

Fr CO2 09

Quantitative Prediction Of Injected CO2 At Sleipner Using Wave-Equation Based AVO

P. Haffinger^{1*}, F. Jedari Eyvazi³, P. Steeghs², P. Doulgeris¹, D. Gisolf¹, E. Verschuur⁴

¹Delft Inversion, ²TNO, ³GESciTech, ⁴Delft University of Technology

Summary

In the context of carbon capture and storage (CCS), quantitative estimation of injected CO₂ is of vital importance to verify if the process occurs without any leakage. From a geophysical perspective this is challenging as a CO₂ plume has a severe imprint on seismic data. While this makes delineation of the plume rather straightforward, for quantitative interpretation a technique is required that takes complex wave propagation, including multiple scattering and mode conversions into account. In this abstract a wave-equation based AVO technique is discussed and successfully demonstrated on a seismic dataset from the Sleipner site. The technique solves the exact wave-equation which means that tuning effects are properly modelled. The scheme directly inverts for compressibility and shear compliance as these parameters are more closely related to saturation than conventional impedances. From this the total amount of injected CO₂ is calculated and found to be in good agreement with the known value at the time when the data was acquired.

Introduction

Permanent storage of CO₂ in the subsurface may provide an important contribution to climate change mitigation. In 1996 the first CO₂ was injected into the Utsira Formation above the Sleipner gas field in the North Sea. Now, about 20 years later injection is still on-going at Sleipner, which makes the Sleipner project not only the first, but also the longest running industrial-scale aquifer CO₂ storage project. In the period 1996-2014 a total of eight repeated 3D time-lapse seismic surveys have been acquired. These data have been not only provided important feedback on the storage reservoir behaviour, but also have been vital for the development of CO₂ monitoring in general.

As of today more than 150 papers have been published about the Sleipner CO₂ monitoring. The majority of these are focusing on the time-lapse seismic interpretation and reservoir characterization with increasingly sophisticated approaches [Furre et al. (2015), Raknes et. al (2015)]. One of the geophysical challenges for CO₂ monitoring is that the injected gas creates very high amplitudes on seismic data with a notable superposition of reflections from different layers. The complex wave-propagation can hardly be explained by conventional linear AVO or imaging methods and a wave-equation based approach should be helpful to de-tune the seismic and get absolute estimates of the stored CO₂.

Wave-equation based AVO

In this paper we demonstrate a wave-equation based AVO technology (WEB-AVO) for quantitative interpretation of the CO₂ plume injected into the Sleipner field. As the wave-equation is solved iteratively, multiple scattering and mode conversions over the target interval are properly accounted for. By de-tuning of seismic amplitudes, a reservoir model can be obtained with a spatial bandwidth wider than what could be expected from the temporal bandwidth of the seismic data. Starting with an incident field in a smooth background model, a first estimate of the reservoir model is obtained, under the assumption of a linear relationship between elastic subsurface properties and seismic amplitudes. In a next step the wave-equation is deployed to include second order scattering based on the first estimate of the reservoir properties. The full scheme consists of an iterative procedure of AVO inversions, using the best estimate of the wave-field in the reservoir, followed by updating the wave-field based on the latest reservoir model. The procedure is repeated until neither the reservoir model nor the wave-field changes any more and convergence is reached.

Another unique feature of the method is that it solves directly for compressibility (inverse of bulk modulus) and shear compliance (inverse of shear modulus) instead of impedances as obtained by conventional linear AVO techniques. Compressibility and shear compliance are highly suitable for quantitative interpretation as they are much more sensitive to porosity and fluid changes compared to acoustic and shear impedance.

Target-oriented AVO

While adding value at several stages of seismic interpretation, the computational costs of solving the wave equation grow strongly with the number of grid cells of the inversion domain. To keep the process feasible, the scheme is applied in a target-oriented mode covering a depth interval of approx. 500 m. The exact depth interval is influenced by the vertical depth sampling which in turn depends on the maximum frequency in the seismic data and the lowest velocity over the target.

Working target-oriented implies that only multiple scattering and mode conversions which are generated over the target interval are properly predicted by the methodology. At the same time, overburden- and surface-related multiples should preferably be removed from the input data by standard processing. While linear AVO techniques inevitably misinterpret these type of events, WEB-AVO shows the tendency to reject this noise as it does not obey the target-oriented wave-equation. This makes the technology very robust even in set-ups with low S/N or where older seismic data is available only, which initially was not shot with the primary purpose of quantitative interpretation studies.

Data input and preparation

In this study we used well 15/9 – 13 to derive seismic wavelets, which are needed as input to the inversion. This step also calibrates the seismic data with respect to angle-dependent propagation effects in the overburden. While only sonic and gamma-ray were logged genuinely, shear sonic and density were derived following the method by Delépine et. al (2011). From this set of logs, compressibility κ and shear compliance M were computed. The obtained seismic wavelets including their frequency spectrum are displayed in Fig. 2. Seismic input were three offset stacks which were interpolated to ten regular slownesses, as the wave-equation, and consequently also our inversion approach, is formulated in this domain. The chosen slownesses translate into an angle range of approx. 16° - 31° at target depth. This step requires the migration velocity model and assumes horizontal stratification of the overburden. To remove dipping noise from the migrated sections (acquisition imprint, migration artefacts, etc.), a mild-dip filter was deployed resulting in a slightly improved S/N of the input seismic. As a starting point the inversion needs background models for κ , M and ρ . Outside the plume these backgrounds were equal to a very smooth version ($f_{max} = 4\text{Hz}$) of the 15/9 – 13 logs, while inside the plume the background values were scaled versions consistent with Gassmann modelling. This procedure requires a rough delineation of the plume based on the energy in the seismic data, but since the CO_2 strongly effects the amplitudes this is a straight-forward exercise. In Fig. 1 the relationship between CO_2 saturation and κ is shown assuming a porosity ϕ of 0.36 [Singh et. al (2010)] and a CO_2 density ρ_{CO_2} of 600 kg/m^3 .

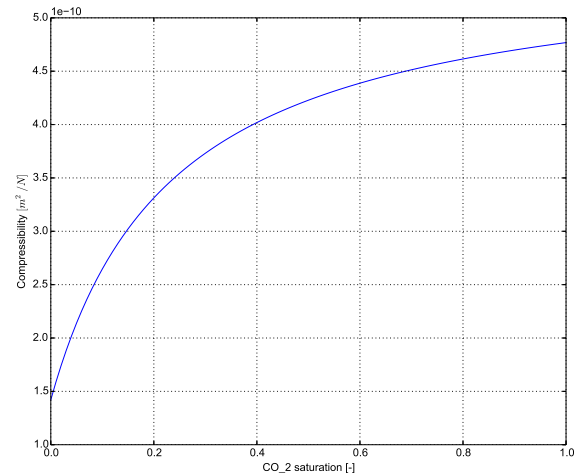


Figure 1 Relationship between compressibility and saturation for a porosity of 0.36 and a CO_2 density of 600 kg/m^3 . The relationship was derived from the Gassmann equations and will be used to translate the inverted compressibilities into CO_2 saturation.

Results

WEB-AVO was applied to a 3D volume of the 2008 survey with a total surface coverage of approx. 11 km^2 . The target interval with a length of 400 m included the Utsira formation and was sampled on a 3 m grid for the inversion. Although a simultaneous two-parameter (κ , M) inversion was performed, in this abstract we focus on the compressibility as it is the relevant parameter for quantitative prediction of CO_2 saturation, while the shear compliance M is independent of the pore fill. This is an intrinsic benefit of formulating the inversion in terms of compressibility and shear compliance. In Fig. 3 the inversion

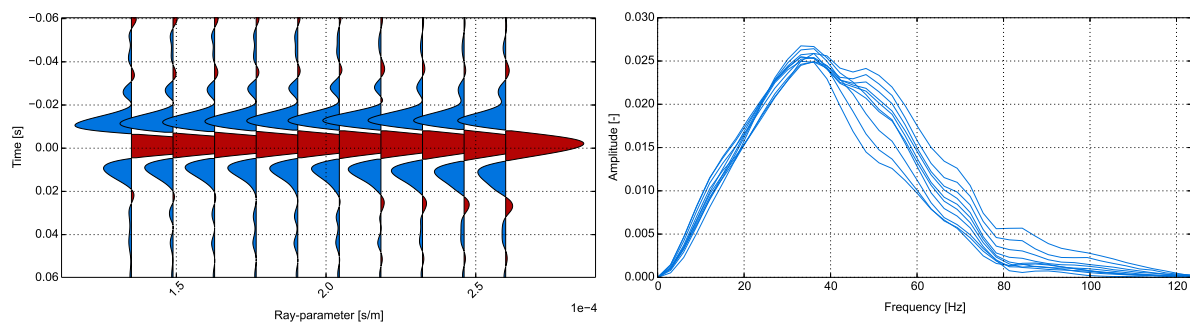


Figure 2 Slowness-dependent wavelets were estimated by tying the seismic to well 15/9 – 13. The wavelets show a slightly negative phase rotation and the center frequency appears at $f = 35 \text{ Hz}$.

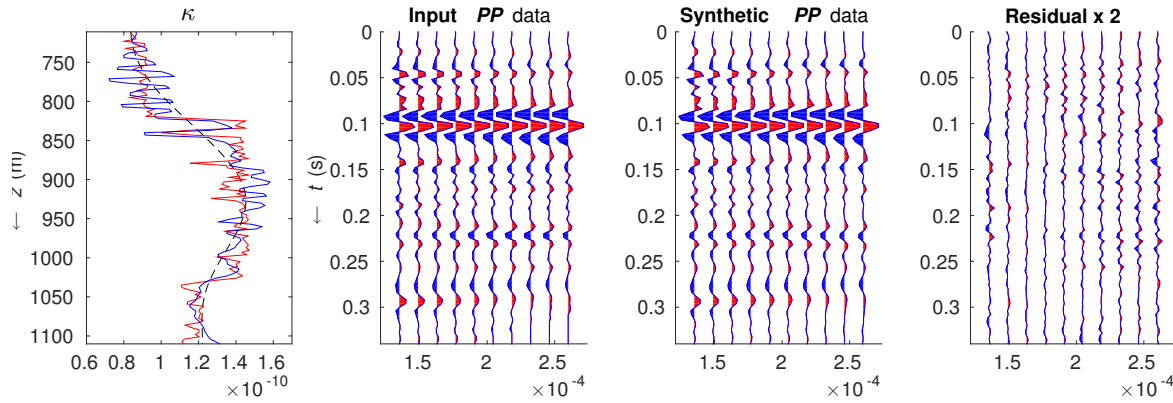


Figure 3 Shown are the inverted compressibility (blue), the logged compressibility (red) from well 15/9 – 13 and the background model (black). The predicted synthetic data matches the input seismic very well. The main event in time is translated into the correct thickness depth demonstrating the intrinsic de-tuning of WEB-AVO. It should be realised that well 15/9 – 13 is located outside the plume while inside, the compressibilities will be significantly higher than the shown values.

result for κ is shown at well location 15/9 – 5. From the obtained κ predictions over the whole volume, a geo-body can be extracted to delineate the extent of the CO_2 at the time when the seismic data was acquired (2008). Fig. 4 shows the background model and the inversion result for κ along one cross-line as well as the extracted 3D geo-body. Within the geo-body, CO_2 saturation can then be predicted using the relationship given in Fig 1. The total mass of CO_2 in place follows naturally from the inversion grid (dx, dy, dz) and the porosity $\phi = 0.36$ as:

$$m_{\text{CO}_2} = \sum_{\text{grid}} \phi \rho_{\text{CO}_2} \sigma_{\text{CO}_2} dx dy dz = \sum_{\text{grid}} 0.36 \times 600 \frac{\text{kg}}{\text{m}^3} \times \sigma_{\text{CO}_2} \times 25\text{m} \times 25\text{m} \times 3\text{m} = 12.1 \text{ Mt} \quad (1)$$

where the density of CO_2 at reservoir conditions ρ_{CO_2} was assumed to be 600 kg/m^3 , which is an average of the expected values. It is known that this parameter can vary notably due to the CO_2 being close to its critical point [Alnes et. al (2011)] and having a clear understanding of the density distribution within the plume would be of advantage. With around 11 Mt of CO_2 injected by 2008, this is a very good estimate although the total amount is slightly overestimated. In Fig. 4 it can be seen that the inverted compressibility, at least locally, exceeds $4.75 \cdot 10^{-10}$, which was predicted for 100 % CO_2 saturation. This can possibly be explained by variations in the porosity or the CO_2 density and estimation of these parameters in 3D would be worthwhile to specify the amount more precisely.

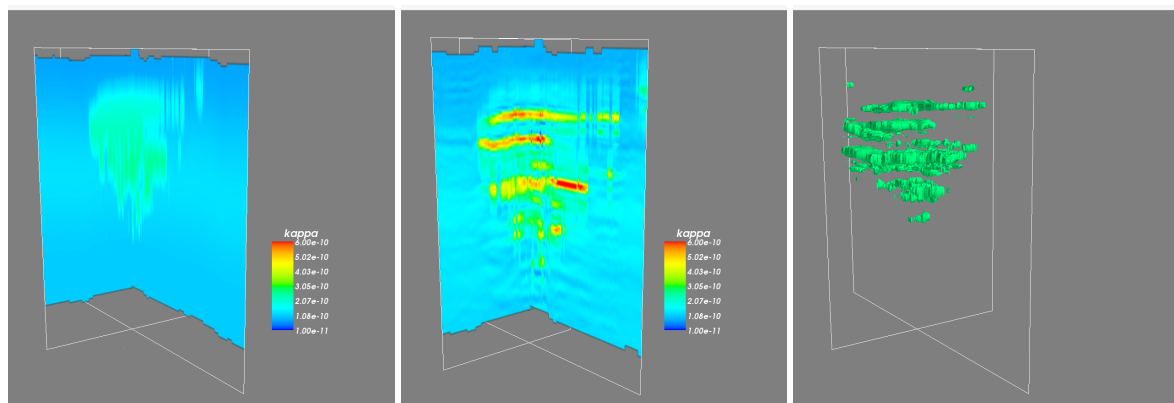


Figure 4 Shown is the background model for compressibility (left) as well as the inversion result for the same parameter (middle). By defining a cut-off value, a 3D geo-body can be extracted in order to delineate the CO_2 plume. In this case a cut-off value for κ of $2.72 \cdot 10^{-10}$ was used.

Summary and discussion

In this abstract a wave-equation based AVO technique (WEB-AVO) was discussed and successfully demonstrated on a 3D seismic dataset from the Sleipner field. The method inverts migrated seismic data in time for absolute reservoir properties (compressibility and shear compliance) in depth. Since the wave-equation is solved, tuning effects due to internal scattering and mode conversion are correctly handled by the process. Using rock-physics modelling, the obtained compressibilities were translated into a saturation model. A total amount of 12.1 Mt CO₂ was calculated to be stored in the area which is in good agreement with the expected value.

For carbon capture and storage, and for underground storage in general, the amount of injected CO₂ (gas) is known beforehand. The geophysical challenge then becomes to investigate if the entire amount is stored safely and securely and without any leakage. While the proposed workflow was successfully applied in this context, several other cases can be thought of, to which WEB-AVO could add value:

- Reserves estimation for improved field development planning.
- Time-lapse monitoring (4D) to accurately understand changes in fluid properties over time.
- Optimise well planning by using compressibility as direct hydrocarbon indicator. [e.g. Beller et al (2015)]

Application of wave-equation based AVO in time-lapse mode is very relevant for Sleipner and several surveys from different acquisition years are available. The discussed technology is highly suitable for 4D monitoring, because the compressibility is most sensitive to changes in pore fill, while the shear compliance only reacts to changes in lithology. Assuming that the lithology will not change for different seismic acquisitions, a simultaneous 4D inversion would need to solve for one shear compliance only, independent of the number of surveys. This reduces the number of unknown reservoir parameters to be solved for, representing a clear advantage of the demonstrated technology compared to conventional AVO methods which are usually formulated in terms of impedances. Application of wave-equation based AVO for simultaneous inversion of time-lapse data will be part of future field applications.

Acknowledgements

We thank the licence holders of PL046 (Statoil, Lotos, ExxonMobil, Total) for making the data available and for their permission to publish this work.

References

- Alnes, H., Eiken, O., Nooner, S., Sasagawa, G., Stenvold, T. and Zumberge, M. [2011] Results from Sleipner gravity monitoring: Updated density and temperature distribution of the {CO₂} plume, 10th International Conference on Greenhouse Gas Control Technologies, Volume 4, Pages 5504-5511
- Beller, M., Doulgeris, P., Gisolf, A., Haffinger, P., Huis in't Veld, R. and Wever, A.K.T. [2015] Resolving Carboniferous Stacked Channel Sequences with a Non-linear AVO Technology, 77th EAGE Conference and Exhibition 2015 in Madrid, Extended abstract
- Delépine, N., Clochard, V., Labat, K. and Ricarte, P., [2011] Post-stack stratigraphic inversion workflow applied to carbon dioxide storage: Application to the saline aquifer of Sleipner field, Geophysical Prospecting, Vol. 59, No. 1, pp. 132-144
- Furre, A.K., Kiær, A. and Eiken, O., [2015] CO₂-induced seismic time shifts at Sleipner, Interpretation, Aug 2015, Vol. 3, No. 3, pp. SS23-SS35.
- Raknes, E.B., Arntsen, B., and Weibull, W., [2015] Three-dimensional elastic full waveform inversion using seismic data from the Sleipner area, Geophys. J. Int. 202, 1877-1894.
- Singh, V., Cavanagh, A., Hansen, H., Nazarian, B. Iding, M. and Ringrose, P. [2010] Reservoir Modeling of CO₂ Plume Behavior Calibrated Against Monitoring Data From Sleipner, Norway, SPE paper 134891 presented at the SPE Annual Technical Conference and Exhibition held in Florence, Italy