Updated Geological Structure and 3D Intrusion Model as Veritable Fracture Driver of Fracture Characterization in Wayang Windu Geothermal Field, Indonesia

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ABSTRACT

Wayang Windu is a two-phase geothermal field located in Indonesia with electricity generating capacity of 230 MW. Several make-up well drilling campaigns have been conducted since the field started commercial operation in 1999, with the most recent campaign resulting in a steam gain that significantly exceeded expectations.

As part of a continuous improvement process for selecting subsurface well targets, Star Energy Geothermal is applying a novel workflow to interpret permeability distributions, especially in relatively undrilled parts of the reservoir. The workflow is referred to as Fracture Characterization and Optimized Well Placement (FCOWP). FCOWP consists of two main processes. The first generates fracture orientations and intensity distributions, then the second models the range of fracture apertures and lengths and includes sensitivity and uncertainty analysis. This paper focuses on the creation of Discrete Fracture Network (DFN) realizations for Wayang Windu which is part of the first process.

The major initiatives related to creation of a DFN include an updated interpretation of geological structures and a model of rock intrusions. The Wayang Windu's FCOWP methodology depends on two fracture drivers. The first fracture driver is related to faults and associated stress, and the second fracture driver is related to intrusion geomechanics and thermal cooling. The input of the fracture drivers in Wayang Windu came from recently updated geological structures and a 3D intrusion model. Each fracture driver was validated by comparing fracture properties generated by the model (dip angle and dip azimuth) with fracture data observed in wells. Fractures from the well data are explained by a certain fracture driver if a fracture with the same properties is developed by that driver in the model. This validation process shows that up to 91% of fractures at Wayang Windu are explained by fracture drivers while the other 9% are not explained and can be dealt with stochastically.

Incorporating all fracture drivers results in a DFN where the fracture properties are comparable to fracture data from the wells. Thus, the updated structural model and 3D intrusion model are considered as reliable fracture drivers to predict permeability distributions in Wayang Windu to improve the selection of subsurface targets and well placement.

1. INTRODUCTION

Wayang Windu geothermal field is one of the geothermal fields located in the southern ring of West Java's geothermal complex. Several high terrain geothermal fields (i.e., Kamojang, Darajat, and Patuha) are situated within the complex (Figure 1). Wayang Windu is located on the slopes of a large andesitic stratovolcano called Mt. Malabar, and on a string of smaller volcanoes trending towards the south, which includes Mt. Wayang and Mt. Windu.

Figure 1: The location of Wayang Windu geothermal field in the southern ring of West Java's geothermal complex. The other high terrain geothermal fields are situated around Wayang Windu.

Wayang Windu hosts a two-phase reservoir that has been producing since 1999 with a total installed capacity of 230 MW. Exploration activity in Wayang Windu was initiated by PERTAMINA when the first discovery well was drilled in 1991. Development began in 1996 by Magma Nusantara Ltd. with electricity generation commenced in 2000. In total, five make up drilling campaigns have been conducted since 2000. The latest drilling campaign was conducted in 2020-2021. The total steam gained from six wells drilled in this campaign exceeded expectations, as it is ~7% above the target.

The Wayang Windu field experiences similar challenges to other mature geothermal fields in finding the best places to drill new wells, particularly considering the total number of wells already drilled in the field. In Wayang Windu, a total of 65 wells have been drilled from 20 well-pads. To improve the subsurface well targets for future drilling campaigns, Star Energy Geothermal (SEG) as the operator of the Wayang Windu geothermal field, is implementing a novel workflow referred to as Fracture Characterization and Optimized Well Placement (FCOWP). Its main objective is to interpret the permeability distribution, especially in the undrilled part of the reservoir. The FCOWP workflow is divided into two parts, the first is creation of a Discrete Fracture Network

(DFN) and the second is to carry out a sensitivity and uncertainty analysis by applying the fractures from the DFN, as permeability controls, using a variety of fracture aperture and fracture lengths.

To create a robust DFN, a series of valid fracture drivers is needed. The fracture drivers define how the fractures are created, in terms of location, length, dip angle, dip azimuth, and fracture intensity along certain areas. The creation of the DFN for FCOWP in Wayang Windu applies four fracture drivers where two of the fracture drivers are associated with the geological structure in Wayang Windu, while the other two drivers are associated with the intrusive body in Wayang Windu.

The geological structure and intrusion model in Wayang Windu has undergone significant updates prior to the commencement of the FCOWP. The updated geological structure is derived from the application of LiDAR which was acquired in 2019. While the 3D intrusion model is constructed based on an integration of gravity data and density data from core rock samples and density logs obtained from several wells. The updating process, modeling process, and the relationship between the geological structure and 3D intrusion model with the fracture driver and DFN creation will be discussed below.

2. GEOLOGICAL STRUCTURE

The Wayang Windu geological structure is mostly based on surface structural lineaments. The updating process was triggered by the new LiDAR data acquired from a comprehensive survey in 2019. The previous geological structure was derived from LANDSAT images, and hence the surface structural lineaments observed regionally.

2.1. Geological Structure - LANDSAT

Before the LiDAR survey, the geological structure in Wayang Windu was mainly derived from LANDSAT observations. As LANDSAT has a wide coverage, the surface structural lineaments extracted from LANDSAT are generally on a regional scale. Some of the regional structural trends defined by several researchers (Silitonga, 1973; Kosoemadinata and Hartono, 1981; Alzwar et al., 1992; Sudjatmiko, 2003 from Hutasoit, 2009 and Gumilar, 2013, Sari et al., 2019), can be related to the Wayang Windu geological structure as follow (Figure 2):

- The NW-SE structure trend is associated with the Puncak Besar and Gambung Selatan faults.
- The WNW-ESE structure trend is associated with Bandung Basin Boundary and the Pejaten and Sukamanah faults.
- The NW-SE structure trend is allied with the Cipanas, Cibitung-1, and Bojongwaru faults.
- The ENE-WSW structural trend is associated with the Kawah Wayang fault, and the N-S structural trend is analogous to the Haneut fault.

2.2. Geological Structure - LiDAR

The LiDAR survey in Wayang Windu shows high quality results. The number of points/area obtained is 27 points/m^2 and Digital Ortho-Rectified Photographic Imagery resolution is 15 to 50 cm. The LiDAR product which is mainly utilized in updating the geological structure is the Digital Terrain Model (DTM). As the resolution of the DTM is increased, the structural lineaments obtained from the LiDAR also become more detailed.

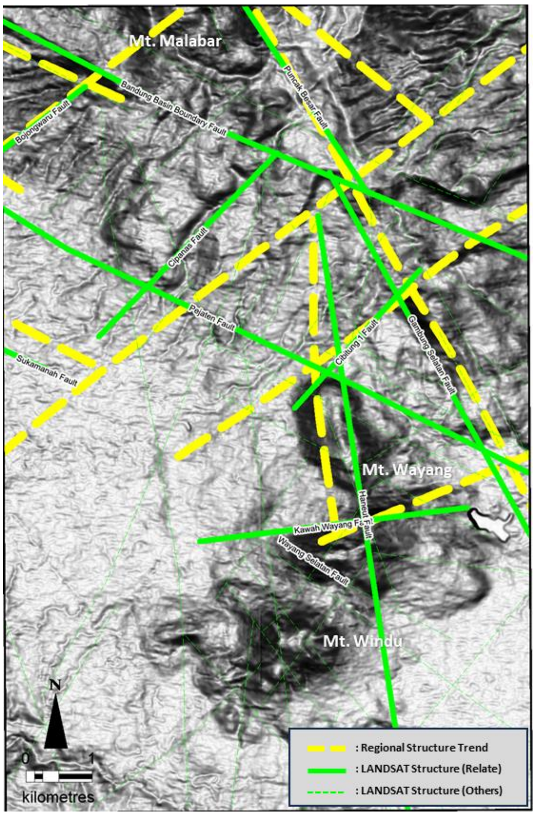

Figure 2: The Wayang Windu geological structure based on LANDSAT can be associated with some regional structural trends which have been observed by several researchers.

2.2.1. LiDAR Lineaments

The four types of data extracted from the DTM and used to update the geological structure in Wayang Windu are as follows:

- Automatically Extracted Lineaments,
- Lineaments of Drainage Patterns,
- Lineaments of Ridge Patterns and,
- Lineaments of Slope Shading.

Lineaments automatically extracted from the DTM are related to several already developed methods, i.e., Zhumabek, et al., 2017; Hung, et al., 2005. The lineaments have been double-checked to avoid false lineaments which might happen because they can represent a manmade object (pipeline, agriculture object, building, etc.). The lineaments are then grouped into small groups which show the degree of azimuth deviation of ±5º. The objective of the grouping is to identify the zones which show lineaments with relatively similar azimuth and avoid areas which are dominated by random azimuths. The former areas will be the focus of identification of structural lineaments (Figure 3).

The drainage patterns and ridge patterns are also extracted automatically from the DTM. Even though the previous automatically extracted lineaments also represent the lineaments of drainage and ridge patterns, additional patterns of drainage and ridge are helpful to define the structural lineaments (Figure 3)

The slope shading lineaments are obtained from four (4) different shading directions (N, S, W, and E) which are applied in the DTM. Lineaments from each shading might resemble lineaments which have been identified during the process of automatically extracting lineaments. However, with the addition of the slope shading lineaments, the valid lineaments can be confirmed (Figure 3).

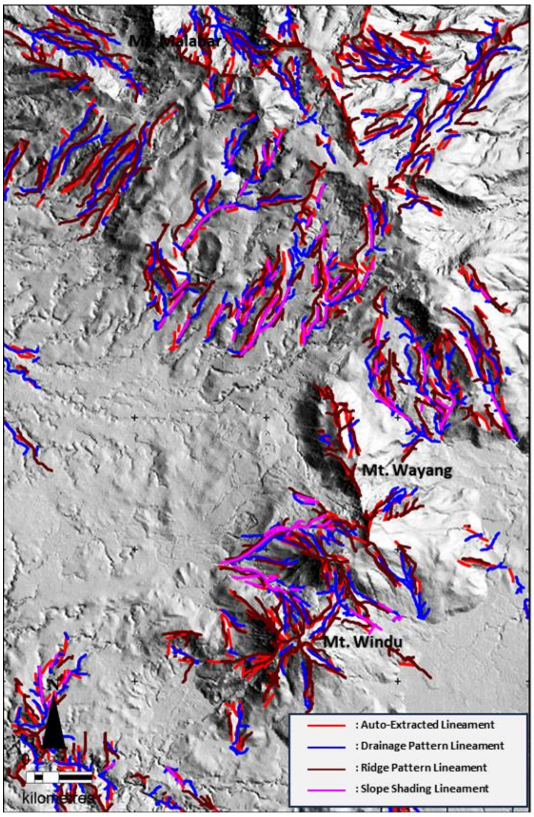

Figure 3: Selected Automatically Extracted Lineaments in the zone that shows the same azimuth, accompanied by Drainage Pattern Lineaments, Ridge Pattern Lineaments, and Slope Shading Lineaments, are ready to be utilized to define structural lineaments.

2.2.2. Gravity Lineaments

In addition to the series of lineaments extracted from the DTM; the lineament set is also enriched by several lineaments derived from gravity data. SEG has been processing gravity data into a Complete Bouguer Anomaly (CBA) map. Innovatively, the gravity data is also processed into a series of enhanced CBA gravity maps. One of these is known as an Automatic Gain Correction (AGC) where it sharpens the distinction of gravity objects in the subsurface. Several lineaments are observed in the AGC map and might add confidence levels by correlating surface lineaments with additional subsurface lineaments (Figure 4).

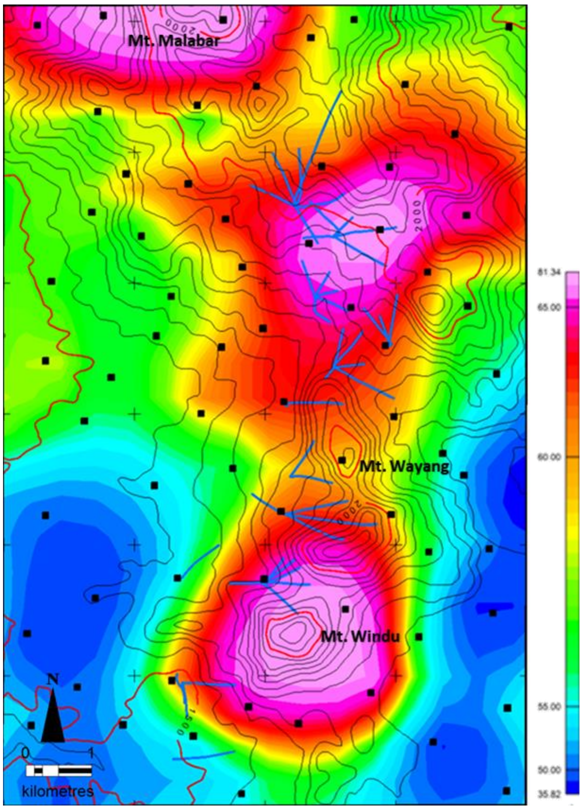

Figure 4: The AGC map of Wayang Windu which displays several subsurface lineaments.

2.2.3 Updated Geological Structure

Combining a lineament automatically extracted from the DTM where it has undergone a confirmation process by involving the drainage pattern, ridge pattern, and slope shading lineament, with the gravity lineament, yields an updated geological structure as shown in Figure 5. Not all surface lineaments are translated into geological structures. Some of the lineaments are considered to be lithological boundaries or lithological structures related to volcanic deposition (crater, material surge, material flow, etc.).

When compared to the regional structures defined by LANDSAT and other researchers, the updated Wayang Windu geological structure reveals a major structure in the northern area with a NW-SE trend (Puncak Besar-Neglasari). The structural trend of WNW-ESE is also observed in the northern area in the form of the major structure, the Bandung Basin Boundary. The same structural trend is also observed in Mt. Wayang-Mt. Windu (southern) area as Bedil Utara, Bedil Selatan, Wayang Utara, Wayang Selatan, Ranca, Windu Utara, Windu Selatan, and Purbasari. The NW-SE structural trend can be seen in the northern and southern areas (Cibitung, Cibitung West, Cibitung-1, Cibeureum, and Cibolang). The ENE-WSW structural trend is not clearly identified; however, the N-S and NNE-SSW structural trends are observed as a major structure at Kertamanah, Ranca-Gambung, and Banjarsari with some structures in between (Kijang, Bedil, Haneut, Haneut-1, and Santosa-Cikakapa).

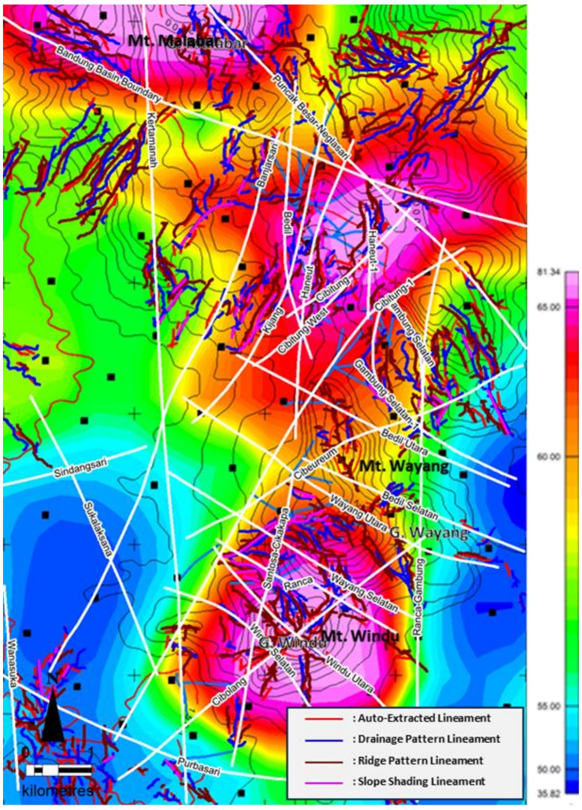

Figure 5: Updated geological structure derived from the integration of surface and subsurface lineaments.

3. 3D INTRUSION MODEL

SEG has conducted 2D intrusion schema using several approaches. The latest effort was aimed at constructing a 3D intrusion model based on inversion.

3.1. 3D Intrusion Model Pre-Inversion

Several intrusions at Wayang Windu have been identified primarily by examining the well data, particularly from cuttings. Based upon this information, several 2-D intrusion schematics were created which show a small dike extending upward through some pathway to the surface. However, there have not been any 3D intrusion models published.

3.2. 3D Intrusion Model Post-Inversion

By combining the gravity and density data from the core samples in the well and well logs (employing an inversion process), a 3D intrusion model was generated. The gravity data is collected from 139 gravity stations across Wayang Windu with an average spacing of 1 to 2 km. This gravity data was processed to generate a Complete Bouguer Anomaly (CBA) map (Figure 6). The CBA map displays high-density bodies located beneath WWA and WWF pads in the south and MBD, MBA, & MBB pads in the north.

The density values from the gravity data and core samples were tied into the well. The density value obtained from the well log was also incorporated. Both data sets have covered the range from the northernmost production wells at MBB to the southernmost injection wells at WWW, providing adequate coverage (Figure 6).

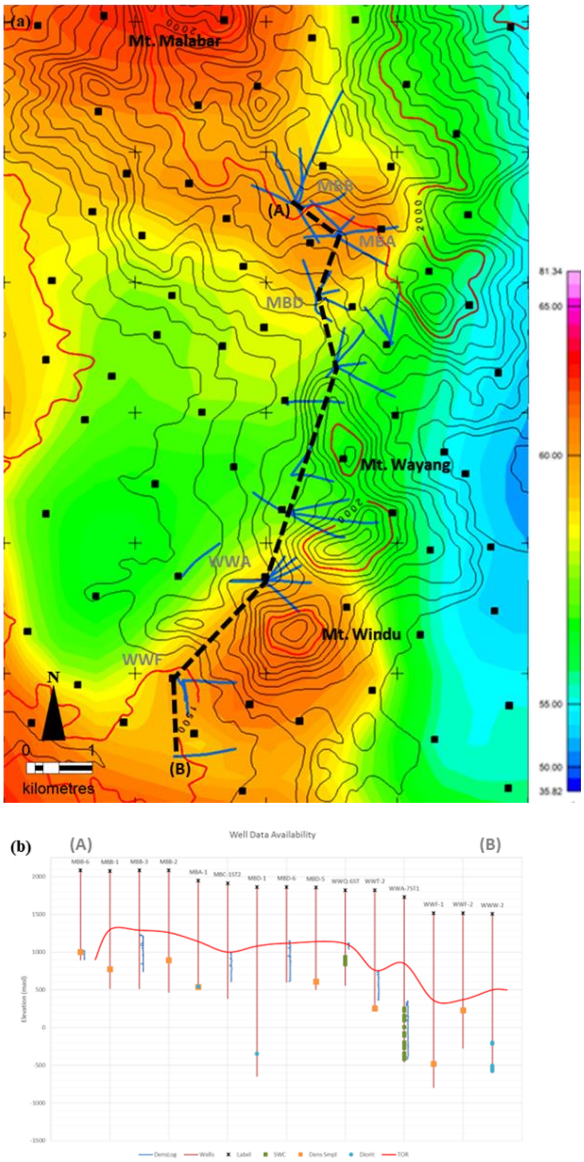

Figure 6: (a) The CBA map of Wayang Windu where the high-density body observed below WWA-WWF in the south and MBD-MBA-MBB in the north. (b) The distribution of density value from the core sample and density log in Wayang Windu with coverage from the northern area (A) to the southern area (B).

A background value of 2.4 gr/cc was used to simulate the intrusion for a CBA. After analyzing the cutting and core samples obtained from Wayang Windu, it can be concluded that the intrusion rock is microdiorite. This microdiorite is assumed to have a density of 2.8 gr/cc (Telford, 1978).

A 3D model of the CBA with the additional constraint of density data from the core and density log gives high-density body (dome pattern) in the southern part and the northern part of Wayang Windu with the empty space in between. Applying 0.4 gr/cc contrast density or matching to 2.8 gr/cc density shows a doming shape of the intrusion model, deeper to the north in the north body but invariant in the south body (Figure 7). This high-density body will be used as a guide to construct the 3D Intrusion model by transferring the information into the iso-surface of contrast density body (Figure 7). Considering the nature of the shape of the high-density body and distribution of the intrusion rock in the well, the 3D intrusion model in Wayang Windu is modeled as a big intrusion body with small dike to the shallowest part (Figure 7).

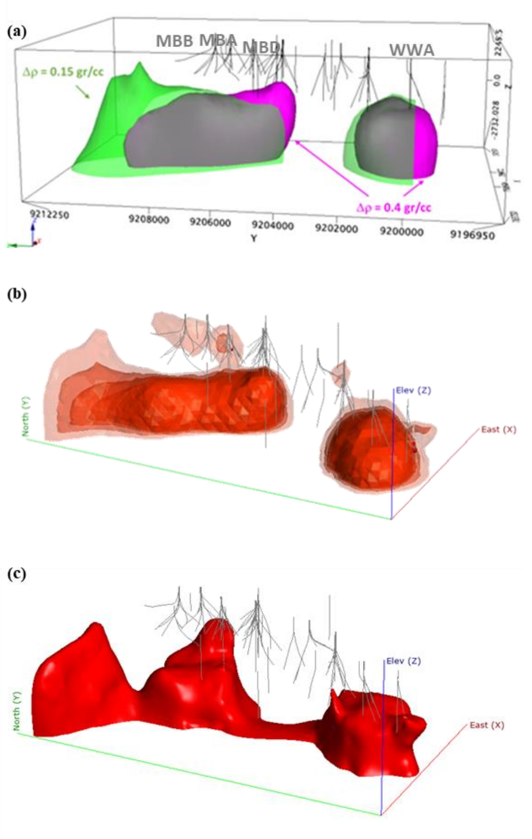

Figure 7: (a) The 3D model of the high-density body from CBA data with an additional constraint of density data from core and density logs. The iso-surface of contrast density uses values of 0.15 gr/cc (green) and 0.4 gr/cc (purple). (b) The iso-surface of the contrast density body which has been transferred into the modeling software, is incorporated with intrusion data obtained from cuttings in the well, as the basis of 3D intrusion model (c) The integrated 3D intrusion model of Wayang Windu was developed after considering the natural shape of 3D high-density body and distribution of intrusion data in the well.

4. FRACTURE DRIVERS AND DFN

4.1. Fracture Drivers

To create a Discrete Fracture Network for FCOWP purposes, Wayang Windu applied four fracture drivers. The simplified explanation and the relationship between the fracture drivers and Updated Geological Structure and 3D Intrusion Model are discussed below:

- Natural Fracture Prediction (NFP) is a fracture driver representing the stress perturbations in the reservoir rock at interpreted fault zone (bends, intersections, and tips of faults). The NFP uses geomechanically simulation and stress inversion techniques to model a heterogeneous local paleo-stress field from the interpreted fault geometry and interpreted regional stress field (Maerten et al., 2016). The updated geological structure is the major input, together with the interpreted regional stress.

- Distance to Fault (DTF) is a fracture driver that explains generated fractures within a damage zone of the faults. The DTF is based on the existence of fractures that are commonly observed at a specific distance on both sides of an interpreted fault with orientations mostly sub-parallel to the interpreted fault plane. Specific decreasing frequency is usually applied at a certain distance which represented by a mathematical equation (decay law). In this driver, the updated geological structure plays a major role, as the basis of the application of the decay law.

- Intrusion Geomechanics (IG) is a fracture driver which controls the fractures produced from to pressurized emplacement of the intrusive body into the reservoir rocks. The intrusion body creates local stress and disturbs the regional stress of the reservoir rock. The 3D Intrusion model is the main input in this driver, accompanied by the interpreted regional stress field.

- Thermal Cooling (TC) is a fracture driver that produces fractures caused by thermal expansion and contraction of the intrusive body and the reservoir rocks. As with the DTF, a specific distance to the intrusion margin is applied where the fracture intensity decaying follows a specific decay equation (decay law). While the fracture intensity is constant inside the intrusion body. The 3D intrusion model is the sole input for this driver.

To validate the fracture drivers, the fractures resulting from each driver, in sequence, are compared to the fractures from the wells. The fractures from the wells which have the same characteristic as the fractures derived from the fracture drivers are identified and categorized as explained fractures. Remaining fractures from this process or unexplained fractures are categorized as residual fractures and can be dealt with stochastically.

Two geochronological orders (scenarios) have been considered in Wayang Windu to compare the impact of the Fracture Drivers on the frequency of explained fracture. The first scenario focused on the impact of intrusion related fracture drivers (IG and TC) then followed by the effect of structure related fracture drivers (NFP and DTF). The second scenario considers the influence of structure related fracture drivers first and followed by the control of intrusion related fracture drivers.

The explained fracture frequency from both scenarios can be seen in Table 1 below. From the total of 6,374 fractures identified from the well logs, each scenario can explain more than 90% of the fractures and both of them have residual fractures of <10% (7.5% and 9.3%, respectively). However, the first scenario gives explained fractures that were dominated by Thermal Cooling (68.8%) while the second scenario determines explained fractures where Thermal Cooling and Natural Fracture Production have comparable percentages (38.4% and 35.3%). Considering the regional setting in Wayang Windu which shows structural controls developed before intrusion controls, it was decided that the second scenario should be used in DFN creation.

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Fracture Drivers	Scenario-1		Scenario-2	
	Number of Fractures	Percentage	Number of Fractures	Percentage
IG	997	15.6%	864	13.6%
TC	4388	68.8%	2450	38.4%
NFP	502	7.9%	2252	35.3%
DTF	12	0.2%	213	3.3%
Residual	475	7.5%	595	9.3%
Total	**6374**		**6374**	

Table 1: The fractures frequency profile for both the first and second scenarios. The residual fractures are < 10%, however, the first scenario is dominated by the TC fracture driver. While the second scenario shows a balanced TC and NFP fracture driver.

4.2. Discrete Fracture Network (DFN)

Applying the second scenario to DFN creation workflows results in ~9.5 million fractures observed in Wayang Windu's DFN. By comparing the properties of the fractures in the DFN with the fractures from the wells, the degree of goodness of fit of both sets of fractures can be obtained. Two fracture parameters are extracted (dip azimuth and dip angle) and compared in the graph below (Figure 8). The distribution of the parameters shows a high degree of goodness of fit.

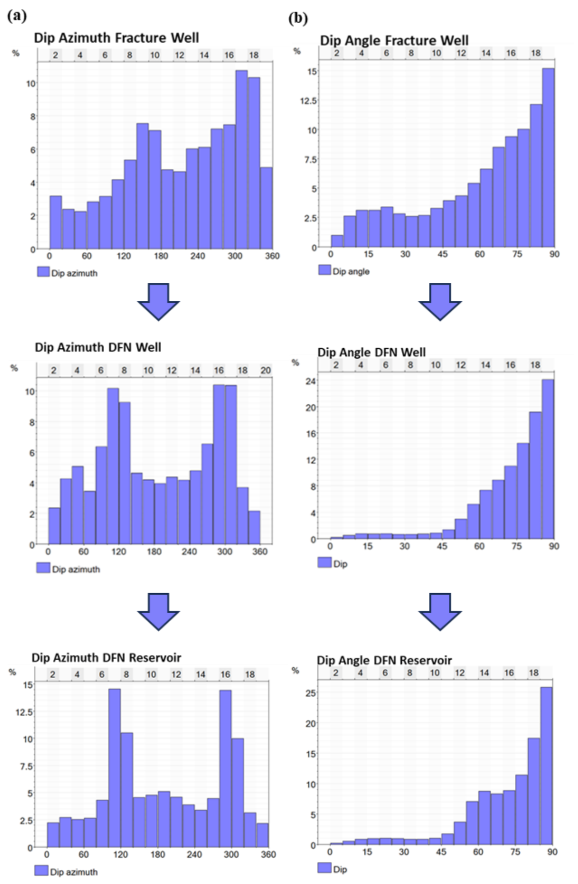

Figure 8: The pattern of fractures dip azimuth (a) and dip angle (b) from the fractures in the wells and from the fractures in the DFN in the well and the reservoir. The peak indicates a high degree of goodness of fit. Thus, it might be concluded that the DFN fractures are representative of actual fracture in the Wayang Windu reservoir.

The dip azimuth of the fractures in the well has twin peaks of between 120-130º and 300º. The dip azimuth of the DFN fractures projected to the well and DFN fractures in the reservoir showing peaks at ~120º and 300º. The dip angle of fractures in the well has a near vertical peak (~90º) where the value increases from the dip angle ~45º. This pattern is also observed in the DFN fractures projected on to the well trace and in the DFN fractures in the reservoir (Figure 8). Thus, it might be concluded that the DFN fractures are acceptable as representations of actual fracture in the Wayang Windu reservoir.

5. CONCLUSION

The latest data and new approaches were used to update the geological structure and 3D intrusion model in Wayang Windu. This output was then used as an input for the fracture drivers to generate a DFN, a part of the FCOWP workflow. Two different scenarios for the sequence of fracture drivers were tested against the actual fractures from the well, with the second scenario being accepted due to its accordance with the regional setting of Wayang Windu. By incorporating validated fracture drivers in the DFN creation, the resulting DFN contains fractures with properties comparable to those from the wells. These updated structural and 3D intrusion models are considered to be reliable fracture drivers to predict permeability distributions in Wayang Windu for better selection of subsurface targets and well placement.

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