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CO2 Monitoring At The Ketzin Pilot Site With Joint Inversion: Application To Synthetic And Real Data

M. Jordan[1]*, D. Rippe[1,2], A. Romdhane[1], C. Schmidt-Hattenberger[2]
[1]SINTEF Industry, [2]GFZ German Research Centre for Geosciences

Summary

To improve the imaging and the subsequent quantification of the injected CO2 at the Ketzin pilot site, as well as to improve knowledge about CO2 storage at Ketzin, we combine different geophysical techniques (e.g., seismics and geoelectrics) using joint inversion. The resulting 3D models of geophysical parameters, and their changes over time, can then be jointly interpreted to obtain reservoir parameters (e.g., pressure and saturation), using rock physics inversion. To accomplish this, a new joint inversion method using structural constraints was developed combining seismic full waveform inversion (FWI) and electrical resistivity tomography (ERT). The joint inversion combines the strength of the different techniques (e.g., high spatial resolution of seismics and the sensitivity of geoelectrics in terms of CO2 saturation), and results in models that are consistent with each other, with all data sets, and any a priori information. This new method is tested using realistic synthetic-, and real data from the Ketzin pilot site in Germany, and the results are presented.

Introduction

Safe and reliable underground storage of CO_2 requires advanced monitoring concepts and efficient data processing methods to provide sufficient information about the subsurface behaviour of the CO_2 and its fate during long-term storage. Important requirements for such monitoring, in particular in terms of containment and conformance, are sensitivity and high resolution with respect to the presence and distribution of CO_2, as well as the quantification of pore pressure and CO_2 saturation. As currently available monitoring data types are not able to achieve this when used individually, the combination of different geophysical techniques (e.g., seismics and geoelectrics) through joint inversion and subsequent joint interpretation (e.g., using rock physics inversion) may provide a solution. Joint inversion combines the strength of the different techniques (e.g., high spatial resolution of seismics and the sensitivity of geoelectrics in terms of CO_2 saturation), and results in models that are consistent with each other, with all data sets, and the *a priori* information.
In this paper, we present the joint inversion method, its implementation, and first results of the application using synthetic full waveform inversion (FWI) and electrical resistivity tomography (ERT) data sets for a realistic Ketzin model, which includes a hypothetical CO_2 distribution based on reservoir modelling. Insights from the joint inversion of the realistic synthetic data provide the basis for the succesful application of the joint inversion to real data from Ketzin. Our goal is to improve imaging and quantification of the injected CO_2 at the Ketzin pilot site, as well as to improve knowledge about CO_2 storage at Ketzin. Using Ketzin data, we aim to mature the joint inversion technology further towards large-scale CO_2 storage applications.

Ketzin site, data and previous results

Europe's longest operating CO_2 storage facility at Ketzin has finished the complete storage site life cycle (Martens et al., 2014). From June 2008 until August 2013, a total amount of 67.000 tons of CO_2 were injected and safely stored in the target reservoir zone of the Upper Triassic Stuttgart Formation at depths of 630-650 m (Figure 1).

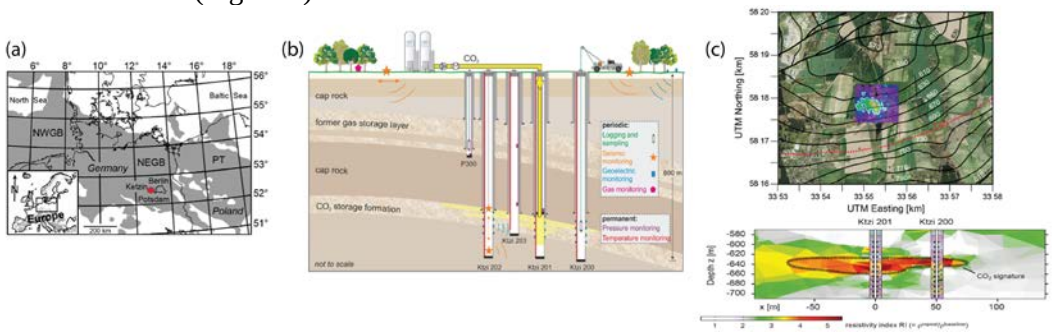

Figure 1 *(a) Location of the Ketzin site in the North East German Basin (NEGB); (b) Schematic section of the Ketzin storage complex, a saline reservoir with injection well (Ktzi201) and observation wells (Ktzi200, Ktzi202, Ktzi203, P300); and (c) Major result from the 3D seismics 2012 repeat at about 61 kt CO_2 (upper panel) and significant resistivity signature from a geoelectric survey at about 13.5 kt CO_2 (lower panel).*

A multi-disciplinary monitoring program, including seismic and geoelectric time-lapse data, has accompanied the whole life cycle including the post-injection and closure phase. A rich archive of geophysical data, acquired on various spatial and temporal scales was established, and the analysis of individual data sets provided insight into the CO_2 plume migration (e.g., Bergmann et al., 2016).
While analysis of the 4D seismic data sets were able to locate the CO_2 plume, not all of the injected CO_2 could be accounted for. The missing ~5-7% (Ivanova et al., 2012) may be due to plume thinning below resolution thickness or dissolution (Ivandic et al., 2015). Seismic and geoelectric methods have complementary properties and capabilities regarding the imaging of geological structures, pore fluids, and in particular changing saturations of CO_2. While seismic methods (e.g., FWI) are able to provide high spatial resolution of the subsurface structure, their sensitivity to changes in the CO_2 saturation is limited. In contrast, resistivity methods (e.g., ERT) are very sensitive to the CO_2 saturation and pore fluid chemistry, but, without further constraints, they provide only limited spatial resolution.

In an initial attempt to integrate seismic and geoelectric data, the ERT inversion was constrained by lithostructural information, extracted from seismic reflection data (Bergmann et al. 2014). To further improve the monitoring of the reservoir and to understand the CO_2 behaviour at Ketzin we combine high resolution seismic and electrical data in a joint FWI-ERT inversion.

Joint inversion method

The joint inversion is based on structural similarity, using a cross-gradient approach (e.g., Gallardo and Meju, 2003, Jordan et al., 2012). The resulting seismic velocity and resistivity models are consistent with each other, with all data sets, and with any a priori information. The structural joint inversion does not require a priori knowledge about the relations between the model parameters and is valid in the whole model space. To be able to handle the high computational cost from trying to resolve a relatively thin layer of CO_2 and corresponding fine model discretizations and large model sizes, the joint inversion code allows a target-oriented approach and the memory usage is optimized.
The calculation of the cross-gradients and their partial derivatives is performed on a common joint inversion grid. The native FWI and ERT models are interpolated onto the joint inversion grid using a Gaussian interpolation. This allows for the maintenance of the different individual model discretizations of FWI and ERT, which are optimized for these methods and their sensitivities (e.g., using grid-based models in FWI, and using grid-based or tetrahedral models in ERT). The joint grid approach also facilitates the handling of different spatial coverage of the individual and joint models.
The discretization of the joint inversion grid (sampling of the individual models) and the interpolation width (smoothing) are key parameters in the joint inversion and have a crucial influence on the joint inversion result. They must be determined new for every application. As a rule, joint inversions should be conducted starting with coarse gridding and larger interpolation width and progressing to finer gridding in subsequent inversions. This is particularly important if the spatial resolution of the individual models is different.

Results for synthetic Ketzin data

In preparation for the application of the joint inversion to real data from Ketzin, synthetic tests were performed to test the inversion strategy. Synthetic data for FWI and ERT were calculated based on a 3D realistic synthetic model of the Ketzin subsurface structure (Figure 2, Huang et al., 2015). The synthetic CO_2 plume structure visible in the "true" velocity and resistivity models (see Figure 3) corresponds to the 2012 Ketzin repeat survey and was calculated using reservoir modelling.

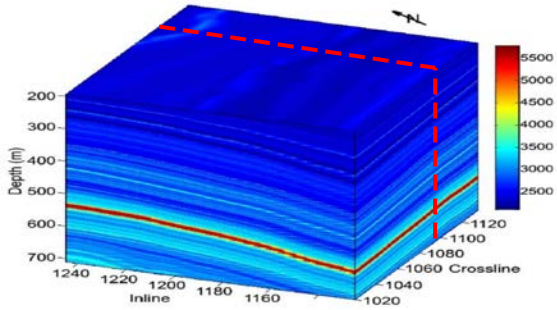

Figure 2 *Synthetic 3D velocity model based on borehole and reflection seismic data. It comprises the CO_2 distribution according to reservoir simulations. The seismic velocities range between 1500 m/s and 5500 m/s. Resistivity changes were determined via cross-property relations based on well-log data.*

To provide FWI and ERT starting models for the joint inversion, independent FWI and ERT inversions were performed. For greater efficiency the joint inversion was applied target oriented in the area around the plume. The initial models for the independent inversions were a smooth background velocity model for FWI and a homogeneous model, based on average observed resistivities for ERT. FWI was performed in the frequency domain, using frequencies between 9 Hz and 50 Hz, with a maximum offset of 1.4 km. The true models, the independent FWI and ERT results, and the joint inversion results are shown in Figure 3. The thin CO_2 plume can be seen best in the FWI result in comparison to the baseline result. The ERT is able to clearly detect and to locate the CO_2 but suffers from a lower spatial resolution.
The comparison of the true models and the independent- and joint inversion results in Figure 3 shows that the joint inversion has a large influence on the ERT model, providing improved structural definition, better reflecting the "true" plume structure. The thickness and the slanting of the plume-

related high resistivity structure is a clear benefit of the joint inversion. In addition, the FWI model was able to improve the location of the thickest part of the plume, at the injection point. The model parameter amplitudes are smaller than in the true model, which means that the resulting velocity- and resistivity values must be calibrated prior to quantitative interpretation of reservoir parameters.

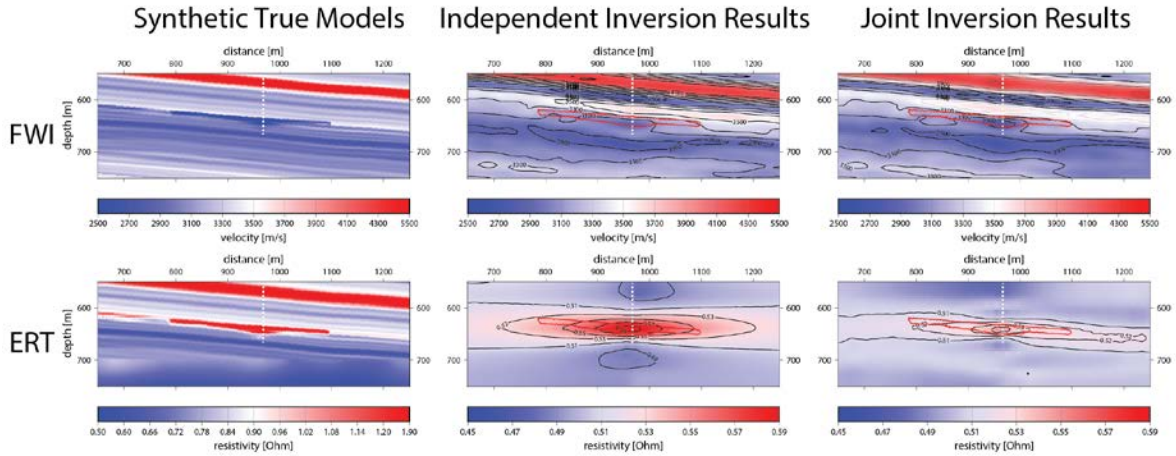

Figure 3 *Comparison of the synthetic true models, the independent inversion results, the joint inversion results. FWI velocity models are shown in the top row, ERT resistivity models are shown in the bottom row. The outline of the CO_2 plume is superimposed as red line onto the joint inversion results and corresponds to the 0.95 Ω contour of the true resistivity model. The location of the Ketzin injection well Ktzi 201 is indicated by the white dashed line.*

Application to real Ketzin data

The joint inversion was applied to real FWI and ERT Ketzin data sets from the baseline and the 2012 repeat surveys. Analogous to the synthetic case, the joint inversion starting models were derived from individual FWI and ERT inversions. The independent FWI inversion was able to identify a low velocity anomaly in the target zone, consistent with the CO_2 plume (Figure 4), even though the FWI resolution capabilities were limited in the reservoir due to data quality, and small maximum offsets (less than 1km) and reduced frequency range (up to 32.8Hz).
Compared to the independent inversion, the joint inversion provides a thinner, more pronounced low velocity anomaly with velocities less than 2,800 m/s, centred around the injection well Ktzi201. This anomaly is also clearly visible in the depth section of the joint inversion result, but not in the independent inversion result. In contrast, the ERT resistivity models from the independent and joint inversion are very similar in structure, showing a pronounced high resistivity anomaly with resistivities between 20 and 30 Ωm centred around the injection well Ktzi201. This high resistivity anomaly is coincident with the low velocity anomaly observed in the FWI, and is associated with the injected CO_2. The lateral extent of the resistivity anomaly is smaller than the CO_2 distribution inferred from the amplitude anomalies of the 2012 3D seismic repeat (detection threshold 7.5 m). This can be explained by the limited sensitivity and coverage of the ERT surface-downhole measurements, which is highest around the wells and drops off with increasing distance.

Application to the realistic synthetic Ketzin data showed how both FWI and ERT benefit from the joint inversion of both data sets compared to the independent inversion. The resulting velocity models exhibit a more pronounced low velocity anomaly at the injection position, which corresponds well with the thickest part of the CO_2 plume. The CO_2 plume related high-resistivity structure is sharpened, reduced in thickness, and has adopted the correct tilt, following the geological layering.
Application of the joint inversion to real data sets from the Ketzin pilot site also proved successful, particularly the FWI benefited from the joint inversion of the 2012 repeat data compared to the independent inversion. Even though the inferred lateral extent of the CO_2 did not fully match the CO_2 distribution inferred from amplitude anomalies, the results certainly constitute a clear improvement during the quantitative interpretation of these results in terms of reservoir parameters and amount of injected CO_2.

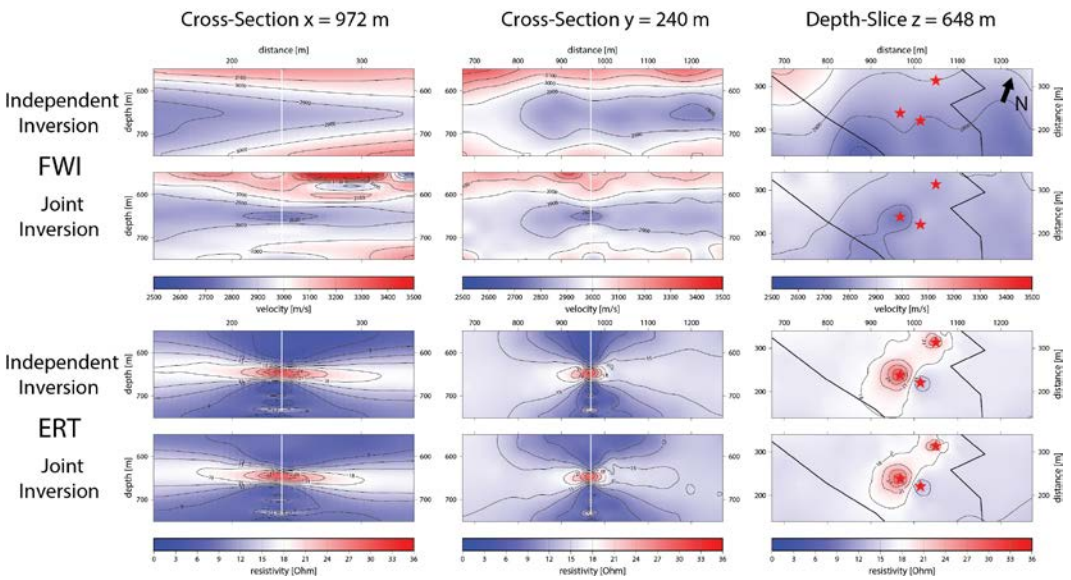

Figure 4 *Joint inversion results in comparison with the independent inversion results for FWI (top rows) and ERT (bottom rows), both as cross-sections at x = 972 m and y = 240 m (intersecting the injection well Ktzi201) and as depth slice at z = 648 m (i.e., reservoir depths).*

Conclusions

To enable improved imaging and aide quantitative interpretation during monitoring of injected CO_2, we developed a joint inversion method for FWI and ERT. The method is tested using realistic synthetic, and real data from the Ketzin site in Germany, and results are presented. The resulting models of seismic velocities and electrical resistivities are consistent with each other and with both data sets, resulting in a visibly improved structural definition of the CO_2 plume structure. In the synthetic case the high spatial resolution of FWI greatly helped to improve the definition and resolution of the ERT result. During the application to the real data, FWI was only able to provide lower resolution imaging, due to data quality, limited offsets, and lower frequency content. However, the results still benefitted significantly from the joint inversion. While additional work will be necessary to further improve the results, in particular the model parameter amplitudes, joint inversion is able to significantly improve monitoring even of a relatively small CO_2 plume.

Acknowledgements

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