Application of time-lapse full waveform inversion of vertical seismic profile data for the identification of changes introduced by CO_2 sequestration

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SUMMARY

Seismic methods are frequently used for the purpose of monitoring of time-lapse changes introduced by CO2 sequestration. Surface seismic is often considered as the main tool for monitoring. Vertical Seismic Profile (VSP) is occasionally applied as an auxiliary method. Standard VSP data processing workflow does not provide a quantitative estimate of the time-lapse changes in the physical properties. However, full waveform inversion (FWI) may be used for the purpose of quantitative interpretation. Its ability to employ the whole seismic wavefield (including transmitted, reflected and converted waves) for the purpose of building the models of physical properties can be considered one of its main advantages.

We show that time-lapse elastic FWI of VSP data is capable of providing quantitative estimates of time-lapse changes in the medium. A feasibility study is carried out on 2D and 3D synthetic datasets created using full-earth models of the CO2CRC Otway CO2 sequestration site. The inversion workflow obtained from the feasibility study is successfully applied to a field single-offset time-lapse VSP dataset. As a result, FWI provides an image of the time-lapse changes introduced by the injection of supercritical CO2.

Key words: full waveform inversion, FWI, vertical seismic profile, VSP, time-lapse, CO_2 sequestration.

INTRODUCTION

Vertical Seismic Profile (VSP) surveys are regularly used for seismic monitoring in CO_2 sequestration. 3D VSP (Harris, et al. 2016), offset VSP (Al Hosni, et al. 2016) and walkaway VSP (Yang, et al. 2014) geometries are applied. However, quantification of time-lapse changes occurring in the subsurface is rarely performed using VSP. Full waveform inversion (FWI) (Lailly 1983, Tarantola 1984) is a method that allows one to reconstruct the models of physical properties of the subsurface using seismic data of any geometry, including VSP.

In our study, we conduct time-lapse FWI of single- and multi-offset synthetic and field VSP datasets in order to acquire an image of the time-lapse changes introduced by the CO_2 injection. Only single-offset or multi-offset VSP geometries are considered due to the fact that they record direct waves, which facilitate the FWI workflow (Neklyudov, et al. 2013). Seismic receivers are placed both above and below the CO_2 plume. We were unable to obtain good-quality images of the injected CO_2 using lookahead VSP geometries, with receivers only above the plume.

We conduct FWI of synthetic time-lapse VSP datasets for both single-offset and multi-offset geometries. Field data application is limited to single-offset geometry. Synthetic datasets were computed using a model of the Otway site in Victoria, Australia. Field time-lapse VSP datasets we invert were acquired during Stage 2C of the Otway project. Stage 2C of the Otway project involved an injection of 15,000 tons of CO_2/CH_4 gas mixture into a saline aquifer at ~1500 m depth. Offset VSP, walkaway VSP and 3D VSP surveys were acquired. Here, we use only offset VSP data. There are four offset VSP shot points on the site. Five surveys were conducted – a baseline and four monitors. For this study, we use a baseline dataset and a dataset from the monitor survey acquired directly after the end of 15,000 t injection. The inversion results from Offset Shot Point 1 were published (Egorov, et al. 2017), so here we present a comparison of time-lapse inversions for different shot points and try to analyse the differences between the images of the plume.

METHOD

We conduct elastic time-domain FWI implemented in an open-source inversion package (Köhn 2011). Multiscale approach is applied by filtering the data with low-pass filters in time domain (Bunks, et al. 1995). For the inversions displayed, we parameterized the medium with V_P, V_S and density, alternative parameterizations (Köhn, et al. 2012) were not considered. The workflow used here is similar to the FWI workflow published previously (Egorov, et al. 2017). The only difference in the workflow is in the time-windowing strategy. For the inversion of multi-offset synthetic data displayed here, full seismic wavefield is used. For the inversion of the field and synthetic single-offset datasets, the source-generated S-waves are included in the inversion only for frequencies below 20 Hz.

Above that frequency, these waves are removed from the inversion. This is caused by the fact that the source-generated S-waves present in the field data lack high frequencies.

For all the inversions on synthetic data, we use 1D starting models created by smoothing V_P, V_S and density values at the well location. For FWI of field data, starting models are created by smoothing and extrapolation of available V_P, V_S and density log data. Sequential/bootstrapping time-lapse inversion workflow is used (Asnaashari, et al. 2015, Kamei and Lumley 2017), i.e. the inversion was carried out in two stages. First, the baseline dataset is inverted. The result of baseline inversion is taken as an input to monitor data inversion.

RESULTS – SYNTHETIC EXAMPLE

In Figure 1, baseline inversion results for multi-offset VSP geometry are displayed. The synthetic data being inverted was generated using a 2D finite-difference code. In Figure 2, time-lapse image of the difference in V_P obtained by the inversion is compared to the true V_P difference between the baseline and monitor models. Sources and receivers are displayed on the models. Maximum receiver depth is 1800 m.

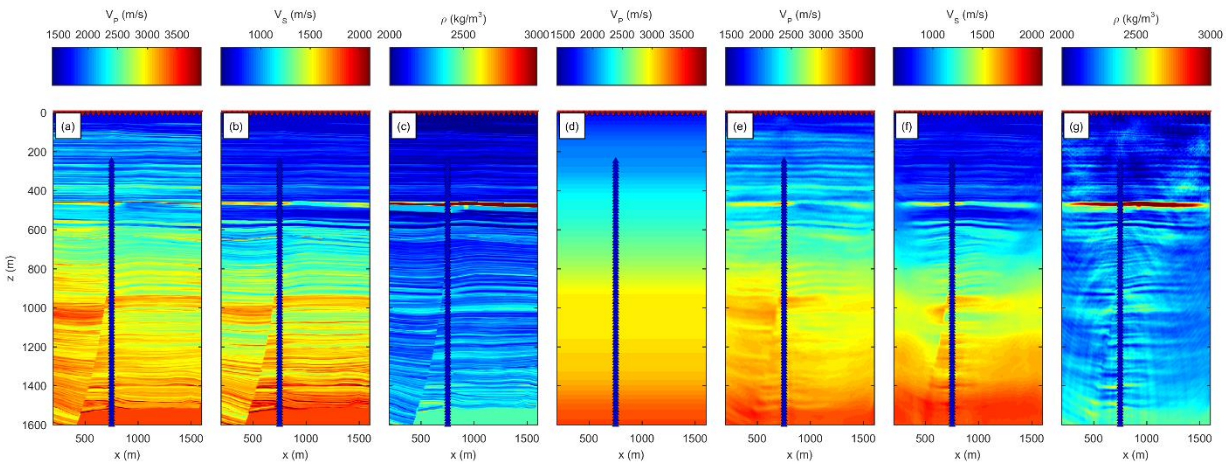

Figure 1: Multi-offset VSP baseline inversion results: true V_P model (a), true V_S model (b), true density model (c), initial V_P model (d), inverted V_P model (e), inverted V_S model (f), inverted density model (g). Initial V_S and density models are not shown, they were created the same way the displayed initial V_P model was created.

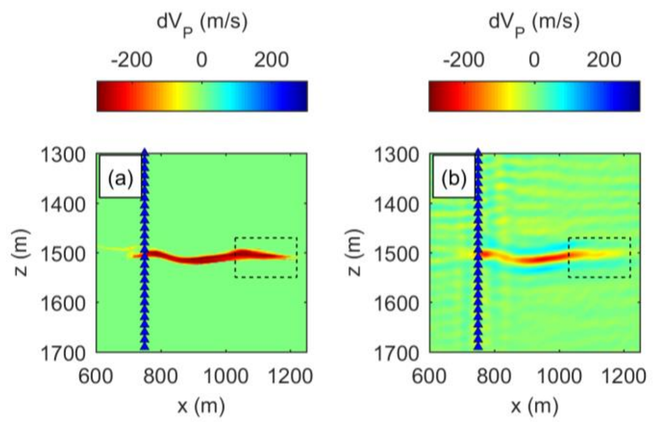

Figure 2: Multi-offset VSP time-lapse inversion results: true change in V_P (a), inverted change in V_P (b). Part of the plume inside the black rectangle is not imaged due to the lack of illumination.

In Figure 3, baseline inversion results for single-offset VSP geometry are displayed. This example is designed to mimic the field examples shown below, so it is modelled using a 3D elastic finite-difference code and a realistic 3D model of the Otway site. This 3D dataset was approximately converted to 2D amplitudes (Pica, et al. 1990). In Figure 4, time-lapse image of the difference in V_P obtained by the inversion is compared to the true V_P difference between the baseline and monitor models. Sources offset from the well is 825 m. Maximum receiver depth is 1800 m.

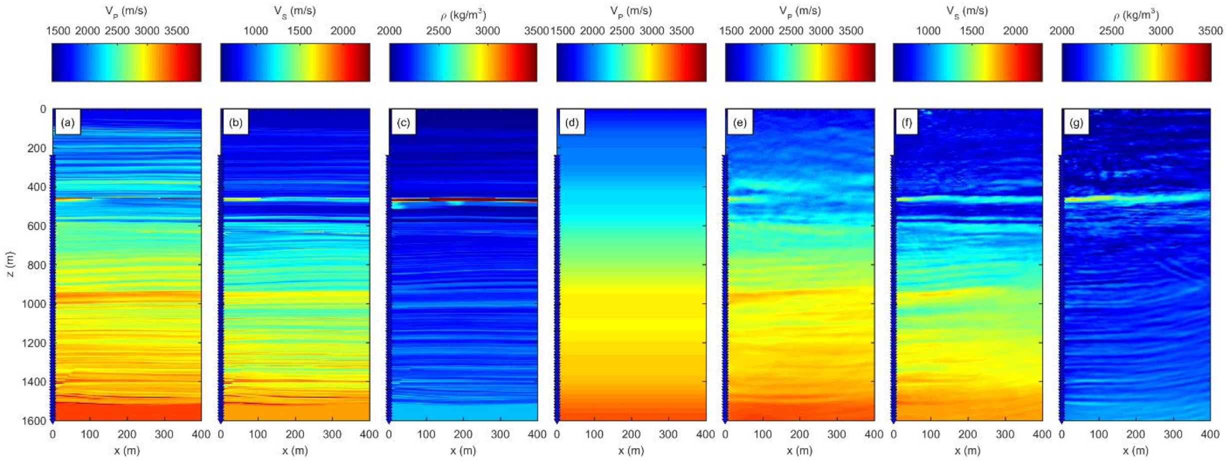

Figure 3: Single-offset VSP baseline inversion results: true V_P model (a), true V_S model (b), true density model (c), initial V_P model (d), inverted V_P model (e), inverted V_S model (f), inverted density model (g). Initial V_S and density models are not shown, they were created the same way the displayed initial V_P model was created.

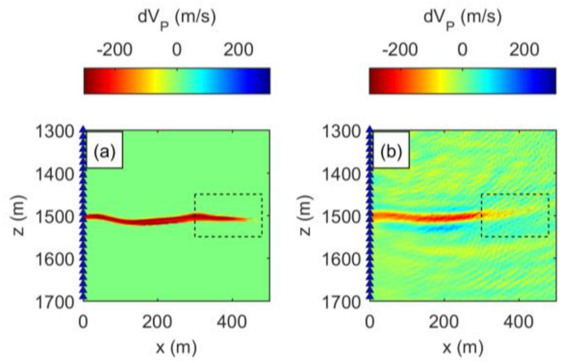

Figure 4: Single -offset VSP time-lapse inversion results: true change in V_P (a), inverted change in V_P (b). Part of the plume inside the black rectangle is not imaged due to the lack of illumination.

RESULTS – FIELD EXAMPLE

Locations of four offset shot points used during Stage 2C of the Otway project are shown in Figure 5. In the same Figure, locations of the injection well (CRC-2) and the monitoring well (CRC-1) are displayed. Seismic geophones were placed in the monitoring well, geophone interval was 15 m, ~100 levels were acquired for each of the surveys. As the four offsets have different azimuths, they provide imaging of different slices of the CO_2 plume.

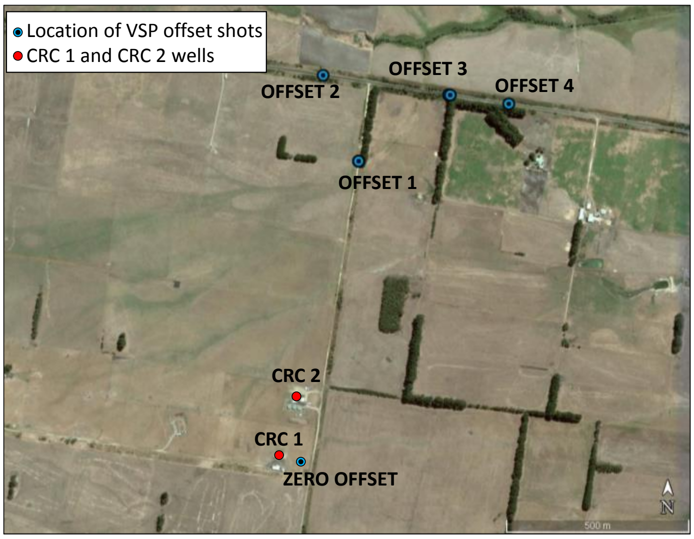

Figure 5: Locations of CRC-1 and CRC-2 wells and four offset VSP shot points.

In Figure 7, we show the FWI result obtained by inverting a baseline field single-offset VSP dataset, shot 2 (offset 1035 m). In Figure 8, we compare the time-lapse images of the CO_2 plume obtained by the FWI of shot points 1 (offset 825 m), 2 (offset 1035 m) and 3 (offset 1082 m). The quality of the inversion result for shot point 3 is lower due to lower repeatability of seismic data for this shot point. In this case, we estimated the repeatability by computing the normalized root mean square parameter between the baseline and monitor surveys (Tertyshnikov, et al. 2017). We tried to run the inversion on the data from shot point 4 (offset 1141 m), but were unable to get an image of the time-lapse anomaly, possibly due to low repeatability and unsuitability of a 1D starting model for such a long offset.

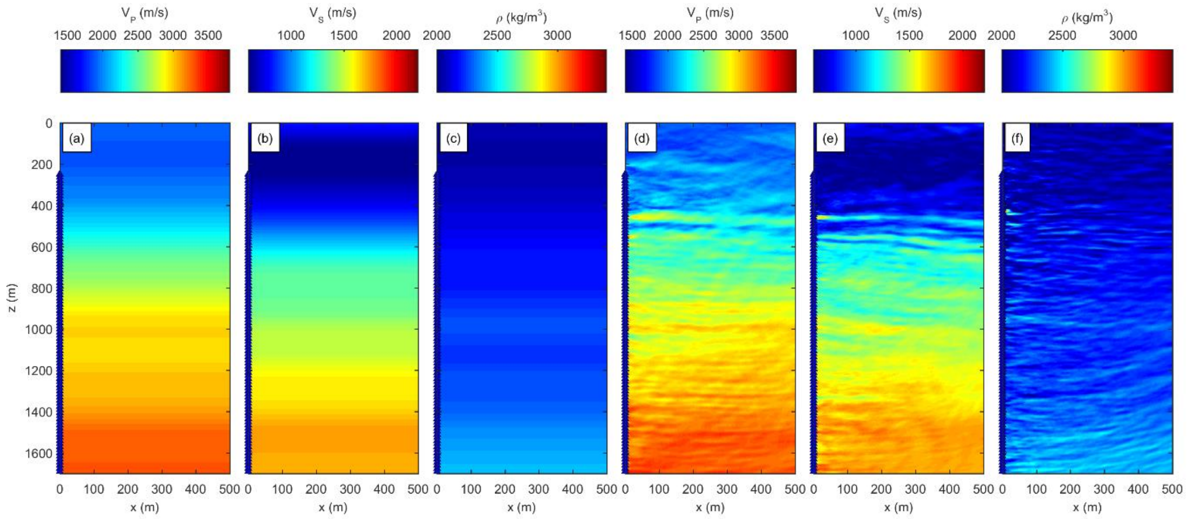

Figure 6: Field single-offset VSP baseline inversion results, offset shot point 2 of Otway Stage2C project: initial V_P model (a), initial V_S model (b), initial density model (c), inverted V_P model (d), inverted V_S model (e), inverted density model (f).

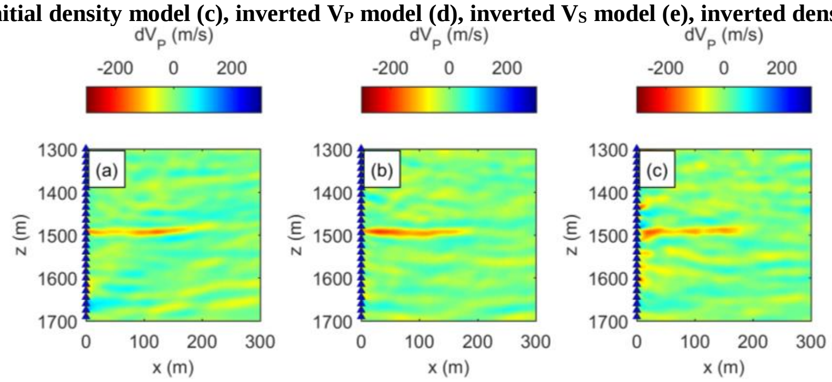

Figure 7: Field single-offset VSP time-lapse inversion results. Images of CO_2 plume identified by the inversion of VSP data from different shot points: shot point 1 (a), shot point 2 (b) and shot point 3 (c).

CONCLUSIONS

This study shows that FWI of multi-offset and single-offset VSP datasets is a suitable tool for seismic monitoring. FWI applied to multi-offset and single-offset VSP provides quantitative estimates of time-lapse changes in P wave velocity introduced by the CO_2 injection. FWI applications to field data prove that this techniques is applicable to real-life monitoring scenarios. Comparison of FWI results for different offsets provides new information about the geometry of the CO_2 plume injected during Stage 2C of the Otway project.

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