Identification of reservoir characteristics based on seismic velocity tomography using microearthquake method in “X” geothermal field

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Abstract. This research studies microearthquake (MEQ) data analysis in “X” geothermal field. The data was recorded in two phases; before and during drilling, with a total number of 2863 events recorded. The quality assessment method was applied using wadati diagram analysis in order to select the best quality data for advance processing. The result shows that the MEQ events are having trend of Vp/Vs ratio around 1.76. The MEQ data then processed using tomography inversion technique to obtain the image of subsurface seismic velocity structure. The results of seismic tomography inversion shows anomaly pattern which consistent with the lithology and geological structure. The result also shows a good agreement with the interpretation of resistivity section from magnetotelluric (MT) data, as well as from geochemical data. The region inferred as reservoir zone are observed with dominantly high Vp/Vs anomaly which indicates incompressible characteristics that may relate to existence of water content, while the low Vp/Vs anomaly which indicates steam cap existence are not observed in this region. This pattern of anomaly leads to inference that the reservoir characteristics are dominated with liquid phase of fluid.

Keywords: Geothermal, exploration, microearthquake method, seismic velocity tomography, reservoir fluid characteristics

1. Introduction
Geothermal areas are often associated with MEQ activity [1, 2], and these earthquakes have often been used to learn more about both exploited and unexploited geothermal systems. Seismically active geothermal areas are well-suited to local-earthquake tomography because earthquakes are often well-distributed throughout the reservoir and production zone [3].

The “X” geothermal field has been explored since 2008, while the MEQ observations was initiated on September 2010. The observations was conducted in two phases; before and during drilling period, each for 7 and 16 months using 10 and 16 seismometers. The observations shows infrequent activity of MEQ before drilling (135 events), while plenteous event of MEQ were observed during drilling period (2728 events). The MEQ data then processed using tomography inversion technique to obtain the image of subsurface seismic velocity structure. The results then correlated with lithology and geological structure, and also with distribution of resistivity from magnetotelluric (MT) data in order to evaluate the results obtained and to identify characteristics of reservoir fluid phase.
2. Methodology

2.1. Geological condition

The “X” geothermal field are situated at one of the graben in Great Sumatran Fault (GSF). Several publications [4, 5] mentioned that the graben in the study area are formed as pull-apart basin from SLT and SLK fault, while physiographic studies using digital elevation model shows that the study area are located in the southeast end of SLT fault (figure 1a) [6]. Further interpretation from regional structure shows the development of complex horse-tail structures under strong extensional tectonic regime (figure 1b) [6], which also affect volcanic area in the west of Mt. “KR” that causing broad lateral collapse. These extensive horse-tail structures are expected to establish substantial permeable structures that can be studied further to develop a better conceptual model of related geothermal system.

Stratigraphic information are summarized refers to geological map of the Painan and northeastern part of the Muarasiberut by Rosidi et al. [7] as shown in figure 2a and figure 2b. Lithology of the study area are consist of surficial deposits, volcanic rocks, intrusive rocks and sedimentary metamorphic rocks (figure 2c). Stratigraphic section are interpreted as a geological model used for further analysis (figure 2d).

2.2. Geochemical condition

Refering to the book of "Potensi Panas Bumi Indonesia" by Ditjen EBTKE et al. [8] Thirteen surface manifestations were founded in the region of “X” geothermal field, labeled as HS for hot springs and F for fumaroles as shown in figure 3. The temperature of hot spring samples are varies in range of 46 to 99 °C, while the temperature of fumarole F2 and F5 are 95 and 139 °C respectively. Based on geochemical data analysis, hotsprings of HS3, HS4 and HS5 were discovered to be dominated by bicarbonate water (HCO_3) indicating mixing process of geothermal fluid with peripheral water. Meanwhile, fumaroles of F2 and F5 were founded to be dominated by sulphate (SO_4) which characterize steam heated waters.

Based on the distribution of manifestations with its geochemical characteristics, it can be inferred that the upflow zone is located in the south region of “X” geothermal field producing fumaroles of F2 and F5 in the surface. The hydrothermal fluid flows to the north region and mixed with peripheral waters producing hot springs dominated with bicarbonate water.

Figure 1. (a) Graben from pull-apart basin, and (b) complex horse-tail structures of “X” geothermal field in Sumatran fault system.
2.3. MEQ data processing

The MEQ events were identified from seismic signal recorded using basic visual method: change primarily in amplitude and frequency [9]. The quality of the picked time arrival data of MEQ events
then assessed using wadati diagram analysis in order to select the best quality data for advance processing, with criteria: detected by at least 8 stations and having at most 2 outliers.

The result shows that the MEQ events are having trend of $V_p/V_s$ ratio around 1.76. The selected MEQ events then processed using HYPO71 [10] and HYPODD [11, 12] program to determine accurate hypocenter locations with initial velocity model based on geological interpretation. The result shows that the hypocenter of events before drilling were distributed along the fault structure, while the hypocenter of events during drilling were gathered around Well 2.

The hypocenter of events data along with its arrival time then used to define 1D corrected velocity model. Using these data, the tomography inversion technique performed using SIMULPS [13] program to obtain the image of subsurface seismic velocity structure. The inversion process were configured using gridding model with size $15 \times 19 \times 13$ (X, Y, Z) node with 0.5 km distance between each node.

3. Results and discussion
Correlation of seismic velocity tomography results to geological stratigraphy are shown in figure 4 and figure 5. In the south side of vertical tomography section (figure 5a, $Y = -2$ km), an anomaly of low $V_p/V_s$ followed by high $V_p$ and very high $V_s$ indicates the existence of rock body with high rigidity which may relate to the existence of volcanic rocks Qyu and Qyl in accordance to the interpretation of stratigraphic section (figure 5b, $Y = -2$ km). The indication is also supported by the anomaly of absolute $V_p$ and $V_s$ structure (figure 5d and figure 5f) which observed having higher velocity than surrounding region. The same pattern of anomaly is also observed in the north side of vertical tomography section (figure 5a, $Y = 4$ km) which indicates the existence of subsurface intrusive granitic rocks (kgr) according to the interpretation of stratigraphic section (figure 5b, $Y = 4$ km).

Another anomaly pattern is observed in figure 5a with high $V_p/V_s$ followed by low $V_p$ and very low $V_s$ at the surface in the north side ($Y = 4$ km) declining to the south ($Y = 2$ km) which indicates layering conditions that having low rigidity. This anomaly may be occur due to the surface layer that has been weathered, supported by the anomaly of absolute $V_p$ and $V_s$ structure (figure 5d and figure 5f) observed having lower velocity than surrounding region.

The result of seismic velocity tomography are also correlated to the distribution of resistivity from MT data by Humaedi [14], as shown in figure 6 and figure 7. The anomaly of low resistivity (< 10 ohm.m) are observed in vertical resistivity section (figure 7b) elongated from the south side ($Y = -2$ km) with thickening in the north ($Y = 3$ km) indicating conductive characteristic which then interpreted as clay cap region. The existence of clay cap may leads to inference that geothermal reservoir lie beneath the clay cap with boundary of about 10 ohm.m as BOC (base of conductor) extended up to the thickening zone in the north, marked by white dotted lines on all figures in figure 7.

The hotter parts of geothermal systems are characterised by higher resistivity than is seen in the overlying conductive zone [15]. Hence, thickening pattern of low resistivity observed in MT data may relate to lower temperature, while thinner part indicates higher temperature. This pattern shows a good agreement with geochemical data as thinner part of conductive layer is situated in the south region which interpreted as an upflow zone, followed by thickening zone elongated to the north region which previously interpreted as an outflow zone.

During drilling phase, an MeB (methylene-blue) data analysis on drill cutting was conducted to asses its clay content [14]. The results are shown in figure 7b as a set of white wiggle overlying drilling trajectory scheme, representing the existence of clay content. Based on this data, the low resistive anomaly at the top layer resulted by MT data has been proven to be clay cap of the geothermal system.

In the vertical tomography section (figure 7a), the anomaly of dominant high $V_p/V_s$ are observed in the region that infered to be reservoir zone. The anomaly could represent incompressible characteristics which may indicates the existence of water content in this region. On the contrary, the anomaly of low $V_p/V_s$ which indicates steam cap existence are not observed in this region. Therefore, the anomaly pattern can be interpreted as reservoir zone that dominated with fluid in liquid phase.
Figure 4. Correlation of Vp/Vs tomography map at 0.5 km asl elevation, (a) with stratigraphic map of the study area (b); the yellow dotted line indicates sectional path in figure 5.

Figure 5. Correlation of tomography section with stratigraphic section interpretation (top right) at X = -0.5 km.
Figure 6. Correlation of Vp/Vs tomography map (a) with MT map, (b) at 0.5 km asl elevation; the yellow dotted line indicates sectional path in figure 7.

Figure 7. Correlation of tomography section with MT section (top right) at X = -0.5 km; white dotted line indicates interpretation of the top and bottom of reservoir.
4. Conclusion
The MEQ data analysis in "X" geothermal field has been carried out in this research. Several consecutive method were applied to obtain the best results of seismic velocity tomography. The final results shows a good agreement with the lithology and geological structure, as well as with the interpretation of geochemical and MT data. The region inferred as reservoir zone are observed with dominantly high Vp/Vs anomaly which indicates incompressible characteristics that may relate to existence of water content, while the low Vp/Vs anomaly which indicates steam cap existence are not observed in this region. This pattern of anomaly leads to inference that the reservoir characteristics are dominated with liquid phase of fluid.

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