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Vertical Seismic Profile (VSP) inversion for Geothermal Reservoirs

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Summary

Australia is the region to have large geothermal resources with the potential to provide cost effective low-emission energy for longer term. During the past two decade, these geothermal resources have been characterised by applying modern seismic methods including Vertical Seismic Profiling (VSP). The main aim of the present work is to predict the soft and hard rocks in a geothermal resource prospective zone form an Australian region and to gain the basic understanding of geological formations. In this work we use VSP data from an Australian region to generate the acoustic impedance sections by maximizing the information from drilled well which is located away form the prospective area and estimated interval velocities. A unique workflow for inverting VSP data is developed and impedance sections have been calculated. We conclude that, if interpreted with caution, alternating soft and stiff sub-layers can be identified, which could help in characterizing the geothermal reservoirs.

Keyword*: Vertical Seismic Profile (VSP), Geothermal Reservoirs, Seismic Inversion*

Introduction

Geothermal energy originates from radioactive decay deep within the Earth and can exist as hot and dry rocks, hot water or steam. Hot Rock geothermal power production utilises buried hot rocks to heat water and generate electricity. In Geothermal environment, a wide variety of seismic methods covering almost every aspect of the seismics have been employed (Nakagome et al., 1998). Owing to complexities associated with heterogeneity, thickness of weathered surface layers on the land and due to limited frequency content the conventional seismic source signal, resolving detailed subsurface characteristics of geothermal reservoir becomes a challenging task (Bevc et al 2002, Kaelim et al 2006). Even with the advent of 3-D seismic, realistic images of subsurface and criticality of assessing the true potentially of geothermal reservoirs remained speculative.

Vertical Seismic Profiling (VSP) overcomes to great extent such hurdles by placing the receivers beneath the highly attenuating and variable surface layer (Gritto and Majer 2003). With such arrangement of source receiver configuration the signal is not required to pass through the surface layer twice, and also by recording the wave field with a vertical array in the borehole, so that up going and down going waves can be identified and separated. The challenge at this point is not a lack of methods but which techniques should be applied and how much one needs to modify the current methods.

Here we evaluate the VSP response from an Australian region and developed a unique workflow of performing VSP inversion for geothermal reservoirs. To this end we utilize the valuable information from drilled wells and estimate the interval velocities for distinguishing hard and soft sediments targets for geothermal resources exploration.

VSP Inversion

Improvements in downhole seismic data acquisition and processing techniques now make it possible to extract a high resolution formational impedance log at the well, from the VSP traces. Impedance is the common data type and is an ideal medium for integrating the direct information and the VSP data since the impedance values from the inversion can be directly related to the layer based rock properties.

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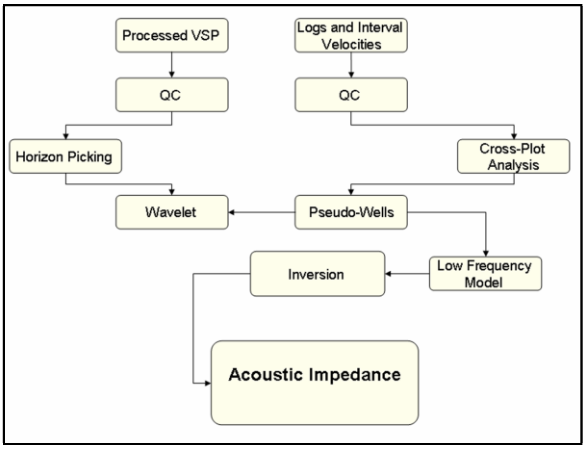

Figure 1: VSP inversion workflow.

Impedance data is generated through seismic inversion, which uses seismic data, log data (wells), seismic velocities (optionally) and picked horizons (Pereyra, 2000). Considering all the possible scenarios, a special workflow has been designed to invert the seismic volume to impedance volume (Figure 1). After correlating the estimated interval velocities and the well (which is located about 20 km away from the target zone) an optimum correlation has been achieved and two pseudo-wells have been extracted at each shot locations. Secondly, an impedance model (layered geologic model) is made by integrating all the available data. Third the impedance model and extracted seismic wavelet are used to invert the seismic data to an acoustic impedance volume. Multiple shots of the stacked VSP data have been used to generate the acoustic impedance. Figure 2, 6 and 8 are showing an example of interpreted VSP sections. Limited coverage of the VSP data constrain the information could be achieved by acoustic impedance. The impedance is calculated at for the well X and for the interval velocity calibrated pseudo well with modeled densities by Gardner's equation.

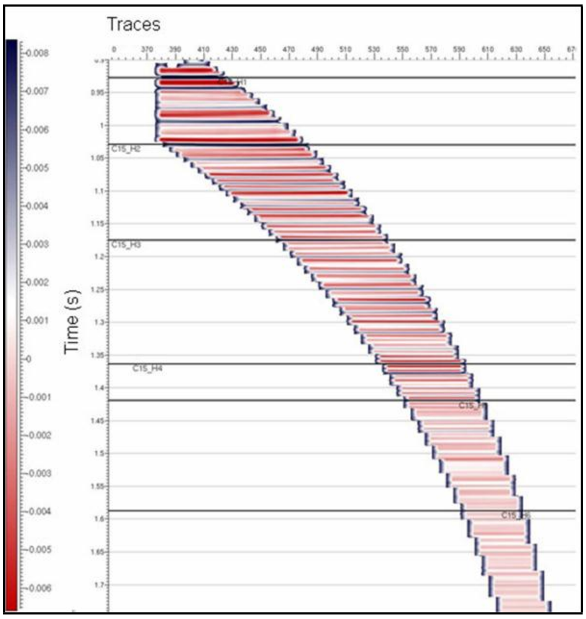

Figure 2: Example of an interpreted VSP section

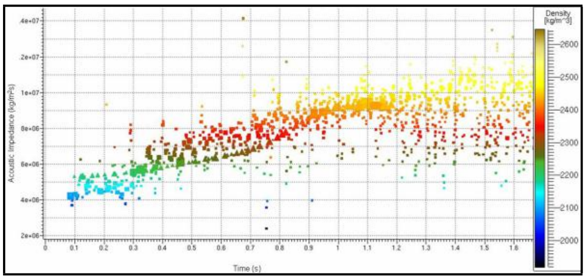

Figure 3: Cross-plot of Acoustic Impedance (AI) from well X and from interval velocities (estimated by processing workflow) colour coded by density.

Based on the relationship from Figure 3 and incorporating the geological constraints, pseudo wells have been extracted at each shot locations and used in inversion processes. In the next step, wavelet estimation process was started by using the generated checkshots as the initial depth-to time (TZ) conversion relationship along with the provided VSP lines. A new TZ function was then generated from P-sonic logs (extracted pseudo-well) and corrected to the checkshots data to provide the initial seismic and well correlation. Using the pseudo-wells a small layered geological model is created for a selected number of traces around the pseudo-wells. A multi trace wavelet estimation method is used and the layered geological model ensures that local stratigraphy is taken into account. Model based wavelet estimation is then conducted by computing filter that best shapes the reflection coefficients from the layered model to the input seismic for selected traces. The extracted wavelet for one shot is shown in Figure 4.

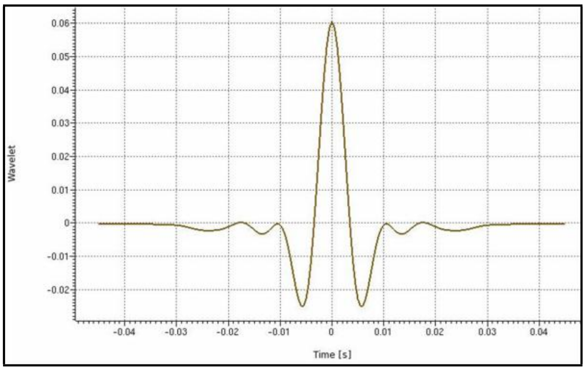

Figure 4: Extracted wavelet for inversion.

The next step is construction the low frequency model. The main role of low frequency model is to infill the low frequencies of the inversion below seismic bandwidth. The low frequency model is also used in the inversion for the trend constraints, which preferentially guide the inversion to a solution. The low frequency models are generated by combining the information from seismic velocities, which controls the lowest frequencies and a geological model that represents the interpolation of well data within a stratigraphic framework.

The geologic model provides the initial estimate of impedance values and provides constraints for subsequent updates in the internally iterative inversion procedure. If the seismic velocities are not if high enough quality they may be omitted and geological model can form the low frequency model on its own. The low frequency model is formed by the merging in the frequency domain of the very low frequency component from seismic velocities with the geological model which has a broad bandwidth. The merge point is assigned based on the frequency content on the seismic velocity based model. Seismic data are influenced by wavelet edge effects and tuning. The data also represent only the contrasts in the impedance between two layers and amplitude contrasts are therefore relative.

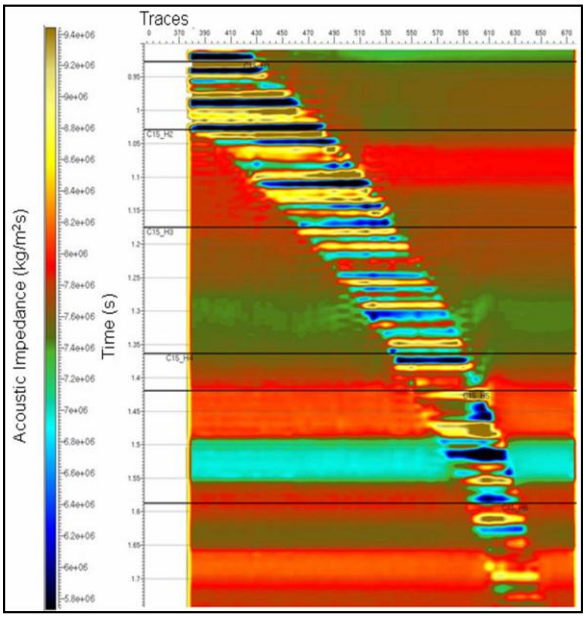

Fig. 5 Absolute impedance model calculated by seismic inversion. Dark blue colour is used for soft sediments (lower absolute acoustic impedance) and yellow represents the hard sediments (increasing acoustic impedances).

To this end we are ready for the next step. Seismic inversion has proven extremely successful for reservoir characterization because it reduces tuning and interference effects of the seismic wavelet and increases the bandwidth compared to the seismic data. In this approach we can force data to integrate and transform from interface properties to layer properties that are the absolute values of the rock themselves.

An independent wavelet has been used for each shot record in the inversion engine. The primary output from the inversion is the impedance volumes for VSP data. The acoustic impedance volumes represents layer properties as it is a physical property of the sub-surface and changes in impedance can often be related to changes in specific reservoir properties such as porosity, lithology and saturation. The example of the impedance section is illustrated in the Figure 5, 7 and 9, where we calculated the absolute acoustic impedance by seismic inversion. The soft sediments are showing low impedance whereas the hard sediments reflecting in the high impedance areas. The hardness scale is varying from blue to yellow.

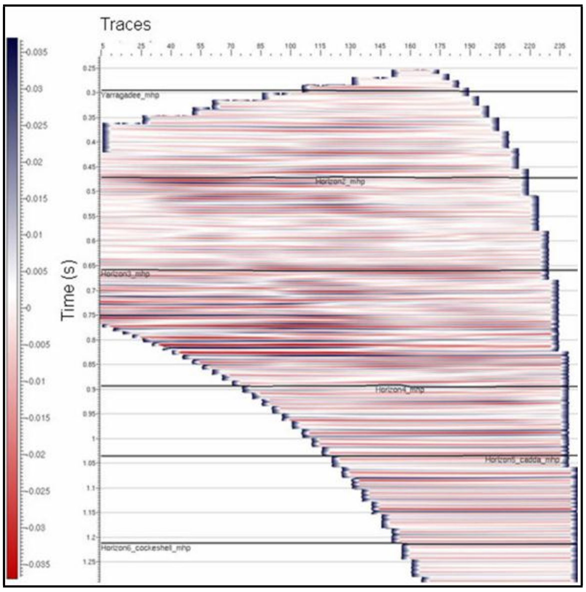

Figure 6: Example of an interpreted VSP section.

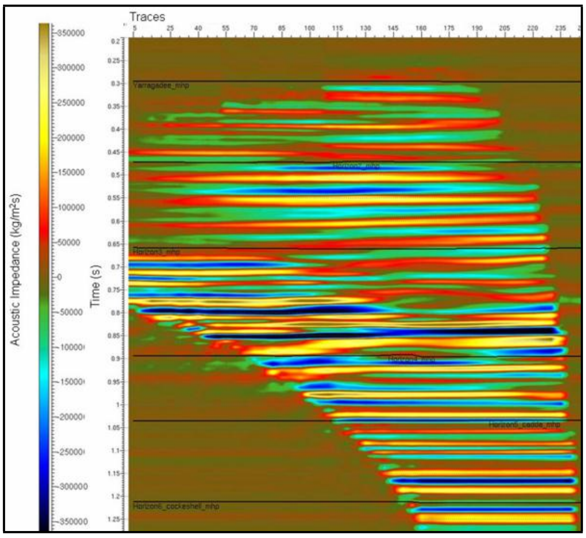

Figure 7: Absolute impedance calculated seismic inversion. Dark blue colour is used for soft sediments (lower absolute acoustic impedance) and yellow represents the hard sediments (increasing acoustic impedances).

Conclusions

We have analyzed the VSP data from three different shot locations from an Australian region, in conjunction with other geological and geophysical information. We have performed seismic inversion by a unique workflow to identify the soft and hard sediments. VSP inversion has been performed with limited direct information available and there are some constraints in the results. The calculated acoustic impedance showed strong lateral and vertical inhomogeneity.

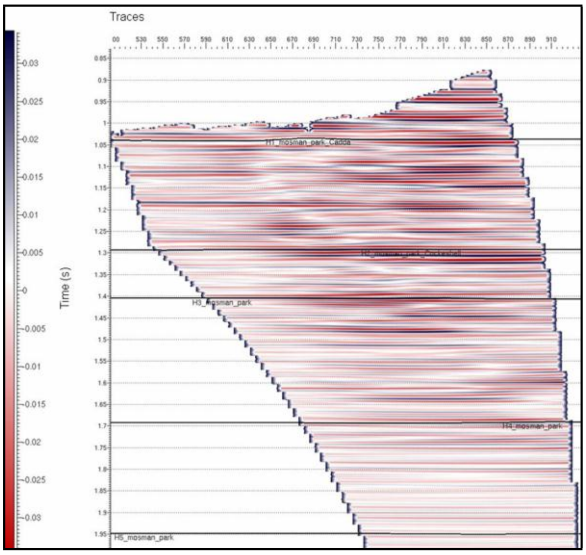

Figure 8: Wave-field propagation at two different time steps (0.018s and 0.050s), (a) is a snapshot of wave-field propagation at 0.018s; (b) is representing the wave-field propagation at 0.050 s.

However, interpreted with caution pseudo-well seismic inversion results may provide benefits in improving the understanding of geothermal reservoirs in the form of better interpretational insight for the search of soft and hard sediments. With the availability direct information (compressional sonic and formation tops etc.), an expert geologist opinion will help in identifying the exact depth of the stratigraphical formations. The hard and soft sediments over the three shot records have been identified by acoustic impedance seismic inversion. Lower values of the impedance show the soft sediments and higher values of the impedance represent the hard sediments.

This study has shown that, the seismic method in conjunction with geologic and other geophysical surveys can delineate geothermal reservoirs if interpreted with caution.

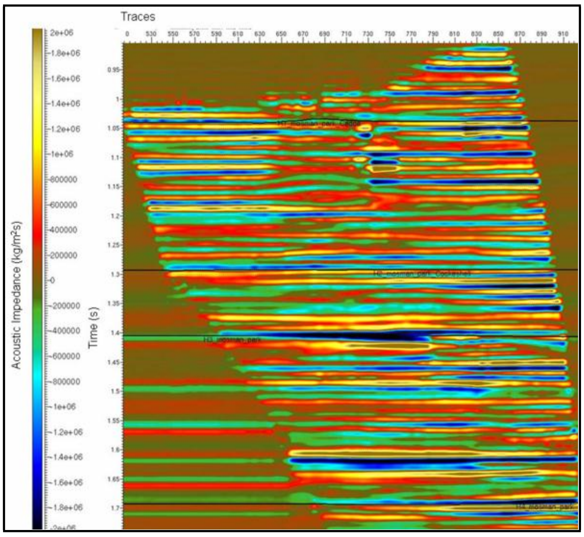

Figure 9: Wave-field propagation at two different time steps (0.018s and 0.050s), (a) is a snapshot of wave-field propagation at 0.018s; (b) is representing the wave-field propagation at 0.050 s.

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