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Steam and Brine Zones Prediction Inside an Operated Geothermal Reservoir Based on Seismic Velocities Produced by Double Difference Tomography

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ABSTRACT

The knowledge about reservoir condition is one of the key factors for sustainable production in a geothermal field. Monitoring of geothermal reservoir by using micro-earthquake (MEQ) method has been implemented recently in several operated fields in Indonesia. Double difference seismic tomography is one of tomographic method that uses the absolute and the relative travel times which could be used to monitor geothermal reservoir by analyzing the distribution of produced Vp, Vs, and Vp/Vs ratio.

This method had been implemented to a set of MEQ data that were recorded within a relatively short period of two months in 2005. Altogether, 17 seismometers were deployed in the field. Catalog data was created by re-picked waveform data in order to determined P and S wave arrival times. Micro-earthquake event were classified based on the difference between S and P arrival times (ts-tp) that were less than or equal to 3 seconds. In total 303 micro-earthquake events had been successfully identified and picked. This number is equivalent to 1798 P-wave and 1750 S-wave picked arrival times. Initial location was calculated using Geiger's method and 1-D two layers system was used as initial velocity model. Hypocenter positions which were determined by Geiger's method were relocated by using VELEST software in order to obtain a better velocity model and hypocenter positions. Furthermore, the double-difference tomographic method is implemented in order to obtain the best 3-D velocity model and hypocenter positions. Altogether, 197 events which have a gap value less than 180^{o} between epicenter and station were used for input data of double difference tomography.

Low Vp and Vs anomaly values from -20 % to -10 % of the background velocity model are concentrated in the northern part of research area. The existence of those anomalies and the appearance of low Vp/Vs ratio from 1.6 to 1.7 at elevation of +0.5 km to 1.0 km are interpreted as steam zone inside geothermal reservoir. The zone which has a high Vp anomaly values from 0 % to 10 % of the background velocity model, low Vs anomaly values from -15 % to 0 %, and high Vp/Vs ratio of 1.8 to 2.0 is interpreted as brine zone.

1. INTRODUCTION

The objective of micro-earthquake in geothermal areas is to contribute to the imaging and monitoring of geothermal systems condition. The imaging of the extension of the geothermal system is possibly to locate the productive fractures, caprocks and heat source etc. Micro-earthquake methods provide the seismic tomography velocity Vp and Vp/Vs structures which is related to the characteristics of reservoirs. Seismic properties (Vp and Vp/Vs) could reflect the properties of rocks, fluid and gas content, and then lithology although they are influenced by variations of pressure, temperature, saturation,fluid type, porosity, and pore type in a complex way (Wuu and Lees, 1999).

The purpose of this research is to image 3-D geothermal subsurface condition base on the seismic tomography velocity analysis derived from tomography double difference. As input, tomography inversion uses seismic travel-time data to be invert in inversion process. The analysis of micro-earthquake data is performed using the micro-earthquake data recorded in the field using seismometers tool.

Double difference seismic tomography uses two type of catalog data which are absolute travel time and differential times. It has the ability to determine the absolute and relative event locations and velocity structure accurately with direct use of more accurate differential travel times (from catalog and/or waveform cross correlation (WCC) data) (Zhang, 2003).

2. DATA AND METHODS

Micro-earthquake data was collected from one of the geothermal fields in West Java, Indonesia. The continuous recording of data for two months with 17 seismometers starts from May up to July, 2005. It shows many micro-earthquake events related to the reservoir activities and reservoir injection which were also recorded by monitoring stations. The P and S wave travel time data were used to construct Vp and Vp/Vs velocity models and to determine the seismicity distribution of local earthquakes.

The workflow included (1) determine the initial location and origin time using Geiger's Adaptive Damping (GAD) (Geiger, 1910), (2) the inversion for the so-called minimum-1D-velocity model (Vp and Vp/Vs) and the relocation of hypocenters using the program code velest (Kissling et al., 1994), and (3) the simultaneous inversion for the 3-D tomographic velocity structure (Vp and Vp/Vs) and the earthquake hypocenter using the program code TomoDD.

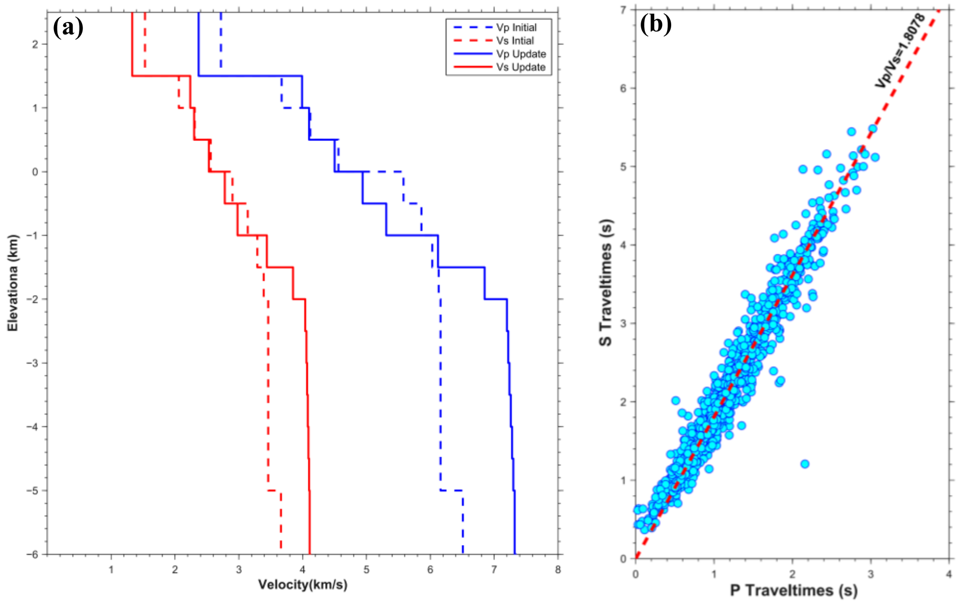

Figure 1 : Figure (a) shows 1-D velocity Vp and Vs initial model (blue and red dash line) and update velocity model (blue and red solid line) derived from velest software invesion. Figure (b) shows wadati diagram. Cyan circel stand for P-and S-wave travel time observation while red dash line indicate regression curve. The slope of regression curve is 1.80 (Vp/Vs ratio value).

Catalog data was derived from re-picked waveform data to determine P and S wave arrival times. We have successfully determined 303 micro-earthquake events (1798 P-wave and 1750 S-wave arrival time phases) for the tomography inversion. We classified the events as micro-earthquake which had differential time between S and P arrival times (ts-tp) less than three seconds in this study. The initial location and origin time of the events were determined using Geiger's Method (GAD).

The hypocenter locations from GAD method served as starting values for VELEST (Kissling et al., 1994), which was applied to relocate the hypocenters and simultaneously determine the 1-D velocity model and the station corrections. The best models and hypocenter locations obtained from the 1-D inversion (VELEST) were used as the initial values for the 3-D simultaneous inversion. A Vp/Vs ratio of 1.8 (Figure 1**)** was used as an initial value in the inversion estimated from a modified Wadati diagram. Along the inversion, we had to exclude some events with azimuthal gap angles larger than 180° which occurred at elevations greater than 6 km and located outside the seismometers distribution. Only 197 events (1185 P-wave and 1156 S-wave arrival time phases) (Figure 2) were selected as the input of double difference seismic tomography. It will be classified as absolute catalog data and differential catalog data.

3. RESULT AND DISCUSSION

Based on previous laboratory experiment by Ito (1979)it was stated that Vp are strongly attenuated in the field's steam-bearing zone. Vp and Vs also decrease from steam-saturated (low pore pressure) to water-saturated (high pore pressure) rock. Vp/Vs ratio will increase from steam-saturated to water-saturated rock. In his study at Geyser geothermal field, Gunasekara (2003) showed the extensive low Vp/Vs value can be attributed to the depletion of pore liquid water in the reservoir and its replacement with steam. Fluid saturation greatly influences the effective bulk modulus of a rock while the shear modulus (Vs) is almost independent of fluid inclusions (Nur and Simmons, 1969). Therefore, the effective bulk modulus of a rock is highly sensitive to the degree of saturation.

Figure 2 and figure 3 show the results of TomoDD inversion in vertical section for North-South and West-East direction through the study area. The mean sea level is located at 0 km elevation. Vp and Vs structures values were plotted in percent of perturbation relative to the initial 1-D seismic velocity models as shown in figure 1while Vp/Vs values was plotted in the absolute value. Blue and red colors indicate high and low anomaly for Vp and Vs structures respectively, whereas blue and red colors indicate high and low value for Vp/Vs ratio.

The existence of low Vp and Vs anomalies with low Vp/Vs ratio in range of 1.60 to 1.70 which are observed at elevation of +0.5 km to -1.0 km is suspected as the steam zone. Vp/Vs values can be attributed to depletion of pore liquid water in the reservoir and replacement with steam. In figure 2 & figure 3, it is clear that at elevation of 0 km the of distribution the steam zone are lateral. High Vp anomaly range from 0% to 10% of the background velocity model with low Vs ranged from -15% to 0% and followed by high Vp/Vs range from 1.80 to 2 is suspected as water zone located under the steam zone.

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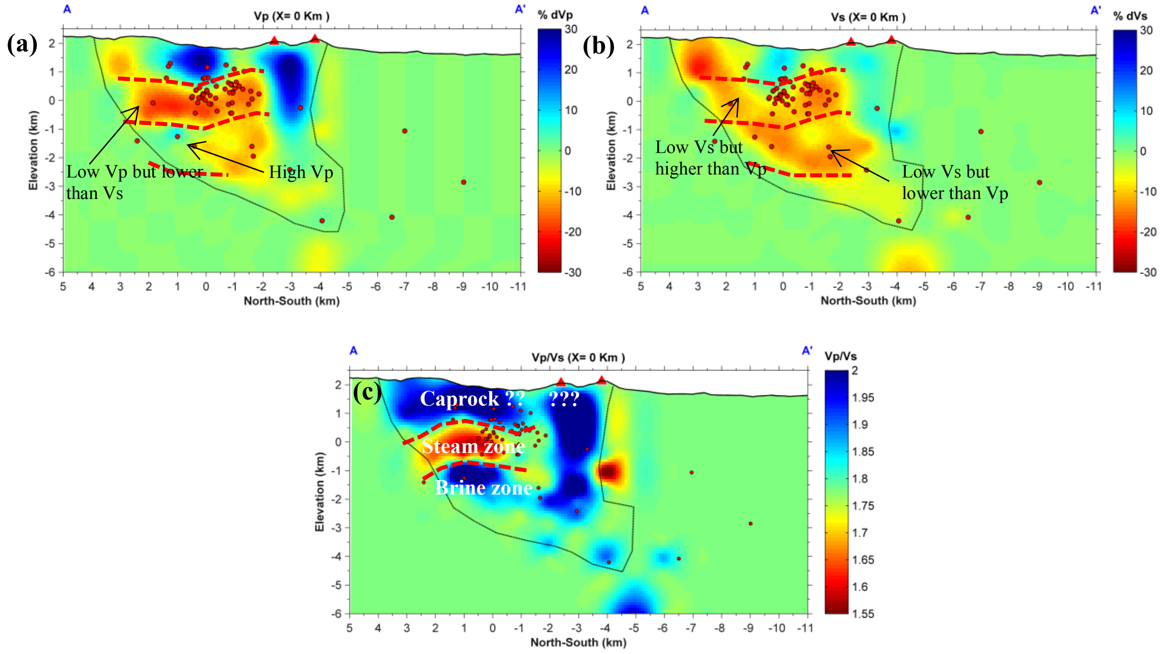

Figure 2 : Figure (a), (b), and (c) show of A-A' vertical section for velocity structures Vp, Vs, and Vp/Vs. Blue and red color indicates high and low value of Vp, Vs, and Vp/Vs ratio. Grey reverse triangle indicates station. Red triangle indicates Mountains. Red circle indicates relocated hypocenters. Solid black line indicates high resolution area. blue dash line indicates low Vp, Vs and Vp/Vs ratio indicated as steam zone.

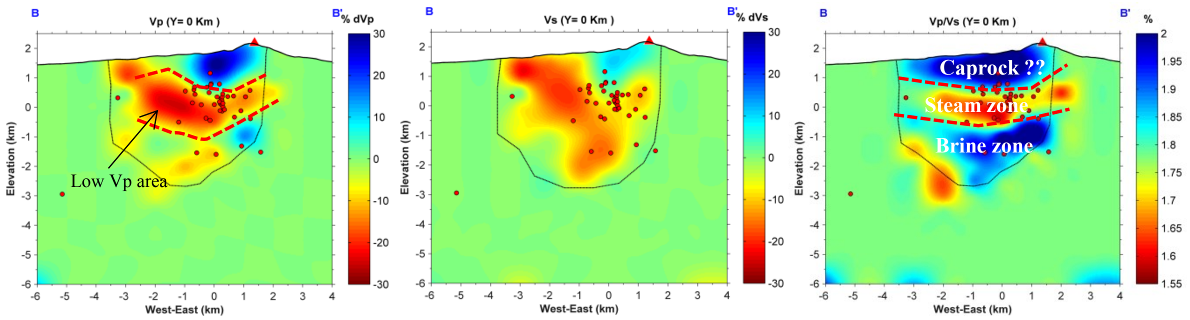

Figure 3 : Figure (a), (b), and (c) show of B-B' vertical section for velocity structures Vp, Vs, and Vp/Vs. Blue and red color indicates high and low value of Vp, Vs, and Vp/Vs ratio. Grey reverse triangle indicates station. Red triangle indicates Mountains. Red circle indicates relocated hypocenters. Solid black line indicates high resolution area. blue dash line indicates low Vp, Vs and Vp/Vs ratio indicated as steam zone.

5. CONCLUSION

Low Vp and Vs anomaly range from -20 % to -10 % to background velocity model are concentrated in the northern part of the research area. The existence of those anomalies and the appearance of low Vp/Vs ratio of 1.6 to 1.7 at the elevation of +0.5 km to 1.0 km are interpreted as steam zone inside geothermal reservoir. The zone which has a high Vp anomaly values from 0 % to 10 % of the background velocity model, low Vs anomaly values from -15 % to 0 %, and high Vp/Vs ratio of 1.8 to 2.0 is interpreted as brine zone.

6. REFERENCES

Geiger, L. (1910). : Herdbestimmung bei Erdbeben aus den Ankunftszeiten. Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen. Mathematisch-Physikalische Klasse, pages. 331-34

Ito H., J.D. Vilbis dan A. Nur (1979) : Compressional and Shear Waves In Saturated Rock During Water-Steam Transition, Rock Physisc Project, Department of Geophysics, Standford University, Stanford, California 94305.

Kissling, E., Ellsworth, W.L., Eberhart-Phillips, D., Kradolfer, U., 1994. Initial reference models in local earthquake tomography. Journal of Geophysical Research 99 (B10), 19635–19646.

Nur, A., and GJ. Simmons (1969) : The Effect Of Saturation On Velocity In Low Porosity Rocks, Earth And Planetary Science Letters 7 (1969) 183-193. North-Holland Publishing Comp., Amsterdam

Waldhauser, F., W. L. Ellsworth, and A. Cole, Slip-parallel seismic lineations on the Northern Hayward Fault, California, Geophys. Res. Lett. 26,3525-3528, 1999.

Wu, H., and J. M. Lees (1999) : Three-dimensional P and S wave velocity structures of the Coso Geothermal Area, California, from microseismic travel time data , Journal Of Geophysical Research, Vol. 104, No. B6, Pages 13,217-13,233, JUNE 10, 1999.

Zhang, H., and C. H. Thurber, Double-difference tomography: The method and its application to the Hayward fault, California, Bull. Seism. Soc. Am., 93(5),2003.

Zhang, H. (2003) : Double-difference seismic tomography method and its applications : PhD thesis, University of Wisconsin-Madison.