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Quantitative seismic monitoring of a saline aquifer: a feasibility study for the CO_2 injection (the pilot site Ketzin, Germany)

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Abstract

Carbon dioxide (CO_2) storage requires a proven monitoring methodology. In this study we investigate whether seismic methods are able to quantitatively detect relatively small amounts of CO_2 (20-60 kilotons) injected into a saline aquifer. The 3D time-lapse (4D) seismic data were acquired at Ketzin. 85-95% injected CO_2 could be imaged quantitatively. Nevertheless this estimate contains considerable uncertainties. Results of 4D seismic forward modeling at four wells penetrating the reservoir prove this quantitative interpretation supporting the conclusion that the 4D seismic method is a suitable technique to monitor even relatively small amounts of injected CO_2 quantitatively.

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Keywords: 4D seismic monitoring; quantitative interpretation, CO_2; seismic modeling; Ketzin

1. Introduction

Capture and geological storage of CO_2 (CCS) is to reduce greenhouse gas emissions into the atmosphere. The 4D seismic surveying is a proven tool for the reservoir characterization and for providing information on injection related processes [1]. The quantitative monitoring of CO_2 is crucial for assessing storage efficiency and monitoring potential leakage [2].

Although CO_2 projects consider various geological formations as candidates for CO_2 storage, the long-termed focus of CCS is on saline aquifers because of their capacity [2]. The Ketzin pilot project was initiated with a saline aquifer as the target reservoir in 2004 [3]. This is the first European onshore CO_2 storage project [4,5]. The Ketzin pilot site is situated west of Berlin close to the town of Ketzin, Germany. The CO_2 storage reservoir is sandstones of the heterogeneous Stuttgart Formation (the Upper Triasic). The Ketzin pilot project is a small-scale CCS project. Its monitoring program covers almost every component of the corresponding large-scale projects [6,7,8]. At the Ketzin pilot site the CO_2 injection started in June 2008. About 67 kilotons of CO_2 were injected into this reservoir at a 650 m depth. In August 2013 the injection at Ketzin was terminated [7].

4D seismic surveying has been proven to be an effective and successful tool to image CO_2 within the target reservoir quantitatively in case of the large scale CCS projects [9].

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Seismic modeling and observations show that the effects of the injected CO_2 on the 4D seismic data from Ketzin are significant [10,11,12,13,14] and CO_2 can be monitored quantitatively with a mismatch of 5-15% only (the total mass) but also with considerable uncertainties. With this research we use the 4D seismic forward modeling at Ketzin at four wells penetrating the target reservoir to confirm the quantitative interpretation of Ivandic et al. [10] and to support the conclusion that the 4D seismic method is a suitable technique to monitor quantitatively even relatively small amounts of injected CO_2 (20-60 kilotons).

2. 4D Seismic Surveying at Ketzin

The right seismic source is one of the most important requirements of the reflection seismic experiment [15]. Three seismic surface sources were characterized with respect to signal/noise ratios, signal penetration, and frequency content by analysis of raw shot gathers and stacked sections along two lines within the planned 3D seismic area at the Ketzin site [16]. All the sources imaged the target horizon. The choice of the source for the 3D surveys at the Ketzin pilot site was based mainly on logistics and cost. The weight drop source was recommended as the primary source for the 3D surveys [16].

At Ketzin, a 3D baseline seismic survey was acquired in 2005 [17]. This baseline revealed a sequence of clear reflections from approximately 150 ms down to 900 ms t.w.t. (two way time) in a stacked volume. After the CO_2 injection started and first 20 kilotons of CO_2 were injected, a smaller 1st 3D seismic repeat survey was acquired in 2009 in the area around the injection well [18]. The 2nd 3D seismic repeat survey was acquired in 2012 after 60 kilotons of CO_2 were injected [10]. Results of processing, including equalization of the 4D seismic data and cross-correlation, indicate that the injected CO_2 can be monitored [10]. The highly irregular seismic amplitude response to the injection in these 4D seismic data can be attributed to rock heterogeneity of the reservoir (Figure 1).

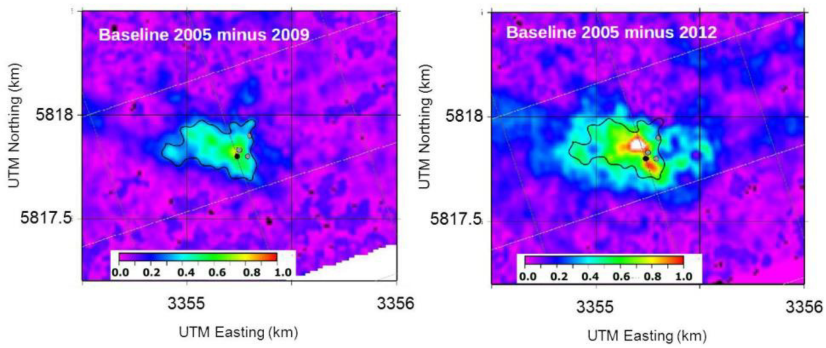

Fig. 1. Maps of normalized seismic difference amplitudes at the top of the Stuttgart Formation from the first repeat survey 2009 (left) and the second repeat survey 2012 (right) [10]. The position of the injection/observation well and three other observation wells penetrating the reservoir are indicated by a black dot and by three grey dots in both maps respectively.

Time-lapse seismic amplitudes (Figure 1), time-delays obtained from differences between the time-shifts of the windows above and below the reservoir (Figure 2), results of petrophysical measurements on core samples from a well penetrating the target reservoir and geophysical logging of CO_2 saturation levels allowed for an estimate of the total amount of CO_2 visible in the seismic data to be made. This estimate is somewhat lower (85-95%) than the actual amount of CO_2 injected by the time of the surveys acquisition and depends on a choice of a number of parameters [18,10].

Lüth et al. in [19] used the 4D seismic data and results of reservoir simulations at the Ketzin pilot site to set up and apply performance parameters for assessing the conformance between observed and simulated CO_2 plume migration in the reservoir. The comparison of the 4D seismic data and reservoir simulations suggests that a significant amount of CO_2, residing in thin layer structures, remains undetected. But the 5-15% mismatch in the CO_2 mass estimation of [10] can be also completely attributed to the amount of dissolved CO_2 [20]. In spite of these uncertainties, the close agreement between the injected and observed amount is encouraging for quantitative monitoring of a CO_2 storage site using seismic methods.

Volumetric estimation of CO_2 based on the 4D seismic data from Ketzin using results from the multiphase fluid flow simulations shows that the impact of temperature in the reservoir at the monitoring time is significant for these estimations [21]. Future issues to be considered include expanding the temperature range (34-38° in this study) to be investigated and the resulting effects on the seismic response.

By integrating seismic modeling and petrophysical experiments on core samples from the target reservoir, the effect of the CO_2 injection on the amplitude versus angle of incident (AVA) response in the acquired 4D seismic data at the Ketzin pilot site was estimated [22]. Two effects were considered: the CO_2-saturation- and the pore-pressure-related effects. The results indicate that the effect of pore pressure on the AVA time-lapse seismic data is very weak and time-lapse changes in pore pressure could not affect considerably results of the CO_2 mass estimation at the Ketzin pilot site from [18,10].

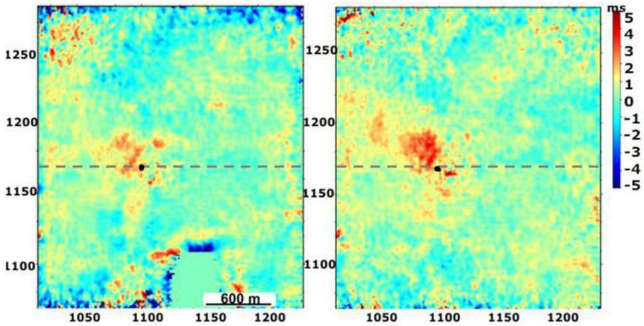

Fig. 2. Maps of time-delays obtained from differences between the time-shifts of the windows above and below the reservoir from the first repeat survey 2009 (left) and the second repeat survey 2012 (right) [10]. The position of the injection/observation well is indicated by a black dot. The grey dashed line is the inline 1165 mentioned in later figure captions.

A new (3[rd]) 3D seismic repeat survey will be acquired at the Ketzin pilot site in 2015 and will allow for new insights in the CO_2 plume at the Ketzin pilot site.

3. Seismic modeling for feasibility of the quantitative seismic interpretation at Ketzin

The aim of this paper is to support the conclusion that the 4D seismic method is a suitable technique to monitor quantitatively even relatively small amounts of injected CO_2 (20-60 kilotons).

For the quantitative interpretation of the 4D seismic from the Ketzin pilot site, Ivandic et al. in [10] used time-lapse seismic amplitudes (Figure 1) and time-delays obtained from differences between the time-shifts of the windows above and below the reservoir (Figure 2). Relative change in the compression wave velocity due to the CO_2 injection was calculated in their study with the following equation based on results of petrophysical experiments on core samples by Kummerow and Spangenberg [23]:

$$\frac{\Delta V_P}{V_P} = -0.46 \cdot S_{CO_2} \qquad (1)$$

were V_P is the compression wave velocity and S_{CO_2} is CO_2 saturation in percent.

Huang et al. [11] generated synthetic 4D seismic data for the Ketzin pilot site by convolving property models at different times with an extracted wavelet. Changes in velocity and density after the CO_2 injection were estimated utilizing the CO_2 saturation distributions from 3D simulations at two repeat times and fluid substitution models based on Gassmann's equations [24]. They have found out that in case of the Ketzin pilot site, their method is suitable in the near-wellbore area but not as reliable outside that area.

In this contribution we use the 4D seismic forward modeling at the Ketzin pilot site at four wells penetrating the target reservoir with the reflectivity method [25]. Changes in velocity and density after CO_2 injection are estimated using the CO_2 saturation distributions from 3D simulations from [11] and fluid substitution models based on Gassmann's equations [24] while incorporating results from petrophysical experiments by [23]. Relative change in V_P due to the CO_2 injection was calculated in this study with the equation (1) as it was done by [10] for the volumetric estimation. The shear wave velocity (V_S) is not affected by CO_2 at the Ketzin pilot site after [23].

The input parameters for the modeling are following: V_P, V_S and density (ρ) near the injection/observation well obtained from borehole logging data [21]. V_P and ρ were vertically averaged from the logs to remove high frequency fluctuations (Figure 3). Values of V_S taken from another well situated 112 m apart from the injection/observation well were vertically averaged over the main lithological units [26]. The resulting V_S model was linearly interpolated to the injection/observation well using the interpreted lithological horizons after [27]. The input wavelet used for the modeling was extracted from the 3D seismic baseline data [17] (Figure 3), yielding a dominant frequency of 40 Hz. Seismic modeling using the previously described V_P, V_S and density models as input parameters resulted in a synthetic trace corresponding to a 3D surface seismic baseline trace near the injection well (Figure 3).

The resulting V_P, V_S and density models of the injection/observation well (Figure 3) were linearly interpolated using the interpreted lithological horizons after [27] to three other wells penetrating the reservoir (Figure 1) and the corresponding synthetic traces were produced the same way as that one for the injection/observation well in Figure 3.

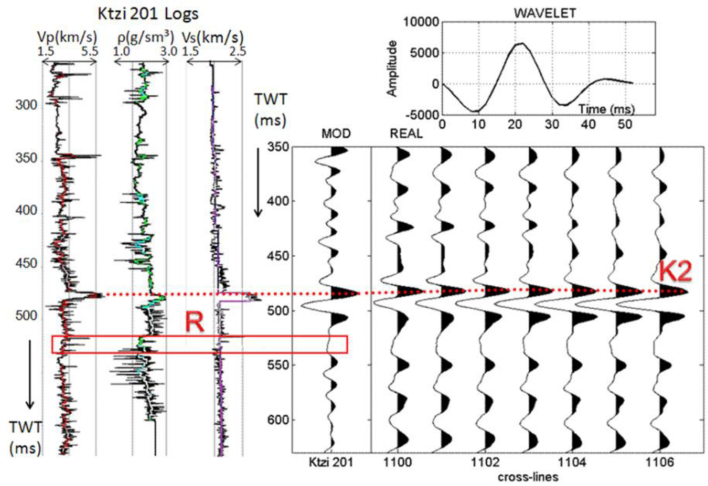

Fig. 3. Well to seismic tie for the injection well. V_P (red line), V_S (purple line) and ρ (green line) were used for the seismic modeling. The reservoir interval is marked with a red rectangle and by "R". "MOD" is a modeled baseline seismic trace at the injection/observation well (Ktzi 201) (Figure 1). A real seismic trace of the seismic baseline in the vicinity (<3 m) of this well is marked by "REAL". The adjoining traces are from the same inline 1165 (Figure 2) as the "REAL" trace [17]. "K2" is a strong reflection from a thick (20 m) anhydrite layer [3]. Upper right: source wavelet [27] extracted from the 3D seismic baseline data [17] in the vicinity of the injection well.

Time-lapse seismic amplitudes and time-delays gained with the 4D seismic forward modeling at four wells penetrating the target reservoir are demonstrated in Figure 4. This seismic modeling shows that the effects of the injected CO_2 on the 4D seismic data from Ketzin are pronounced both in terms of time-lapse seismic amplitudes and time-delays. They follow the main tendencies (increase/decrease) in the corresponding real time-lapse seismic amplitudes and time-delays obtained from differences between the time-shifts of the windows above and below the reservoir by Ivandic et al. [10] in the 4D seismic data at the Ketzin pilot site for both 2009 and 2012 3D seismic repeat surveys. The modeling results for the repeat of 2012 are in a better correlation with the real 4D seismic data from the Ketzin pilot site than the modeling results for the repeat of 2009. This may be due to the fact that the noise content is less in the corresponding data of 2012 than in the data of 2009 [10].

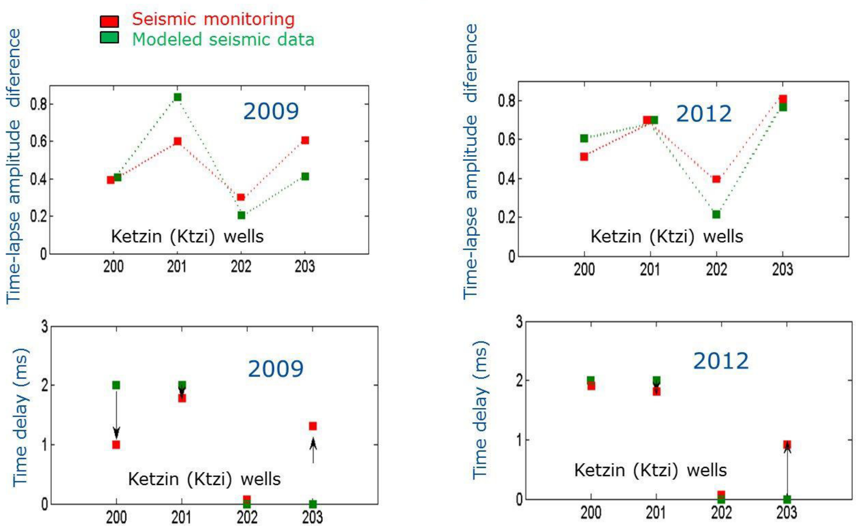

Fig. 4. Results of seismic forward modeling of the CO_2 response with the reflectivity method in 2009 and 2012 at four wells penetrating the reservoir at the Ketzin pilot site compared to the corresponding real 4D seismic data [10] in terms of time-lapse amplitudes and time-delays. The horizontal axis indicates the project number of each well after [6]. The wells are within 112 m of each other (Figure 1).

The seismic forward modeling with the reflectivity method at the wells penetrating the reservoir using simulated 3D parameters supports results of the quantitative 4D seismic interpretation at the Ketzin pilot site both for 2009 and 2012.

4. Conclusion

The 4D seismic processing, petrophysical measurements on core samples and geophysical logging of CO_2 saturation levels allowed for an estimate of the total amount of CO_2 visible in the seismic data at the Ketzin pilot site to be made. This estimate is 5-15% less than the actual amount of CO_2 injected by the time of the surveys acquisition and it depends on a choice of a number of parameters. The seismic forward modeling with the reflectivity method at the wells penetrating the reservoir using simulated 3D parameters supports results of the quantitative 4D seismic interpretation at Ketzin both for 2009 and 2012. In spite of uncertainties, the close agreement between the injected and observed amount is encouraging for quantitative monitoring of a CO_2 storage site using seismic methods in a saline aquifer even in case of relatively small amounts of injected CO_2.

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