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Seismic modeling of the AVO/AVA response to CO_2 injection at the Ketzin site, Germany

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Abstract

Over 64 kilotons of CO_2 have been injected (May, 2013) into a heterogeneous sandstone reservoir (saline aquifer) at 630-650 m depth. 4D seismics have been applied to monitor CO_2 at the Ketzin site. However, the obtained time-lapse seismic signals have been so far interpreted as being caused by fluid saturation changes only. Modeling of the AVO/AVA response allows us to study two kinds of effects: CO_2-saturation- and pore-pressure-related effects. Our results indicate that it is rather infeasible to discriminate between both these effects at the Ketzin site dealing with the real seismic data with limited signal/noise ratios.

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CO2 storage; seismic monitoring; AVA/AVO; petrophysics; pore pressure; fluid saturation

1. Introduction

Repeated 3D seismic surveys (“4D seismics”) have proven to be an essential tool for reservoir monitoring on a wide range of CO_2 storage projects [1] [2] [3]. In addition to the 4D monitoring that is generally based on post-stack data sets (e.g. [4]), pre-stack amplitude-versus-offset/angle (AVO/AVA) techniques exploit changes in seismic wave amplitude as a function of the incidence angle [5]. The AVO/AVA response is determined by contrasts in compressional wave velocity (Vp), shear wave velocity

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(Vs) and density (ρ) across an interface. Analysis of the AVO/AVA response is a relevant technique for monitoring CO_2 storage since changes in the AVO/AVA parameters (i.e. intercept and gradient) are related to fluid substitution processes in the subsurface [5]. However, conventional AVO/AVA analysis has failed in some cases, for example at the Sleipner CO_2 storage project, due to interference of reflected waves from several thin layers [1]. For most reservoirs, pressure changes in combination with fluid-saturation changes create anomalous seismic responses in terms of velocity analysis. It is often difficult to separate the two effects from seismic data only by analysing post-stack data [6]. M. Landro [6] presented a direct inversion method based on a linearization of R.T. Shuey's [7] reflection parameters in terms of changes in pressure and fluid saturation. Fluid substitution processes and pressure changes affect the petrophysical properties of rocks differently in most cases. Therefore, they typically yield different changes in the AVO/AVA response [6]. The method of M. Landro [6] contains two parametric equations that solve for pressure and fluid saturation changes in terms of the AVO/AVA gradient and intercept parameters. C. Juhlin and R. Young [8] presented a method to model the AVO/AVA response of a thin bed by computing the interference effects of the reflected compressional wave with all internal multiples (compressional waves and converted shear waves).

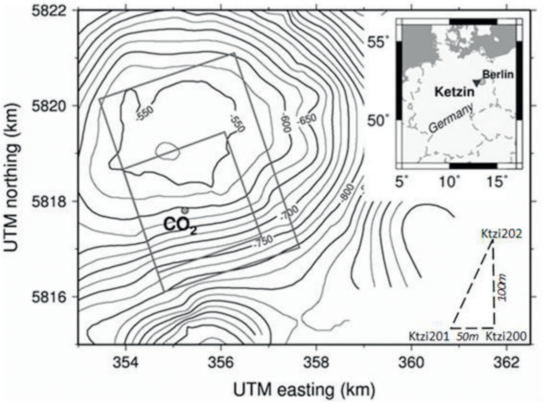

Fig. 1. Depth contour lines of the top Stuttgart Formation, showing the dome of the Ketzin anticline [10]. The grey rectangles indicate the areas covered by the baseline and repeat 3D seismic surveys. The larger rectangle presents the 2005 baseline survey, the smaller rectangle presents the 2009 repeat survey concentrating on the area near the injection site ("CO_2") at the southern flank of the dome. The upper inset indicates the location of the Ketzin Site close to Berlin. The lower inset shows relative location of the wells.

The Ketzin project in Germany is the first onshore CO_2 geological storage project in Europe. It started in 2004 with the following main aims: (1) to improve our understanding of underground storage of CO_2 (2) to build confidence for further CO_2 geological storage in Europe and, (3) to provide operational field experience for CO_2 injection [9]. The Ketzin site is located near Berlin in the North German Basin (Fig. 1). Three boreholes were drilled to depths about 800 m in 2007, the injection well (Ktzi 201) and two observation wells (Ktzi 200 and Ktzi 202), after the site characterization period. These wells penetrate the saline aquifer reservoir that CO_2 is being injected into since June 2008. A multidisciplinary monitoring concept has been developed for this project [11]. As of May 2013, over 64 kilotons of CO_2 have been injected. The target reservoir is the lithologically heterogeneous Upper Triassic Stuttgart Formation with injection in the depth interval 630 to 650 m. The Stuttgart Formation consists of a system of incised-valley deposits in which sandy-channel-facies rocks of good reservoir quality are interlaced with floodplain-facies rocks of poor reservoir quality [9]. The formation is overlain by a c. 160 m thick caprock section consisting of Upper Triassic playa-type rocks of the Weser and Arnstadt Formations, comprised mainly of mudstone and anhydrite [9]. An anhydrite layer within this section is approximately 20 m thick and produces a well defined reflection on seismic data [12] and is known as the K2 reflection. This is the most important regional seismic marker.

The seismic monitoring program at the Ketzin site includes vertical seismic profiling (VSP), moving source profiling (MSP) [13], cross-hole [14], pseudo-3D [15], 2D [16] and full 3D surveys [12] [4] [17]. At Ketzin, the 3D baseline seismic survey was acquired in autumn 2005. A smaller 3D seismic repeat survey was acquired in autumn 2009 in the area around the injection site. The outlines of the surveys are shown in Fig. 1. This first 3D seismic repeat survey showed a pronounced time-lapse amplitude anomaly at the top of the storage reservoir [15] [4]. This anomaly, as well as delayed arrival times of reflections below the reservoir ("velocity push-down effect"), demonstrated that CO_2 injected at the Ketzin site could be monitored by means of surface-based seismic surveying. Estimation of the CO_2 amount in the reservoir as imaged by the seismic measurements provided a satisfactory match with the mass of injected CO_2 (+/- 5-7%) [4]. Petrophysical studies indicate a nearly linear dependence of Vp versus CO_2 saturation for the sandstones of the Ketzin reservoir [18] [4].

In this contribution we integrate the seismic modeling of the AVO/AVA response to a thin layer after C. Juhlin and R. Young [8] with petrophysical experiments on core samples from the target reservoir ([18], [4], this paper). We evaluate the impact of the CO_2 injection at the Ketzin site on pore pressure and CO_2 saturation and the resulting AVO/AVA response on the 4D seismic data from Ketzin.

2. Petrophysical effects of pore pressure on reservoir rocks at the Ketzin site

Interpretation of time-lapse seismic data depends on the relationship between the seismic response and typical reservoir parameters to be mapped such as pore pressure changes and fluid saturation changes [19]. Petrophysics provides a link for bridging the gap between these two types of parameters. Although the Gassmann equations [20] underestimate the interaction between adjoining pores [19], they still form a reasonable working basis enabling us to make quantitative estimates on how the seismic response changes versus, for example, CO_2 saturation [21]. However, the theoretical basis is weaker for the case pore pressure changes influence the seismic response and we have to rely on ultrasonic core measurements in order to establish a link between pore pressure changes and corresponding changes in the seismic response [22]. One major problem with core measurements is that a core sample gets damaged during the coring process [23]. Artificial cracks may be formed during anisotropic stress uploading. Even if the core sample is reloaded to simulate in situ stress conditions for ultrasonic core measurements, it is not very likely that the original crack state of the sample is reproduced [22]. Furthermore, we have to deal with the upscaling question for the core measurements and, namely, if the ultrasonic experiments made on small core samples are representative at the seismic scale.

Previous experiments on sandstone samples from the Stuttgart Formation have shown a slight decrease of Vp and Vs with increasing pore pressure (maximum 50 m/s for both Vp and Vs for corresponding pore pressure changes from 6 to 8 MPa under confining pressure 10-20 MPa) [24]. Here we report on two porous sandstone samples (B2-3b and B3-1b with porosities of 28.07% and 28.45%, respectively) with fine clay laminates [18] [4] that were obtained directly from the target reservoir at the Ketzin site (the well Ktzi 202). These samples have been experimentally characterized for their Vp and Vs dependence on pore pressure. The experiments were conducted under the following simulated reservoir conditions: confining pressure Pconf = 15 MPa, pore pressure Ppore = 7.5 MPa, and temperature T = 40°C. The equipment used for the petrophysical experiments on these samples is described in [18]. In contrast to former experiments [24] , the B2-3b and B3-1b samples were saturated with formation brine before being placed in the experimental set-up in order to avoid salt precipitation and clogging of the pore space.

The experiment was conducted as follows. The set-up was installed in the pressure vessel and a low confining pressure of 1 MPa was applied until an in-situ temperature of 40°C was reached. The confining pressure was then stepwise (by 1 MPa) increased up to the in-situ confining pressure of 15 MPa. Now the formation brine was charged and the in-situ pore pressure of 7.5 MPa was applied step by step (by 1.5 MPa steps). Ultrasonic velocities were measured at each pressure step. As expected, with increasing pore pressure Vp and Vs slightly decreased (approximately 70 m/s for both Vp and Vs corresponding to pore pressure changes from 6 to 7.5 MPa) (Fig. 2).

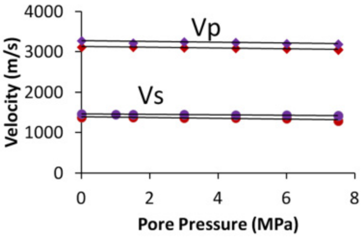

Fig. 2. Results of petrophysical experiments Vp (diamonds) and Vs (circles) versus pore pressure for the samples B2_3b (red) B3_1b (purple).

3. Thin bed AVO/AVA response modeling at the Ketzin site (baseline – before the injection)

If a layer is thin enough, reflections from its top and bottom will interfere and appear as a single reflection [25]. M.B. Widess in his classic paper entitled "How thin is a thin bed" published in "Geophysics" in 1973 [25] concluded that for thin beds (below 1/8th of a wavelength, which is approximately 9.5 m in the target reservoir at the Ketzin site assuming Vp=3000 m/s in the reservoir (sonic log) and a frequency of 40 Hz) that the seismic character, peak/ through time, does not change appreciably with thickness, and also that amplitude varies almost linearly (along the almost linear portion of a sinusoid) with thickness and goes to zero at zero thickness. Below 1/8th of a wavelength, the only characteristic of the seismic response that changes appreciably with thickness is the amplitude and there is no way to separate reflection coefficient changes from thickness changes. This is the case for the Ketzin reservoir near the well Ktzi 202 with its thickness of 8.5 m [26].

C. Juhlin and R. Young [8] presented a time delay modeling strategy for how the AVO/AVA response of a thin bed can be approximated by the interference between plane P-waves and converted S-waves from this layer. One assumption was that the contrast in elastic properties between the layer and surrounding rocks is small. The Ketzin site fulfills this requirement (Fig. 3, Table 1). They used a three layer elastic model as input for the thin bed layer and the overlying and underlying layers to compute synthetic seismograms that include the AVO/AVA response.

In order to exploit this modeling approach, we averaged the Vp sonic and density (ρ) logs from the well Ktzi 202 (Fig. 3, Table 1) and established the following three layer model that represents the baseline case at this well: (1) caprock (the mudstone of the Weser Formation), (2) reservoir (upper part of the Stuttgart Formation in the well Ktzi 202), and (3) formation beneath the reservoir (mudstone with interbedded thin sand layers of the Stuttgart Formation further down in the well Ktzi 202). The thickness of the reservoir in this well (8.5 m) was used for the AVO/AVA response modeling. In [27] an average baseline Vs value from Vs sonic logs at the Ketzin site (1678 m/s, Table 1) was used for the seismic modeling. In this study we used the same Vs baseline value.

Using a Ricker wavelet (40 Hz) we computed a synthetic seismogram for the baseline AVA response of the reservoir from the Ketzin site. Our results show that the AVA effect is small before the injection with only a slight increase of the combined reflection coefficient with angle. The modeled values of the AVA gradient (G) and intercept (R_0) for the baseline [12] near the well Ktzi 202 are 0.048 and -0.118, respectively. The combined reflection coefficient response only differs slightly from that of the simple interface response from the overlying layer and the reservoir.

4. Modeled AVO/AVA response to the CO_2 injection

We modeled the AVA synthetic response to the CO_2 injection at the Ketzin site by changing the reservoir parameters in our initial elastic model (Vp, Vs and ρ from Table 1) to new ones corresponding to conditions in the reservoir after a given amount of CO_2 injection.

First of all, we applied the fluid saturation-related changes using the elastic model based on [26]: we assumed linear dependences for Vp and density versus CO_2 saturation with slopes of 0.46 and 0.1, respectively. We did not change Vs with respect to CO_2 saturation. Note that the linear dependence of Vp assumes that the patchy saturation model rather than the homogeneous Gassmann model is valid for the Ketzin site. This assumption is supported by the core measurements [26]. The resulting seismogram for the time of the repeat survey according to the level of CO_2 saturation (30%) in the well Ktzi 202 from the pulsed neutron-gamma (PNG) logging [4] shows a stronger AVA response in comparison to the baseline (Table 2) in terms of the AVA intercept.

Secondly, we modeled the pore-pressure related changes in the AVA response at the time of the 1st 3D seismic repeat survey at the Ketzin site [4] based on our petrophysical data on pore pressure (Fig. 2). We assumed linear dependences of Vp and Vs versus pore pressure using Equations 1 and 2 which correspond to linear least squares approximations of measured Vp and Vs data, respectively, for both samples B2-3b and B3-1b:

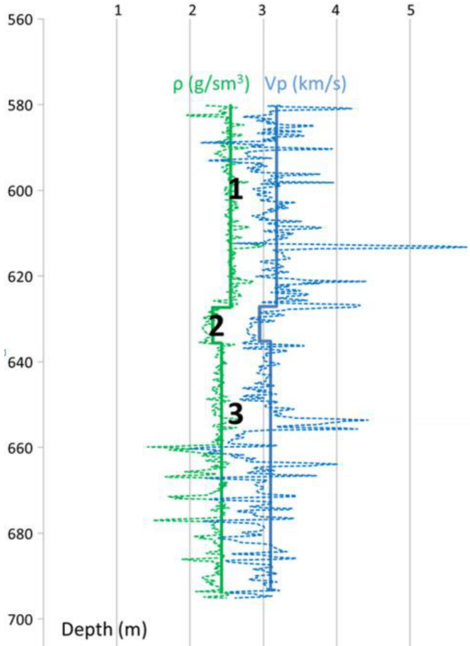

Fig. 3.Vp and ρ logs of the well Ktzi 202 (dashed lines) and three layer models (solid lines) averaged from the logs.

Table 1. Baseline three layer elastic model for the well Ktzi 202.

	Vp (m/s)	Vs (m/s)	ρ(density) (g/cm³)
Overlying layer (1)	3221	1648	2.554
Reservoir (2)	2936	1648	2.256
Underlying layer (3)	3165	1648	2.412

$$Vp(Ppore) = -0.0102 * Ppore + 3212 \qquad (1)$$

$$Vs(Ppore) = -0.0075 * Ppore + 1430 \qquad (2)$$

where *Ppore* is pore pressure in the reservoir. These equations were applied to the AVA response modeling for pore pressure changes. We assumed that density will not be changed with respect to pore pressure due to the injection. Results of the time-lapse AVA modeling related to the pore pressure change from 6 to 7.5 MPa in the reservoir, corresponding to the values measured before the injection at Ketzin (baseline) and by the time of the 1st seismic 3D repeat survey in autumn 2009 [28], are shown in Table 2. There is a small change in the AVA response in comparison to the baseline. The fluid saturation related changes give a significantly more pronounced signature. This is due to the CO_2 saturation (slope 0.46) influence on Vp [27] being almost five times greater than the pore pressure dependence (slope 0.0102 in Equation 1) and the relatively small change in pore pressure.

The AVA response to changes in CO_2 saturation from 0% to 100% (in steps of 10%) in the reservoir at the Ketzin site with a constant thickness of the CO_2 layer (8.5 m) was also modeled. Results of this modeling are shown as a cross-plot of the AVA gradient (G) with the AVA intercept (R_0) in Fig. 4.

5. Discussion

The AVO/AVA modeling applied to predict the seismic response to CO_2 injection at the Ketzin site is non-trivial because the CO_2 is injected into a quite thin layer beneath a very strong reflector (a c. 20 m thick anhydrite layer). For example, conventional AVO/AVA methods failed when applied to thin layer reflections at the Sleipner project [1]. The heterogeneity of the reservoir at the Ketzin site is also a challenge for the AVO/AVA analysis.

Our results indicate that an increase in pressure leads to an increase in the AVA gradient, whereas the AVA intercept remains almost unchanged and that an increase in CO_2 saturation leads to a decrease in the AVA intercept and an increase in the AVA gradient (Fig. 4). The results show it is theoretically possible to discriminate between the CO_2-saturation-related changes at high CO_2 saturations and pore-pressure-related changes. However, the modeled changes in the AVA gradient are rather small and therefore unlikely to be retrievable from the field data [4] with a signal/noise ratio of 2-3. In addition, the actual seismic response is probably due to a combination of saturation and pore pressure effects, which is a further complication for any true discrimination.

If the CO_2 saturation effect dominates the response, then the cross-plots of the modeled AVA gradient and intercept (Fig. 4) can be potentially used to determine CO_2 saturation levels in the reservoir at the Ketzin site on the real seismic data (the AVA intercept and gradient). Results from PNG logging show quite significant changes in the CO_2 saturation with time at the three wells. Given that a 2nd repeat 3D seismic survey was acquired in autumn 2012 [17] with nearly 3 times the amount of CO_2 having been injected at the time of the survey, it would be useful to attempt to monitor changes in the AVA/AVO response between the 2nd repeat and the baseline. It is more likely that real changes can be detected between the 2nd repeat and the baseline than between the 1st repeat and the baseline.

6. Conclusions

By integrating seismic modeling of the AVO/AVA response of a thin layer and petrophysical experiments on core samples from the Ketzin reservoir we estimated the effect of the CO_2 injection at the Ketzin site on the AVO/AVA response on the acquired 4D seismic data. Two effects were considered: the CO_2-saturation- and the pore-pressure-related effects. Our results indicate that it is rather unlikely that we can discriminate between these effects in the real seismic data when comparing the 1st repeat survey with the baseline given the known signal/noise ratios. However, it is worth investigating if it is possible to discriminate the effects through a study of the AVO/AVA response of the 2nd repeat 3D survey compared to the baseline. In the latter case the CO_2 saturations levels are expected to be significantly higher in the area around the injection well.

Table 2. The AVA gradient (G) and intercept (R_0) modeled for the 4D seismic data from Ketzin [4] using the method of C. Juhlin and R. Young [8].

	Baseline: CO_2 saturation – 0% Pore pressure – 6 MPa	Repeat: CO_2 saturation related change (30%)	Repeat: Pore pressure related change (7.5 MPa)
AVA Gradient (G)	0.048	0.0572	0.0577
AVA Intercept (R_0)	-0.118	-0.171	-0.119

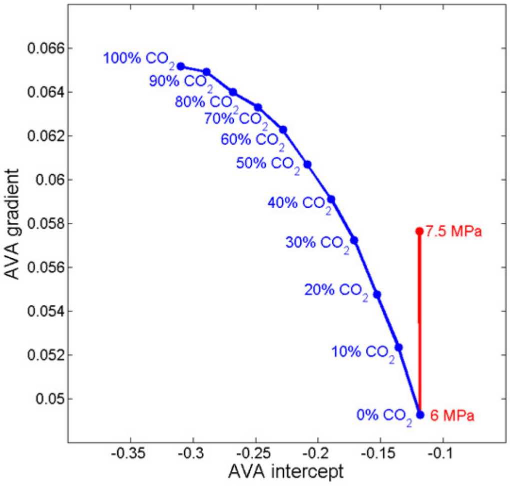

Fig. 4. The AVA gradient versus the AVA intercept corresponding to changes in CO_2 saturation (the blue line) and pore pressure (the red line) using results of modeling with the method of C. Juhlin and R. Young [8].

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