

## Reservoir Characterization Based on Hypocenter Location Analysis and 3-D Seismic Velocities.

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### ABSTRACT

Fluid injection process for hydraulic fracturing was conducted for two months from May 19-July 20, 2005 and was observed using the Micro-earthquake (MEQ) method. MEQ is a powerful method to assess the effectiveness of hydraulic fracturing treatments and to image the subsurface by delineating fluid in the reservoir for geothermal reservoir characterization.

A total of 357 events of MEQ waveform data were used for this research from at least 17 installed stations. Initial MEQ locations were determined using Geiger's method with Adaptive Damping (GAD) and two-layer 1D velocity models as input. Data were processed using VELEST's software for updating event travel time and a 1D velocity model. VELEST's output was used for input of travel time tomography application using SIMULPS12's software. Total data used included 1,173 P-wave and 1,068 S-wave travel times. The tomographic method was applied to generate an image of the 3-D velocity structure and relocate hypocenters simultaneously.

Our result show several prominent features: [1] hypocenters formed some clustering scattered, indicated as high permeability area; [2] strong low Vp anomaly, low Vs anomaly, and low Vp/Vs ratio at an elevation of 500 m above mean sea level (asl) were interpreted as related to the steam zone in the reservoir; [3] an underlying zone below the lower steam reservoir zone with low Vp, very low Vs, and high Vp/Vs ratio may be related to pore fluid pressure zone or the brine fluid zone.

Based on the results, we can conclude that the tomographic method can give good information of hypocenter relocation and 3-D seismic velocity models for geothermal reservoir characterization. A steam zone at an elevation of 500 m above mean sea level (asl) and a brine zone below can be predicted from travel time tomography implementation.

### 1. INTRODUCTION

In 2005, fluid injection process for hydraulic fracturing was conducted for two months from May 19-July 20, in a geothermal field. The process of hydraulic fracturing was conducted to improve the performance of production wells (Mulyadi, 2010). Fluid injection processes were performed in several injection wells and were monitored using the micro-earthquake (MEQ) method by at least 17 installed stations (Geosystem, 2005).

Seismic data recorded and data processing is expected to provide results that can be interpreted further, to determine accurate hypocenter positions, and to simultaneously provide a model of seismic wave velocity below the surface in the research area of the geothermal field. The high quality seismic mapping data of the area can be also used as a base-line for estimating the depth of the reservoir, i.e., taking into consideration earthquakes under the reservoir zone (Asrizal et al., 2006).

The objective of using tomography in the geothermal field is to contribute imaging, i.e., 3-D velocity, P, S, and Vp/Vs ratio structure, and monitoring hydraulic fracturing.

### 2. SEISMIC TOMOGRAPHY

According to Thurber (1993), body waves spreading from the micro-earthquake source to the recorded station are shown using the theory of wave propagation:

$$T_{ij} = \int_{source}^{receiver} u \, ds \quad (1)$$

where  $u$  is the slowness (1/velocity) and  $ds$  is the wavelength. Observed arrival time is formulated:

$$t_{ij} = \tau_i + T_{ij} \quad (2)$$

where  $\tau_i$  is the origin time of the micro-earthquake source. In seismic tomography, micro-earthquake source coordinates ( $x_1, x_2, x_3$ ), origin time, ray path, and slowness are unknown (the model parameters). Known parameters in tomographic inversion include the receiving station location and the observed arrival time. Residuals of observed data  $T_{ij}^{obs}$  and calculated arrival time  $T_{ij}^{calc}$  are expressed as:

$$r_{ij} = T_{ij}^{obs} - T_{ij}^{calc} \quad (3)$$

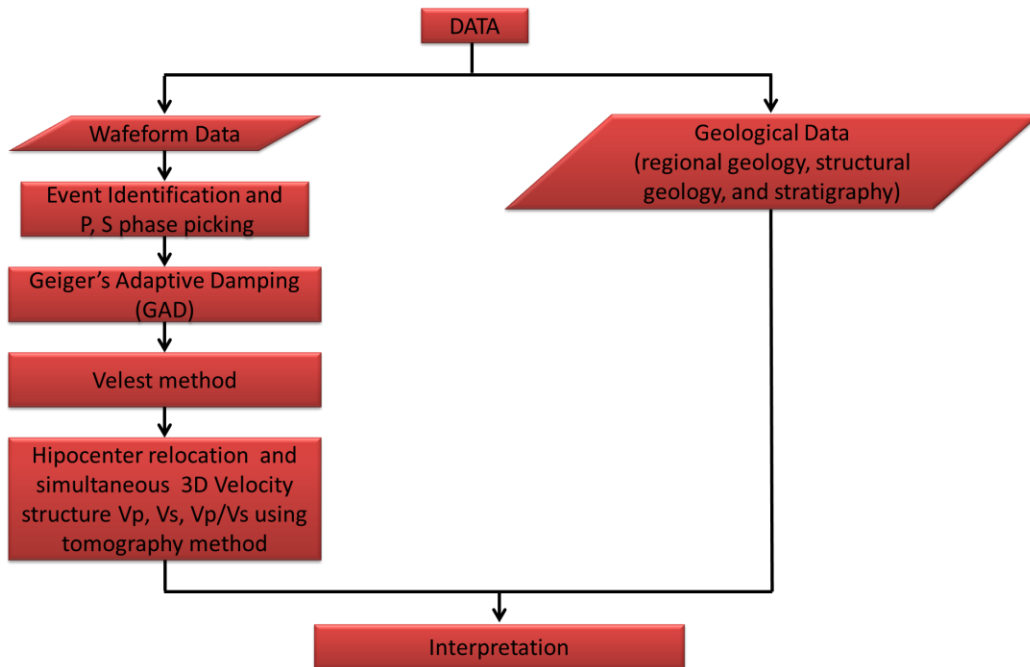
In SIMULPS12 (Evans et al., 1994), the calculated arrival time can be determined from equations (1) and (2) using the hypocenter and origin time, initial velocity model, and ray tracing pseudo-bending method (Um and Thurber, 1987). Residual values can be related to perturbation of the hypocenter and velocity structure by using a linear approach:

$$r_{ij} = \sum_{k=1}^3 \frac{\partial T_{ij}}{\partial x_k} \Delta x_k + \Delta \tau_i + \int_{source}^{receiver} \delta u \partial s \quad (4)$$

### 3. DATA AND METHODOLOGY

The initial step of this study is to collect and prepare data and other information in the area of research that is needed. The prepared data consists of waveform, 1D velocity model, and station location data. Observed arrival times are obtained from accurate picking of the waveform data. Picking was done manually and a total of 357 events were identified. The initial P and S velocity model that was used consisted of two layers based on trial and error method until reasonable hypocenter positions were found relevant to the hydraulic fracturing process.

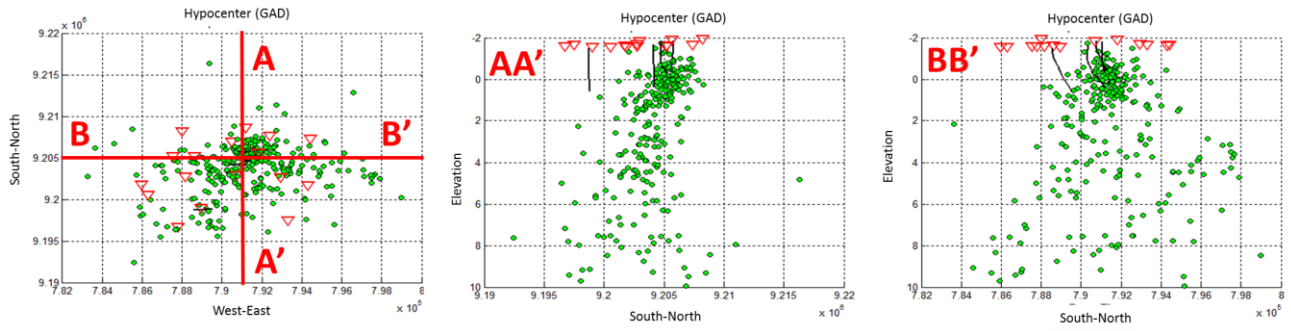
All the prepared data was processed using several methods. The first step was to determine the initial location of micro-earthquake events by using the Geiger Adaptive Damping method (GAD; Nishi, 2005). Initial positions still have quite large errors because the processing assumed a two medium layer. The VELEST method (Kissling, 1994) was used to update hypocenter positions and the initial velocity model. Velocity was updated in many layers (more than two layers). In VELEST, some hypocenters or events were reduced based on GAP. GAP is the angle between two outermost stations with an event position. If GAP is greater than 180 degrees, it means the event is outside of the seismometer network and the event position is unstable. The event will be reduced. The fixed hypocenter and updated velocity were used as the inputs for further processing using tomography to obtain 3-D velocity and an updated hypocenter position simultaneously. The 3-D velocity model can be used for reservoir characterization. The flowchart for this research process is shown in Figure 1.



**Figure 1: Flow Chart of Research.** First step was identified event and picked P and S phase of Waveform data. Arrival time resulting from phase picking was processed using Geiger's Adaptive Damping (GAD) with 1 D Velocity model. Next processing step used the Velest method for updating 1D velocity model and reduced event based on GAP. Tomography method using SIMULPS12 is used for final processing to relocate hypocenters and simultaneously update the 3D velocity structure Vp, Vs, and Vp/Vs.

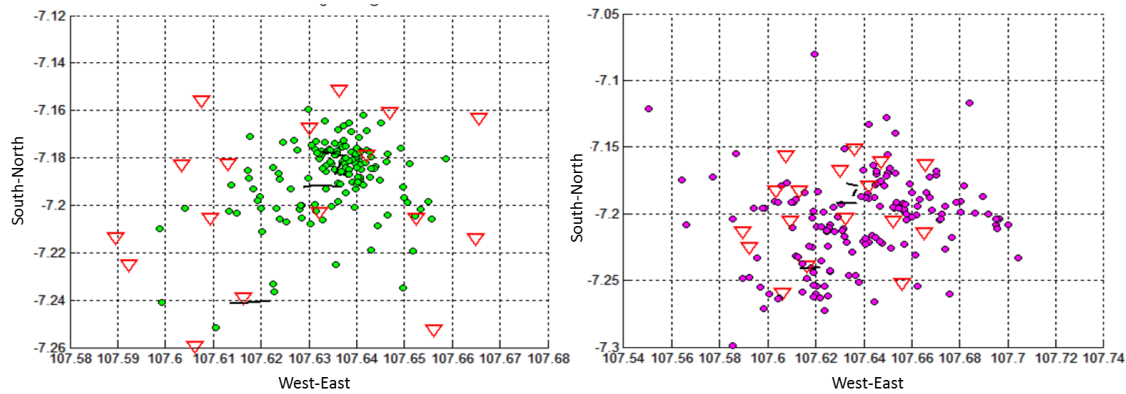
### 4. RESULT AND DISCUSSION

Good seismic response was observed in the "VAM" geothermal field, and it is evident from the hypocenter distribution that there is some clustering near the injection wells (Figure 2).



**Figure 2: Hypocenter distribution identified using Geiger's Method with Adaptive Damping (GAD). Plan view map and cross sections (AA' and BB') depict station positions, injection well locations, and hypocenter distribution. Stations are shown by red upside down triangles, hypocenter distributions are shown by green circles and well trajectories are shown by black lines. 357 events were used in GAD processing method. The events were reduced until 303 events based on the event position, which are called air-quake events.**

In the VELEST step, events which have  $GAP > 180$  degrees are indicated outside of the seismometer network and will be reduced. The number of remaining events from  $GAP < 180$  degrees were 1,173 P-wave and 1,068 S-wave arrival time phases and these events were included in the tomography method processing. Using this method, velocities were also updated several times until they achieved stable values, which were interpreted to be closest to the real condition (Figure 3).

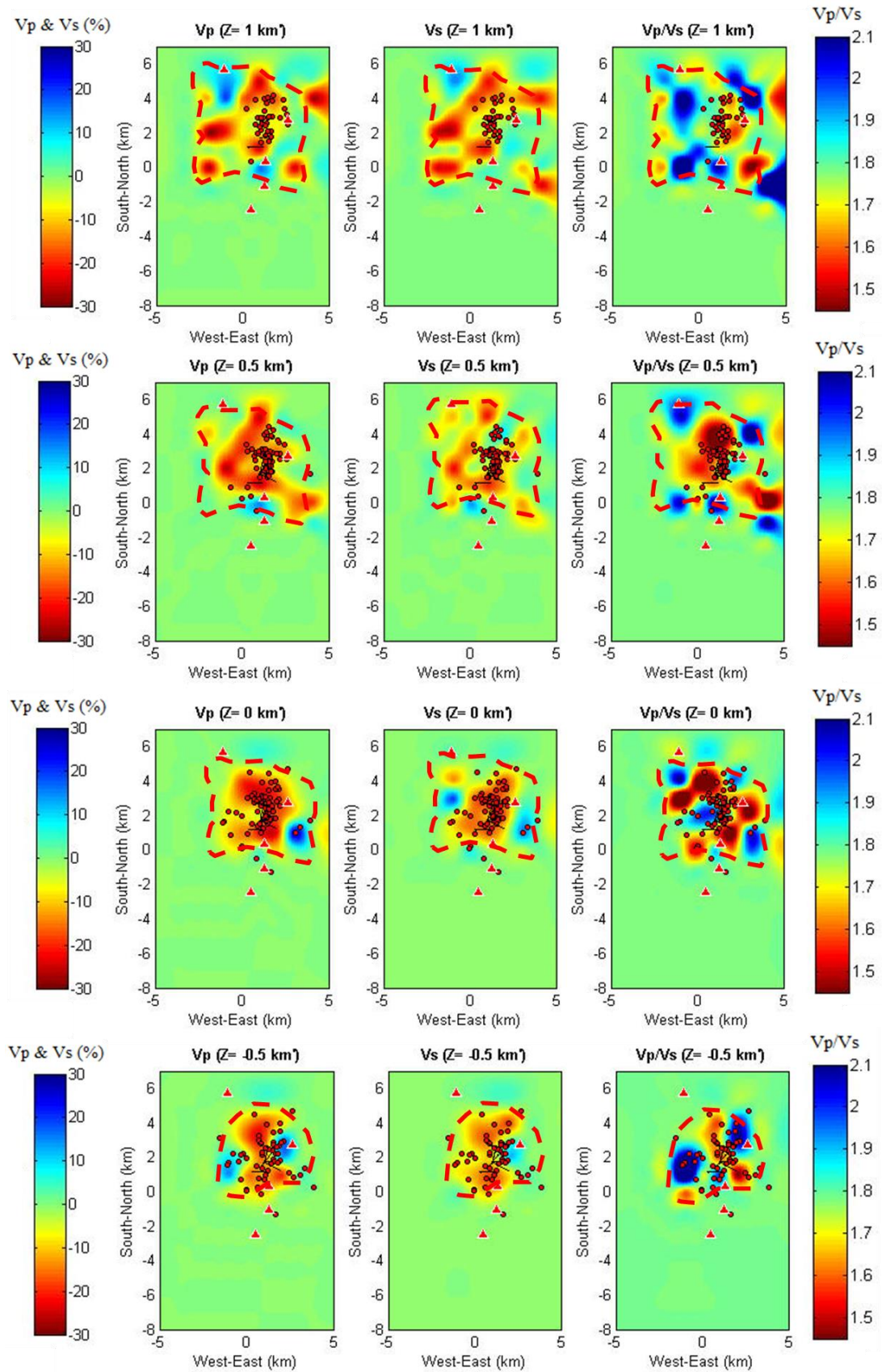


**Figure 3: Events reduced based on  $GAP > 180$  degrees by Using Velest Method, which indicates the event is outside the network of seismometers and not included in tomography methods processing. Reduced events marked by purple circles (right) and the green circles are the events (left). The number of remaining events from  $GAP < 180$  degrees were 1,173 P-wave and 1,068 S-wave arrival time phases. Using this method, the velocities were updated several times until they achieved stable values which were interpreted as being closest to the real conditions. Updated velocities in some layers and hypocenter positions were used as inputs for the tomography process.**

Figure 4 depicts horizontal depth-section tomograms of  $V_p$ ,  $V_s$ , and  $V_p/V_s$  at elevations of 1 to 0.5 km asl, msl, and 0.5 km bsl. In the resulting 3D velocity model, we observe low anomaly  $V_p$ , strong low anomaly  $V_s$ , and high anomaly  $V_p/V_s$  ratio at an elevation of 1 km asl (above sea level). These features can be interpreted as a zone that contains a lot of water. The layer containing a lot of water in the geothermal field is interpreted to be an alteration zone that contains  $OH^-$ , in essence a clay-rich zone.

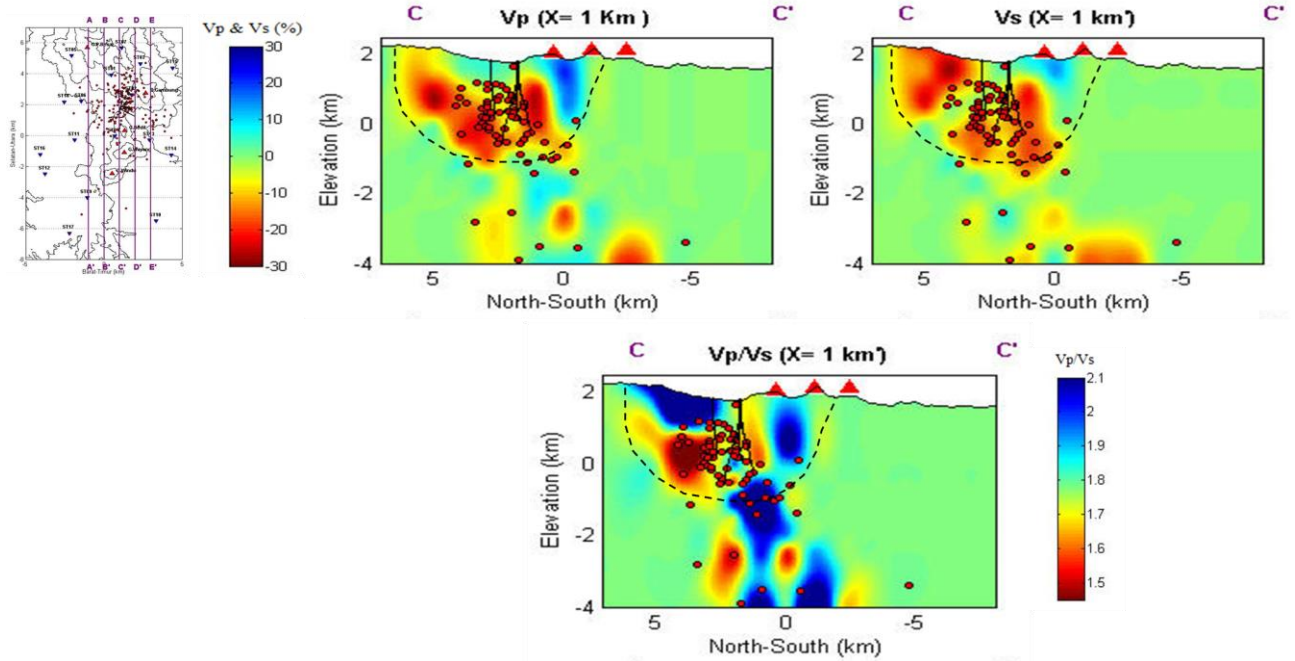
At an elevation of 0.5 km above sea level, the combination of strong low anomaly  $V_p$ , low anomaly  $V_s$ , and low anomaly  $V_p/V_s$  ratio is interpreted as a steam zone (based on previous study; Gunasekera, 2003). This similar condition is still found to persist at mean sea level. Below this steam zone, we observe low anomaly  $V_p$ , strong low  $V_s$ , and high anomaly  $V_p/V_s$  ratio, which are interpreted as brine zone at an elevation of 0.5 km below sea level (bsl). This anomaly is stronger and greater until an elevation of 1.0 km below sea level (bsl) and we can suspect the brine zone persists down to the bottom of the reservoir (based on previous study; Gunasekera, 2003).

For vertical cross-section tomography, we choose a vertical cross section that intersects the x-axis = 1 km and y-axis = 2 km, which is the most representative of the "VAM" geothermal field. Vertical cross-section tomography at  $x = 1$  km shows us very low anomaly  $V_p$ , low anomaly  $V_s$ , and low anomaly  $V_p/V_s$  ratio at an elevation of 500 m above mean sea level until mean sea level. From previous study, we can confirm that the low  $V_p/V_s$  ratio may be related to the steam reservoir zone. There is also an anomalously high  $V_p/V_s$  ratio that indicates the presence of brine. At the other side, there are also the same anomaly, i.e. high anomaly  $V_p/V_s$ , beneath the mountain that is also associated with high  $V_p$  and  $V_s$  (Figure 5).

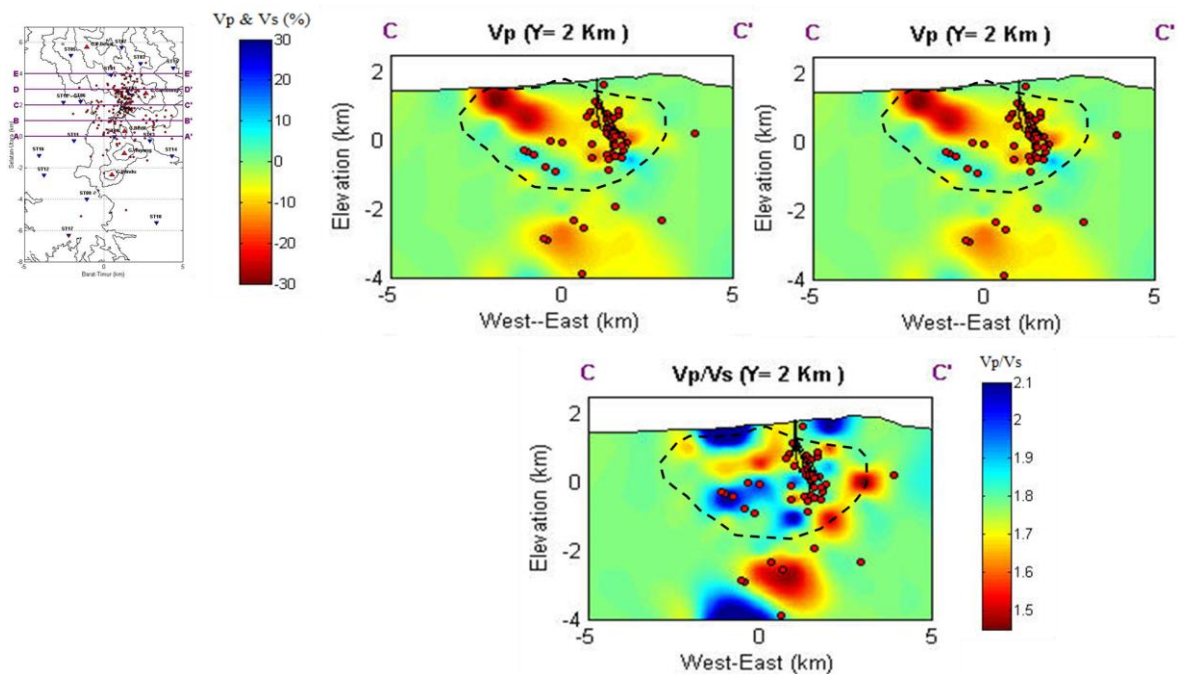


**Figure 4: Horizontal depth-section tomograms Vp, Vs, Vp/Vs at elevations of 1 to 0.5 km asl, msl, and 0.5 km bsl. Red triangles show location of mountains in “VAM” Geothermal Field. The figures show us very low Vp anomaly, low Vs anomaly, and low Vp/Vs ratio at elevations of 500 m above mean sea level down to mean sea level, and from previous study, we can confirm that the low Vp/Vs ratio may be related to the steam reservoir zone. In addition, there is a feature underlying the broad steam reservoir zone with low Vp, very low Vs and high Vp/Vs and from previous study, we can confirm that the high Vp/Vs ratio may be related to pore fluid pressure zone reflecting the presence of brine.**





**Figure 5:** Vertical cross-section tomography Vp, Vs, and Vp/Vs at x = 1 km. Cross section show low anomaly Vp, Vs, and Vp/Vs at 0.5 km asl-0.5 km bsl depth range which indicate the presence of steam and there is also high anomaly Vp/Vs beneath steam zone, which is interpreted to be a brine zone. High anomaly Vp/Vs beneath the mountain is also coincident with high anomaly Vp and Vs.



**Figure 6:** Vertical cross-section tomography Vp, Vs, and Vp/Vs at y = 2 km, which indicates the presence of steam and brine. The two separate sets of anomalies are interpreted to indicate the presence of a vapor zone above the zone of fluid. Both of them are interpreted as the delineation of the geothermal reservoir in the ‘VAM’ Geothermal Field. This is consistent with the observed geological conditions in this area.

In the vertical cross-section tomography y = 2 km (Figure 6), we can find presence of very low anomaly Vp, low anomaly Vs and low anomaly Vp/Vs ratio, which are interpreted as the steam zone. That anomaly is thin enough. Anomaly Vp/Vs at 1.5 is lower than the initial value Vp/Vs of 1.78. There is a high anomaly Vp/Vs ratio that is interpreted to indicate a brine reservoir zone at an elevation of mean sea level that continues down to the bottom of the predicted reservoir.

## 5. CONCLUSION

MEQ is a powerful method to assess the effectiveness of hydraulic fracturing and tomography method can give good information on hypocenter relocation and 3-D seismic velocity models to image the subsurface by delineating fluid in reservoir for geothermal reservoir characterization. In the “VAM” geothermal field, travel time tomography implementation was used to predict that a steam zone is present at an elevation of 500 m above sea level (asl) and that there is a brine zone below it.

## 6. ACKNOWLEDGMENTS

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