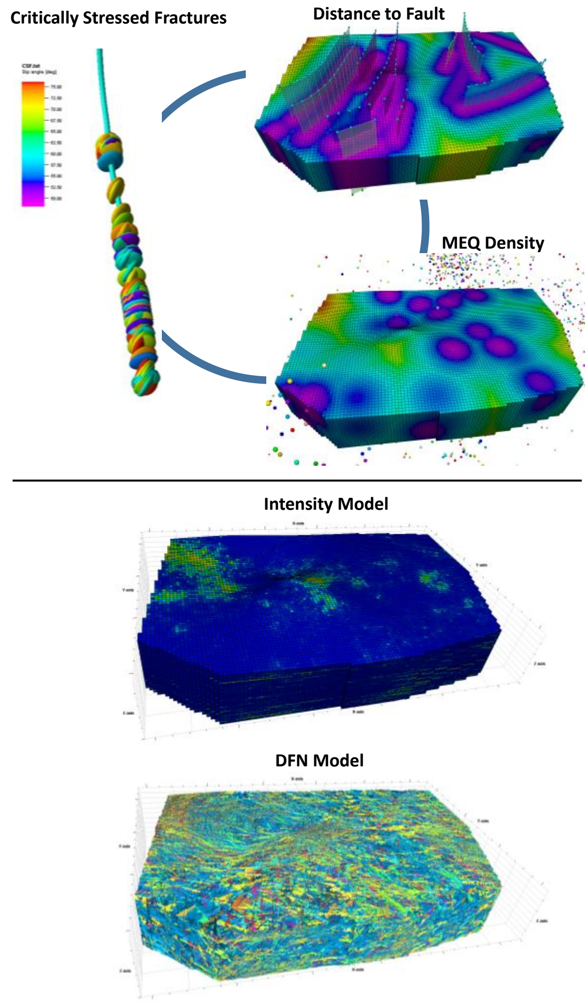


**Figure 4: Three main data inputs are combined into one single intensity model by using the geostatistical method. The intensity model will be the generator to mode the DFN.**

## 3. RESULTS

The permeability model construction is strongly correlated with the density of the modelled fractures in 3D space. A higher fracture intensity area will give a higher permeability magnitude due to more fracture intersections being developed creating the continuous secondary permeability. The resulting model is shown in Figure 5. The permeability magnitude from the upscaled DFN model range from 0 to 20 mD. This value seems reasonable to refer to the secondary permeability, such as fracture, magnitude range suggested by Rowland & Simmons (2012). The permeability model was filtered so only the relatively high permeability area was displayed. The cut-off of the filtering process is acquired by adjusting the permeability magnitude that fit the actual feedzone interval derived from the well-test. Then the adjusted cut-off value was set to 6 mD. By using this cut-off the distribution of the permeability model mostly fit the production interval that was proved by the production wells (only the two wells with the production interval zone displayed).

To test the model before drilling, we can use the actual sweet spot zone recorded in the well by using the spinner test data. Most of the actual feedzone from wells will fit the high permeability magnitude zone. However, it is only the feedzone that is controlled by fracture intensity will likely fit this permeability model. Because the feedzone in geothermal could also be controlled by other parameters such as matrix porosity or lithological contact.

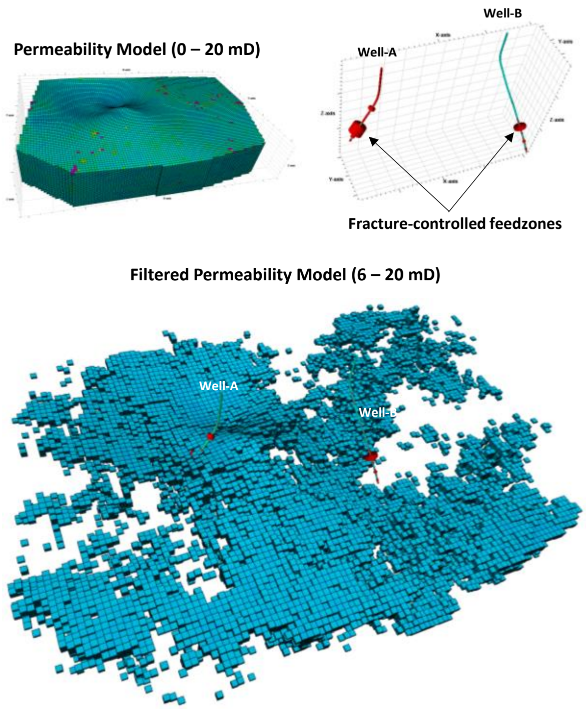


**Figure 5: The permeability model filtered to 6 – 20 mD and match the existing production or feedzones interval in wells, especially the fracture-controlled feedzones.**

## 4. DISCUSSION

This fracture modelling method is suitable for a fracture-controlled geothermal reservoir. However, a lot of geothermal fields, especially volcanic-hosted geothermal fields, also could be controlled by another parameter such as matrix porosity. So permeability identification is mandatory before doing this modelling. The challenge to this fracture modelling in a complex volcanic-hosted geothermal reservoir is, how confident are we in the modelled fracture distribution, due to the heterogeneity of geological conditions in the subsurface. Many cases in the complex-volcanic hosted geothermal field the surface condition does not always represent what is developed in the subsurface. The complex geological condition might include the volcano-stratigraphy and fault continuity and geometry in the subsurface. More well data will be a benefit when working on modelling like this. The fracture model might not necessarily match the actual fracture condition. Yet from this modelling, we can expect the probable sweet spot identification from the upscale permeability model. This model extremely can be elaborate with any relevant data available, to reshape the geometry and distribution of the fractures model. However, this model is not a silver bullet in geothermal well targeting strategy. It should be combined with the geothermal conceptual model and other geoscience data to have the optimum well design and trajectory.

## 5. CONCLUSION

Most of the permeability control in a conventional geothermal system is controlled by fractures and faults. Thus, modelling the fracture distribution is essential in their correlation with the permeable zone in the reservoir. Fracture modelling in a natural hydrothermal system is doable despite the lack of essential subsurface data. The geomechanics method can be applied to filter the fracture input so only the potential permeable fractures in the image log will be used as the fracture control. Geoscience data such as modelled prominent fault planes and microseismic events are also useful to distribute the fracture spatially, considering their role to influence the fracture geometry and distribution. These fracture generators combined to yield an intensity model that will dictate the fracture model. The fracture model was later upscaled into the permeability model to image the potential sweet spot zone in a fracture-controlled geothermal reservoir. The permeability model is relatively matched with the actual feedzone interval in the existing wells, concluding that the model is reliable to use. Therefore, the potential sweet spot zone from the permeability model represents the favourable spot in the reservoir to drill, so it can support the well-targeting strategy. Further work in this fracture modelling could include the flow simulation to calculate the contribution of the permeable fracture in the reservoir quantitatively in the reservoir numerical modelling process.

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