Rock-physics based time-lapse inversion in Delivery4D: synthetic feasibility study for CO2CRC Otway Project

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SUMMARY

Conventional approach to 4D seismic inversion consists of parallel inversions applied to seismic vintages. Only then, the inverted changes of seismic attributes are converted into petrophysical properties using rock physics. The paper develops a robust approach to 4D seismic inversion based on a Bayesian approach along with rock physics constraints. This means that observed time-lapse seismic response along with the baseline amplitudes are inverted directly into rock properties via pre-defined relations to the seismic properties.

To this end, we extend the functional of Delivery - an open-source stochastic inversion software.
We illustrate efficiency of Delivery4D using synthetic 4D dataset generated for Stage 2C of CO2CRC Otway project, Victoria. Complexity of the synthetic wavefield resembles field data acquired for the Otway project while all unknown sources of noise/uncertainty are excluded and we have 'ground-truth' subsurface properties.

Despite the relatively thin CO2 plume, the 4D inversion reduced detected time-lapse anomaly to the location that closely corresponds to the actual CO2 plume. Estimated distributions of the plume characteristics (thickness, saturation and CO2 mass) are overall similar to the static and dynamic geomodels. However, the values inverted at a particular trace may differ significantly. We attribute these discrepancies to the limited seismic resolution and imperfections of the amplitude-preserved seismic processing.

Key words: seismic inversion, rock physics, time-lapse seismic, Bayesian approach

INTRODUCTION

Time-lapse or 4D seismic became a routine method for monitoring subsurface fluids movement/alteration, which may occur during petroleum exploration, CO2 geosequestration etc. Often interpreters limit themselves by qualitative interpretation of lateral extent and overall intensity of the observed 4D seismic response. To go beyond that one has to establish a consistent model relating petrophysical parameters of the modified rock mass (lithology, porosity saturation etc.) to its seismic properties and observed seismic response.

Conventional approach to 4D seismic inversion consists of parallel inversions applied to seismic vintages, which results in a set of difference cubes showing evolution of the reservoir elastic properties (Johnston 2013). Only then, the inverted changes of seismic attributes may be converted into petrophysical properties using rock physics modelling (Dvorkin et al. 2014). However, this last step is not a trivial procedure because rock physics merely provides relations – often nonlinear - which reasonably match to calibration data affected by errors and noise (laboratory measurements, well logs etc.). That makes estimation of rock and fluid properties from seismic attributes inverse problem suffering from ill-posedness and uncertainty of the results (Grana 2016).

We think that a robust solution is a rock physics based approach to 4D seismic inversion, meaning that observed time-lapse response is inverted directly into rock properties via pre-defined relations to the seismic properties. Such an approach has been already implemented in Delivery an open-source stochastic inversion software (Gunning and Glinsky 2004). The software operates with rock properties directly, hence it was straightforward to be expanded to a simultaneous interpretation of seismic vintages and time-lapse differences between them in terms of petrophysical changes. The resultant software was released as Delivery4D.

This paper illustrates functional of Delivery4D in application to characterisation of evolution of sequestered CO2 To this end we use synthetic 4D dataset generated for Stage 2C of CO2CRC Otway project (Glubokovskikh et al. 2016). Complexity of the synthetic wavefield resembles field data acquired for the Otway project while all unknown sources of noise/uncertainty are excluded. Thus the synthetic dataset allows us to demonstrate capabilities of the rock-physics based 4D inversion implemented in Delivery4D.

DELIVERY4D INVERSION MODEL FOR OTWAY SITE

Delivery4D implements Bayesian approach to stochastic model-based seismic AVO-inversion based on convolutional model of seismic trace. A subsurface model consists of 1D ‘layered cakes’, inverted independently for each trace. Each layer is characterised by a model vector m

$$\mathbf{m}^{i,j} = \left\{ t^{i,j}, d_{\text{rock\_curves}}, \text{LFIV}, V_{Ps}, V_{Ss}, \phi_S, V_{Pm}, V_{Sm}, \rho_m, V_{Ph}, V_{Sh}, \rho_h, NG_m, NG_h, \mathbf{fl} \right\}, \quad (1)$$
$$\mathbf{fl} = \{ c_b, V_{Pb}, \rho_b, c_o, V_{Po}, \rho_o, c_l, V_{Pl}, \rho_l, c_g, V_{Pg}, \rho_g \},$$

Where i denotes number of the layer; j – trace index; t – horizon time of the layer; drock_curves – depth trend; LFIV – low-frequency model of interval velocities; VP – compressional velocity; VS – shear velocity; □□– density; NG – net-to-gross; c - saturation; fl – vector of fluid properties; indices s, m, h, b, o, l, g correspond to permeable facies, impermeable facies, hard impermeable facies, brine, oil, low-saturation gas and free gas. An effective model reflectivity sequence is computed for particular trace by taking into account buoyancy of fluids and via Gassmann-Wood fluid substitution in permeable facies followed by Backus averaging using NG information (Dvorkin, Gutierrez and Grana 2014).

Such a rock physics model perfectly suits to the small-scale CO2 injection into a clastic saline aquifer (presented in Figure 1a) for Stage 2C of CO2CRC Otway project because:

- No noticeable geomechanical response is predicted;
- Geological structure is flat with no severe deviation from a horizontally-layered medium;
- The reservoir (Figure 1a) consists of permeable sandstones (green) and fluid flow baffles: soft shales (yellow) and hard cemented sandstones (blue).

Despite the fact that we deal with synthetic data, the inversion workflow has all the features of the real one. Because of the imperfect velocity analysis and imaging, we do not know how given source function and depth horizons were transformed into time-domain images. As a first step, we perform a well-tie with the log values extracted from the seismic model used for FDTD modelling. Figure 2 shows that the well and seismic data match well (90% correlation) in the reservoir interval (250 ms).

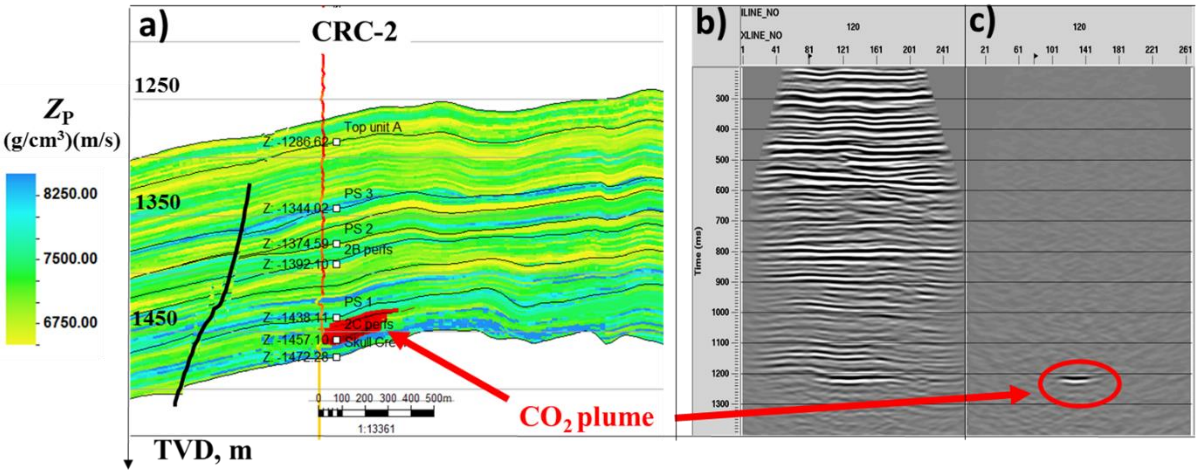

Figure 1 Synthetic 4D seismic dataset for Stage 2C of CO2CRC Otway project: a) a fragment of vertical section of the full-earth static geological model at the injection well with red area indicating injected CO_2 plume obtained by fluid flow modelling; b) vertical section of the monitor final post-stack migrated seismic cube through the injection well; c) the same vertical section through the difference seismic cube (baseline - monitor) with the time-lapse response from the plume surrounded by the red oval.

INVERSION RESULTS

Next step is building of 3D layered model of the inversion interval. Due to small thickness of the modelled CO2 plume we have to operate with relatively thin layered model. It requires picking of 13 layers horizons corresponding to distinct geological units. It was impossible to do in seismic data themselves, so we run a sparse-spike inversion of the post-stack migrated seismic with the extracted wavelet (Figure 2b-c). We consider the layered model to be sufficiently good approximation for the subsurface, because of the good agreement between the inverted and actual acoustic impedance ZP in Figure 1a and seismic traces in Figure 1d.

After numerous tests, we set up parameters of the inversion algorithm: time-lapse noise level, reliability of horizons picks, number of stochastic samples per iterations etc. As a result, CO2 plume size (Figure 3a and 3c) reduces significantly as compared with the time-lapse seismic anomaly (green and black contours in Figure 3a-c).

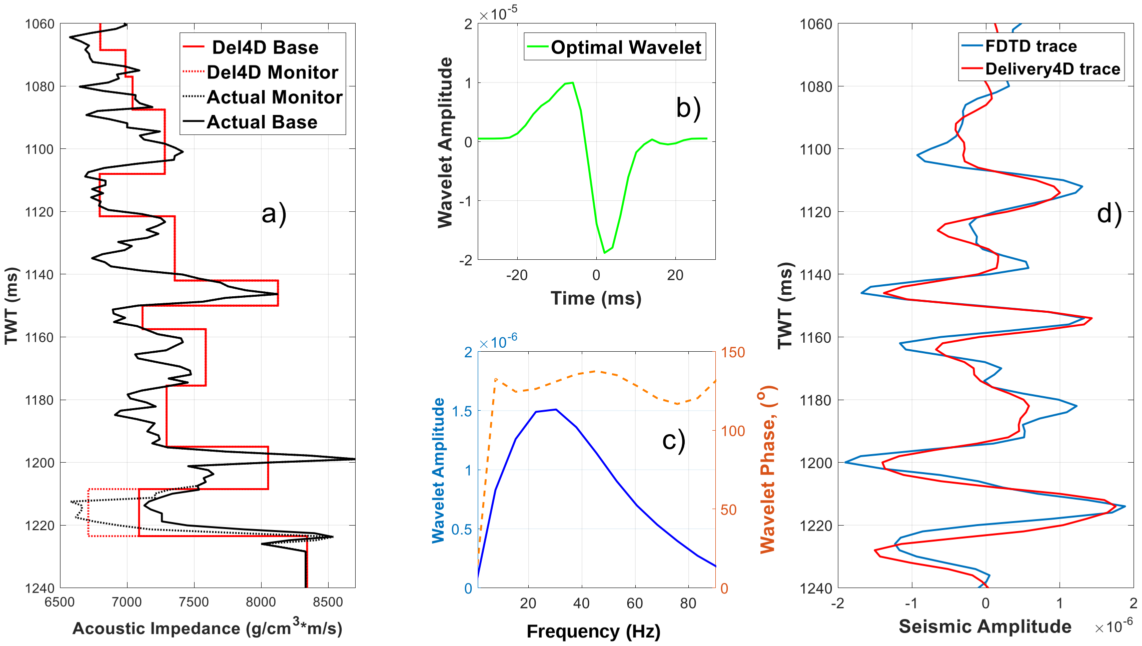

Figure 2 Well-tie of the baseline seismic post-stack migrated cube at the injection well: a) actual (black) and inverted (red) Z_P acoustic impedance logs corresponding to baseline model (solid lines) and monitor (dotted); b) optimal wavelet obtained through a well-based wavelet extraction along with c) its frequency spectra; d) synthetic FDTD seismic trace along the well (blue) against the 1.5D computed seismic (red).

We estimated several important characteristics of a potential CO2 leakage: thickness, saturation distribution, mass of the leaked CO2. The bulk distribution of the estimates resembles the actual model (see the plume thickness histograms in Figure 3d), there is no good one-to-one correspondence between the values at each trace. This result is expected because of the thin plume ~ 15 m in average. Given the average VP ~ 3000 m/s and dominant frequency ~40 Hz, the thickness corresponds to quarter of the wavelength, which is traditionally considered to be a limit of vertical resolution for reflection seismology.

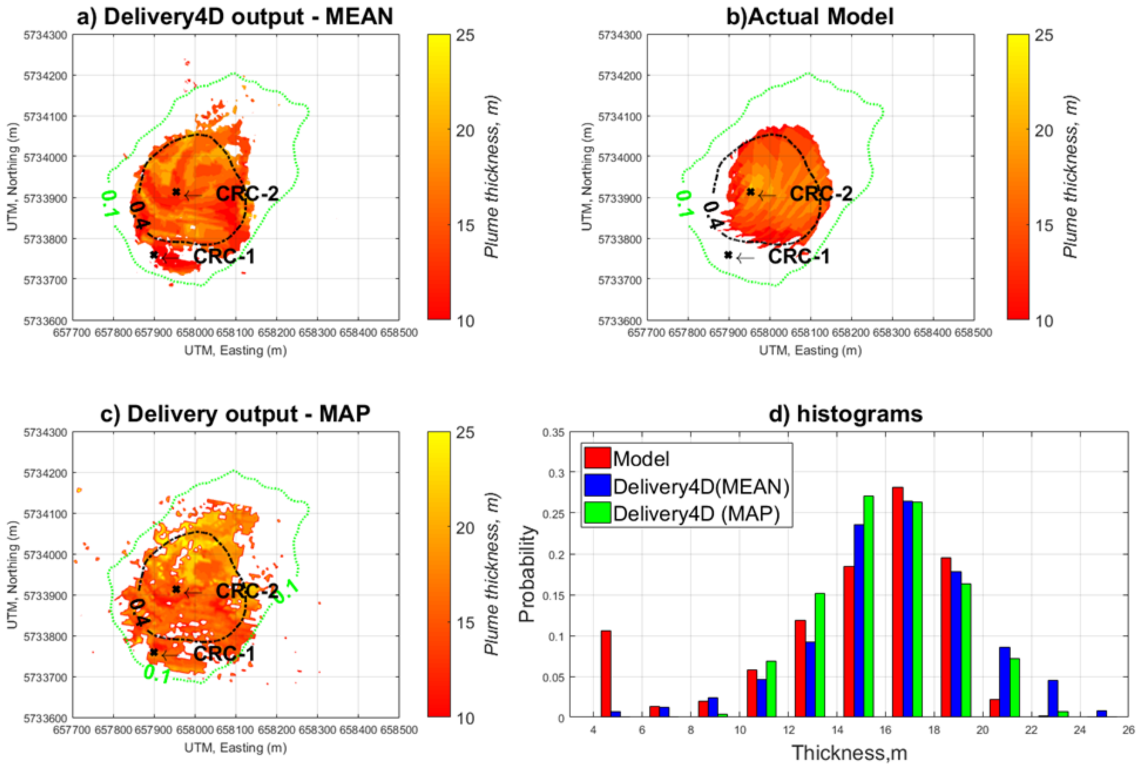

Figure 3 Plume thickness maps corresponding to the threshold of acoustic impedance variation dZ_P>3%: a) mean inverted thickness; b) actual model; c) Maximum Aposteriori Probability (MAP) thickness along with d) histograms of the plume thickness values. The dashed contours denote root mean square intensity (green - 0.1; black – 0.4) of the time-lapse anomaly in the difference seismic cube.

Another potential reason may be an issue with amplitude-preserved processing. To check its quality we perform a well-tie of the difference seismic cube. Theoretically, such an approach allows to get rid of the effects of imperfect time-to-depth relation and time-dependent amplitude correction. The 'difference' wavelet has very similar frequency spectra to the 'baseline' wavelet while the amplitude is almost twice larger. Such a discrepancy affects inverted time-lapse changes of the acoustic impedance.

CONCLUSIONS

We presented a rock-physics based stochastic seismic inversion program Delivery4D. Its functional was illustrated using 4D FDTD synthetic dataset generated for Stage 2C of Otway CO2CRC project. The implemented inversion model suits well to the studied subsurface and CO2 injection scenarios.

Despite the relatively thin plume, the 4D inversion reduced detected time-lapse anomaly to the location that closely corresponds to the actual CO2 plume. Estimated distributions of the plume characteristics (thickness, saturation and CO2 mass) are overall similar to the static and dynamic geomodels. However, the values inverted at particular trace may differ significantly. We attribute these discrepancies to limit of the seismic resolution and possible shortcomings of the amplitude-preserved processing

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