Lueth, S., Bergmann, P., Huang, F., Ivandic, M., Ivanova, A., Juhlin, C., Kempka, T. (2017): 4D Seismic Monitoring of CO 2 Storage During Injection and Post-closure at the Ketzin Pilot Site. - *Energy Procedia*, *114*, pp. 5761—5767.

DOI: http://doi.org/10.1016/j.egypro.2017.03.1714

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ScienceDirect

Energy Procedia 114 (2017) 5761 – 5767

Energy Procedia

13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland

4D seismic monitoring of CO_2 storage during injection and post-closure at the Ketzin pilot site

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Abstract

At the Ketzin pilot site for geological CO_2 storage, about 67,000 tons of CO_2 were injected during the period June 2008 – August 2013. Since August 2013, the site is in its post-closure phase. Before and during the injection phase, a comprehensive monitoring programme was established. In the early post-injection phase, a majority of the monitoring activities have continued. The stepwise abandonment of the pilot site, which is planned to be accomplished in 2018, marks also the termination of most monitoring activities. Four 3D seismic surveys were acquired between 2005 and 2015 for characterizing the reservoir structure and its overburden and for monitoring the propagation of the injected CO_2 in the storage formation. The first and second repeat surveys revealed the lateral extension of the CO_2 plume after injecting 22 and 61 ktons, respectively. In autumn 2015, the third 3D repeat seismic survey, serving as the first post-injection survey, was acquired. The survey was acquired using the same acquisition geometry as for previous surveys, consisting of 33 templates with five receiver lines and twelve source profiles perpendicular to the receiver lines. Seismic processing of the recently acquired data has resulted in preliminary observations which can be summarized as follows: As in previous seismic repeat surveys, a clear CO_2 signature is observed at the top of the storage formation. No systematic amplitude changes are observed above the reservoir which might indicate leakage. Compared to the second repeat survey acquired in 2012, the lateral extent of the CO_2 plume seems to have been reduced, which may be an indication for ongoing (and relatively fast) dissolution of the CO_2 in the formation brine and diffusion into very thin layers indicating pressure release.

Peer-review under responsibility of the organizing committee of GHGT-13.

Keywords: 4D seismic monitoring; pilot scale storage, Ketzin; post-closure phase; conformance

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doi:10.1016/j.egypro.2017.03.1714

1. Introduction

The Ketzin pilot site for CO_2 storage, located close to Berlin, Germany, is one of the pilot scale laboratories which have been operated in the past years offering a broad range of opportunities to observe the fate of CO_2 after its injection into a storage formation [1,2,3,4]. Monitoring of CO_2 storage at Ketzin included geophysical, geochemical and microbial observations [5]. Geophysical observations consist mainly of seismic, geoelectric and borehole logging surveys, providing a comprehensive data set for imaging the propagation of the CO_2 in the storage formation at a range of scales, from the near-borehole area (borehole logging), the volume covered by the injection and monitoring wells (Electrical Resistivity Tomography, surface-borehole seismic surveys), up to the full reservoir scale (repeated 2D and 3D seismic surveys).

The geological setting of the storage site has been described in detail in various publications (e.g. [6]). The storage formation consists of sandstone layers within the Upper Triassic Stuttgart Formation. It is overlain by mudstones of the Weser Formation, acting as the immediate caprock. The top of the Weser Formation is marked by a 10 – 20 m thick layer of anhydrite which appears as a strong reflective event in the seismic sections (e.g., [7]). Salt-tectonic deformation has resulted in the formation of an anticlinal structure, at the southern flank of which CO_2 injection has been performed, approximately 1.5 km south of the top of the anticline.

The operational phase of the site, the injection, lasted from June 2008 until August 2013. In this period, about 67,000 tons of CO_2 were injected. In the post-injection phase, CO_2 back-production and brine injection experiments were carried out and the geophysical and geochemical monitoring programme continued, including 4D seismic monitoring.

2. Acquisition of 4D seismic data

In total, four 3D seismic acquisition surveys were acquired at Ketzin for site characterization and monitoring the injected CO_2. The first survey, acquired in summer and autumn 2005, before start of CO_2 injection, served as a baseline data set and for setting up a geological model of the site at high resolution [7]. Three repeat surveys were acquired in 2009, 2012, and 2015, the most recent survey presenting the first seismic data set after approximately two years of post-injection phase. All surveys were acquired using identical acquisition geometry, consisting of up to 41 templates (baseline survey 2005). Smaller areas comprising between 20 and 33 templates were acquired in the repeat surveys, according to the expected maximum lateral extent of the stored CO_2 (Figure 1). The acquisition area of the 2015 repeat survey was extended to the west by two new templates (5:0, 6:0) as reservoir simulations indicated that the CO_2 plume might possibly continue propagating in north-western direction. The data acquired on this extension area may serve as a baseline data set for possible future repeat surveys assessing the long-term behavior of the CO_2 plume.

3. Time-lapse results

In order to enable extracting an undisturbed time-lapse signal, the processing was kept relatively simple [7]. Particular attention had to be paid to varying static corrections due to variable environmental conditions in spite of all repeat surveys being acquired in the same season of the year. Furthermore, non-injection related time-lapse noise was removed by cross-equalization as implemented in the Hampson Russell Pro4D module. Figure 2 shows time-lapse amplitude difference sections across the CO_2 injection well for the three repeat surveys. Significant amplitude changes can be observed between 515 ms and 535 ms TWT which denote the presence of the injected CO_2 within the reservoir [8,9,10]. The amplitude anomaly in the reservoir grew in extent between the first and second repeat surveys, during ongoing CO_2 injection. Range and intensity of the amplitude anomaly have decreased between the second and third repeat surveys. Above the K2 horizon (indicated by dashed lines in the time-lapse sections), no significant time-lapse amplitudes are detected indicating that there is no leakage detected by the 4D seismic monitoring surveys.

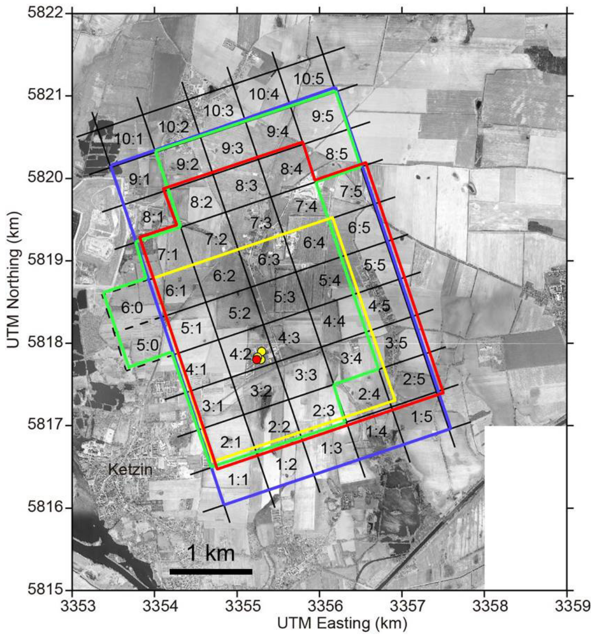

Fig. 1. Map of the acquisition area, covered by the repeated 3D seismic monitoring surveys. The area of the 2015 repeat survey is outlined by a green line. The baseline, first, and second repeat surveys are outlined by blue, red, and yellow lines, respectively. The locations of injection and monitoring wells on the CO_2 pilot site are indicated by red and yellow dots. The town of Ketzin is located at the south-western edge of the map. Acquisition templates are indicated by numbers (1:1, 1:2, etc.). For the third repeat survey, the acquisition area was extended to the West by templates 5:0 and 6:0.

To assess the lateral extent of the CO_2 distribution and its migration in the reservoir, the normalized amplitude difference between the baseline and repeat surveys was extracted along a horizon near the top of the storage (Stuttgart) formation. Resulting amplitude distribution maps are shown in Figure 3 for all three repeat surveys. The maps confirm the observations previously made in the difference sections, indicating a growing CO_2 plume from the first to the second repeat survey and a shrinking plume between the second and third repeat surveys.

The amplitude maps show a clear amplitude signature, related to the injected CO_2 around the injection site, but at larger distances from the injection site, patches of high normalized difference amplitudes can be identified as well. These patches, particularly strong in the north-western edge of the map area, are considered to be time-lapse noise due to difficult weather conditions and road traffic noise. Note that, in contrast to the CO_2-related anomaly in the central area, these noise patches occur in the first and third repeat surveys but are not observed in the second repeat survey which rather indicates an origin related to (unstable) near surface conditions and not being related to CO_2 migration in the reservoir level which should result in more stable amplitude anomalies in the maps. Another observation made on the amplitude maps is that it is difficult to exactly delineate the threshold between “noise” and “CO_2-signature”. A statistical analysis of the noise amplitude distributions suggests that the noise-signal amplitude threshold is between values of 0.2 and 0.3 normalized amplitude [11], so the contour line indicating “0.3” in the middle amplitude map (Figure 3) can be regarded as indicating the central part of the CO_2 plume with some probability of more CO_2 residing in a thin layer outside of the contour line. The same contour line is plotted in the amplitude maps of the first and third repeat surveys demonstrating the areal distribution of plume growth and shrinkage. In the initial storage phase (the first year; data from 2009), CO_2 has migrated mostly into western and north-western directions. In 2012 (second repeat survey), the mostly western and north-western directed migration continued, but also more CO_2 migrated east of the injection well. Two years after injection stopped, most of the eastward migrated CO_2 is not imaged in the amplitude maps any more suggesting it may have dissolved in the reservoir brine or migrated into thin layers undetectable for land surface time-lapse seismic measurements.

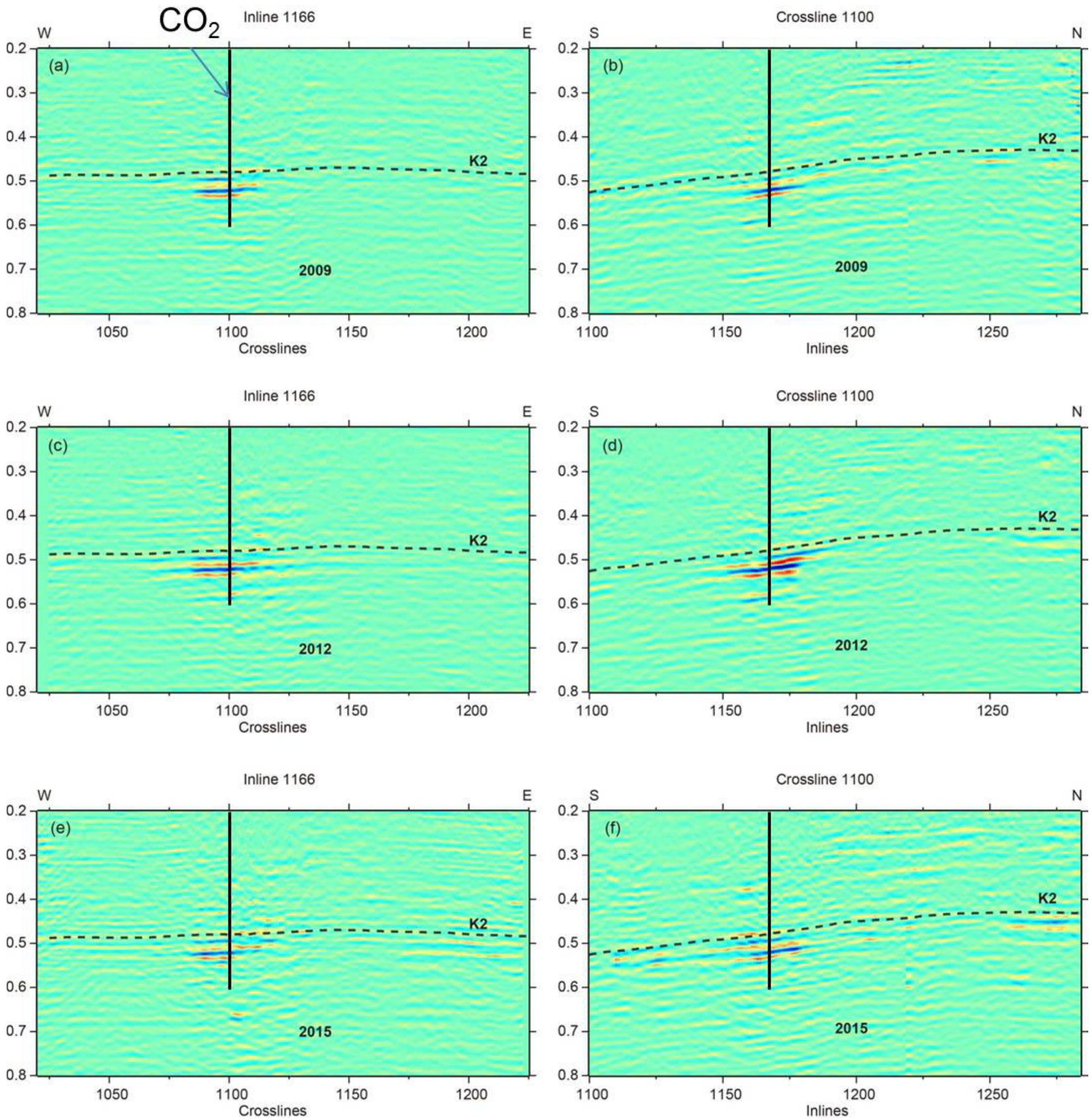

Fig. 2. Time-lapse amplitude differences along an inline (left panel) and a xline (right panel) which are adjacent to the injection well. From top to bottom: the first repeat results, second repeat results and first post-injection results. The dashed line represents the K2 reflector in the Weser Formation (caprock). The location of the CO_2 injection well is indicated by a black vertical line in all panels. Figure modified from Huang et al. [10].

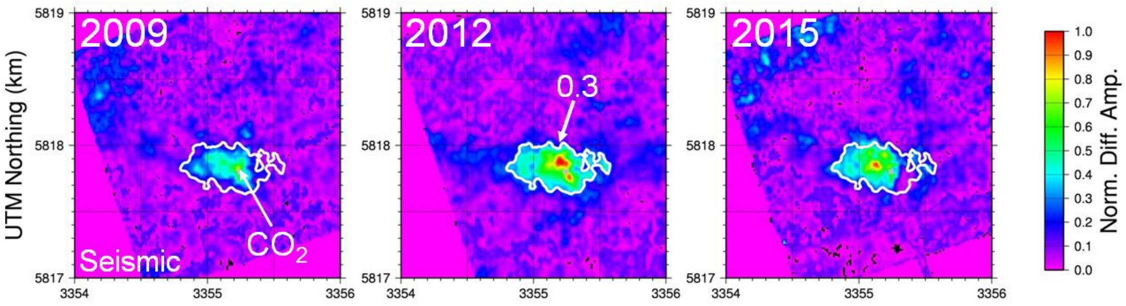

Fig. 3. Normalized seismic difference amplitudes at the top of the Stuttgart formation from the three 3D repeat surveys indicating the lateral extent of the CO_2 plume in the storage formation. The location of the injection well is indicated by a white arrow in the 2009 panel. White contour line indicates the difference amplitude value of 0.3 in the second repeat data set, plotted into the amplitude maps of all repeat surveys for comparison.

4. Quantitative conformance assessment

Demonstration of conformity between simulated reservoir performance and monitoring observations is one of the three key regulatory requirements which have to be fulfilled according to EU CCS regulations [12]. A site operator has to fulfill these requirements in order to be able to transfer storage site liability. To date, the relatively general statements of EU CCS regulations still need to be complemented by appropriate workflows supporting statements on whether a storage site is behaving according to the requirements or not. The approach of simulating reservoir behavior and monitoring data used for conformance assessment strongly depends on the storage site conditions. Case studies from different types of storage sites are therefore needed to provide operators and regulators with criteria for choosing appropriate assessment approaches. For the Sleipner storage project, Chadwick and Noy [13] presented a case study based on fluid flow modelling and interpretation of 4D seismic data sets demonstrating converging conformity with increasing availability of monitoring data allowing updates and enhancements of the reservoir model. They used rather simple performance criteria which describe geometrical features of the CO_2 plume and which can be derived from fluid flow simulations and from time-lapse seismic data. A slightly modified approach using effective geometrical parameters was used to assess the conformity of fluid flow simulations and results of time-lapse seismic monitoring for the Ketzin pilot site [11]. As effective conformance criteria, these geometrical parameters were used: plume footprint area, maximum lateral migration, and plume volume. The case study, presented by Lüth et al. [11], was based on monitoring data collected in two seismic repeat surveys (2009, 2012).

Figure 4 summarizes the results of the conformance assessment using the plume footprint area as a performance criterion for the second and third seismic repeat surveys (2012, 2015). Determination of the plume footprint area is affected by uncertainties, for the seismic data as well as for fluid flow simulations. Seismic data are not noise free and the exact outline of the plume footprint depends on the noise level in the time-lapse amplitude data. The plume footprint area from seismic amplitudes is shown in Figure 4 for a range of amplitude thresholds. For a realistic amplitude threshold for the CO_2 signature between 0.2 and 0.3, the seismic plume footprint ranges between 200,000 and 400,000 m^2, which is significantly smaller than the plume footprint predicted from reservoir simulations. Fluid flow simulation predicted a CO_2 plume footprint of approximately 1.2×10^6 m^2 and 1.5×10^6 m^2 for 2012 and 2015, respectively. However, significant proportions of these areas are characterized by low thickness. More than 50% of the simulated plume footprint areas are 5 m thin or thinner which may be difficult to detect with land-seismic monitoring surveys. Comparing the simulated plume footprint area for a range of thickness detection thresholds and the range of seismic plume footprint areas for a range of realistic amplitude threshold values in Figure 4 shows that simulated and observed plume footprint areas are in conformance for a thickness detection threshold of approximately 5 – 7 m. As for the temporal evolution of the CO_2 plume footprint, Figures 2, 3, and 4 show that the seismic plume footprint area decreased from 2012 to 2015, which was interpreted as an indication of CO_2

dissolution and its diffusion into thin and undetectable layers. Reservoir simulations do not reproduce this shrinking of the plume footprint area. In Figure 4, the simulated plume footprint increases for all thickness detection thresholds investigated.

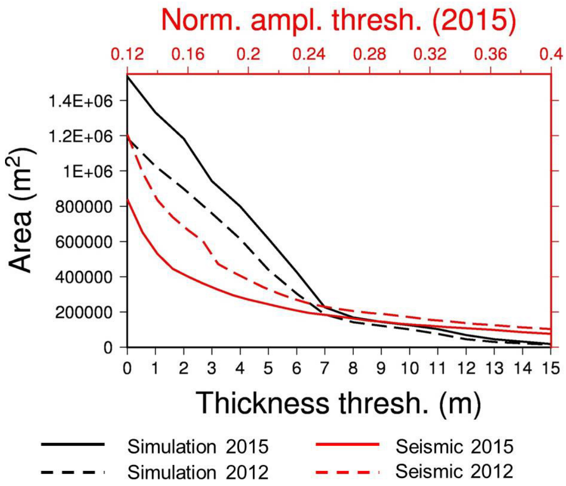

Fig. 4. Conformance assessment of seismic monitoring and reservoir simulation using the "plume footprint area" as performance criterion. For the reservoir simulations, the plume footprint area is shown considering minimum detection limits from 0 m (full plume area) to 15 m. For the seismic plume footprint area, normalized noise-signal amplitude thresholds from 0.12 to 0.4 are considered.

5. Conclusions

The pilot scale CO_2 storage operations at the Ketzin site were monitored using several different geophysical and geochemical methods, among which 4D seismic surveys provided the most comprehensive overview of the stored CO_2 at reservoir scale. The interpretation of difference amplitudes at the top of the storage formation resulted in signatures showing the lateral extent of the stored CO_2. Over the injection and post-injection phases, the growing CO_2 plume was imaged by the first and second seismic repeat surveys (2009, 2012). The third repeat survey, acquired two years after the post-injection phase started, showed decreased lateral extent of the CO_2. These results were compared to fluid flow simulations using performance criteria such as the plume footprint area. Conformity between observed CO_2 distribution and reservoir simulations was achieved for a minimum plume thickness of 5 – 7 m suggesting the seismic thickness detection threshold lies in this order of magnitude. Remaining unconformity is related to limited detectability of CO_2 accumulated in thin layers and to unknown lateral and vertical internal heterogeneity of the storage formation. Also, reservoir simulations did not predict a decreasing lateral extent of the CO_2 plume in 2015, compared to the plume extent in 2012, even when taking into account possible detectability issues due to diffusion of the CO_2 into thin layers. This observation may imply that the quantitative contribution of CO_2 dissolution has been underestimated by reservoir simulations and/or that CO_2 diffusion may have occurred with horizontal fingering further affecting detectability, which will be subject to further assessment in the near future.

Acknowledgements

The authors gratefully acknowledge the funding for the Ketzin project received from the European Commission (6^{th} and 7^{th} Framework Programme, projects CO_2SINK, CO_2CARE), two German ministries – the Federal Ministry of Economics and Technology and the Federal Ministry of Education and Research – and industry since 2004. The ongoing R&D activities are funded within the project COMPLETE by the Federal Ministry of Education and

Research. Further funding is received by VGS, RWE, Vattenfall, Statoil, OMV and the Norwegian CLIMIT programme.

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