

Fracture Characteristics of Mount Pandan Geothermal Complex, East Java, Indonesia

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ABSTRACT

Fracture characterization and geological mapping had been performed in Mount Pandan area, East Java, Indonesia. This study area is composed by Tertiary sedimentary and Quaternary igneous rocks. Mount Pandan is one of an extraordinary stratovolcano in Java Island. It located in the middle of Kendeng Basin and in the north of Quaternary and Recent Volcano in Java Island.

A total of 765 shear fractures have been measured and analyzed in different lithologies and age. The common fracture orientations are NW - SE, W - E, and NE - SW trends. Fractures developing in Mount Pandan area controlled by Kendeng thrust fault, sinistral and dextral strike-slip fault, and normal fault. Fractures intensity and density also controlled by lithology in this area. Fracture intensity and density in Kalibeng marl is higher than other lithologies. 12 manifestations are mainly controlled by E-W trust fault, NE-SW sinistral fault, and NW-SE dextral fault. This fault becomes main porosity for geothermal fluid storage and flow. Fault Fracture Density (FFD) method was conduct to understand the correlation between fault and manifestation. The manifestation occurrence in high density value ranges between 0.002 - 0.0039 m/km².

The best way to distribute fracture in study area is by using model which built from discrete fracture network. Discrete fracture network aims to determine fracture porosity by using field data. The value of fracture porosity is varied from 0 - 0.0029 m³/m³ (0 - 0.29 %) with average porosity 0.0002 m³/m³ (0.02 %). This study is used to be an analogue of fault, fracture distribution and characteristic of Moun Pandan. Hopefully, the result of this study can be used for Mount Pandan geothermal development.

1. INTRODUCTION

Mount Pandan is located in Java Island, the most crowded island in the western part of Indonesia, the location is about 688 km SE from Jakarta (Figure 1). Mount Pandan is one of an extraordinary stratovolcano in Java Island. It located in the middle of Kendeng Basin and in the north of Quaternary and Recent Volcano in Java Island. Agastya et al. (2017) interpreted that the presence of the Mount Pandan at the same time with the process of folding and uplifting of Kendeng Basin. Hussein (2016) expected the Kendeng Basin is to begin uplift at the beginning of the Klitik limestone deposition, in early Pliocene. MEMR (2017) expected geothermal power capacity of Mount Pandan amounts to 60 MW and the plan of development (POD) is 40 MW.

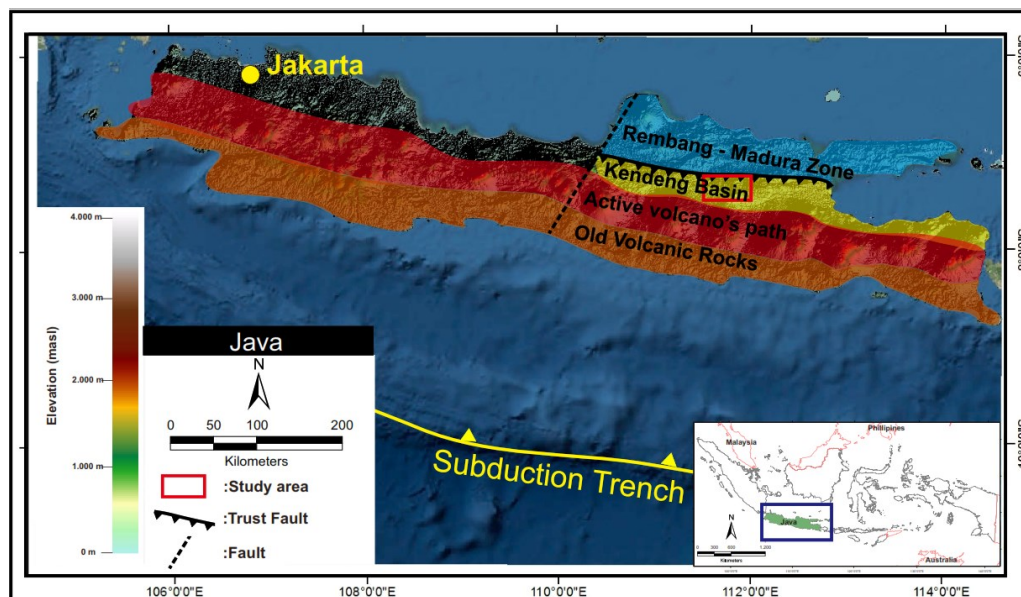


Figure 1: Location of studied area, Mount Pandan, East Java, Indonesia.

The geothermal resource in Mount Pandan is indicated by the presence of manifestations consisting of warm springs which associated with the late Neogene and Quaternary Fault along Quaternary volcanic in the middle of Kendeng Basin. In this study we use a combination of surface observation data. This research was assisted by using structural analyses and petrography thin section by using polarization microscope. This information is used to reconstruct geological setting and structural kinematic which associated with surface manifestation. Geological framework includes the distribution of lithology and structural environment, the presence of geothermal manifestation which integrated into Mount Pandan geothermal fracture model. This study methods adapt Sapiie et al. (2017) in Melange Bantimala Complex, South Sulawesi. This model was built by using discrete fracture network (DFN) with very limited measured fracture attribute. Hopefully, the result of this study can be used for Mount Pandan geothermal development.

2. MATERIALS AND METHODS

This study integrating several stages such as fieldwork observation and laboratory activity to achieve research objectives. Geological mapping is part of fieldwork activity to understand geological structure and stratigraphy within the area. Geological mapping also modified geological map of Bojonegoro which conducted by Pringgoprawiro and Sukido (1992) with new lithology boundary and structural interpretation. This fieldwork also supported by petrography thin section by using polarization microscope to support geological interpretation.

Geological structure interpreted from DEM SRTM (Digital Elevation Model Shuttle Radar Topographic Mission) and surface fieldwork observation. DEM SRTM help to provide regional structural lineaments which support by surface structural observation and measurement to interpret Mount Pandan geological structure. Structural lineaments also used to generate Fault and Fracture Density (FFD). FFD is a simple method used to assess highly structure density areas formed by interconnection of faults and fractures and it is applied in geothermal exploration to locate highly fractured areas (Suryantini and Wibowo, 2010). FFD values usually correlate well to thermal manifestations and associated subsurface reservoirs. There are 12 location which fault and fracture observed and measured.

A total of 765 shear fractures have been measured and analyzed in different lithologies and age, normal fault scrap, trust fault and strike-slip fault outcrops. The fracture modeling was constructed to perform conceptual visualization using DFN algorithm (Winberg et al., 2003 as cited in Sapiie et al, 2017). 3D modelling is constructed by using Petrel 2015. Main input data which used to generate DFN are fracture properties (length, aperture, orientation, dip angle, intensity) and lithology and fault distribution. Fracture geometry distribution is distributed by using stochastic based on Fisher Method (Fisher et al., 1987 as cited in Sapiie et al, 2017). The length of fractures is distributed using the power law and the aperture distributed using log normal. The main objective of 3D modelling is to determined and distributed fracture porosity using Oda method (Oda, 1985 as cited in Sapiie et al, 2017).

3. GEOLOGY OF STUDIED AREA

3.1 Stratigraphy

The stratigraphy of Mount Pandan can be simplified into Neogene sediments overlain by Quaternary volcanics, volcanoclastic and Recent sediments (Figure 2). Pringgoprawiro and Sukido (1992) explains that Neogene Sedimentary rock consisting Kerek Formation (Tmk), Kalibeng Formation (Tmk), Klitik Formation (Tpk), and Sonde Formation (Tpso). Kerek Formation consists marl, sandstone, claystone, and limestone. Kalibeng Formation consists of Globigerina massive marl, greenish and silty marl. At the upper of Kalibeng Formation, there is interfingering of Atas Angin Member characterized by volcanic sandstone, tuff, conglomerate and breccia. Klitik Formation consists of limestone, marl, and clay. Sonde Formation consists of intercalation between claystone and volcanic sandstone as an end of marine depositional series in the Upper Pliocene. The sedimentary rocks uplifted, folded, faulted and locally metamorphosed by Quaternary Andesite Intrusion. Pringgoprawiro and Sukido (1992) explain that Mount Pandan Formation consists of Pleistocene Andesite Breccia (Qpv) and Pleistocene Andesite Intrusions. Kabuh consists of conglomerate, sandstone and locally marl and clay intercalations. Notopuro consists of tuff, tuffaceous sandstone, and conglomerate.

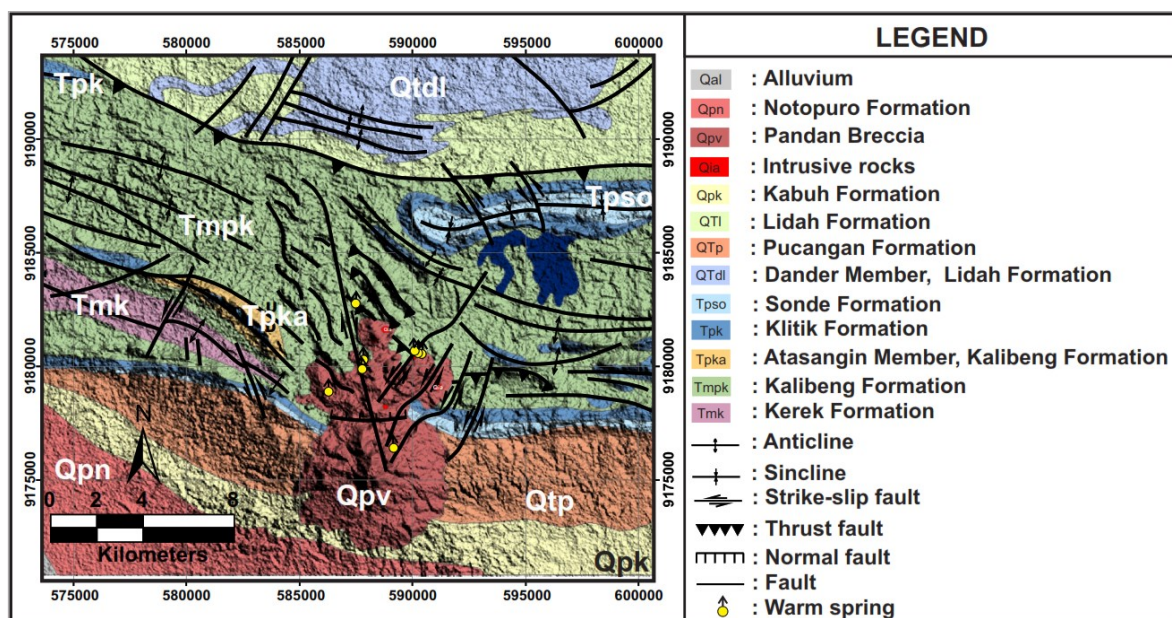


Figure 2: Geological map of Mount Pandan (modified from Pringgoprawiro and Sukido, 1992).

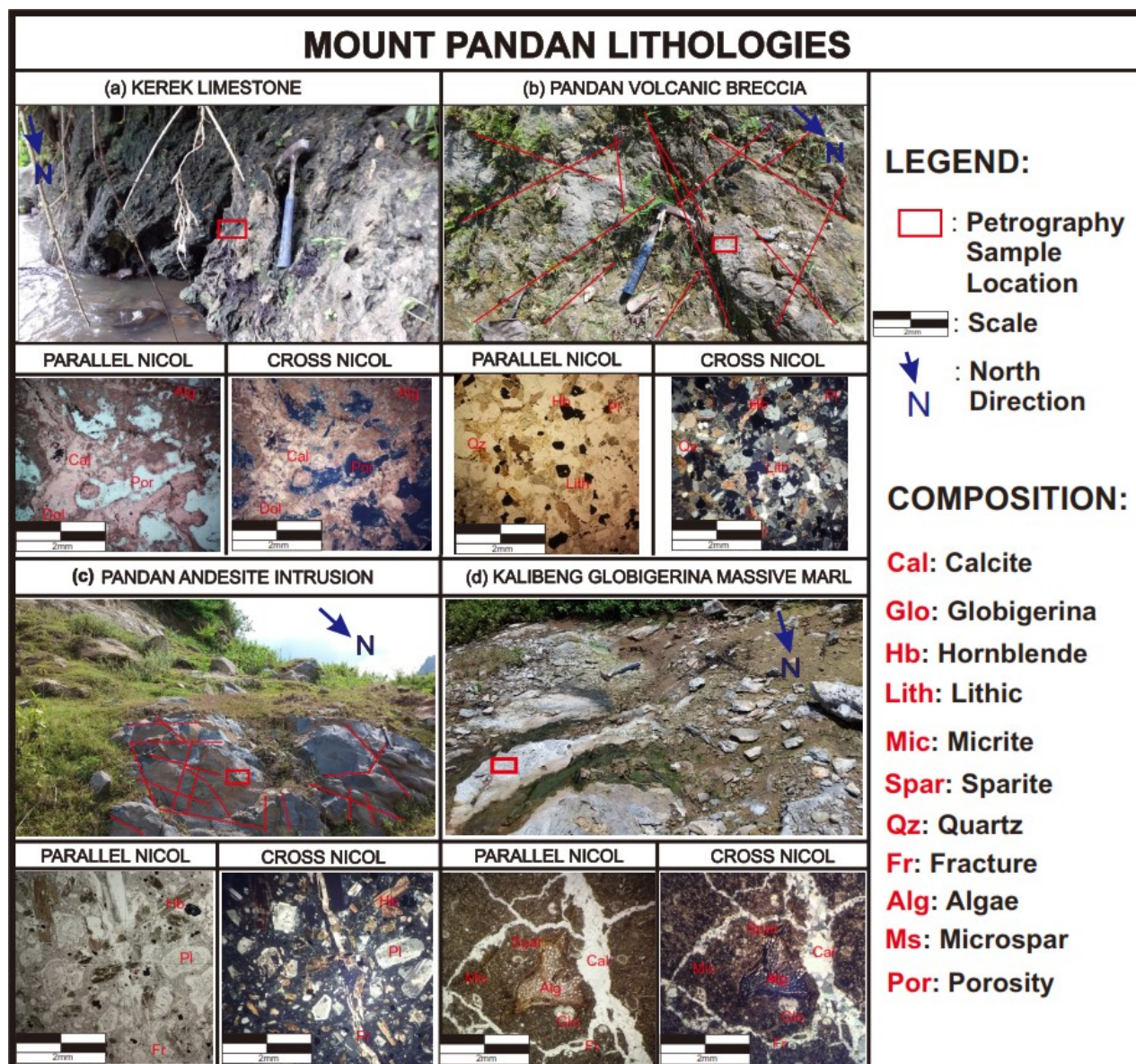


Figure 3: Mount Pandan rock characteristic. Top image is the outcrop and the bottom image is thin section analyzed with polarized microscope in parallel and cross nicol.

3.1.1 Kerek Limestone

This lithofacies consists of massive gray limestone. Based on the composition, the presence of algae fragment, organic clasts which almost changed into calcite, and carbonates cements like micrite and microspar indicate significant reworking of carbonate rocks. High intraclast porosity showed that this lithofacies is highly dissolved (Figure 3a).

3.1.2 Pandan Volcanic Breccia

This lithofacies is composed of angular to subangular fragments in a brown, grey, and black of coarse sand to pebble. The outcrop is mainly weathered and fractured. They occur in widely in study area. The fragment size usually is in the range of pebbles and cobbles with andesite fragment. The matrix of the deposits is commonly composed of lithic and tuff (Figure 3b).

3.1.3 Pandan Andesite Intrusion

The intrusion which identified in study area classified as intermediate and shallow intrusion. The texture is hypocrySTALLINE. Intermediate plagioclase is the most abundant phase with subordinate hornblende, clinopyroxene, amphibole, and quartz. The distribution of this andesite is localized in narrow area around 300-700m. Andesite characteristic can be seen in Figure 3c.

3.1.4 Kalibeng Globigerina Massive Marl

This lithofacies consists of gray carbonate siltstone and claystone (Figure 3d). Massive and parallel lamination is the dominant sedimentary structure. However, cross-bedding and convolute is also common. Based on the composition, the presence of foraminifera especially Globigerina, organic clasts, and carbonates cements indicate significant reworking of carbonate rocks. This lithofacies is spreaded widely in study area. From thinsection, this lithology is highly fractured and it filled by calcite.

3.2 Structure

Mount Pandan is located in fold-trust belt system. Major structure identification by using DEM SRTM help to provide regional structural lineaments. Study area has major E-W orientation based on structural lineaments (Figure 4). If we divide Mount Pandan and Kendeng area lineaments (Figure 4), Kendeng basin has E-W major orientation Mount Pandan has NE-SW. Some microfracture can be seen in Kalibeng marl and Pandan andesite intrusion (Figure 3). Kalibeng Marl shows high intensity of fracture than Pandan volcanic breccia.

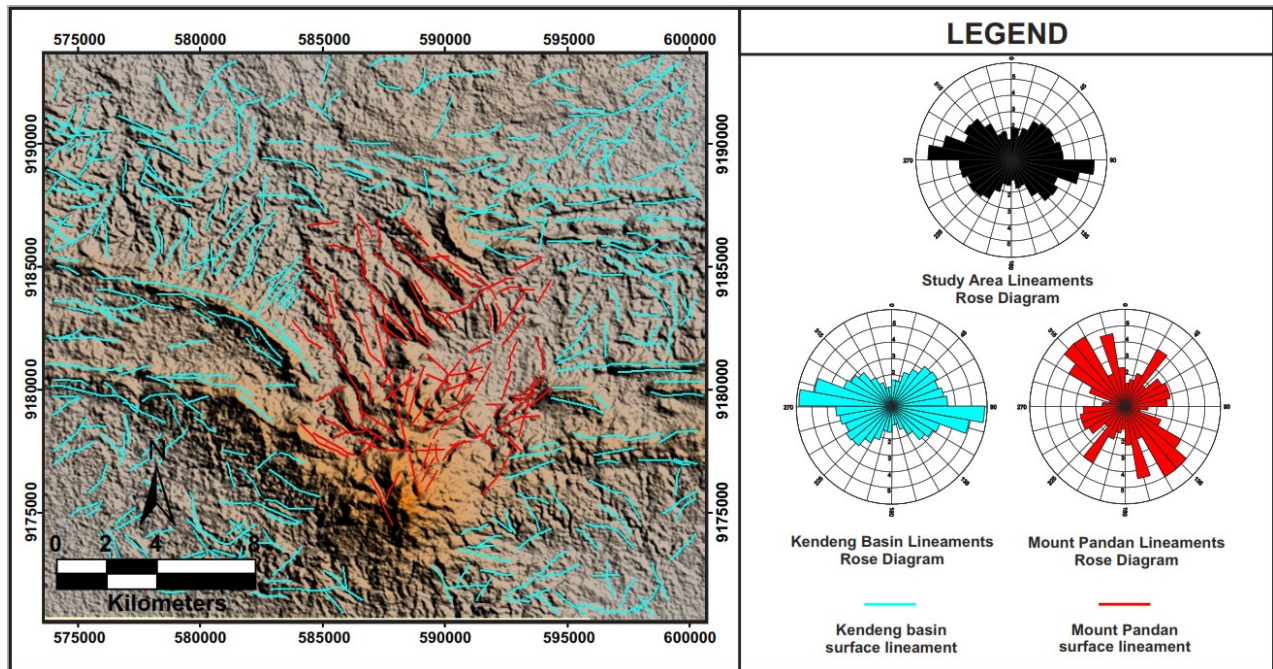


Figure 3: Mount Pandan rock characteristic. Top image is the outcrop and the bottom image is thin section analyzed with polarized microscope in parallel and cross nicol.

Structure data that has been collected are shear fracture data and fault with data. Faults data from outcrop (Figure 4) that had been collected and measured fault plane orientation. From field observation it can be seen that normal fault scrap has strike orientation N 268° E (fault plane relatively E-W). Left-slip fault plane has strike and dip orientation N 246° E/ 72° (fault plane relatively NE-SW), and trust fault has strike and dip orientation N 85° E/ 61° (fault plane relatively E-W). Outcrop fault represent major fault in Mount Pandan especially fault orientation.



Figure 4: Mount Pandan outcrop fault: (a) normal fault scrap outcrop (E-W orientation), (b) left slip fault outcrop (NE-SW orientation), (c) trust fault outcrop (E-W orientation).

A total of 765 surface measurements of shear fractures (minor faults). This data measured in andesite intrusion, Kalibeng marl, and Pandan volcanic breccia (Figure 5). Fracture properties such as orientation, dip angle, aperture and length can be seen in Figure 6. These fractures are shown in stereonet using lower hemisphere equal area. Kalibeng marl relatively has varied fracture orientation and dip angle than Pandan volcanic. Fracture orientation and dip angle depend on lithology and fault control. Dominant fracture orientation are NE-SW and NW-SE based on all fracture in all lithologies (Figure 6).

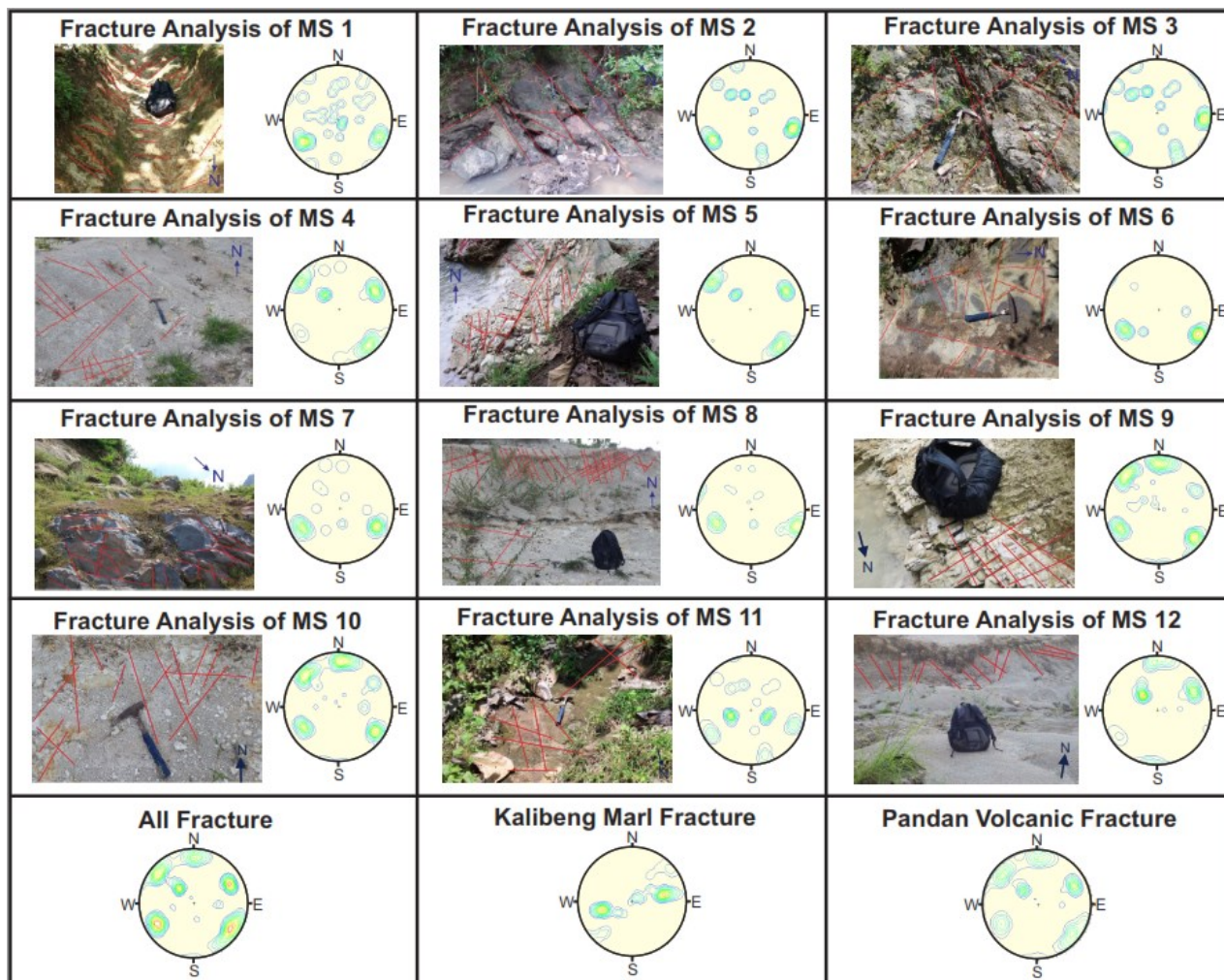


Figure 5: Mount Pandan fracture outcrops. Fracture orientation and dip angles showed by fracture intensity contour in stereographic projection.

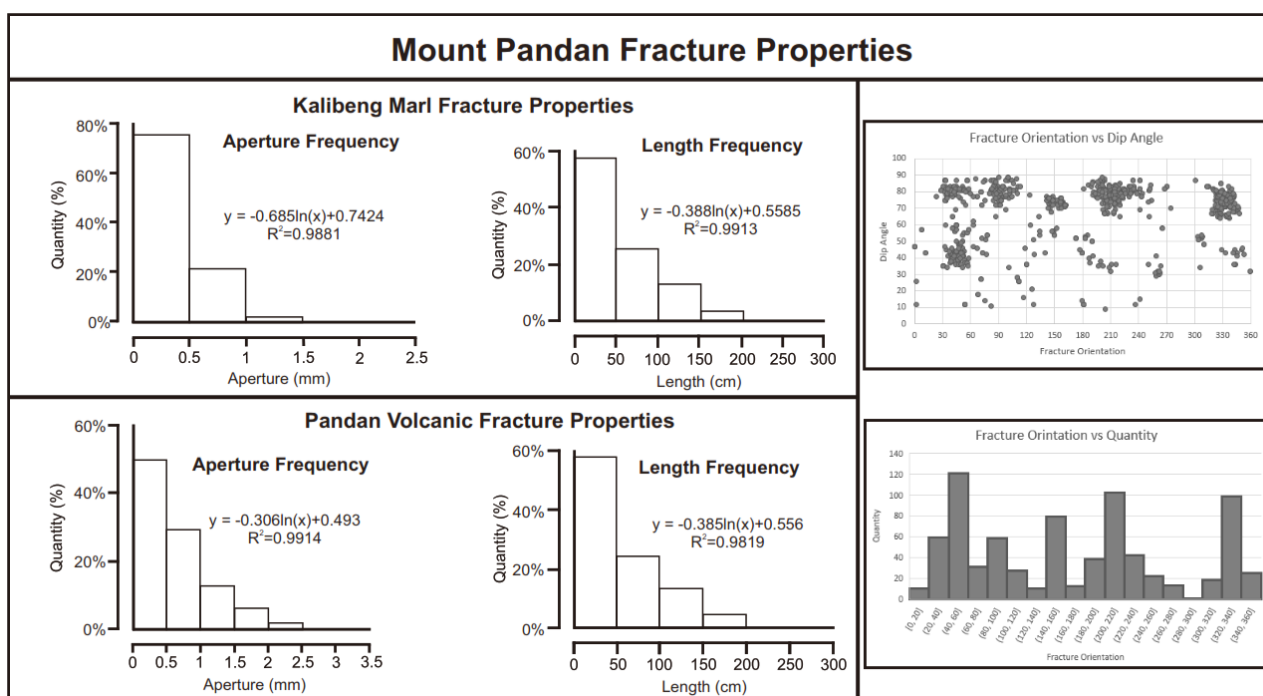


Figure 6: Mount Pandan fracture properties (aperture, length, orientation, and dip angle).

Besides fracture orientation and dip angle, there are another properties such as aperture and length. On figure 6, the best correlation equation between fracture size (aperture and length) is log normal correlation. Kalibeng marl has aperture range between 0-0.3 mm with an average value of 0.63 mm. Therefore, Kalibeng volcanic has larger values between 0-0.5 mm with an average value of 0.9 mm. Fracture length of Kalibeng marl and Pandan volcanic range between 0-200 m. Fracture properties are used for fracture modelling.

The location and distribution of measured data can be seen in Figure 7. Based on field measurement, Pandan breccia has average fracture intensity range 9 – 22.5 /m andesite has fracture intensity range between 20-22 /m, and Kalibeng Marl has major intensity range between 27-5-37.5 /m. Based on lineaments, fracture, and microfracture, it can be seen that Kalibeng marl has the highest intensity than other lithologies. Faults identified in the Mount Pandan field were interpreted using a variety of data including surface lineaments, surface fracture measurements, lithologic offset, and complement structure. The integration of these data has allowed us to resolve the structural pattern from surface to depth. Based on lineaments (Figure 3), fault analyses and fractures (Figure 5 and Figure 7), there were correlation between those.

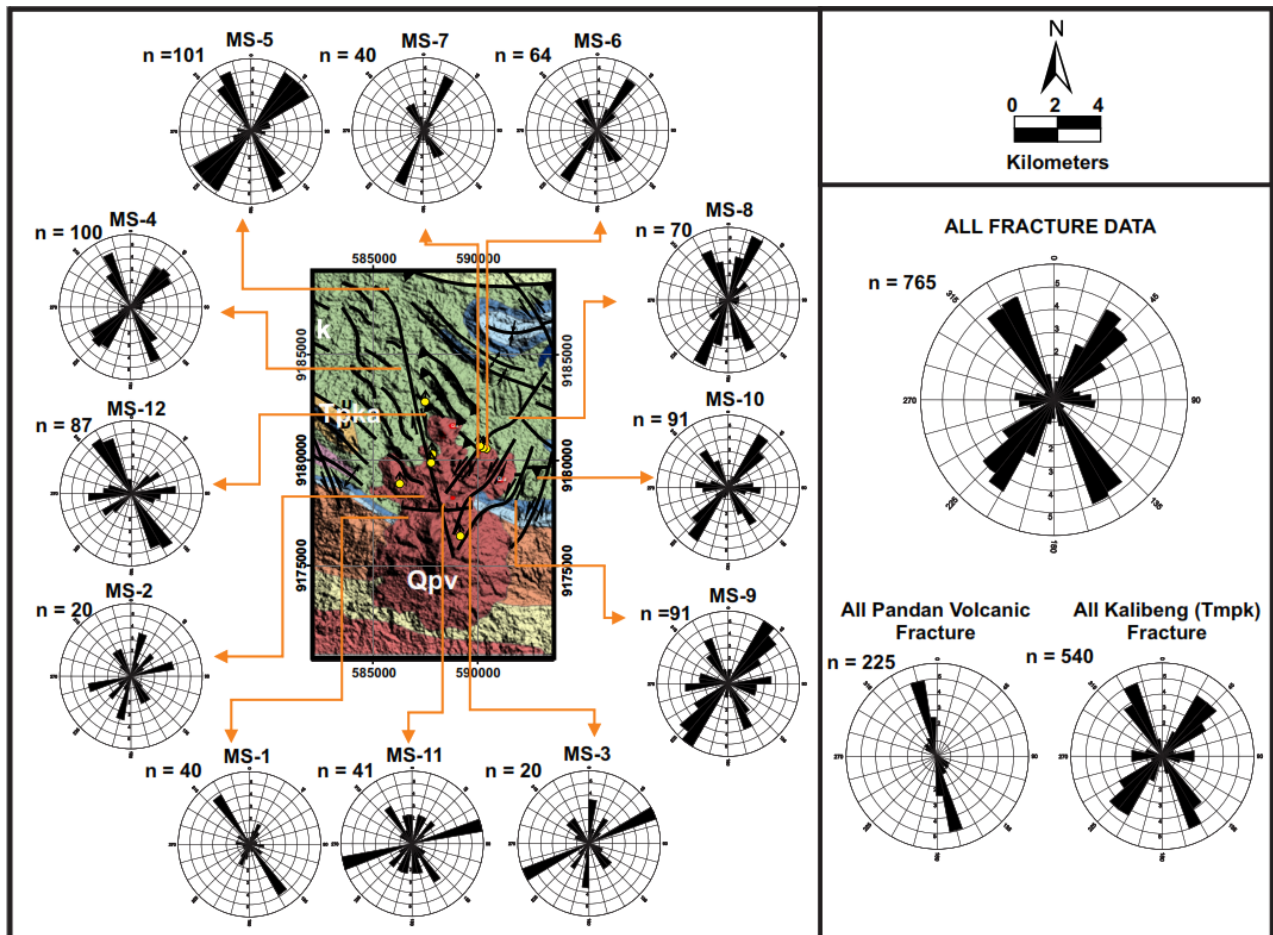


Figure 6: Map of interpreted geologic structures with fracture data from field geology mapping, rosette diagrams of surface fractures.

Fracture orientation depends on structural style. In Mount Pandan complex there were combination between fracture from different fault mechanism and fracture from fold. All paleostresses relatively show same direction, however we can divide into three processes based on structural forming mechanism and their forming time. The first process related to E-W trust fault formation and the second process related to NE-SW and NW-SE strike-slip fault, and the third process is related to E-W normal faulting. The tectonic process is related to regional contraction from subduction product in the south Java Island and volcanism of Mount Pandan. From field observation it started by deposition of Kerek and Kalibeng Formation during Middle Miocene – Lower Pliocene. It is being uplifted, folded, and faulted during Middle Pliocene – Late Pliocene. During Late Pliocene Klitik Formation formed and some of Kerek and Kalibeng Formation is eroded. The presence of the Mount Pandan at the same time with the process of folding and uplifting of Kendeng Basin during middle Pliocene and formed E-W trust fault and E-W fold. After that process, fold trust belt system is cut off by strike-slip and normal fault system.

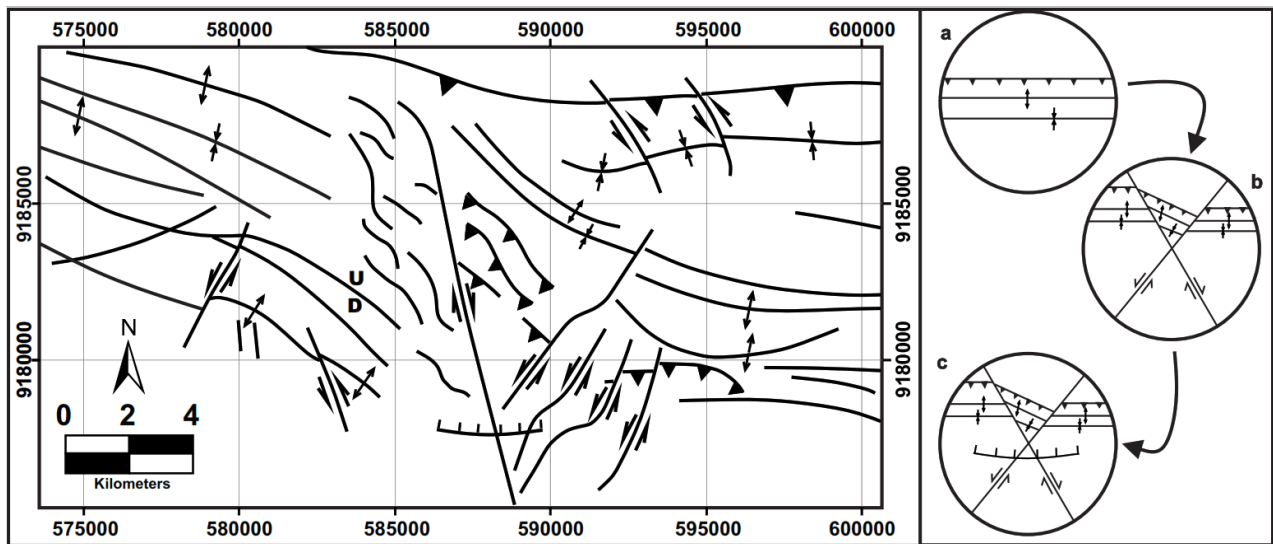


Figure 7: Structure map of Mount Pandan complex. (a) Fold and thrust fault forming (first phase), (b) strike slip fault forming (second phase), (c) normal fault forming (third phase).

Lineaments (Figure 3) also analyzed by using FFD method. The main objective is to see the correlation between lineaments (fault) and Pandan manifestation. There are 12 warm springs spread in Mount Pandan area. In this study area, FFD analyzed by calculating line density per kilometer square. From Figure 8, manifestation majority at high values. The values of manifestation occurrence between $0.002 - 0.0039 \text{ m/km}^2$. The main control of those surface manifestation is trust fault, strike slip, and intersection between those faults.

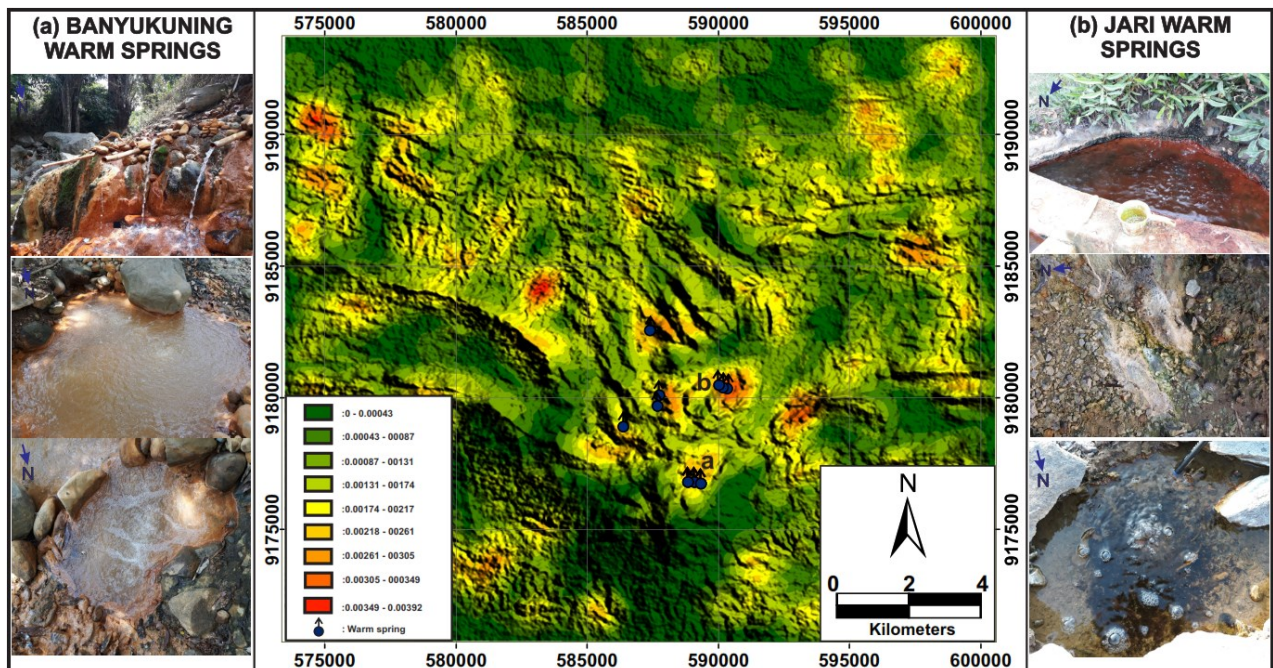


Figure 8: Fault Fracture Density map of Mount Pandan complex. (a) Banyukuning warm springs group and (b) Jari warm springs group.

4. FRACTURE MODELLING

In these study, fracture modelling was built by using Petrel 2015 software from Schlumberger. 3D cube model was generated by DEM SRTM and data from surface geology with constant base depth 250 m below sea level. This model was built by using structural gridding. The lithology was distributed using facies modelling from geological map. There are eleven lithology distributed into 3D cube model (Figure 9).

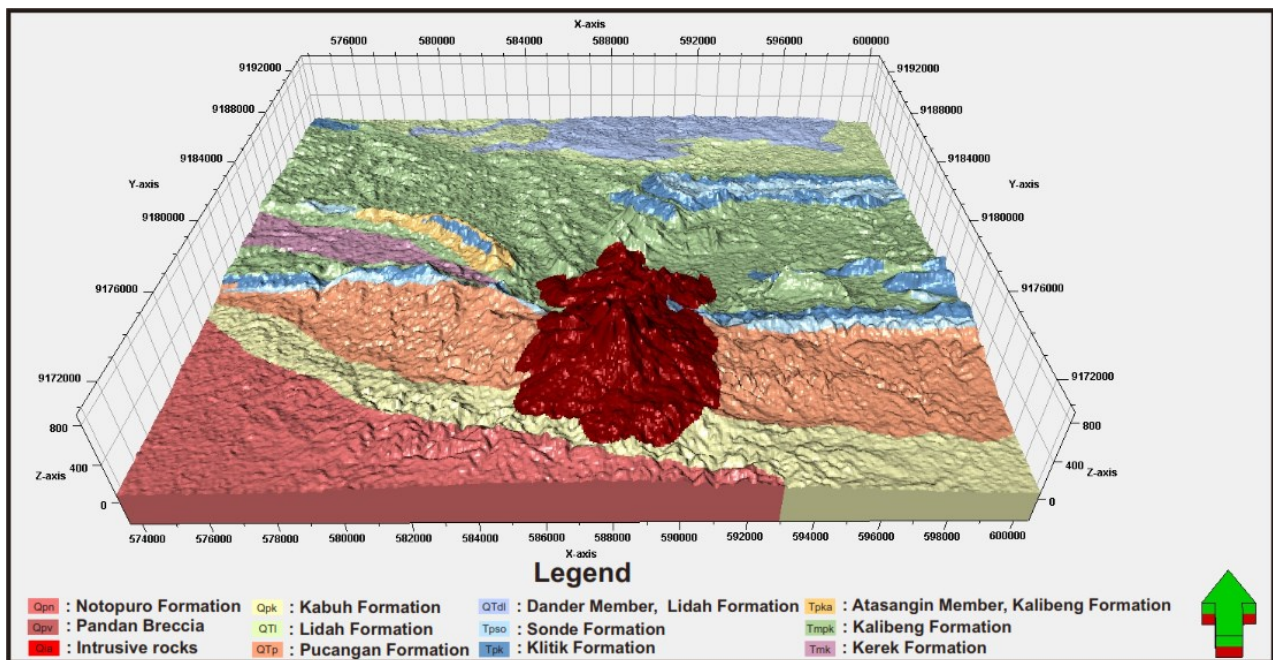


Figure 9: 3D geological model of Mount Pandan complex showing formation distribution.

Structural framework in this model was built by using fault framework. Fault delineated by using fault plane orientation in study area. To simplify the model due to no subsurface data, all fault dip was made vertical (90°). Total of 40 fault was built in this model (Figure 9). Those fault represent normal fault, thrust fault, and strike slip fault in study area.

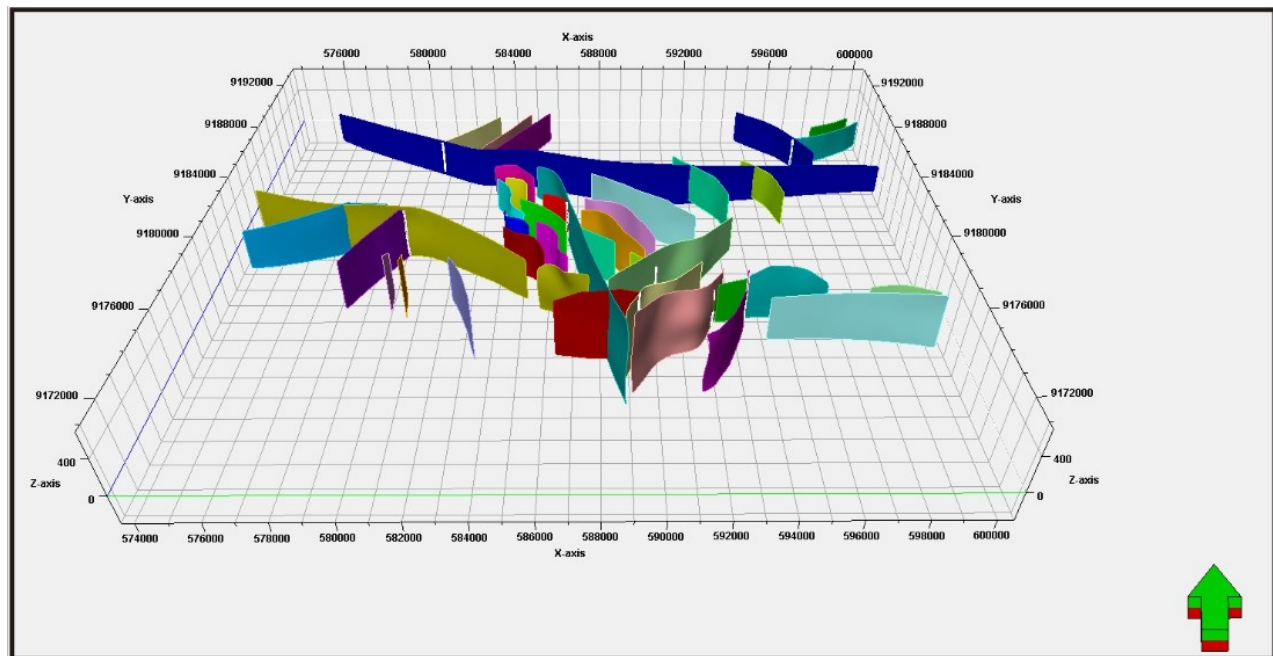


Figure 9: 3D fault model and distribution of Mount Pandan Complex.

The fracture data simulated to conduct fracture intensity for each location. These fracture intensity scaled up into grid model. Fracture intensity distribution (Figure 10) was built by using fracture intensity from field measurement and distance to fault core zone. The farther away from the fault make fracture intensity reduced. There are 12 location of fracture measurement. To distribute fracture properties, DFN method is needed to describe fracture network in the field as a model (Dershowitz et al., as cited in Sapiie et al., 2017). Fracture properties such as fracture orientation, dip angle, aperture and length is needed to be parameter of modelling. Fracture orientation and dip angle from 12 field measurement (Figure 6) were generated using Fisher method (Fisher et al., 1987 as cited in Sapiie et al., 2017). Fracture measurement in this study was collected in Kalibeng Marl, Pandan igneous and volcanic rocks around Mount Pandan complex. In these case the distribution only applied in Kalibeng marl (TmPk) and Pandan volcanic (Qpv). The distribution of fracture angles in much same way as for continues variable and gives more isotropic data for fracture deviation by using Fisher method (Sapiie et al., 2017). The length of fracture were distributed using power law. The aperture were distributed using log normal with width of aperture in Kalibeng marl range from 0 – 1.5 mm with average aperture 0.63 mm and aperture width from Pandan volcanic has range from 0 – 2.5 mm with average aperture 0.9 mm. Discrete fracture network result with stochastic can be seen in Figure 11. There are two major dominant fracture set for each lithologies. Kalibeng marl has major dip azimuth/dip angle N 135° E/40° and N 242° E/73°. Pandan volcanic has major dip azimuth/dip angle values N 74° E/57° and N 258° E/61°.

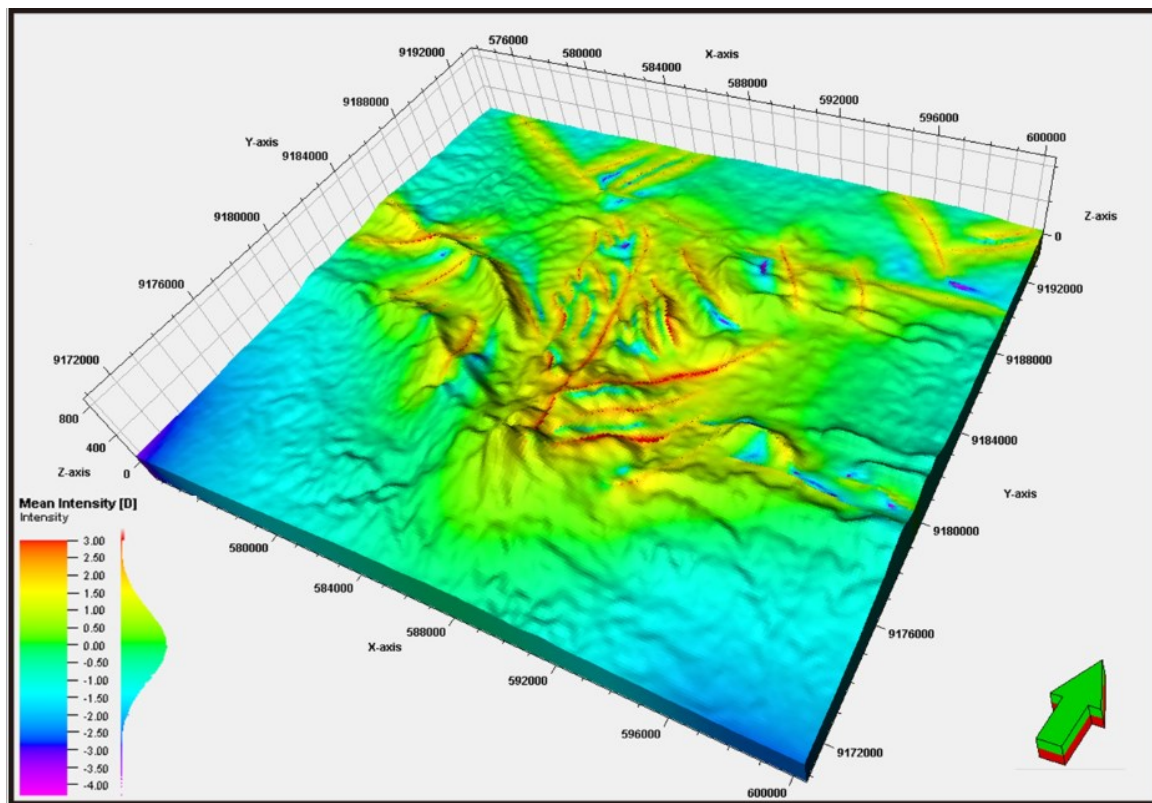


Figure 10: 3D fracture intensity of Mount Pandan Complex.

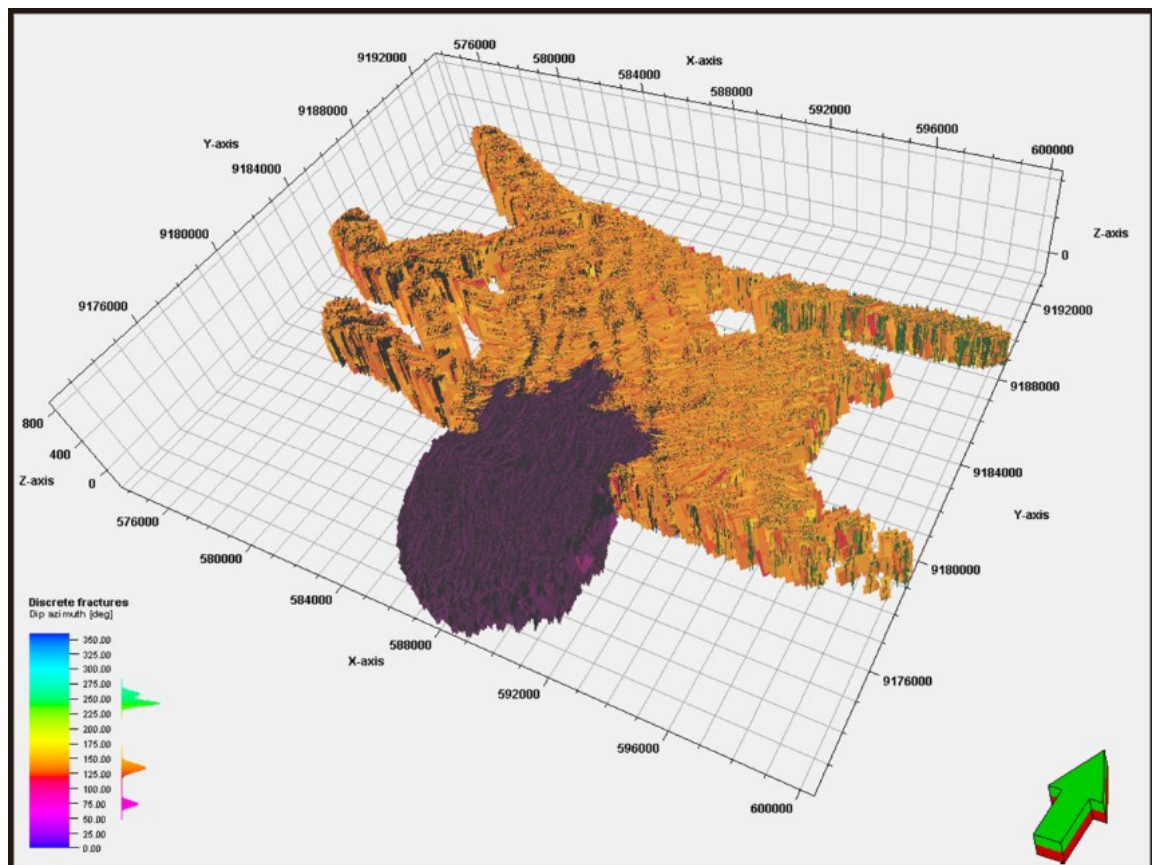


Figure 11: Discrete Fracture Networks (DFN) of Mount Pandan Complex.

Fracture can be a permeable zone for geothermal fluid movement and migration. The distribution of fracture porosity can be generated by using Oda method (Oda, 1985 as cited in Sapiie et al, 2017). The fracture porosity model can be seen in Figure 12. The porosity value is varies from 0 – 0.0029 m^3/m^3 (0 – 0.29 %) with average porosity 0.0002 m^3/m^3 (0.02 %). Fracture porosity values mainly controlled by faults properties, intensity, and lithology. The result of this modelling is prediction of fracture porosity based on surface fracture data on several lithologies in Mount Pandan area. This result may be different with subsurface due to lithology control and

another structure in subsurface. Lithologies is the main control of fracture distribution in subsurface especially in Kalibeng Marl or shale. As we know shale or marl is very ductile and it still have fluid trapped in their matrix shallow depth. Tectonic effect of this lithology is different from volcanic product of Mount Pandan. The result of these model can be used for well targeting and field development.

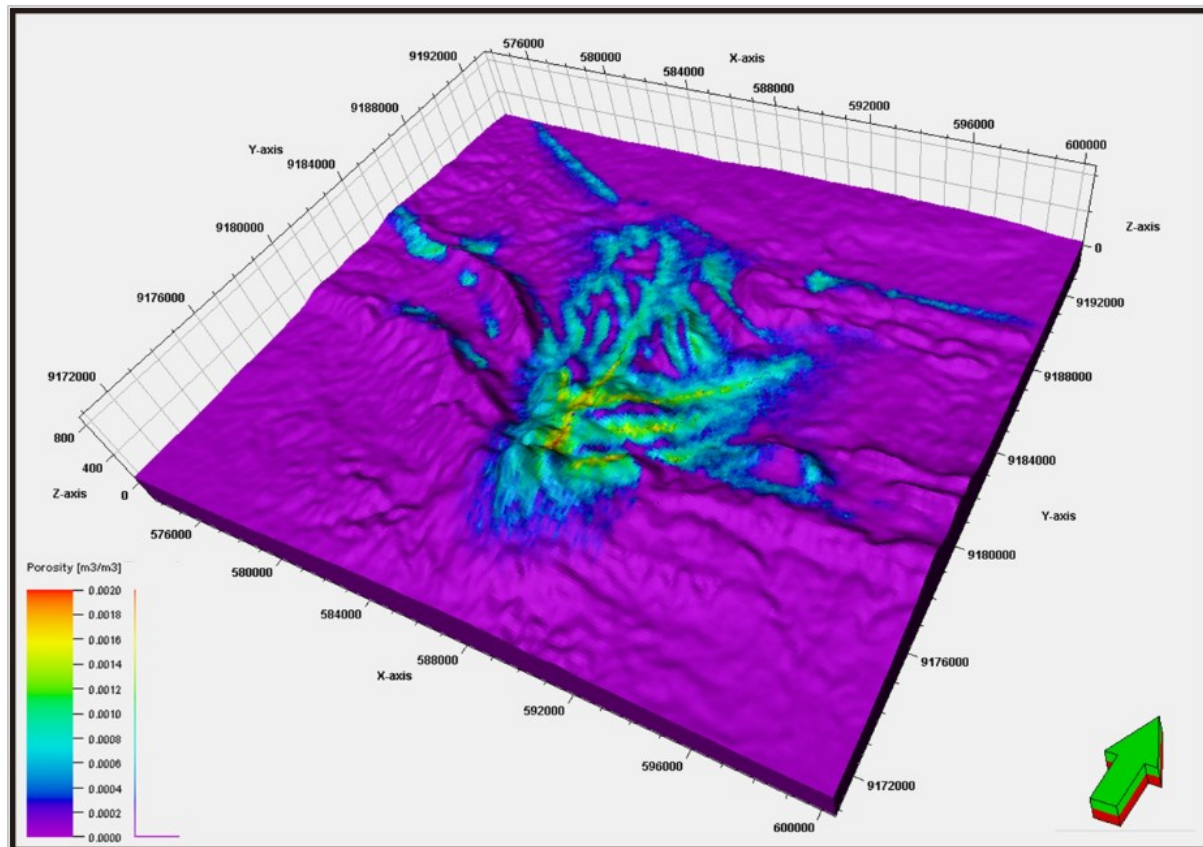


Figure 12: Fracture porosity distribution model of Mount Pandan Complex.

5. CONCLUSION

A total of 12 location of fracture and fault measurement with 765 shear fractures. The main fracture orientation are relatively NE-SW, NW-SE, and E-W. Kalibeng Marl has highest intensity than the other lithologies due to fault control in this lithology. There are three major faults in study area consists of trust fault (E-W), left slip fault (NE-SW), right slip fault (NW-SE) and normal fault (E-W). The manifestation occurrence in high density value ranges between 0.002 – 0.0039 m/km². Major control of these manifestation are left slip fault, right slip fault, and trust fault. The distribution of DFN fracture sets is different for each lithology. Kalibeng marl has major dip azimuth/dip angle N 135° E/40° and N 242° E/73°. Pandan volcanic has major dip azimuth/dip angle values N 74° E/57° and N 258° E/61°. The fracture value is varies from 0 – 0.0029 m³/m³ (0 – 0.29 %) with average porosity 0.0002 m³/m³ (0.02 %). Surface fracture may be different with subsurface fracture especially the values of fracture porosity, but it can be an analogue for fracture properties and distribution in Mount Pandan area for further research. Mount Pandan complex can have high potential geothermal prospect based on structural features, especially the values and distribution of medium to high fracture porosity to well targeting and geothermal development.

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