Timelapse DAS VSP Viscoelastic FWI for CO2 Monitoring

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Timelapse DAS VSP Viscoelastic FWI for CO2 Monitoring

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Summary

Changes in reservoir properties resulting from the CO2 injection and migration can be monitored using time-lapse seismic data. Conventional analysis gives only qualitative information about the changes of the acoustic impedance contrasts in the reservoir. In order to differentiate the pore-pressure from CO2 saturation effects, it is necessary to evaluate the changes in the elastic properties. Borehole seismic data contain strong converted shear waves at the level of the reservoir that will allow determining S-velocity changes. FWI is an appropriate method to estimate elastic parameters. As CO2 saturation increases in the reservoir, P-waves undergo strong attenuation. Hence, it is necessary to estimate as well the bulk modulus Q-factor Q_κ. We demonstrate the feasibility of timelapse multi-Offset DAS VSP inversion for CO2 sequestration monitoring, by inverting synthetic seismic data based on a virtual CO2 injection site study. The timelapse FWI recovers P-wave and S-wave velocities for the baseline model; and, the perturbations of the velocity models associated to 3 years of CO2 injection are also well recovered for a distance of a few hundreds of meters from the well. The bulk modulus Q-factor Q_κ is not well recovered but it is needed for the correct estimation of the velocity models.

Introduction

Changes in reservoirs during large-scale CO2 injections are observed using time-lapse seismic surveys. The long-term monitoring of underground CO2 injection zones to characterize fluid migration and potential leakage over time is crucial for ensuring safe and reliable carbon storage (Bickle et al., 2007).

Conventional analysis of time-lapse surface seismic data only gives qualitative information (Arts et al., 2004). Impedance contrasts and seismic response changes have been used to characterize CO2 accumulations in thin layers, and "velocity pushdown effects" have been identified that cause slower propagation of seismic waves through the CO2 saturated area. However, these changes have not been modeled. Ma & Morozov (2010) suggest that 3D/3C surface seismics are necessary to extract the shear-wave properties of the reservoir by using advanced AVO analysis. They used forward modelling to develop AVO attributes that could be used for separating the pore-pressure and CO2 saturation effects within the reservoir. However, as CO2 saturation increases in the reservoir, P-waves undergo severe attenuation. Fitting the recorded data with synthetic data generated with an elastic modeling method that neglects attenuation obviously results in a biased estimation of the elastic parameters. For that reason, in the process of FWI, it is necessary to take into account P-wave attenuation by estimating simultaneously the bulk modulus Q-factor Q_κ with the elastic parameters.

To demonstrate the feasibility of the multi-Offset DAS VSP inversion for CO2 sequestration monitoring, we propose a synthetic seismic experiment based on the reservoir simulation results and the derived velocities anomalies for a virtual CO2 injection site (Tsuchiya et al, 2017), complemented by an evaluation of P-wave attenuation anomalies associated to the CO2 saturation. We will also compare the FWI results obtained with DAS data cemented behind casing and those obtained with classical vertical geophone component VSP data.

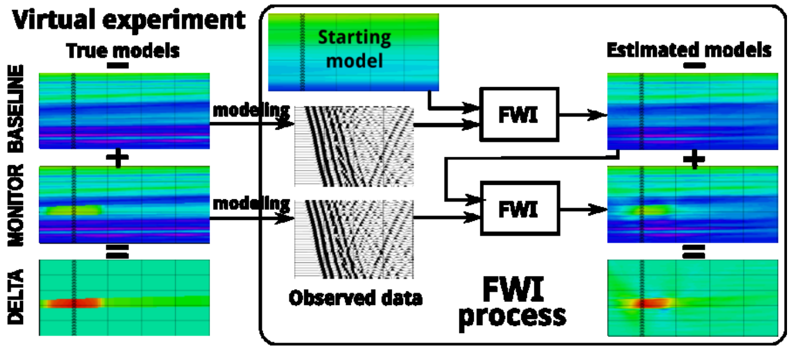

Figure 1 *The workflow of the present virtual FWI-monitoring experiment. The colored images zoom on the reservoir zone where small triangles represent the geophones of the antenna (see Figure 2). The BASELINE indicates the model/data before injection while MONITOR denotes the model/data after 3 years of CO2 injection. For better display purposes, DELTA is the difference between MONITOR and BASELINE. Baseline and monitor observed data for FWI are obtained by modelling wave propagation, respectively in the baseline and monitor true models. The estimated baseline model is obtained by applying FWI on baseline observed data and using the Starting model. The estimated monitor model is obtained by applying FWI on the monitor observed data and starting from the estimated baseline model.*

Borehole seismic monitoring for virtual CO2 injection site

Tsuchiya et al. (2017) studied a virtual CO2 injection site within the area F3 block in the Dutch sector Southern North Sea. An injection well is assumed to be drilled to a position within an interpreted sand-rich formation. Interval of the defined injection formation at the pseudo well is 855-930m. A

monitoring experiment has been designed to evaluate the applicability of elastic FWI of VSP data for CO2 injection monitoring. The goal is to extract two independent physical parameters from the data, namely P- and S-wave velocities in order to determine the pore-pressure and CO2 saturation effects within the reservoir. To complement this study, an attenuation model Q_κ has been derived from experimental relationship between the ratios V_P/V_S and Q_S/Q_P . We assume that Q_P varies with CO2-saturation but not Q_S and that Q_P and Q_S are not affected by the pressure buildup for the frequencies of interest, i.e., below 40Hz.
The MO-VSP consists of 9 shots located every 200m (no zero offset shot) with a vertical antenna from 300 down to 1200m and a 10m geophone interval (see Figure 3). For comparison purposes, we performed two FWI experiments: one with DAS data set (Figure 2; Right) and, a second one, with vertical geophone component (Figure 2, Left).

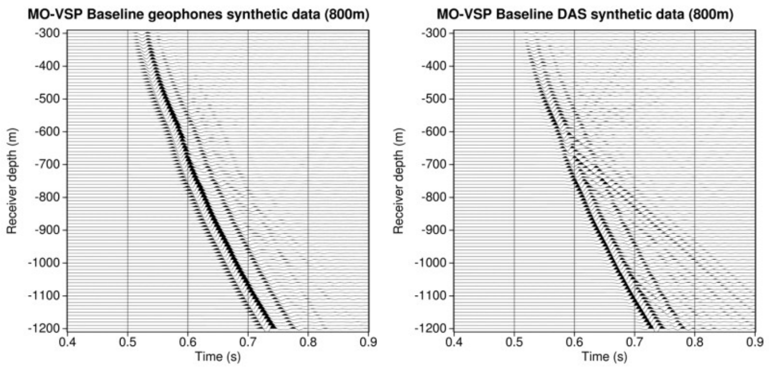

***Figure 2** One shot of* the *MO-VSP observed data obtained by full-wave modeling. Left: The vertical component of a geophone measurement; Right: The vertical strain of a DAS measurement.*

Timelapse Visco-Elastic Full Waveform Inversion

Full waveform inversion can be solved by local optimization methods (Tarantola, 1987). For the case of least squares, the misfit function is a scalar function defined over the model space as $S(\mathbf{m}) = \Delta\mathbf{d}^T\Delta\mathbf{d}$, where $\mathbf{m}$ is a model, and $\Delta\mathbf{d} = \mathbf{d}_{obs} - \mathbf{g}(\mathbf{m})$ are the residuals; i.e. the difference between the observed data $\mathbf{d}_{obs}$ and the synthetic data $\mathbf{g}(\mathbf{m})$ obtained by simulation of the wave equation. For this purpose, we use a 2.5D finite difference scheme for a viscoelastic rheology. The expressions of the Fréchet derivatives for the viscoelastic parameters and the details of the approach for VSP data can be found in Charara et al. (2000). Like for surface seismic data FWI, the density field cannot be recovered with accuracy, only the contrasts can be. However, it is necessary to invert for the density in order to retrieve properly the other elastic parameters. As density is not used for further evaluation, we omit to display the inversion results for the density field.

The timelapse viscoelastic FWI consists, first, in inverting the baseline MO-VSP DAS data acquired prior to any CO2 injection to obtain the estimated baseline model. Then starting from this baseline model, invert the monitor MO-VSP DAS data acquired after a certain interval of time of CO2 injection (3 years in our case) to obtain the estimated monitor model. Figure 1 summarizes the timelapse viscoelastic FWI approach.

Baseline elastic FWI before injection

The viscoelastic FWI for the baseline (detailed results not shown here) is able to recover with reliability both P- and S-wave velocity parameters in the illuminated region from the sources to the receivers. One can increase the illuminated region by using more offsets or deeper antenna but a few hundreds of meters are a typical lateral resolution for borehole seismic data. However; this is not the case for Q-factor Q_κ field which is not well resolved like the P- and S-wave velocity. The obtained viscoelastic parameter fields are taken as initial models for the next stage of monitoring (see Figure 4, gray profiles).

Monitor elastic FWI after 3 years injection

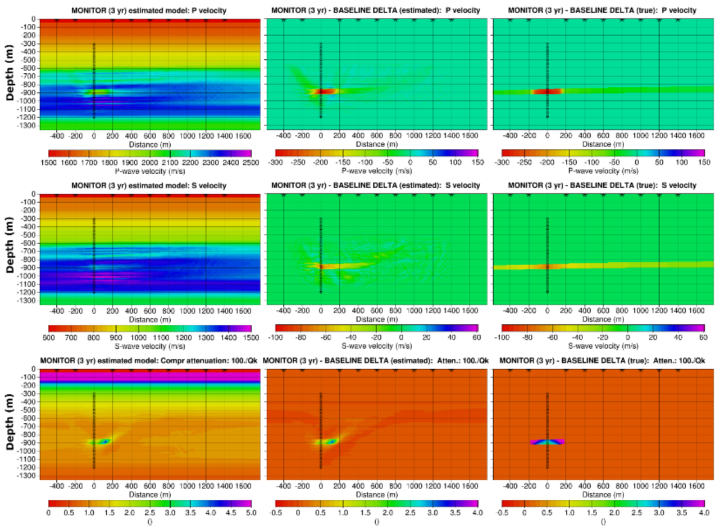

Figure 3 *Results of the FWI for the monitor MO-VSP DAS data. Top: The P-wave velocity fields, Middle: the S-wave velocity fields and Bottom : the bulk modulus Q-factor Q_κ (100/Q_κ for display purposes). Left, the FWI estimated models; Middle, the estimated delta between monitor and baseline; and Right, the true delta we want to retrieve. The extension of the perturbation on the right side is correct up to 300 m from the well for velocities but it is underestimated for the attenuation parameter.*

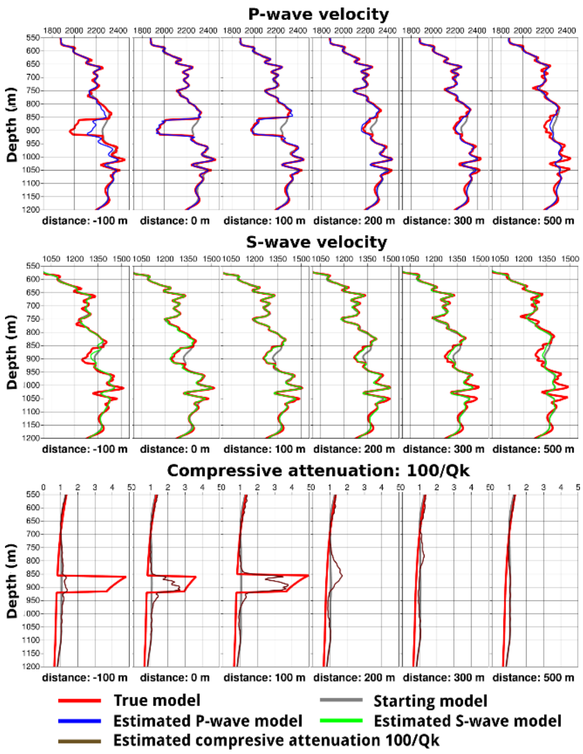

Figure 4 *Top: P-wave velocity profiles; Middle: S-wave velocity profiles and Bottom: bulk modulus Q-factor Qκ (100/Qκ for display purposes). The different plots correspond to different distances from*

the well. The starting model, from the baseline data FWI, is denoted by the gray line. The true model is denoted by the red line while P- and S-wave velocities are denoted respectively by the blue and the green lines. The fit between estimated and true model is good from 0 to 300 m for P- and S-wave velocities and only qualitatively good for Q-factor Qκ (denoted by the brown line).

The 3-year timelapse monitoring experiment is based on the reservoir perturbations of P- and S-wave velocities, density and Q-factor Q_κ fields in the reservoir. The results of the FWI applied to the monitor data are displayed in 3. The extension of the perturbation on the left side of the well is not sufficient due to lack of shots on this side (only 2) and the extension on the right side is correct up to 300 m from the well. This allows us to predict the CO2 saturation and the pore pressure within this interval (Tsuchiya et al., 2017).

Here also the Q-factor Q_κ field is not well resolved. The global trend is correctly retrieved. However the attenuation is underestimated. Moreover, the sharp interfaces are partly smoothed and the anomaly perturbations have a tendency to spread beyond their actual locations.

The FWI using with vertical geophone component (not shown here) gives very similar results to the DAS data. Note that in our FWI experiments, the data are noise free.

Conclusions

This virtual experiment illustrates the concept of the multi-Offset DAS VSP inversion for CO2 sequestration monitoring. It allowed us to correctly recover the P- and S-wave velocity fields for a few hundreds of meters from the well, which is a typical lateral extent of the resolution region for borehole seismic data. The accurate quantitative knowledge of P- and S-wave velocities enables to differentiate the pore pressure and CO2 saturation effects within the reservoir. However, the results show that the bulk modulus Q-factor Q_κ parameter is not well recovered but contribute significantly in the determination of the elastic parameters by fitting the attenuated phases in the data. Most likely, the bulk modulus Q-factor Q_κ needs to be constrained in order to use it for quantitative interpretation.

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