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Time-lapse seismic surface and down-hole measurements for monitoring CO₂ storage in the CO₂SINK project (Ketzin, Germany)

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Abstract

Ketzin is an European pilot site for onshore CO₂ storage in a saline aquifer. Injection started in summer 2008 and to date, more than 37.000 tons of CO₂ have been injected into the Stuttgart Formation at approximately 650 m depth. A wide range of monitoring methods are being applied at Ketzin, among which are active seismic observations at various scales. 3D reflection seismic, combined surface-downhole measurements and crosshole tomographic surveys were performed before injection and after the start of injection in order to image the reservoir and to track the CO₂. Time-lapse signatures of the injected CO₂ were observed by all active seismic methods. The CO₂ could be detected by increased reflectivity at the top of the injection reservoir, by a change in the attenuation behaviour and also by reduced propagation velocity within the reservoir. The ongoing injection of CO₂ during the next years will be followed by further repeat surveys. Current investigations focus on the still difficult problem of the quantification of the CO₂ imaged by the geophysical measurements.

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1. Introduction

At Ketzin, close to Berlin (Germany), the first European onshore CO₂ storage site started injection in June 2008 [1]. From June 2008 through August 2010, approximately 37.000 tons of food grade CO₂ have been injected into the storage reservoir, a saline sandstone aquifer, formed as an anticlinal structure by salt tectonics, at a depth of approximately 650 m (Figure 1). The rate of the CO₂ injection, the relatively small size of the storage reservoir which is defined by a local anticlinal structure [2], as well as the relatively shallow depth of the injection are not

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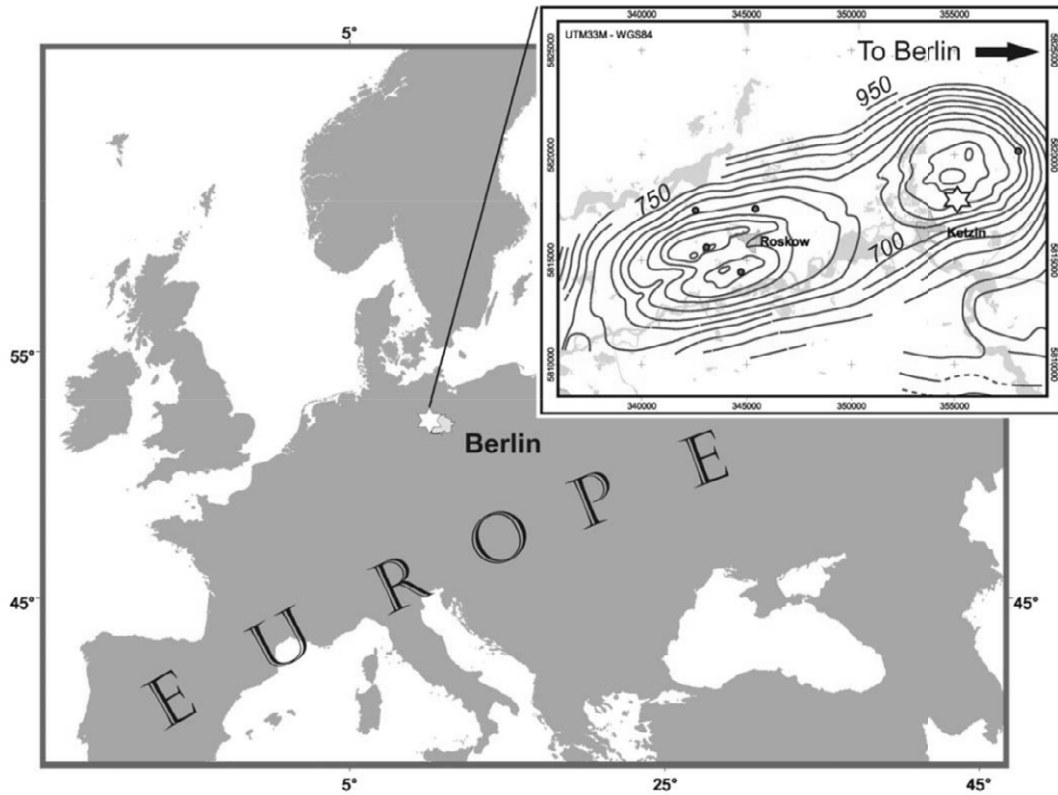


Figure 1: Location map indicating the position of Ketzin (star symbol W of Berlin). The inset shows the depth contour lines of the K2 horizon representing the geometry of the Roskow-Ketzin Anticline. The injection site is located on the southern flank of the Ketzin part of the anticline (star).

typical for industry scale storage sites. However, being a saline aquifer in an onshore environment makes the site an important prototype for future demonstration projects which in many cases will be at sites with comparable properties, but at larger scale. The main objective of the Ketzin site is to provide a field laboratory to test in a multi-disciplinary way different monitoring technologies. To this end, a wide range of geophysical, geochemical, and microbial monitoring methods have been and are being applied at Ketzin in order to track the CO₂ in the underground [3]. In this contribution, we give an overview of the seismic monitoring programme which had been established on the site from the beginning of injection. This programme consists of surface seismic measurements, surface-downhole, and crosshole observations which were initiated before the injection and were repeated after the start of injection.

2. Surface monitoring

For a detailed description of the geometry of the reservoir and its overburden, and as a baseline for later surveys in order to image the distribution of the CO₂ in the underground, a 3D seismic survey was acquired in Autumn 2005 [4]. The baseline survey provided a clear image of the geological layers in the depth range 100 m - 1000 m (the interpreted surfaces of these are shown in Figure 2), however, the internal structure of the reservoir, which is expected to be highly heterogeneous according to its origin as a intercalation of fluvial sandy channels and muddy flood-plain facies rocks of poor reservoir quality, could not be resolved directly. In the northern part of the survey area, approximately 1.5 km from the injection well, a fault-and-graben system was imaged which had not been

detected by old 2D vintage data, but which had been inferred from well and production data gathered during the

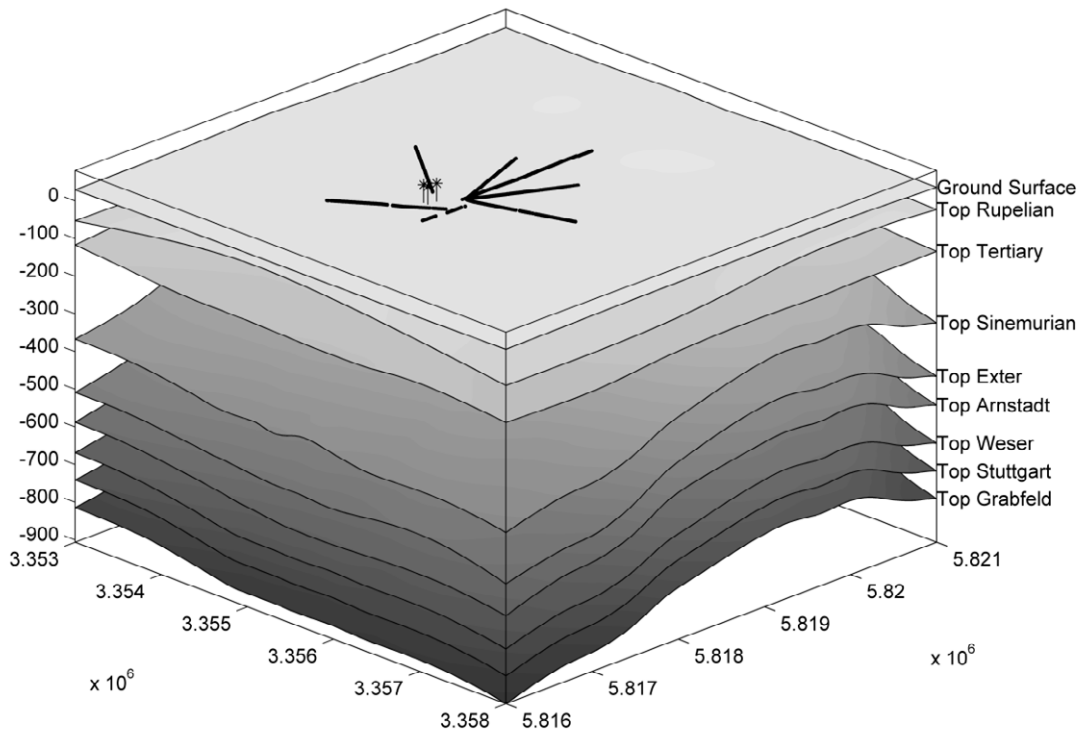


Figure 2: Structural interpretation of the 3D baseline showing the Ketzin anticline and the most important layer boundaries. The injection takes place within the Stuttgart Formation. Black lines on the ground surface indicate the position of 2D seismic lines acquired around the injection site which is located in the centre of the seismic lines.

operational phase of a former natural gas storage facility operating at Ketzin until 2004.

A combined geoelectric and seismic modelling study [5] has shown that, based on the available structural models, petrophysical properties and fluid flow simulations, a clear time-lapse signature of the CO₂ propagation in the underground was to be expected. Modelling of a surface seismic survey, albeit under ideal conditions, indicated a detection limit of CO₂ layers within the reservoir in the order of 2 m. Combined petrophysical and seismic modelling [6] of CO₂ injection at the Ketzin site shows that once injected, the CO₂ migrates away from the injection well in gaseous state which will even enhance the time-lapse amplitude due to changed impedance contrast at the top of the reservoir. The results of the modelling studies provide a valuable basis for the interpretation of the first comprehensive seismic time-lapse data which were acquired at the Ketzin site in Autumn 2009. The surface repeat survey consisted of the repeated acquisition of 2D seismic reflection data along seven radial profiles around the injection site and of the first repeat of the 3D survey, focusing on an area covering about 50 % of the baseline survey [7].

A repeat of the full 3D baseline survey was not considered as fluid flow simulations indicated that considering the amount of CO₂ injected, it was not expected to have propagated to the exterior regions covered by the baseline survey. The 3D repeat survey was acquired during six weeks from end of September 2009 until November 2009. Injection was not stopped in that period, such that the amount of CO₂ in the reservoir increased from about 22.000 tons to about 25.000 tons during the seismic survey.

The most critical task for onshore time lapse seismic surveying is to perform the surveys under reproducible conditions. Aspects to be considered are the acquisition geometry which should be reproduced within a small range, comparable equipment in order to avoid differences caused by varying geophone characteristics or internal filters of acquisition units, reproducible seismic source characteristics, and reproducible surface and near surface underground conditions. Whereas the former three aspects can be assured by proper planning and accurate operation in the field, there is usually little control on the surface and near surface underground conditions which are subject to seasonal changes of, e.g., the groundwater table or moisture content in the vadose zone. It is a common practice to perform repeated onshore surveys in the same season, e.g. shortly after the harvesting season in early Autumn. However, the 2009 repeat survey at Ketzin showed that this practice does not guarantee identical weather and ground conditions.

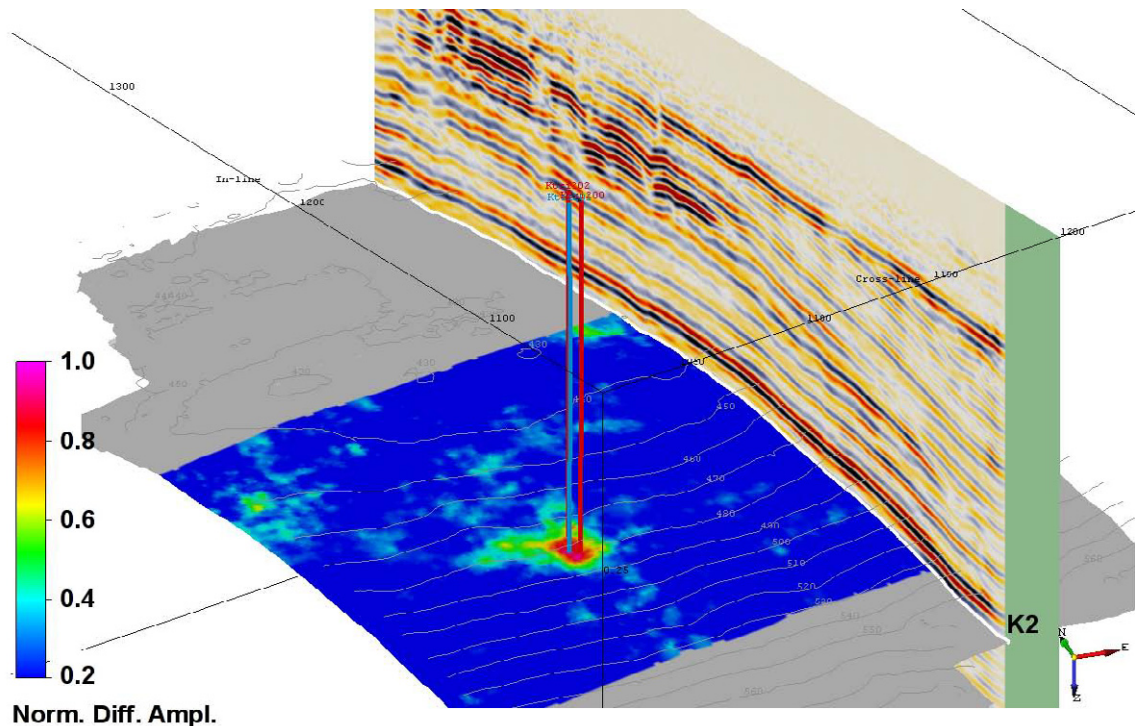


Figure 3: 3D map of the normalized time-lapse amplitude at the top of the CO₂ injection layer. The time-lapse amplitude (color coded) is projected onto the topography of the top of the reservoir. As a reference horizon, the K2 reflection is used. This horizon is marked in the seismic section. The injection well (CO₂ Ktzi 201/2007) is indicated by a blue vertical line. Two red lines indicate the observation wells (CO₂ Ktzi 200/2007 and CO₂ Ktzi 202/2007).

A comparison of the 3D seismic baseline and the repeat data showed considerable near surface velocity variations which are most likely due to completely different weather conditions (dry weather in 2005, heavy rainfall during almost the complete campaign in 2009). This was accounted for by a new processing for static corrections, and the changed frequency content of the repeat data was accounted for by a re-processing of the baseline data. The time lapse effect of CO₂ injection in the storage reservoir was estimated by the following analysis:

A reference horizon (the so-called K2 reflector) was defined. The reflection amplitudes of this horizon, which represents an anhydritic layer at the top of the cap rock formation, are expected to remain constant for the baseline and the repeat surveys. The amplitudes of this horizon were picked for both data sets (baseline and repeat time migrated 3D volumes) and used for scaling the repeat data. Then, the amplitudes were picked for a horizon 42 ms below the K2 horizon which corresponds to the top of the Stuttgart Formation. The amplitudes of the repeat survey were subtracted from those of the baseline survey and then scaled by the maximum value. The result of this analysis is displayed in Figure 3. There is a significant concentration of positive time-lapse amplitudes close to the injection

well, with a decreasing trend moving away from the injection well. Therefore, we interpret this time-lapse amplitude anomaly being due to the concentration of CO₂ in the Stuttgart Formation. The distribution of CO₂ is obviously not rotationally symmetric indicating an anisotropic propagation in a laterally heterogeneous reservoir.

3. Surface-downhole monitoring

Performing 3D seismic surveys from the surface in populated or farmland areas is logistically demanding and can also potentially affect the public acceptance of storage operations in the underground. Therefore, it is desirable to reduce the need for 3D surveys while maintaining an acceptable degree of spatial coverage and resolution at the reservoir level. In addition, mere surface measurements often lack resolution at reservoir depth, especially for deep and thin structures. Here, combined surface-downhole and downhole measurements provide a valuable extension of the surface monitoring.

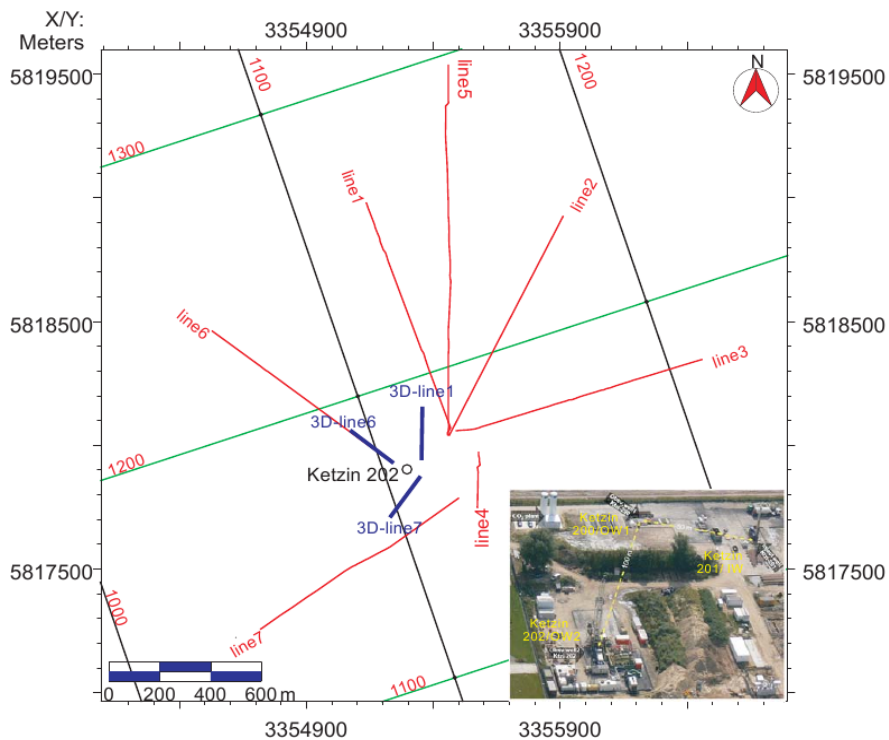


Figure 4: Location map of the combined surface-downhole monitoring program. Red lines indicate 2D reflection profiles and source lines for walk-away VSP (or MSP - Moving Source Profiling) surveys. Blue lines show the locations of the CDP lines that were extracted from the 3D volume to be compared with the MSP images [8].

VSP (Vertical Seismic Profiling) and MSP (Moving Source Profiling, or walk-away VSP) consist in shot-point locations on the surface, close to the observation well, and the acquisition of seismic waves using receivers (geophones or hydrophones) in a well. VSP uses a small receiver point interval and a high number of receiver positions while keeping the number of shotpoint positions at the surface to a minimum. MSP uses a high number of shotpoint positions along surface profiles and the acquisition uses a small number of receiver points in the observation well. In Figure 5, MSP migrated images for three lines (see Figure 4) are compared to the 3D data, showing the different characteristics of these observations. While the 3D data provide full spatial coverage at a large scale around the reservoir and for a large depth scale, the MSP image focus at higher resolution onto the reservoir.

Whereas the baseline 3D data did not image the reservoir layer, the MSP migrated images show coherent reflections from the top and bottom of the Stuttgart Formation, allowing for a more detailed characterization of the reservoir close to the observation well.

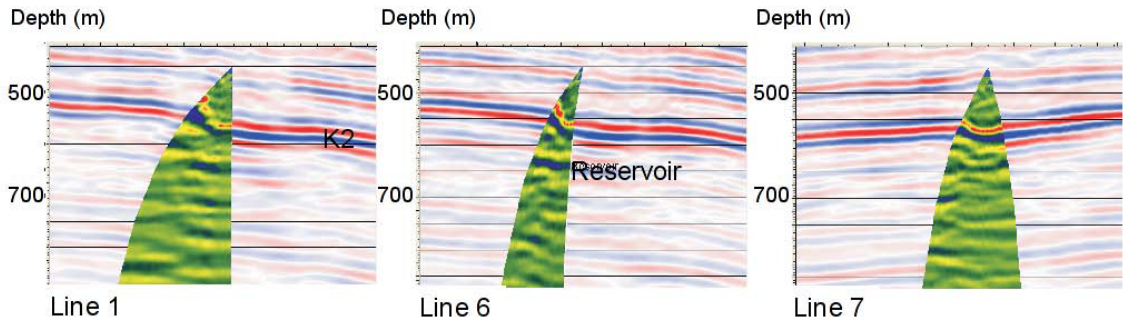


Figure 5: Comparison of the MSP migrated images with CDP lines from the 3D volume that have been extracted so that they approximately cover the same sub-surface points. The temporal and spatial resolution of the MSP images is significantly higher. Signs of a reflection from the uppermost sandy layer in the Stuttgart Formation are seen, especially on MSP line 6. Note that the slices from the 3D are true planes, but that the MSP data images are projections on to these planes [8].

4. Crosshole tomography

Crosshole tomographic surveys were performed between the two observation wells CO₂ Ktzi 200/2007 and CO₂ Ktzi 202/2007. The baseline survey and two first repeats were acquired in Spring and Summer 2008, a third repeat took place in Summer 2009. The crosshole surveys were performed after the injection of 0, 630, 1.750, and approximately 19.000 tons of CO₂, respectively. Figure 6 shows the acquisition geometry and demonstrates that, as the crosshole surveys are performed between the observation wells CO₂ Ktzi 200/2007 and CO₂ Ktzi 202/2007, a time-lapse signature of CO₂ propagation in the reservoir can only be observed after the CO₂ has reached the observation well closer to the injection (CO₂ Ktzi 200/2007). The first two repeat surveys were carried out within about six weeks after the CO₂ reached the first observation well. The time-lapse observations at this early stage of injection did not show any significant traveltime changes due to CO₂ saturation in the Stuttgart Formation (Figure 6). A time-lapse signature could be identified in the data by a more sensitive estimate of the change in seismic response consisting in a multiplication of the cross-correlation of corresponding baseline and repeat records with the logarithm of their amplitude ratios, in a 20 ms window after the picked P-wave times (Figure 7). The tomographic projection of amplitude variations between baseline and repeat surveys is concentrated to the vicinity of observation well CO₂ Ktzi 200/2007. Obviously, at the time of these crosshole repeat surveys, the amount of CO₂ between the two observation wells was sufficient to slightly affect the amplitudes of transmitted seismic waves (change in attenuation) but it was not sufficient to significantly affect the average propagation velocities between the observation wells.

5. Conclusions and outlook

A wide range of active seismic measurements have been performed in order to image the CO₂ injection reservoir at Ketzin and to track the CO₂ propagating in the reservoir. The first repeat of the 3D surface seismic measurements has shown that the CO₂ in the reservoir can be detected and amplitude variations in the depth range of the top of the reservoir indicate the shape of the current CO₂-plume. Current investigations focus on stabilizing the imaging results and on a quantification of the amount of CO₂ imaged by the 3D data, which is a difficult task due to the small amount of CO₂ used and the thin layers forming the storage reservoir. Seismic surface downhole and crosshole

tomographic surveys were performed additionally which, as well, showed a signature of the injected CO₂ at smaller scales close to the injection well and proved to provide high resolution imaging potential. Due to their limited spatial coverage, they will not completely replace 3D surveys but they are important for a high resolution observation close to the injection, especially in the initial phase of a storage project.

The injection of CO₂ is intended to continue for the next approximately two or three years and further repeat surveys of the seismic measurements are foreseen. Additionally, combined active and passive seismic observations have been initiated during the injection phase and will continue to be performed during the ongoing injection (e.g. Arts et al., this volume [9]). Thus, the wide range of different technological solutions tested for monitoring at the Ketzin CO₂ injection site will be a valuable basis for further large scale projects.

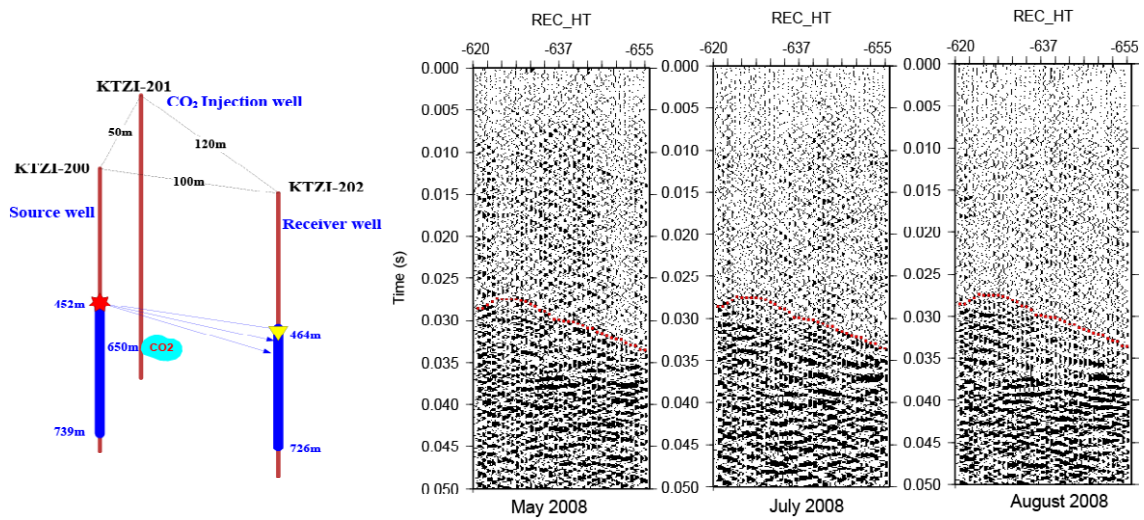


Figure 6: Sketch of acquisition geometry (left) and data examples from the baseline, first and second repeat crosshole surveys (right).

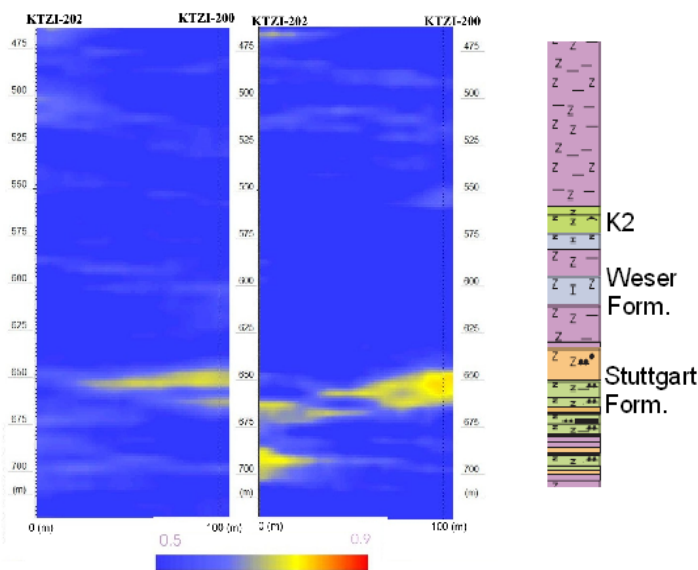


Figure 7: Covariance tomographic reconstruction of the differences between baseline and first repeat line (left), difference between baseline and second repeat line (right). CO₂ Ktzi 202/2007 borehole is to the left and the CO₂ Ktzi 200/2007 borehole is to the right. A part of the lithological description of well CO₂ Ktzi 200/2007 is shown on the right (Förster et al., 2009). K2: Gypsum, anhydrite; Weser Formation: mudstone, clay; Stuttgart Formation: sand- and mudstone intercalations.

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