# Subsurface characterisation using full waveform inversion of vertical seismic profile data: Example from the Curtin GeoLab well

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## SUMMARY

Full-waveform inversion (FWI) uses the complete seismic wavefield (transmitted, reflected and converted waves) to build the models of subsurface physical properties. We conducted a feasibility study of a 2D elastic FWI applied to the synthetic and field single offset vertical seismic profile (VSP) datasets. A good correlation is demonstrated between VSP migration image, FWI results, gamma-ray log and stratigraphy even though the ray coverage is limited for a single offset VSP and numerous artefacts are observed in the images built by using FWI. The described approach allowed imaging of a subsurface, identification of geological contacts and their shapes.

**Key words:** vertical seismic profile, full waveform inversion, imaging, subsurface characterisation

## INTRODUCTION

Full-waveform inversion (FWI) attracts a lot of interest due to its potential to give an accurate velocity model often needed for seismic imaging in complex geological environments. This accuracy is achieved by minimising the difference between modelled and field data (Tarantola, 1984). It is mainly used for inverting the surface reflection seismic data, where it relies on low frequencies and very large offsets that produce diving waves. Charara et al. (1996) showed that due to the rich wavefield information (presence of transmitted, converted, and reflected waves) in vertical seismic profile (VSP) datasets, the VSP data is also suitable for the inversion. The FWI of VSP data can be applied to data collected using geophone and distributed acoustic sensors (DAS) (Egorov et al., 2018).

In this study, we use VSP data collected at the GeoLab Research facility, located at the Curtin University campus, Perth, WA. The facility has a 900 meters deep borehole suitable for testing borehole geophysical equipment and new technologies. The borehole is drilled in a geologically representative part of the Perth Basin. It comprises Quaternary, Tertiary, Cretaceous and Jurassic-aged sediments. Previous experiments at this facility provided insights on numerous subjects: the comparison of different borehole seismic receivers (Correa et al., 2017a, Correa et al., 2017b, Van Zaanen et al., 2017, Correa et al., 2018), a better understanding of distributed acoustic sensing measurements (DAS) (Pevzner et al., 2018, Dean et al., 2019, Sidenko et al., 2020, Zulic et al., 2020), testing different seismic sources (Tertyshnikov and Pevzner, 2019), testing three-component VSP with DAS (Tertyshnikov and Pevzner, 2020), and examining the use of the well for passive registration of earthquakes and technogenic activities (Pevzner et al., 2018, Shulakova et al., 2020).

The walkaway VSP experiment was carried out in June 2020 (Zulic et al., 2020). For this feasibility study, we limit to analysis of the geophone data recorded from 130 m to 870 m depth with a 10 m interval from a single source location. The source location is 715 m north of the well and we refer to this shot as S63. An Inova 26,000 lbs vibroseis truck was used as a seismic source. We process and migrate the single-shot dataset and apply FWI workflow to invert for P- and S-wave velocities (Vp and Vs, respectively) and demonstrate the applicability of FWI applied to a single shot VSP data.

## METHODS

The processing flow applied to the field dataset involves the following steps: loading data to the seismic processing software, correlating with the pilot sweep, assigning the field geometry, editing bad traces, orienting the horizontal components towards the source, stacking, applying deterministic deconvolution, performing wavefield separation, building the velocity model and performing the migration.

In addition to the described processing, we applied a 2D elastic FWI workflow (Egorov et al., 2017) to synthetic and field datasets. The workflow is implemented in an open-source software package IFOS2D (Köhn, 2011, Bohlen et al., 2016). Pre-processing steps for FWI are the same as for the conventional flow (correlation with the pilot sweep, assigning field geometry, the orientation of horizontal components towards the source, stacking). Then, we convert the data to minimum phase, correct to 2D amplitudes and use the corrected vertical and radial components coupled with an elastic model as inputs for the FWI.

Synthetic VSP data are calculated using Vp estimated from a near offset DAS VSP experiment at GeoLab (Correa et al., 2017b) and Vs and density calculated using empirical relations (Castagna, 1985, Gardner, 1974). We refer to this model as a true model. We use the forward modelling results to test imaging parameters and assess the performance of FWI for single-shot data. We invert the data from a shot location distanced 715 m using receivers from 130 m to 870 m depth interval for the frequency range 6-65 Hz. A smoothed version of the elastic model used in the forward modelling is a starting model (M1) for FWI.

For inversion of the field data, as the starting model (M2), we use the 1D Vp distribution obtained by inverting the first arrival travel times using fast marching eikonal solvers (Kroon, 2021) and Vs and density derived using the same empirical relations as for the synthetic model. We inverted field data from S63 using receivers 130 m to 870 m depth interval for the frequency range of 11 – 105 Hz.

## RESULTS AND DISCUSSION

**Figure 1** shows the true and starting Vp models used in the synthetic study and the inverted Vp models from FWI. We observe that the inverted model converges to the true model resolving thin layers of different velocities at depth (indicated by red arrows in the figure). Most of the model updates occur within the ray coverage area and wave propagation artefacts affect the rest of the model. The 10 m-thick high-velocity layer (indicated by a red dashed box in the figure) at a depth of 130 m could not be reconstructed, probably due to inadequate coverage and maximum inversion frequency of 65 Hz. The synthetic modelling results confirm that the FWI of single-shot VSP data produces an adequate subsurface image.

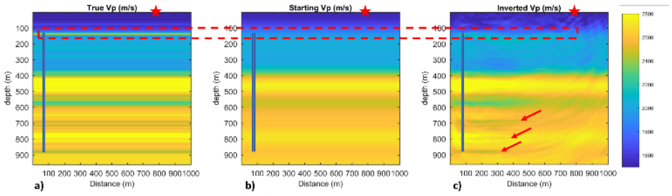

**Figure 1. Vp models used for synthetic data: (a) True model (b) Starting model M1 (c) Inverted model. Blue line show receivers and red star source location. The arrows point to the well-resolved thin layers.**

For the field data, we first used the same FWI parameters as in the synthetic study. However, the inversion of the field data did not converge even for low frequencies, indicating that the starting velocity model was not sufficiently accurate. Although the zero offset VSP is the most accurate method to obtain seismic velocities along the borehole (Cassel, 1990), the use of these velocities away from the borehole assumes lateral homogeneity and such assumption that is not always met in practice. We applied travel time tomography to create a new starting velocity model with the picked first arrival travel times from S63. We used a 1D-eikonal solver based tomography that accounts for the refracted waves present on raw gather to construct the velocity model. The results from FWI applied to field data using M2 are shown in **Figure 2** for three frequency stages: 11 Hz (top), 40 Hz (middle) and 105 Hz (bottom). As the number of iterations and frequency increase, the contribution of converted and reflected waves increases, while misfit decreases.

**Figure 3** shows the starting M2 model (Vp and Vs) and the results of FWI. Because the single offset VSP has a limited ray coverage, which we additionally reduced by excluding low signal to noise traces from the inversion (see the missing traces in Figure 2), the FWI images of Vp and Vs contain strong artefacts. However, FWI seems to resolve thin velocity layers around the well, indicated by the red arrow in **Figure 3**. These layers correlate to interbedded sandstone and siltstone units observed in the gamma-ray log, particularly within Yarragadee (Jy) Jurassic sediments, as shown in **Figure 4**.

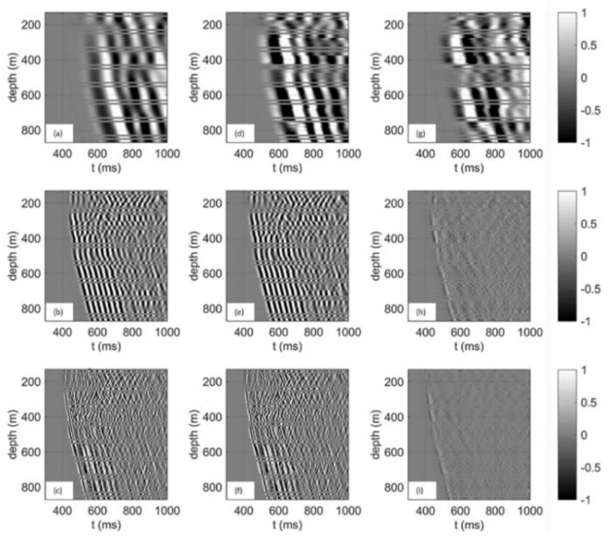

**Figure 2. VSP gathers from different frequency stages (11 Hz (top), 40 Hz (middle) and 105 Hz (bottom). From left to right: modelled (2a-2c), field (2d-2f) and calculated misfit (2g-2i) gathers.**

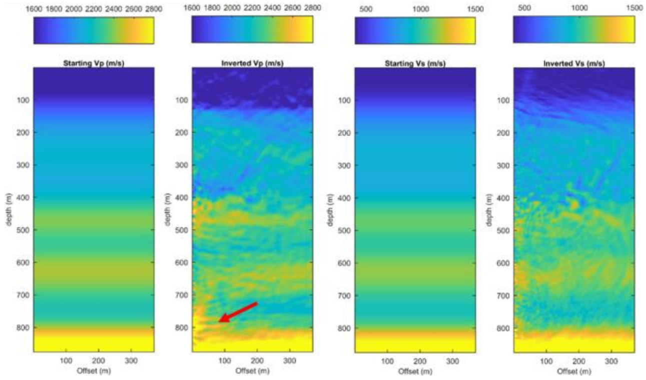

**Figure 3. Results from FWI of data with source S63. From left to right: Starting Vp model (M2), Inverted Vp model, Starting Vs model, Inverted Vs model.**

For further interpretation and understanding of the FWI results, in **Figure 4,** we superimpose them over VSP migration image and additional logging data (gamma-ray, stratigraphy log indicating base of unit). Based on the inverted Vp and Vs images from FWI, we calculate the image of Poisson's ratio - PR (Birch, 1961), which can assist with rock characterisation. Results from both imaging methods (VSP migration and FWI) indicate some form of heterogeneity at a depth of 400 m. VSP migration has a distinctive reflector at this depth, while the FWI Vp image has a substantial change in velocity characterised by an undulating shape. Additionally, we observe a significant decrease of PR in one of the undulations, which can indicate more compacted material than in its surrounding. From the stratigraphic log, we can correlate these observations to the contact between Tertiary (Tkc) and Cretaceous (Kwlw) sediments, Kings Park Unconformity, a major paleovalley (Rockwater, 2016). This local heterogeneity can also explain the observed diffracted waves on the shot records.

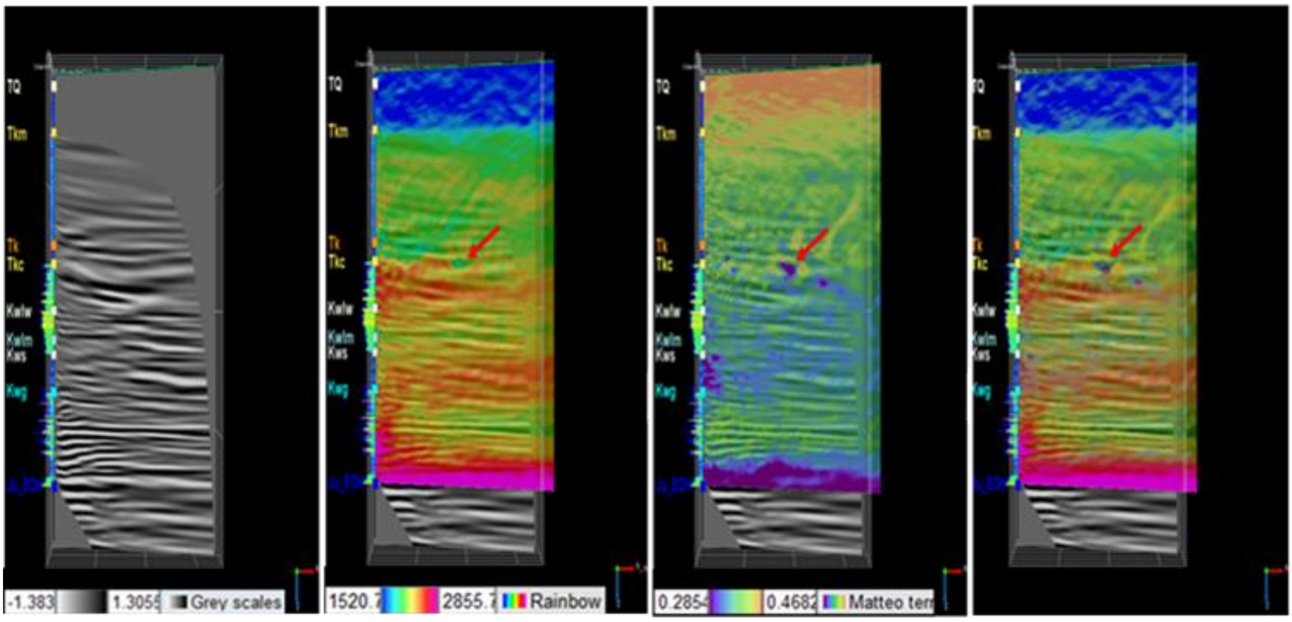

**Figure 4. Superimposed results with logging data (gamma-ray and stratigraphy). From left to right (a) VSP migration image M2; (b) migration Vp image over VSP migration; (c) Poisson's ratio image over VSP; (d) superimposition of Poisson's ratio, Vp and VSP migration image.**

## CONCLUSION

The FWI workflow applied to VSP data can provide additional value for the subsurface characterisation. The critical step for successful FWI application is having an appropriate starting velocity model, which can be obtained by tomography. While the ray coverage is limited for a single offset VSP and numerous artefacts are observed in the images built by using FWI, there is a good correlation between VSP migration image, FWI results, gamma-ray log and stratigraphy. The artefacts could be reduced by including data from additional source locations. Overall, the described method allowed to some extent, the imaging of a subsurface, identification of geological contacts and their shapes.

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