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ScienceDirect

Energy Procedia 76 (2015) 536 – 542

Energy Procedia

European Geosciences Union General Assembly 2015, EGU

Division Energy, Resources & Environment, ERE

4D seismic monitoring at the Ketzin pilot site during five years of storage – results and quantitative assessment

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Abstract

The 3D seismic and surface-downhole time-lapse monitoring at the Ketzin pilot site for CO_2 storage has provided the data base for a quantitative estimation of the amount of CO_2 detected by the seismic surveys and of the CO_2 plume thickness. The monitoring results have been compared to reservoir simulations, considering noise and thickness threshold values and indicating that conformity between monitoring and simulation results can be achieved when a thickness detection threshold of between 1 and 7 m is taken into account.

Peer-review under responsibility of the GFZ German Research Centre for Geosciences

Keywords: Ketzin; 4D seismic monitoring; quantification; monitoring and simulation conformance.

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Peer-review under responsibility of the GFZ German Research Centre for Geosciences
doi:10.1016/j.egypro.2015.07.905

1. Introduction

The Ketzin pilot site for CO_2 storage offers a rich portfolio of monitoring data, and is provided with relatively well constrained geological data as a basis for the reservoir model [1,2,3]. This contribution summarizes the quantitative interpretations performed with the previously acquired monitoring data. The high-resolution seismic monitoring data and reservoir simulations based on a revised reservoir model [4] were investigated and assessed if and to what degree conformity between monitoring and simulation can be achieved. These investigations can significantly contribute to demonstrating that the applied monitoring methods are able to detect the stored CO_2 in the reservoir and that the governing reservoir processes are generally understood.

2. Surface based 3D time-lapse seismic monitoring

Repeated 3D seismic surveys have been an essential component of the multi-disciplinary characterization and monitoring programme of the Ketzin pilot site throughout the phases of site development and active CO_2 injection. Before site development, 2D seismic profiles and borehole information were available to construct an initial model of the storage complex, including a simplified reservoir model [5]. Before drilling the injection and monitoring wells for the Ketzin pilot site, a first 3D seismic survey was acquired in autumn 2005 around the injection site in order to provide detailed information about the geometry of the reservoir and its overburden [6]. This survey served as a baseline for further repeat surveys, aiming at a comprehensive and detailed observation of the CO_2 propagation within the reservoir complex during and after the active injection period. The first repeat of the 3D seismic survey was acquired on a smaller area, compared to the baseline survey, in autumn 2009 [7]. This survey was acquired during ongoing injection, and the cumulative amount of CO_2 injected was between 22 ktons and 25 ktons at the beginning and the end of the survey, respectively. The lateral extent of the CO_2 plume, as imaged by the seismic survey, was about 300 to 400 m, with dominating westward propagation of the injected CO_2 from the injection well (Figure 1). The second seismic repeat survey was acquired in autumn 2012 [8]. This survey was acquired during an injection stop related to the drilling of the third observation well CO2 Ktzi 203/2012 [9]. The cumulative amount of CO_2, injected into the storage formation, was 61 ktons. Figure 1 (right) shows the seismic amplitude signature of the CO_2 in the Stuttgart Formation, indicating increased lateral extent of the plume to 600 to 700 m, and still dominating westward propagation of the injected CO_2.

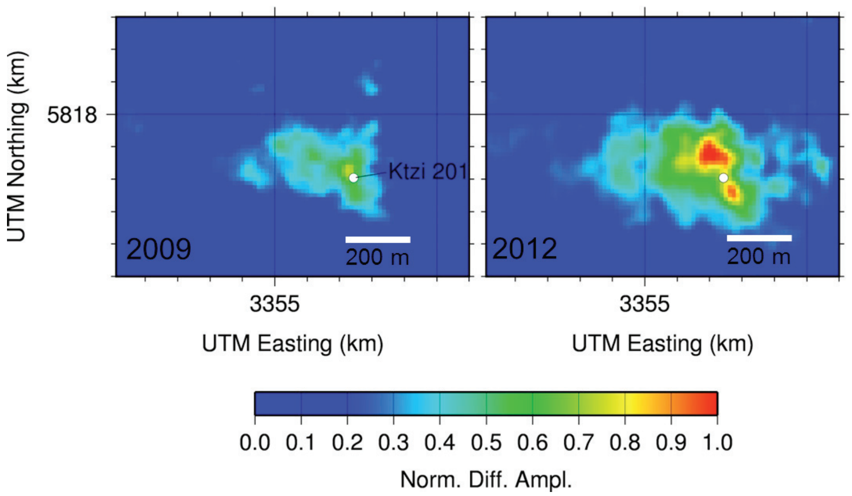

Fig. 1. Maps of normalized seismic difference amplitudes at the top of the Stuttgart Formation from the first repeat survey 2009 (left) and the second repeat survey 2012 (right). The position of the injection well (Ktzi 201) is indicated by a white dot in both maps.

3. Surface-borehole seismic monitoring

The surface based seismic monitoring programme at the Ketzin pilot site was complemented by surface-borehole surveys including zero-offset VSP and offset VSP observations [10]. The purposes of these surveys were to:

- Provide seismic time-depth measurements supporting correct time-depth conversions of the surface based reflection data.
- Deliver enhanced structural resolution of reflective structures at the depth level of the storage horizon.
- Demonstrate the absence of CO_2 accumulations in shallower aquifer horizons along the wellbore.

A comprehensive overview of the surface-borehole surveys acquired at Ketzin is provided in [10]. The vertical extent of the CO_2 plume in the vicinity of the monitoring well CO2 Ktzi 202/2007 was investigated by a wedge modelling study, the result of which is summarized in Figure 2. An elastic model (Vp, Vs, density) was derived from sonic and density logs [11]. The thickness of the CO_2 reservoir layer, characterized by a 30% P-wave velocity reduction, derived from laboratory observations and impedance inversion results [10], has been modified stepwise between 1 m and 12 m. The reservoir is not resolved by separate reflection events from top and bottom, but the wavefield is characterized by the interference of reflections from top and bottom of the reservoir. Interference tuning is observed, when the vertical expansion of the CO_2 saturated layer is reduced in the model. When using the NRMS error as a measure for the similarity between the modelled and recorded repeat traces, the best match is achieved for a plume thickness of 6–7 m within the reservoir sandstone of 8 m thickness, which is an indication of that the only the upper part sandstone reservoir is filled with CO_2 (Figure 2). PNG logging, performed in March 2011 [12], found a higher CO_2 saturation of >50% in the upper 4m of the sandstone layer at the same monitoring well. In the lower part, the saturation was found to be reduced to ~30%. Within the resolution limits of the seismic observations, these results may be regarded as conforming to each other.

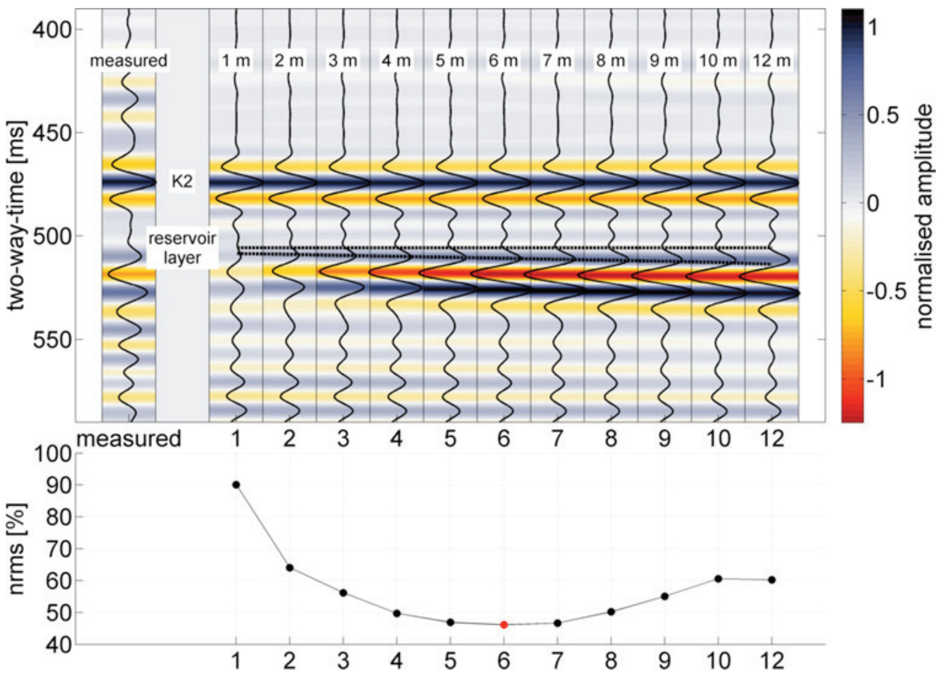

Fig. 2. Wedge modelling results gained from VSP observations at the Ketzin monitoring well CO2 Ktzi 202/2007 (Götz et al., 2014).

4. Mass estimation

At Ketzin, CO_2 has been stored at pilot scale, approximately two orders of magnitude smaller than a typical full scale storage project. The quantity of the stored CO_2 is therefore rather comparable to what may be expected to accumulate in an indicator horizon in the case of CO_2 leakage out of the storage horizon along a defective wellbore or through a previously undetected fault zone. The 4D seismic time-lapse surveys at the Ketzin pilot site have shown that relatively small amounts of injected CO_2 (2009: ~22 – 25 ktons; 2012: 61 ktons) can be detected. The amplitude anomalies (Figure 1) were then investigated further in order to assess the proportion of the CO_2 detected by geophysical monitoring, compared to the full amount of injected CO_2. For the mass estimation, the following data were considered [7]:

- Time-lapse amplitudes at the reservoir level and velocity-pushdown of seismic reflections below the reservoir for lateral extent and thickness of the CO_2 plume.
- CO_2 and brine saturation from PNG logging surveys.
- Average reservoir rock porosity from core analyses.

These data were used to estimate the mass of CO_2 imaged by seismic observations for each CDP bin and then summed up for all CDPs. The following mass estimations were made for the first and second repeat surveys (2009 and 2012, respectively): Ivanova et al. [7] estimated the amount of CO_2 imaged by the first 3D seismic repeat survey (2009) to be between 20.5 and 23 ktons, which is approximately 5 - 10 % less than the cumulatively injected mass of CO_2 in autumn 2009. The same approach for the quantitative assessment was extended by additionally acknowledging uncertainties related to the amplitude and traveltime threshold values, and applied to the autumn 2009 and the autumn 2012 data (first and second repeat surveys) by [8]. The mass estimations for the first repeat survey range between 19.8 and 27.4 ktons, and for the second repeat survey from 46.1 and 58.8 ktons. These values indicate a relatively high degree of uncertainty, and in the case of the first 3D repeat survey even potentially overestimating the mass of CO_2 detected by seismic surveys. The estimations may be a viable approach to demonstrate that geophysical anomalies represent a significant proportion of the injected CO_2, but they are not appropriate to demonstrate full conformance between monitored and expected behavior of a storage site, as required according to EU CCS regulations.

5. Conformance of monitoring and simulation

As shown above, mass estimations based on integrative interpretation of multidisciplinary data sets are only able to provide rough approximations of the mass of CO_2 injected. Comparable observations were made at large scale storage sites such as Sleipner, where a quantitative analysis of seismic amplitudes and velocity pushdown was performed detecting 85 % of the injected mass of CO_2 [13]. For demonstrating conformance between monitoring data and simulated behavior of a storage site, an assessment approach is needed which acknowledges physical detection thresholds of monitoring methods as well as limitations related to the numerical process simulation. Performance criteria, allowing for a certain degree of deviation between monitoring results and simulated reservoir behavior, are related to geometrical properties of the CO_2 plume without necessarily requiring an exact description of the full plume shape. These performance criteria are [14]:

- Plume footprint area.
- Maximum lateral migration distance of CO_2 from the injection point.
- Area of CO_2 accumulation trapped at top reservoir.
- Volume of CO_2 accumulation trapped at top reservoir.
- Area of all CO_2 layers summed.
- Spreading coefficient (storage efficiency).

For the small CO_2 plume at the Ketzin pilot site, these criteria were slightly modified, acknowledging that the plume is thin and seismic data are unable to resolve several plume layers. Plume footprint areas and plume volumes were compared for the seismic monitoring data and reservoir simulations, based on a revised static model of the storage formation [4]. Figure 3 summarizes the results of the conformance assessment using plume footprint area and plume volume as performance criteria. For the seismic data, the performance criteria were computed depending on a range of amplitude threshold values, indicating the separation of "noise" and "CO_2-signature" in the data. The amplitude thresholds range from 0.12, which is clearly in the noise range, to 0.4 which can be clearly attributed to the CO_2 signature (see Figure 1). For the reservoir simulations, the performance criteria were computed using minimum plume thickness thresholds, acknowledging the fact that geophysical monitoring is unable to detect thin layers (with thickness significantly less than a quarter of the dominant seismic wavelength). Considering the seismic amplitude maps, shown in Figure 1, the true amplitude threshold value separating noise from CO_2 signature is assumed to lie between 0.2 and 0.27. Assuming these amplitude threshold values, the plume footprint area sizes and plume volumes are compared to the simulated footprint area and volume values in Figure 3. In Figure 3 a, the plume footprint area is investigated for the first 3D repeat survey (2009). For the above mentioned noise threshold values, the seismic plume footprint area ranges between 357,000 m^2 and 128,000 m^2, which is between 85% and 30% of the full simulated plume footprint area and which conforms with a part of the simulated plume of minimum thickness between ~1 m and ~5 m (Figure 3 a). Similar observations can be made for the plume footprint area of the second repeat survey (Figure 3 b) and the plume volume (Figure 3 c and 3 d). The equivalent thickness of the simulated CO_2 plume, conforming to the seismic CO_2 plume, ranges between 1 m and up to ~7 m. This may be regarded as an indication of the range of detection threshold attributed to the seismic observations.

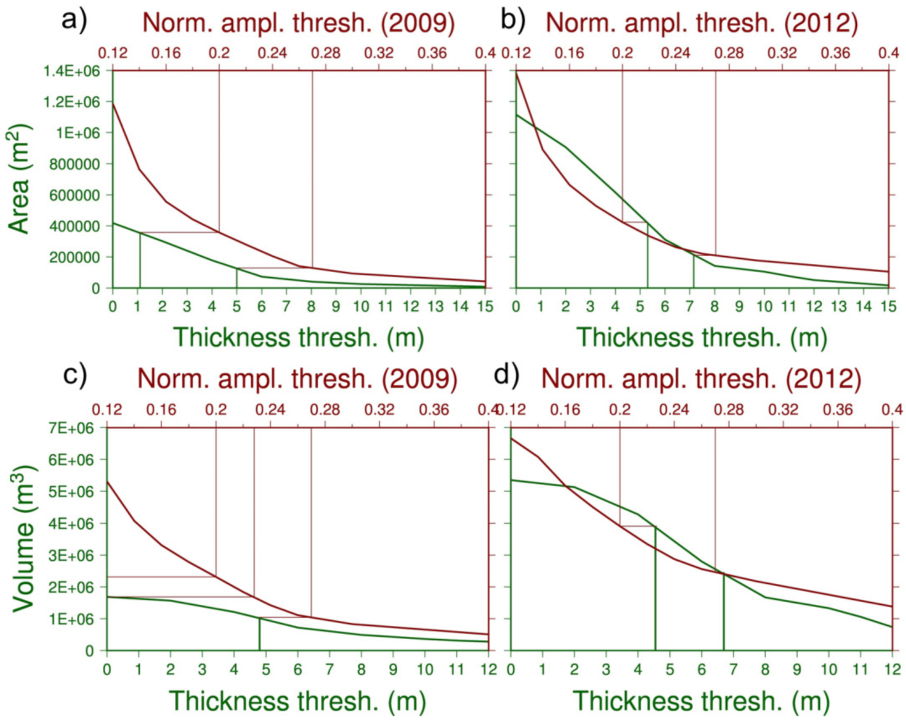

Fig. 3. a) Plume footprint area from seismic data (red curve), depending on amplitude threshold (2009) and from reservoir simulation (green curve), considering minimum thickness threshold from 0 to 15 m (2009); b) the same as in a for 2012; c) Plume volume from seismic data (red curve), depending on amplitude threshold (2009) and from reservoir simulation (green curve), considering minimum thickness threshold from 0 to 12 m (2009); d) the same as in c for 2012.

6. Summary and conclusions

Repeated 3D seismic surveys acquired at the Ketzin pilot site for CO_2 storage were able to detect clear signatures of the injected CO_2. The integrated interpretation of the seismic plume footprint with logging data and rock physical laboratory studies have provided quantitative estimations of the amount of CO_2 imaged by geophysical monitoring. However uncertainties, which were difficult to quantify, remained. The results of the seismic monitoring and reservoir simulations were compared using performance parameters such as the plume footprint area and the plume volume. This comparison indicated that full conformance between monitoring and simulation could not be achieved due to physical detection limits of the monitoring method and due to the approximative character of the reservoir model and the process simulations. Considering a realistic detection limit of geophysical monitoring in the order of ~1 to 7 m, simulations and monitoring results were in acceptable conformance, taking into account the small amount of CO_2 stored at the pilot site in a highly heterogeneous environment which poses particular challenges to the monitoring methods as well as to a realistic simulation of the storage process.

Acknowledgements

The authors gratefully acknowledge the funding for the Ketzin project received from the European Commission (6th and 7th Framework Program), 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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