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THE ESTIMATION OF FRACTURE INTENSITY AND PRESSURE DISTRIBUTION USING ANALYSIS OF SHEAR WAVE SPLITTING ON "LANDAK" GEOTHERMAL FIELD

Muhammad Al Thariqsyah [1], Irvan Ramadhan [2], Sudarmaji *[1]

[1] Geophysics Lab., Gadjah Mada University, Yogyakarta, Indonesia

[2] PT. Supreme Energy Rantau Dedap, Menara Sentraya Lantai 23, Jl. Iskandarsyah Raya No. 1A, Kebayoran Baru, Jakarta 12160, Indonesia

*corresponding author: ajisaroji@ugm.ac.id

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ABSTRACT

Shear wave splitting is a study that utilizes the differences between arrival times of two shear waves (slow and fast) propagating from a source to a receiver to identify the magnitude of the anisotropic medium through which they propagate. Aside from generating a delay time between two shear waves, the anisotropic medium also shifts the polarization of fast shear wave from its initial polarization which is indicated as the main orientation of the related fracture system. The study was conducted on Landak Field, located around Bukit Besar Mountain range by analyzing provided data from December 2011 to April 2012. The results of this study show that the polarizations of fast shear waves in several stations are as following; NE-SW orientation at station R09, R17, R25, and R26, N-S orientation at station R08, and NW-SE orientation at station R17. Not only do these orientations of polarization show a good correlation with structural analysis in this area, but also important to be noted that all microseismic stations encounter a wide-spreading polarization phenomenon as an effect of complex anisotropy. The delay time from all stations ranges from 0.03 to 0.07 seconds. The normalization between delay time and length of ray path for all stations results in a fracture intensity parameter ranging from 0.004 to 0.011 seconds/km. This intensity is measured in slowness parameters, which shows increased value towards the Bukit Besar area, which potentially becomes the upflow zone of the geothermal system. The study shows that the distribution of fracture intensity and pressure have correlation and identical trend with temperature distribution

Keywords: Shear wave splitting; polarization; delay time; fracture intensity; pressure; temperature

INTRODUCTION

In general, permeability in a geothermal system is heavily affected by the presence of fractures with various characteristics. Thus, identifying fracture intensity in a geothermal system becomes one of the important steps to understand the conceptual model of a geothermal system, as well as finding potential drilling targets. These dynamic characteristics of fractures potentially occurred due to the several geological processes which happened before within the geothermal system. Several geophysical methods are required to obtain a comprehensive understanding of the system, and one of the methods is by using the shear wave splitting study.

Parameters measured in the shear wave splitting study are delay time (δt) between two S waves and polarization of fast shear wave (Φ) which is assumed as the main orientation of fractures. In many cases, delay time obtained from the analysis could not identify seismic anisotropy in the study area due to large differences in hypocenter depth. Thus, as applied in this study, a normalization between delay time and length of ray path (assumed to be a straight path) is important to identify bulk fracture intensity on the study area $(\delta t/l)$ which is measured in slowness parameter (seconds/km).

“Landak” geothermal field located around the mountain range of Bukit Besar which is known as a part of the Great Sumatra Fault system. This area is mainly composed of quaternary volcanic rocks serving as cap rocks of the reservoir system. It is safe to say that the formations of geological features on the “Landak” geothermal system are heavily affected by the activity of the Great Sumatra Fault itself, specifically the Manna Segment [1]. The tectonic phase of the “Landak” geothermal field consists of 3 sequences, that is the initiation of the Manna Fault, the initiation of Kikim Fault, and the subsequent re-initiation of the Manna Fault which pull the left block of Bukit Besar Fault towards the south direction. The three tectonic phases produced structural strikes with the orientation of WNW-ESE, N-S, and NE-SW, respectively. Sidik et al. (2016) has successfully attempted to map the structural strike on the study area [2]. Based on the said study, each strike orientation is inversely proportional to the tectonic phase which most likely will correlate to the results of this study as well.

The stratigraphy of the study area is mainly composed of volcanic rocks. These volcanic rocks came from several identified formations that are the Hulusimpang Formation (Tomh) which intruded by granitic rock (Tmgr), then mixed with Gumai Formation (Tmg) on the northern area and Seblat Formation (Toms), mostly composed of marine sediment, on the southern area. Meanwhile, Gumai Formation is mostly composed of mixed marine sediment deposition with volcaniclastic deposits. Hulusimpang Formation composed of an interfingering relationship between andesitic volcanic rock and sandstone, some observed quartz veinlets, and sulfide mineral which distributed along the Great Sumatra Fault system. In general, the “Landak” regional geology consists of Tertiary to Quaternary age of volcanic rocks [1].

Bacquet et al. (2016) modeled the distribution of temperature and pressure across the “Landak” geothermal system. The increasing temperature and pressure points toward the Bukit Besar upflow zone is a common agreement as described by Bacquet et al. (2016) [3]. In the study area, the top of reservoir is located around the elevation of 1200 masl on upflow zone and observed to be a relatively flat surface with a temperature of 230 OC. NE-SW-oriented faults became the main thermal discharge path on the upflow zone.

This study mainly focused on the “Landak” geothermal field, Muara Enim, South Sumatra by analyzing microseismic events prior to the drilling activity, notably from December 2011 to April 2012 to identify delay time (δt) and fast shear wave polarization (Φ) parameters in this area.

METHOD

Data processing to seismic records will be done using the shear wave splitting method. Theoretically, it’s known that there are two differently polarized S waves on a propagating wave, i.e: the firstly S wave which is polarized parallel to its propagation direction, and the second S wave which is polarized perpendicular to its propagation direction. The second S waves have similar velocities on an isotropic medium and different velocities on an anisotropic medium. This different velocity results in the occurrence of delay time (δt). The phenomenon in which the second S waves split as an effect of the anisotropic medium is called the shear wave splitting phenomenon. The length of delay time between second S waves is proportional to the magnitude of anisotropy of the medium. Silver and Chan (1991) described the splitting with the splitting operator [5]:

$$\Gamma(\Phi, \delta t) \equiv e^{-i\omega\delta t/2}\hat{f}^{T} + e^{i\omega\delta t/2}\hat{s}^{T} \tag{1}$$

Where $\Gamma(\Phi, \delta t)$ is the S wave splitting operator as a function of Φ, δt and $\delta t/2$ is the shifting in time on the polarization of the fast S wave $(\hat{f})$ and the slow S wave$(\hat{s})$. Equation (1) when applied to an unsplit S wave will result in a split S wave as shown below.

$$u_s(\omega, t) = \Gamma(\Phi, \delta t)u(\omega, t) \tag{2}$$

The obtained split S wave equation requires an unsplitting operator to obtain the initial wave condition using the best split parameter. Hence, an inverse operator is needed as shown below.

$$\begin{aligned}\tilde{u}(\omega, t) &= \Gamma^{-1}(\Phi', \delta t')u_s(\omega, t) \qquad (3)\\ &= \Gamma^{-1}(\Phi', \delta t')\Gamma(\Phi, \delta t)u(\omega, t)\end{aligned}$$

A shear wave splitting study analyzes two splitting parameters, which are the polarization direction of fast S wave$(\Phi)$and the delay time (δt). In this study, analysis was done by both minimization of eigenvalue $\lambda 2$ and cross-correlation (Figure 1).

- **Cross-correlation was** applied by Bowman and Ando (1987) to find a maximum correlation between two horizontal components of seismogram with the assumption that the signal is noiseless [4].
- **Minimization of eigenvalue $\lambda 2$** developed by Silver and Chan (1991) to find the most singular matrix (minimum eigenvalue) after rotation process. The most singular matrix can be derived from the Φ and δt which best match the real condition of the study area [5].

Several data may show the presence of a null-splitting phenomenon on the analyzed seismogram, which show no splitting effect at all. This may be caused by excessive noise, isotropic medium, or unchanged polarization of fast S waves.

Data processing will be done among to seismic data record from six stations, e.i: from station R09, R17, R25, and R26 for NE-SW orientation at station; from station R08 N-S orientation; and from station R17 NW-SE orientation. Data processing was conducted using the shear wave splitting method on Splitlab 1.9.0 program, with both cross-correlation method [4] and the minimization of eigenvalue $\lambda 2$ [5]. This aims for the best fitting δt and Φ splitting parameters by applying a window on 2 horizontal components of the seismogram (Figure 2). The window should cover both fast S wave and slow S wave phases which will be included in further computation later.

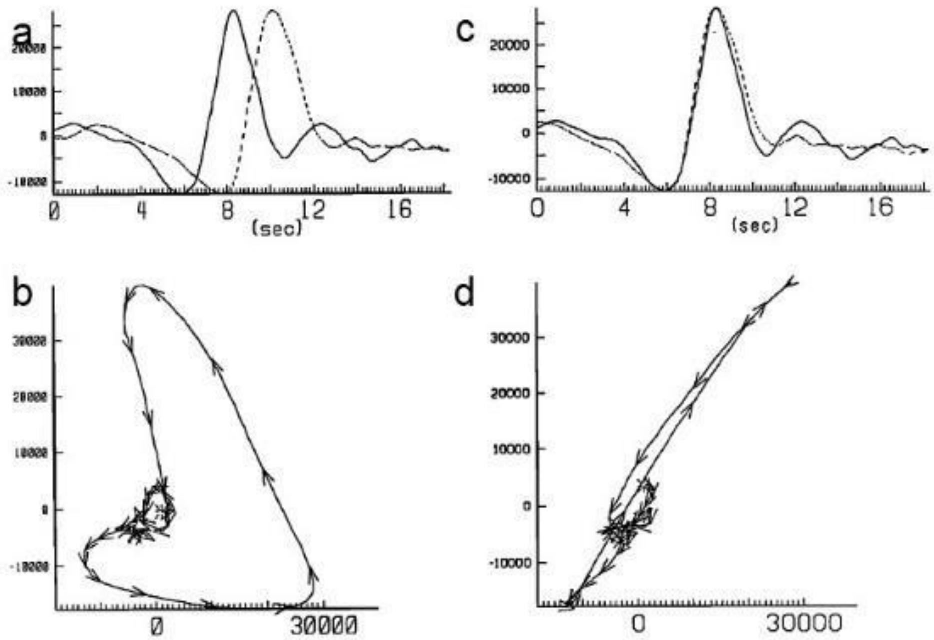

Figure 1. Minimization of eigenvalue $\lambda 2$. (a) and (b) are both initial seismogram and particle motion diagrams, respectively, whereas (c) and (d) are seismogram and particle motion post-splitting process, respectively. Note the nearly linear characteristic of (d) [5]

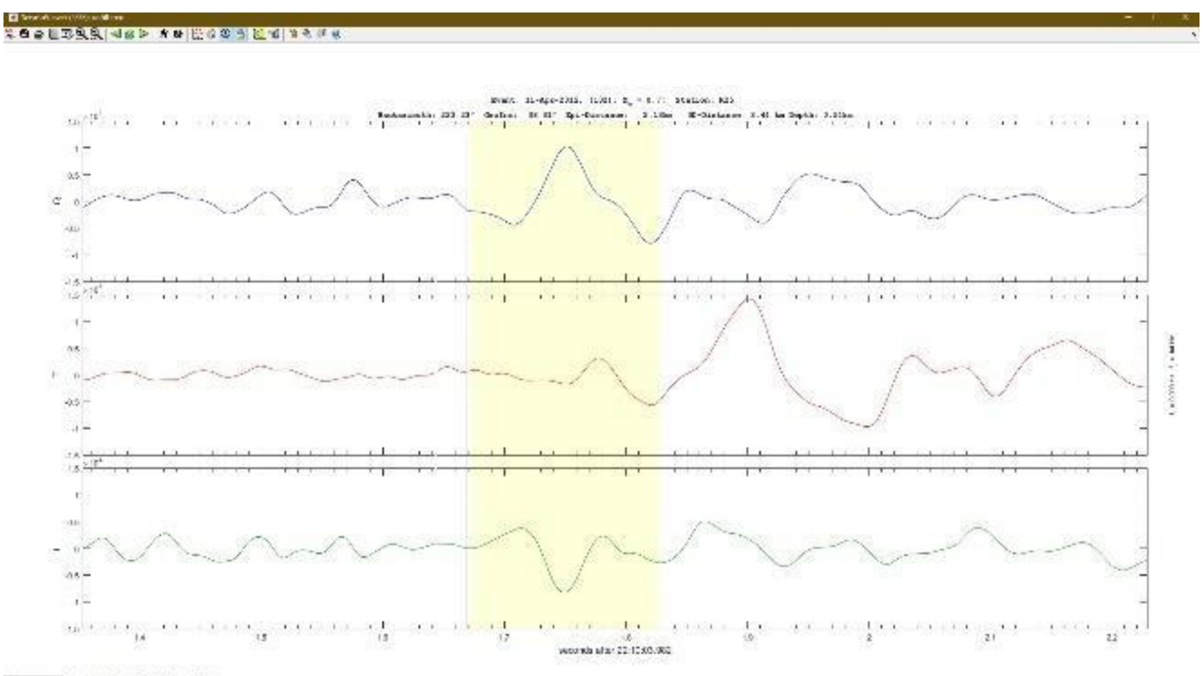

Figure 2. An example of a window (yellow shade) applied on one seismogram from R25 station

Obtained results will be summarized as shown in Figure 3. These results include Φ, δt, signal quality, and other statistics which are located inside the red box.

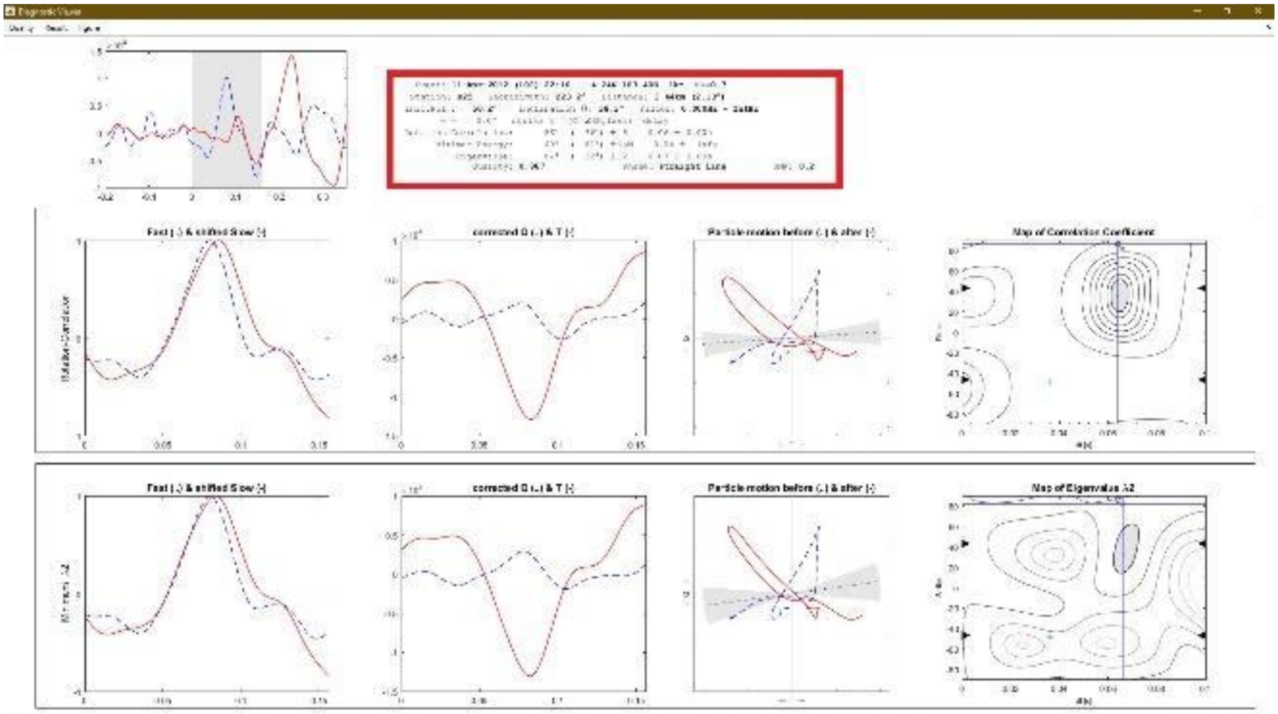

Figure 3. Obtained results of shear wave splitting analysis based on the data shown in figure 7. Main statistics grouped inside the red box

RESULTS AND DISCUSSION

Previous analysis results in sets of splitting parameters for the 6 analyzed stations. Due to major differences in average hypocenter of each station, a normalization between delay time and each respective ray path (assumed to be a straight line) was carried out. This normalization results in a new parameter called the bulk crack intensity which better represents the strength of anisotropy scattered along the study area. The summarized result is as shown in Table 1.

Table 1. Summarized result of shear wave splitting

Stasiun	X (m)	Y (m)	Elevation (m)	Average depth (km)	Average dt(s)	Average L(km)	Average dt/L(s/km)
R03	324170.3	9539053	1480	8.089	0.070	10.798	0.0065
R08	318896.5	9536891	1635	5.035	0.062	7.066	0.0088
R09	321224.9	9535725	1870	5.614	0.049	7.599	0.0064
R17	326197	9532116	1947	4.102	0.036	8.326	0.0043
R25	323736.4	9532908	2159	0.380	0.037	2.811	0.0131
R26	319282.1	9533009	2233	1.228	0.060	5.130	0.0117

Distribution of Polarization Direction of Fast S Wave

Theoretically, the polarization direction of the fast S wave aligns parallel to the direction of its local maximum stress (Φ). A study by Zhang et al. (2007) has shown that each recording station shows a parallel alignment between polarization direction and the direction to which the San Andreas Fault elongates [6].

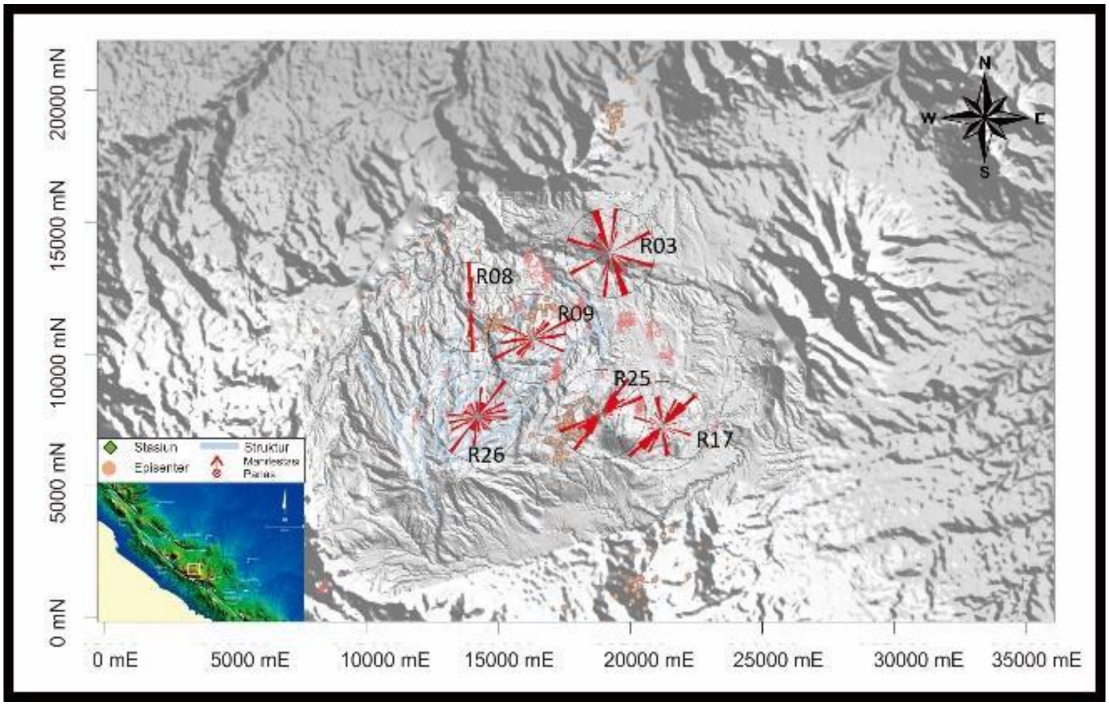

Figure 11. Distribution of polarization direction of fast S wave on 6 recording stations. Average direction orienting NE-SW

Based on the obtained results from 280 events among 6 stations, it is then obtained the distribution of polarization of fast S wave (Φ) from each respective station (figure 9). Although 4 out of 6 stations show a main orientation of NE-SW (structures produced by recent tectonic activity), the polarization directions scattered to nearly all azimuth, indicating an existing spatial heterogeneity around each recording station with the exception of station R08 which has a stable orientation of N-S[7]. This scattering may correlate with the older tectonic sequence of this area. However, this may become a consideration material in analyzing the main orientation of fractures in the area which may be either the real distribution of fractures or an error in processing.

The depth of the structure cannot be determined, however. This is mainly because of the uncertain depth where the S wave splits.

Distribution of Delay Time

The anisotropy of a medium is proportional to its S wave delay time, which is calculated from differences in arrival time between fast S wave and slow S wave. According to Figure 10, the longest delay time was recorded on station R03, followed by R08, R26, R09, R25, and the shortest was recorded by R17. A delay time shorter than 0.3 seconds sourced from events shallower than 30 km shows that the anisotropy is mainly sourced from the upper crust [8].

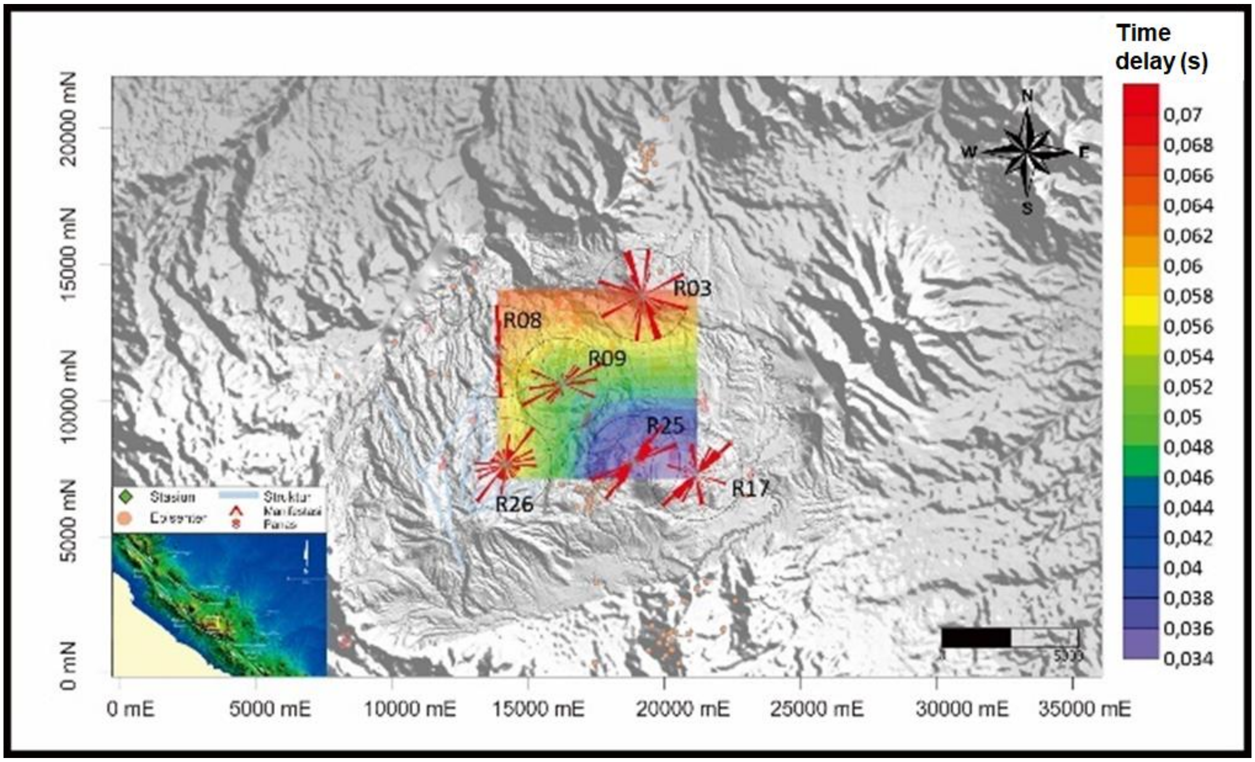

Figure 10. Distribution of average delay time on 6 recording stations

Distribution of Fracture Intensity

Fracture intensity discussed in this study is the normalization between delay time and wavelength which is assumed to be a straight line. Thus, the specific ratio between conductive and non-conductive fracture cannot be determined. However, this data may be used as a reference to the area’s permeability in general. As shown in Figure 11, the fracture intensity is at its highest around the upflow zone (Bukit Besar), and generally declining towards the downflow zone in NE direction. The high level of fracture intensity around Bukit Besar is evident by the existence of geothermal manifestations which are dominated by fumaroles. Existing minor faults produced by intersecting Cawang Fault and Bukit Besar Fault may have enhanced the fracture intensity, thus enhancing permeability around the upflow zone.

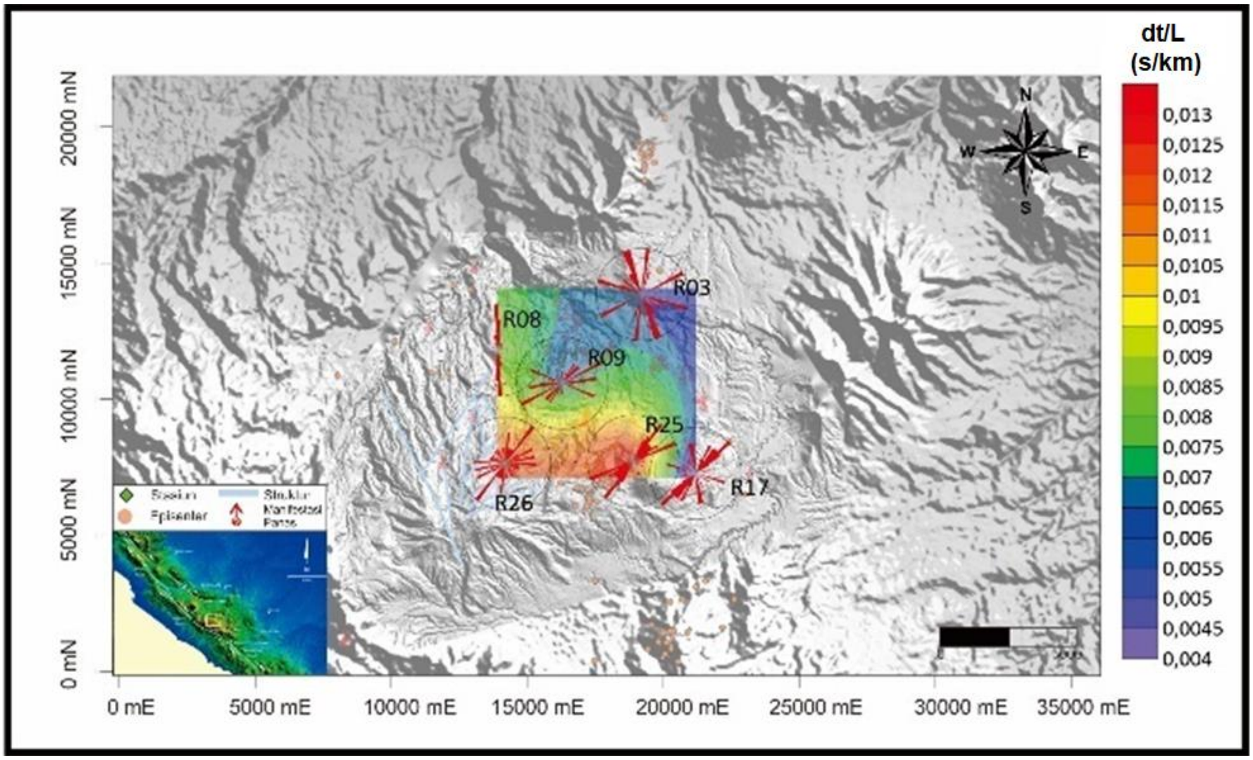

Figure 11. Distribution of average fracture intensity (measured in slowness) on 6 recording stations

An increasing trend of fracture intensity toward the up flow zone on the SW direction (0.0117 s/km) is observed. This increasing trend also correlates with the increasing trend of temperature and pressure. A high level of pressure and temperature is known to promote the forming of fractures on upflow zone. The high pressure and temperature impact the fracture intensity distribution (Figure 12).

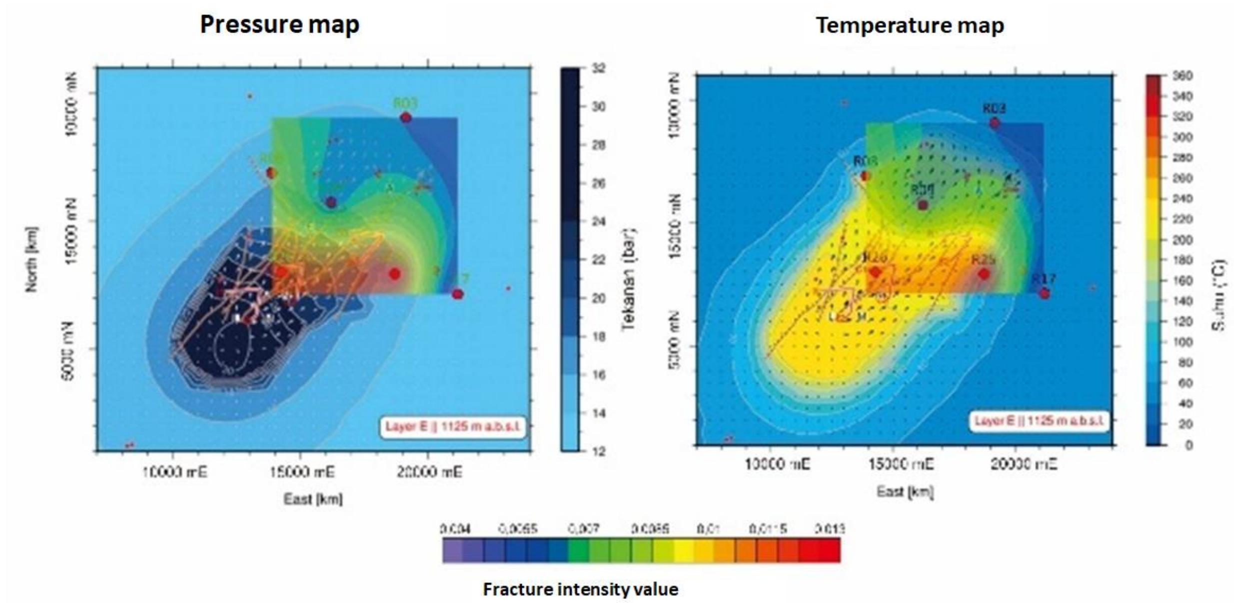

Figure 12. An identical trend between the distribution of fracture intensity and pressure (left) and temperature (right) [4]

CONCLUSION

Based on the study, several results can be summarized as follow. The polarization direction of fast S wave(Φ)from the 6 recording stations mainly oriented NE-SW, with the exception of R08 and R03. However, the existence of local spatial heterogeneity may have impacted the scattering of the distribution of polarization direction. This may reflect either the real condition of the field or an error during processing. On the other hand, the depth of the structural orientation cannot be determined because of the uncertain nature at which depth the S wave splits. Delay time of 6 stations correlates with the anisotropy level of the medium. Average delay time of each station ranges between 0.036 to 0.070 seconds and this shows that the anisotropy is mainly located in the upper crust. Normalization between wavelength results in fracture intensity which is measured in slowness (s/km). An increasing trend of fracture intensity toward the up-flow zone on the SW direction (0.0117 s/km) is observed. This increasing trend also correlates with the increasing trend of temperature and pressure. A high level of pressure and temperature is known to promote the forming of fractures on upflow zone.

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