Joint Inversion and Segmentation of the 4D Sleipner Seismic Dataset

Introduction

The Sleipner CO_2 project in the Norwegian North Sea is the world's first commercial carbon storage project aimed at carbon emission mitigation. More than 19 million by-product tonnes of CO_2 from the Sleipner West field gas production have been injected since 1996 into the shallower Utsira Formation. To understand the behavior of the injected CO_2 in the subsurface and to prevent potential geohazards, a continuous seismic monitoring program with nine seismic surveys has taken place around the injection area (Furre et al., 2017). The subsurface CO_2 is observed in post-stack seismic data as a series of high amplitude reflections that expand laterally with time (Chadwick et al., 2010), present amplitude variations, and suffer from tuning effects due to thin layering of sands and shales in the Utsira formation (Furre et al., 2015). These characteristics promote the implementation of 4D seismic inversion to better interpret the lithological and fluid-related seismic effects. Pioneering work in 4D seismic inversion of the Sleipner data has been carried out on post-stack data (Ghosh et al., 2015), pre-stack data (Ghaderi and Landrø, 2009), and full-waveform based (FWI), showing that it is possible to estimate reliable reservoir property changes through time. However, one limitation across these methodologies is represented by the non-repeatable noise present in the data, which is carried over to the inversion products, possibly hindering the interpretation of real geological time-lapse changes.

In this work, we apply the 4D joint inversion-segmentation (JIS) algorithm proposed by Romero et al. (2022) to two vintages of the 4D Sleipner seismic dataset around the CO_2 plume. To begin with, well data are used to build the background model for the inversion, and time-shift variations in the monitor seismic data are estimated via non-linear inversion and removed from the monitor data prior to inversion. Our inversion scheme produces high-resolution acoustic impedance models and a volumetric classification of the time-lapse changes into user-defined classes. We show that this approach has 3 main advantages compared to standard least-squares 4D inversion methods: 1. mitigates the non-repeatable noise imprint from the data in the inverted models by jointly inverting for the baseline and monitor datasets, 2. produces high-resolution baseline and model estimates (with better-defined geological units and CO_2 plume) due to the presence of Total-Variation and segmentation constraints, and 3. classifies the time-lapse changes into expected 4D scenarios. The segmentation product helps the 4D interpretation process and might be used as input for reservoir simulations. Finally, the inversion results are compared with state-of-the-art 4D least-squares inversion.

Method

The JIS methodology (Ravasi and Birnie, 2022; Romero et al., 2022) inverts time-lapse seismic data to retrieve the underlying baseline and monitor models and a partition of the baseline-monitor difference into time-lapse classes. JIS solves the following bi-objective optimization problem:

$$\underset{\widetilde{m},V}{\arg\min} \frac{1}{2}\left\|\widetilde{G}\widetilde{m}-\widetilde{d}\right\|_2^2+\alpha\|\widetilde{m}\|_{TV}+\delta\sum_{j=1}^{N_c}\sum_{i=1}^{N_xN_z}V_{ji}(\Delta m-c_j)^2+\beta\sum_{j=1}^{N_c}\|V_j^T\|_{TV}. \quad (1)$$

Here, $\widetilde{m}$ is the stack of the baseline and monitor acoustic impedance models m_1 and m_2, $\Delta m = m_2 - m_1$, $\widetilde{G}$ is a block-diagonal matrix composed of the modeling operators G_1 and G_2 ($G_p = w_p \star \partial/\partial t$, w_p is the wavelet of each survey), d_1 and d_2 are the baseline and monitor post-stack seismic data, V is the segmentation matrix that contains the probabilities of the model to belong to a certain class c_j and $\|\cdot\|_{TV}$ denotes the Total-Variation norm. α, δ, and β are the weights of the regularization and segmentation terms. For the Sleipner dataset, the classes c_j are chosen to be: $c_1 = -50\%$ decrease in the acoustic impedance, $c_2 = 0\%$ no impedance changes, and $c_3 = 50\%$ increase in the acoustic impedance.

The Sleipner dataset

The Sleipner dataset is a publicly available 4D Seismic dataset that is composed of one baseline seismic survey acquired in 1994 and six monitor seismic surveys (not all surveys are publicly available) acquired in 1999, 2001, 2004, 2006, 2008, and 2010 to monitor the continuous injection of CO_2 into the saline aquifer of the Middle Miocene/Early Pliocene Utsira Formation (Chadwick et al., 2010). The seismic data cover an area of approximately 4×7 km^2, with a record length of 2 seconds and a sample rate of 2 ms. For this work, we use the 1994 and 2001 vintages from the latest re-processing in 2010.

Well-analysis

The exploratory well 15/9-13 and the injection well 15/9-A-16 are the only two wells available in the vicinity of the subsurface CO_2 plume. We use the 15/9-13 well, a nearly vertical well with a more complete well-log set for this work. The well-to-seismic tie was performed using an edited version of the check-shot corrected sonic log and the density log. The time-depth relationship was further calibrated by linking the well-picks and the regional time reflectors identified in the seismic volume for the seabed and the top and base of the Utsira Formation. The resulting time-converted well-logs were used to build the background model for the inversion and to validate the inversion results.

Time-shift inversion

In 4D seismic, time-shift refers to the amount of time mismatch between equivalent reflectors (hence geological events) in the baseline and the monitor datasets. Such time-shift is caused by velocity changes in the subsurface due to geomechanical effects (e.g., strain fluctuations in the overburden/reservoir) and/or dynamic fluid saturation (MacBeth et al., 2019). The relationship between the baseline $b(t)$ and monitor $m(t)$ seismic data can be described as:

$$b(t) \approx m(t + \tau(t))$$

where $\tau(t)$ is the time-shift function. In this work, we used the nonlinear inversion approach proposed by Rickett et al. (2007) to find a time-shift volume (Δt) by solving a nonlinear optimization problem through a Gauss-Newton scheme as follows:

$$\Delta\tau_i = \underset{\Delta\tau}{\arg\min} ||b(t) - (m(t+\tau_{i-1}) + J_m \Delta\tau)||^2 + \varepsilon^2 ||\nabla^2(\tau_{i-1} + \Delta\tau)||^2, \quad \tau_i = \tau_{i-1} + \Delta\tau_i$$

where $J_m = -diag\{\frac{db}{dt}|_{t=t+\tau_{i-1}}\}$ is the Jacobian matrix, ∇^2 is the Laplacian operator and ε is the regularization parameter. The regularization ensures smooth time-shift estimates in the spatial or time axis.

Results

The well-to-seismic tie (Figure 1) shows a fair match between the modeled seismic and real seismic in the reservoir interval. Seismic wavelets are independently computed from each seismic data and scaled to match the real seismic traces at the well location. The (time-converted) impedance model obtained from the well-logs is smoothed to provide a low-frequency input model for JIS.

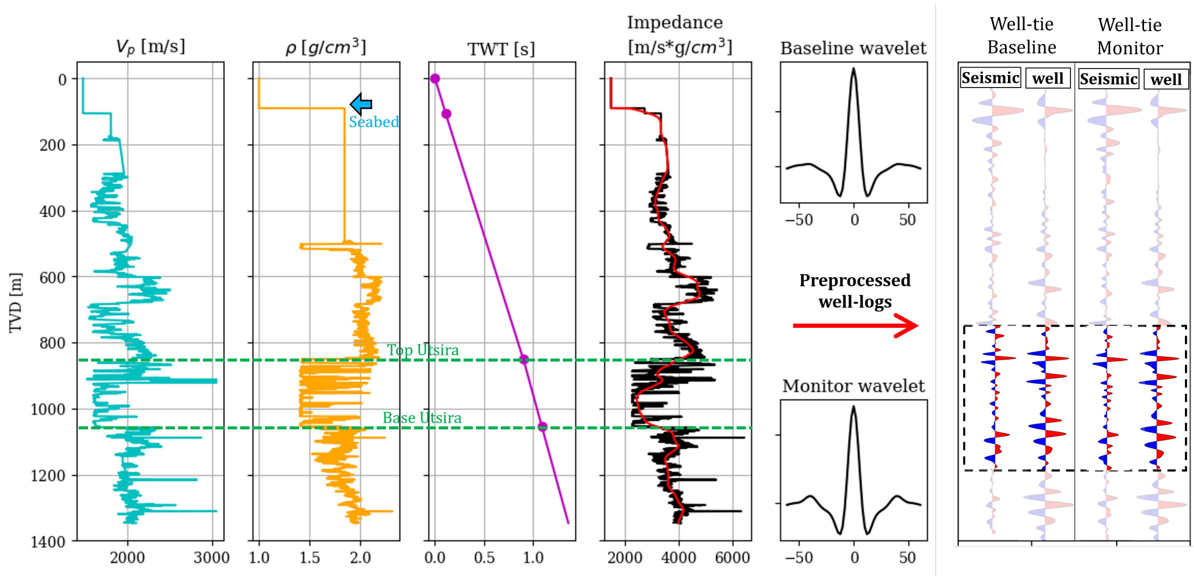

Figure 1 *Workflow of the well-analysis and well-to-seismic tie. From left to right, sonic and density logs (edited to eliminate spikes), TD-TWT relationship obtained from correlating regional seismic surfaces with well-picks, impedance log (black) smoothed to create the background model for the inversion (red), real and synthetic seismic traces at well location for both baseline and monitor seismic surveys, the latter computed with amplitude-calibrated statistical wavelets.*

The estimated time-shift volume (Figure 2) shows values around 10ms in the surroundings of the reservoir. These values are in agreement with previous time-shift estimations computed through cross-correlation (Bergmann and Chadwick, 2015) and need to be further calibrated to account for wavelet distortion (Furre et al., 2015). We observe minimal time-shift in the overburden, possibly caused by non-repeatable noise, whereas the highest time-shift values are restricted to the reservoir and the underburden. This time-shift distribution may be due to velocity changes in the reservoir as a result of the injection of CO_2 (MacBeth et al., 2019). As we show in Figure 3, this may also reflect the geomechanical changes at the reservoir interval.

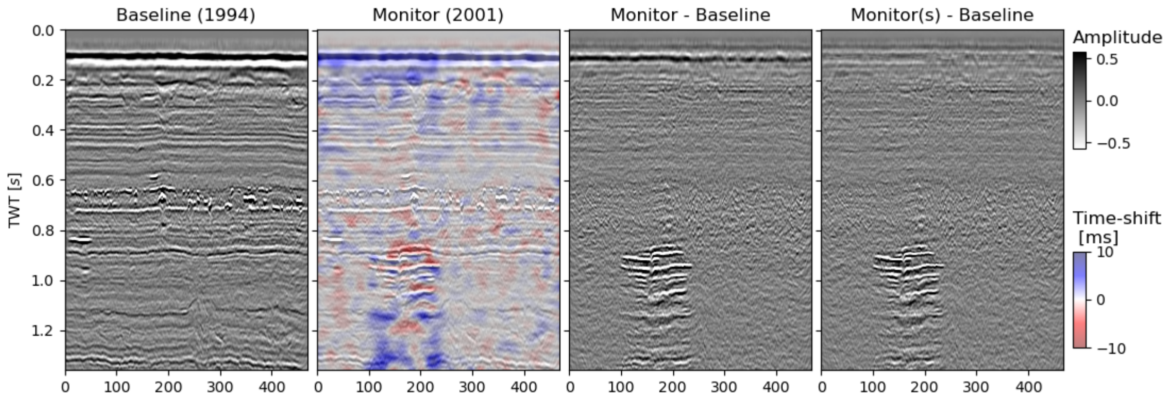

Figure 2 *Time-shift results. From left to right: baseline seismic data, monitor seismic data with time-shift overlayed, and the monitor-baseline difference before and after time-shift correction.*

After correcting the monitor seismic dataset for the estimated time-shift volume, we apply our 4D JIS. The inversion results in Figure 3 show that the JIS algorithm is able to obtain high-resolution models, with considerably less non-repeatable noise and better-defined time-lapse changes compared to standard least-squares spatially regularized 4D inversion. The monitor-baseline JIS difference in Figure 3 also highlights some time-lapse changes unrelated to the CO_2 plume, like the seabed and the overburden in the reservoir. We believe these changes are non-geological and are caused by an amplitude mismatch in the data, which is most likely a consequence of different data scaling used during processing. All optimization algorithms used in this work are implemented using the Python libraries PyLops (Ravasi and Vasconcelos, 2020) and PyProximal.

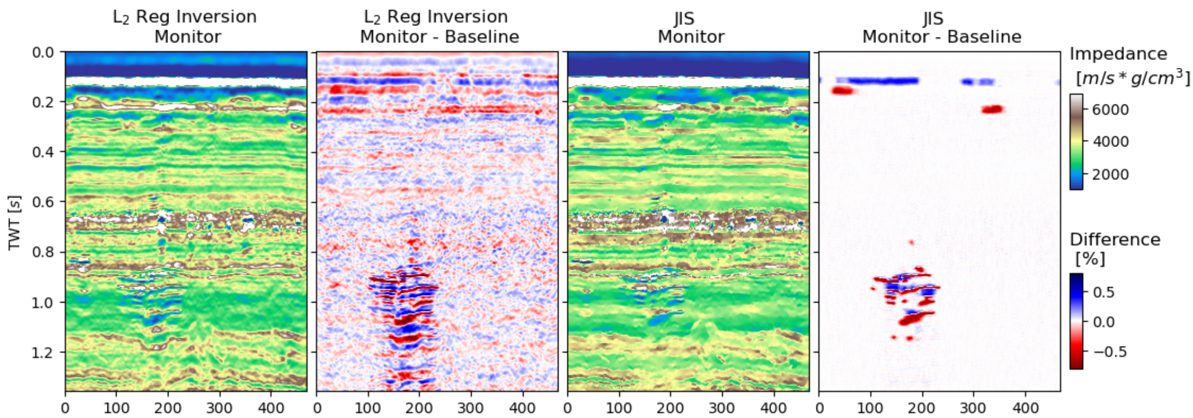

Figure 3 *Comparison of 4D L_2 regularized inversion and 4D JIS. The inverted monitor impedance model and the difference between the inverted monitor and baseline models are shown for both approaches.*

Additionally, JIS retrieves the classification of the segmented baseline-monitor differences shown in Figure 4. This volumetric model represents cells that underwent an increase or a decrease in the acoustic impedance. The presence of both phenomena at the reservoir interval might suggest that the interbedded shale and sandstone rock layers are experiencing compaction and dilation, respectively, caused by the CO_2 injection that increases the pore pressure at the sandstone layers. However, it is important to consider that these values need to be corrected as part of the response might still be affected by amplitude tuning.

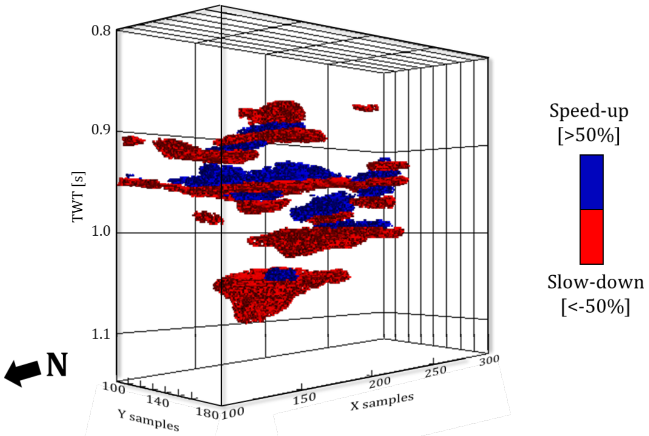

Figure 4 *Volumetric model of the segmented time-lapse changes at Sleipner.*

Conclusion

In this work, we have applied the 4D joint segmentation-inversion (JIS) method to the baseline and one monitor survey of the 4D Sleipner seismic dataset. The data have been pre-processed by performing well-to-seismic correlation and correcting for time-shift differences between the baseline and monitor seismic datasets arising from fluid and geomechanical-related changes in the subsurface. Our results show that JIS outperforms standard least-squares 4D inversion approaches by producing high-resolution acoustic impedance models and strongly reducing the non-repeatable noise in the inverted difference. As a result, the subsurface changes due to CO_2 injection are clearly visible. Furthermore, JIS provides a segmented volume of the expected time-lapse changes that can ease 4D seismic interpretation and might be used as the input geobodies for reservoir simulations.

Acknowledgements

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