Fault-related fractures characteristic of Kijang fault at Wayang Windu Geothermal field

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Abstract. Understanding the characteristic of permeability in the reservoir is a challenge in order to enhance well targeting success ratio. The permeability of a geothermal field is often related to the structure control and/or the rock type of the reservoir. The availability of interconnected fractures as the secondary permeability in the reservoir is believed to give larger contribution to the production instead of matrix permeability. This study is aimed to gain more insights of fractures characteristic related to Kijang fault zone, as one of the most productive fault zone in the Wayang Windu geothermal field. Kijang fault zone is a NE-SW trending interpreted fault located at the northern part of the field, where the wells with the highest production rate are located. Better understanding of the permeable fractures related to the fault is expected by having further analysis of geologic and geophysics data. The approach using borehole image as main data and using both microearthquake focal mechanism and shear-wave splitting as support data for beyond the wells concluded NE-SW dominant fracture orientation. The dominant fracture orientation derived from borehole image ranged from N 40°E to N 50°E, while from microearthquake analysis ranged from N 30°E to N 50°E.

1. Introduction

The Wayang Windu geothermal field is located about 40 km south of Bandung, capital province of West Java (Figure 1). The commercial production was started on 2000 for Unit-1 and continued by Unit-2 on 2009. The current total installed capacity of the field is 227 MWe from both Unit-1 (110 MWe) and Unit-2 (117 MWe). It needs 450 kg/s of steam to maintain generation of 227 MWe.

The field is associated with andesitic stratovolcanos of the Sunda Volcanic Arc, resulted from subduction of Australian plate underneath the Eurasian plate at the southern part of West Java. This process controls structure and volcanism in the area. A number of geothermal fields associated with high terrain andesitic stratovolcanoes can be found neighboring Wayang Windu field, such as: Darajat, Kamojang, Salak, Tampomas, Tangkuban Perahu, Karaha-Talaga Bodas, and Patuha.

Wayang Windu geothermal system is interpreted as transitional between vapor-dominated and liquid-dominated. The vapor-dominated reservoir is elongated from the northern part of the field towards the south, where the thickness decreases. From central to southern area, the reservoir is more liquid-dominated \cite{2}. About 90\% of the steam production is extracted from vapor-dominated reservoir at the northern part of the field.
The study will focus on understanding fracture characteristic at the northern part of the field and its correlation with the interpreted fault. Data used in this study are interpreted fault, borehole images of the northern wells, and microearthquake advance processing results, such as moment tensor/focal mechanism and shear-wave splitting.

Figure 1. Location of geothermal fields in West Java, Indonesia.

2. Geology Structure
The major faults in the Wayang Windu geothermal field is dominated by WNW, NW, and NE structure trends. This condition is a result of combination between regional (tectonic) and local (volcanism) activities. Different ages of volcanism in Java is shown by having early Tertiary volcanoes at the northern part of West Java, whilst volcanoes of late Tertiary to Quaternary can be found in its southern part of the island [11], where Wayang Windu geothermal field is located.

The interpreted faults (Figure 2) in the Wayang Windu geothermal field were derived from integrated surface and subsurface structure data. The interpretation of surface structure was analyzed from image data (satellite imageries and aerial photos) and validated by using ground data from geological structure mapping data (clay gouge, slickenslide, brecciation, and thermal manifestations: alteration, hot spring and fumarole). The surface data were integrated with subsurface data from wells, i.e. feedzones location from PTS surveys, fracture distribution and orientation from borehole image (BHI), and drilling information [6].

Based on the production data, wells at the northern area are the most productive wells. How to correlate the structure-related permeability in the area became interesting. The “favorite” faults in the northern part of the field, where the biggest steam producer are located, are Kijang, Cibitung, and Cibitung-1 faults. This paper will be focused on representing fracture characteristic of Kijang fault that is penetrated by MBB-2, MBB-5, MBA-3, MBA-4, MBD-3 and MBD-6 wells with current total steam productivity more than 77 MWe.
2.1. **Fault Damage Zones**

A damage zone is a three-dimensional area of wall rocks deformation around the fault surface. It is caused by initiation, propagation, interaction and buildup of slips along the faults [8]. The variety of fault damage zones depends on its position within and around the fault. It was divided into wall-, linking- and tip-damage zones (Figure 3).

Fault damage zones will be permeable if it has interconnected open space fractures, where fluid could travel through. In terms of a geothermal field, understanding permeable fault damage zones is more complicated due to alteration that occurs as the result of hydrothermal activities. It needs more information such as borehole image data to understand the characteristic of fracture that occurs in the fault damage zones.

![Figure 2. Wayang Windu interpreted structure map based on integrated surface and subsurface data (red line).](image-url)
Figure 3. Schematic diagram of the principal location of damage zones in the strike-slip faults regime [8].

2.2. Fracture Data
There are 20 wells with borehole image data (FMS, FMI, and xRMI), located mostly in the northern part of the field. Borehole image data are best representing in situ fracture distribution along the wells. Natural fractures typically appear in sinusoidal shape of pre-existing discontinuities.

Open fractures normally have darker color sinusoidal appearance, while the sinusoidal of partial open fractures are not continuously dark (Figure 14). The dark color indicates higher value of conductivity, since the wireline logging measures the resistivity of the formation. The conductive readings is interpreted as open space/fracture filled with conductive fluid during survey. Both open and partial open fracture are believed to be the conduit of the fluid flow in the reservoir.

Kijang fault is intersected by four wells with borehole image data. Figure 5 below illustrates the orientation of fracture trending of MBB-2, MBA-4, MBA-3, and MBD-6 wells. The fracture orientation is dominated by NE-SW trend with azimuth of N 40° E to N 50° E. MBB-2 well fracture data shows a discrepancy in the direction of -30° to 45° NE. The divergent fractures orientation of this well is probably due to penetrating the multiple faults, i.e. Kijang, Gambung Selatan, and the tip of Haneut faults.

The interval depth of fractures data varies in each well. The fracture data used for this study are selected within the reservoir section, with elevation range of 600 to 1200 masl.

Figure 4. Example of borehole image (xRMI) interpretation. The open fractures (blue) and partial-open fractures (red).
3. Microearthquake

Microearthquakes are small earthquake with moment magnitude less than 3 [10], with the frequency ranging between ~2 to >50 Hz, and the differences between P-wave and S-wave tend to be less than 3 seconds [9]. Generally, microearthquakes occurs in the reservoir due to the stress distribution changes. The significant changes to produce events can be caused by injection or exploitation activities, local tectonic, and volcanic activities.

The first microearthquake monitoring in Wayang Windu geothermal field was carried out in 1998. The aim was to monitor seismicity induced by injection test carried out in wells WWA-2, WWW-1 and...
WWF-1. Followed by the surveys in 2005 to monitor water injected to WWS-1, WWQ-3, and MBD-2 wells; and in 2007 water injected to MBB-1. The first continuous monitoring network was deployed in 2011, by installing 10 permanent seismic stations throughout the field. Additional monitoring stations were deployed in 2012, with more than 30 seismic monitoring stations installed. Thousands of events were successfully detected since the first monitoring (Figure 6). The cluster located at the northern part of the field is reasonable, due to most of the steam productivity coming from that area.

![Figure 6](image)

**Figure 6.** Microearthquake hypocenters location of 1998 – 2015 data acquisition.

Different approach of analysis and processing was applied on the data to enrich understanding of the reservoir characteristic. Those are hypocenter determination, hypocenter relocation, seismic tomography, focal mechanism, local magnitude calculation, and shear-wave splitting analysis. Two
methods were highlighted in this study: focal mechanism and shear-wave splitting analysis. Focal mechanism will give an idea of the hypocenter fracture plane orientation, whilst shear-wave splitting will help understand the medium anisotropy where the seismic waves propagated through.

3.1. Shear-Wave Splitting Analysis
The phenomena of shear-wave splitting occur when shear-wave travels through the anisotropic media and polarized to be Sfast and Sslow. Both shear waves are known to be orthogonal to each other. Sfast is parallel to the fracture orientation or anisotropic surface. Results of the Sfast polarization orientation calculation will be similar to the anisotropy fracture strike orientation identification. Therefore, calculation was conducted for the analysis.

There are 1142 microearthquake events detected along 2014 and 2015, distributed mostly within the interval elevation of 1 km asl to 6 km bsl. The calculated VP/Vs ratio from Wadati Diagram is about 1.7 (Figure 7) and the critical angle is ~36° [4]. Critical angle defined by \( i_c = \sin^{-1} (VS/VP) \) and was stated as the important restriction to the shear-wave splitting analysis. [5]. The critical angle was used to limit the arriving rays, because if the incidence was greater than \( i_c \), then the incoming waveform will be distorted due to strong interaction with the free surface [3].

![Wadati Diagram](image)

**Figure 7.** Wadati diagram of events of 2014 - 2015 shows VP/Vs ratio of 1.7 [4].

Strike of the leading shear-waves was calculated by utilizing rotation correlation method. Rotation correlation was applied to both horizontal components, NS and EW. Both waveforms were rotated at the interval angle from 0° to 180° with the increment of 0.01 second. The correlation applied within the time window of -0.1 second before Sfast and +0.1 second after Sslow [4]. The polarization of the rotated particle motion of the maximum correlation was interpreted as the strike of fracture anisotropy under the assumption that the splitting waves are induced by the presence of oriented fractures in a homogeneous medium [5].
Figure 8. Distribution of MEQ events 2014 - 2015. Rose diagrams represent $S_{\text{fast}}$ orientation of each monitoring stations.

Above are the location of seismic stations and its representative rose diagram of $S_{\text{fast}}$ orientations. There is one station (S35) located at the apex of Kijang fault and close to the intersection with Pejaten fault. The rose diagram in Figure 8, shows two direction having the maximum occurrence of $S_{\text{fast}}$ azimuth, N 45° E and N 100° E. S37 is located near MBE pad, with NE-SW $S_{\text{fast}}$ trending, while S22 and S36 represent E-W orientation.
3.2. Focal Mechanism
Focal mechanism results give information about the orientations of fault plane and the movement based on geographical coordinate system. There are two types of focal mechanism occurring, double-couple (DC) and non-double-couple (non-DC). The double couple mechanism is caused by the tectonic activities, while non-double couple is commonly found in the reservoir case caused by the fluid flow in the reservoir. Thus, the focal mechanism model in the reservoir case needs full moment tensor inversion that accommodates DC and non-DC components, which could represent better information of microearthquake mechanism [9].

![Figure 9. Focal mechanism analysis result (beach balls) near Kijang Fault (thick red line) of 2014 data. Rose diagram represents the dominant fractures trending.](image-url)
Figure 9 illustrates fracture plane of events observed during continuous monitoring in 2014. The fractures show dominant strike of NE-SW and NW-SE [1]. The strike orientation of focal mechanism near Kijang fault show N 30° E to N 50° E trends, with dip inclination mostly between 60° to 90°. Minor NW-SE orientation can be found especially at the west of interpreted Kijang fault (see thick red line on Figure 9).

Another analysis was conducted on the swarm events occurred on May 20, 2015. Although the swarm events are located along the Cibitung fault, it gives similar general fractures strike of NE-SW trending (N 50° E to N 60° E) with dip inclination of 75° to 85° (see Figure 10). It gives better understanding of the extension of fracture strike towards the east.

**Figure 10.** Focal mechanism of swarm event on May 20, 2015 near Cibitung fault [7].

### 4. Summary and Conclusion

It was mentioned previously, that the fractures data acquired were located at elevation of 600 to 1200 masl, and events analyzed were located deeper than 1 km asl. The dominant strike orientation of fractures data ranged from N 40° E to N 50° E. Meanwhile, the fracture derived from microearthquake data have several orientations.

The rose diagram of the leading shear-waves polarization at station S35 shows two dominant orientation, N 45° E and N 100° E. The station is located within the perimeters of the two faults intersection, Kijang and Pejaten faults. This condition leads to the interpretation that two general trends of S\text{fast} are caused by fracturing system related to both faults. On the other hand, the focal mechanism resulted in having similar azimuth trend with the fracture data, which is N 30° E to N 50° E (Figure 9). The strong evident of fractures orientation related to Cibitung fault, is the azimuth trend of N 50° E to N 60° E, concluding that the fractures of Kijang fault might be extended or even have the same “origin” with Cibitung fault.

Meanwhile, the location of S22 and S36 are bounded by many faults (Figure 8). It became understandable knowing the fractures underneath both stations show sporadic distribution. This
condition could be due to damage zones of each fault which are superimposed with one another (Figure 3).

The fractures of Kijang fault are well distributed vertically and horizontally. The fractures orientation in the deeper part (below 600 masl) varies at the northern part of the field, as a result from the damage zones of the superimposed faults. Whilst in the shallower part along the fault from north to south, the fractures orientation is more convergent and have the same orientation as borehole image interpretation.

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