Environ Earth Sci (2012) 67:323–334
DOI 10.1007/s12665-012-1672-5

SPECIAL ISSUE

Europe's longest-operating on-shore CO_2 storage site at Ketzin, Germany: a progress report after three years of injection

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Received: 30 November 2011 / Accepted: 2 April 2012 / Published online: 25 April 2012

Abstract The Ketzin pilot site, led by the GFZ German Research Centre for Geosciences, is Europe's longest-operating on-shore CO_2 storage site with the aim of increasing the understanding of geological storage of CO_2 in saline aquifers. Located near Berlin, the Ketzin pilot site is an in situ laboratory for CO_2 storage in an anticlinal structure in the Northeast German Basin. Starting research within the framework of the EU project CO_2SINK in 2004, Ketzin is Germany's first CO_2 storage site and fully in use since the injection began in June 2008. After 39 months of operation, about 53,000 tonnes of CO_2 have been stored in 630–650 m deep sandstone units of the Upper Triassic Stuttgart Formation. An extensive monitoring program integrates geological, geophysical and geochemical investigations at Ketzin for a comprehensive characterization of the reservoir and the CO_2 migration at various scales. Integrating a unique field and laboratory data set, both static geological modeling and dynamic simulations are regularly updated. The Ketzin project successfully demonstrates CO_2 storage in a saline aquifer on a research scale. The results of monitoring and modeling can be summarized as follows: (1) Since the start of the CO_2 injection in June 2008, the operation has been running reliably and safely. (2) Downhole pressure data prove correlation between the injection rate and the reservoir pressure and indicates the presence of an overall dynamic equilibrium within the reservoir. (3) The extensive geochemical and geophysical monitoring program is capable of detecting CO_2 on different scales and gives no indication for any leakage. (4) Numerical simulations (history matching) are in good agreement with the monitoring results.

Keywords Ketzin · Carbon dioxide storage · Saline aquifer · CO_2 injection · Monitoring · Modeling

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Introduction

The research activities at the pilot site Ketzin have received funding from 15 German and European projects so far. The major ones are **CO_2 S**torage by **I**njection into a **N**atural Saline Aquifer at **K**etzin (CO_2SINK) (2004–2010) and **CO_2** Reservoir **Man**agement (CO_2MAN) (2010–2013). The Ketzin activities began in 2004 with research and development on CO_2 storage in a saline aquifer within the project CO_2SINK, funded by the European Commission. CO_2SINK with its consortium of 18 partners from research institutes, universities and industry from nine European countries continued to March 2010. Together with further nationally funded projects, CO_2SINK covered the preparatory work prior to the CO_2 injection, baseline surveys and characterization (Förster et al. 2006), drilling and instrumentation of three wells (Prevedel et al. 2009), set-up of the injection facility and a multidisciplinary monitoring concept (Giese et al. 2009). The CO_2 injection finally began within the framework of the CO_2SINK project on June 30, 2008.

Following CO_2SINK, recent research and development activities such as further CO_2 injection and well construction, complementary monitoring, laboratory studies, modeling and public outreach are funded by the national project CO_2MAN. CO_2MAN is coordinated by the GFZ German Research Centre for Geosciences and comprises a consortium of 13 partners. Research activities are complemented by the European project CO_2CARE (CO_2 Site Closure Assessment Research) with 23 global partners (2011–2013). Within CO_2CARE, Ketzin is one site in a portfolio of nine storage sites worldwide (e.g. Sleipner/Norway, Otway/Australia), most of them in operation for years now, with some of them close to or within the abandonment phase.

Preparatory work prior to the CO_2 injection at the Ketzin pilot site was described by Schilling et al. (2009). Förster et al. (2006) summarize the first results of the baseline measurements, including geology, seismic, reservoir modeling, laboratory experiments on rock samples, and geochemical monitoring. Key results and experiences from the first and second year of operation were described by Würdemann et al. (2010) and Martens et al. (2011), respectively. The present paper summarizes the progress after three years of injection.

Site setting and injection operation

Geographical and geological setting

The Ketzin pilot site is located about 25 km west of Berlin within the Federal State of Brandenburg, Germany (Fig. 1). The Ketzin anticline is well explored by a number of boreholes as natural gas was seasonally stored in Lower Jurassic strata at about 280 m depth since the 1960s up to 2004 when the operation was abandoned due to economical reasons. Based on the existing data and results from further site characterization (Förster et al. 2006), three wells were drilled in 2007 to depths of 750–800 m for CO_2 injection and monitoring (Prevedel et al. 2009).

The target saline aquifer for CO_2 storage is the lithologically heterogeneous Stuttgart Formation of Triassic Age (Middle Keuper) at about 630–710 m depth (Fig. 1) that was deposited in a fluvial environment. The Stuttgart Formation consists of sandstones and siltstones interbedded with mudstones. In the lower and middle part of the Stuttgart Formation sandstones layers are typically thin (dm- to m-thick) and interpreted as flood plain facies whereas the main sandstone units (9–20 m thick) in the upper part are typical channel facies (Förster et al. 2010).

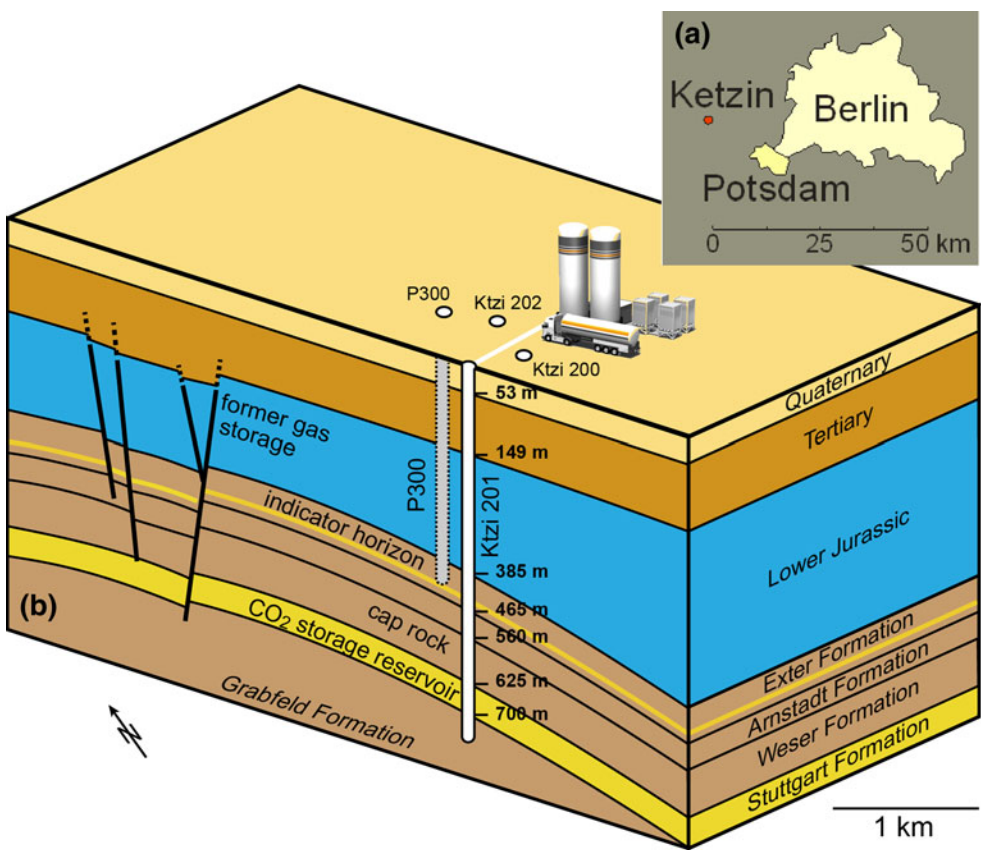


Fig. 1 **a** Location of the Ketzin pilot site, **b** schematic block diagram of the Ketzin anticline showing the principal structural and stratigraphic features. Target reservoir horizon for CO_2 injection is the Upper Triassic Stuttgart Formation. Position of wells only schematic and not to scale, well P300 only schematic to visualize different depth compared to wells Ktzi 200, 201 and 202. Block diagram is vertically exaggerated (modified after Liebscher et al. 2012)

These channel facies sandstones in about 630–650 m depth are the primary target reservoir for CO_2 storage at the Ketzin pilot site. The overlying first caprock is represented by mudstones and anhydrites of the Weser and Arnstadt Formations with a cumulative thickness of about 165 m. The overburden of this system comprises sedimentary rocks of the Exter Formation (Keuper) and Jurassic strata overlain by Tertiary and Quaternary deposits (Fig. 1).

One well (CO2 Ktzi 201/2007, abbreviated as Ktzi 201), out of the three which were drilled in 2007, serves as an injection and observation well, while the other two (CO2 Ktzi 200/2007 and CO2 Ktzi 202/2007, abbreviated as Ktzi 200 and Ktzi 202, respectively) are solely used for observing the injection and migration of the CO_2 (Fig. 2). Those three wells form the corners of a right-angled triangle and are completed as "smart" wells with permanent downhole sensors and cables cemented behind casing for borehole and reservoir monitoring (Prevedel et al. 2009). In order to complement the Ketzin infrastructure with a focus on above-zone monitoring, one comparably shallow groundwater observation well (Hy Ktzi P300/2011; abbreviated as P300) was drilled and completed from June to August 2011. This 446 m deep well reaches into the lowermost sandstone of the first aquifer (Exter Formation) that lies directly above the first massive caprock of the Stuttgart Formation. 40.9 m of the Exter Formation were cored and the well P300 was equipped with a U-tube fluid sampling system and high resolution pressure gauges for periodic fluid sampling and pressure monitoring. The entire drilling and completion campaign of well P300 was completed on August 24, 2011 after 65 drilling days. Core analysis, laboratory experiments and planning for hydraulic testing are currently underway.

CO_2 injection

As a pilot site, the Ketzin project with its focus on a multidisciplinary monitoring is considerably smaller in terms of the injected CO_2 mass compared to industrial scale projects. As a research and development project the maximum amount of stored CO_2 is limited by legal regulations to <100,000 tonnes.

Liquid CO_2 is delivered by road tankers to Ketzin. Since the start of the CO_2 injection on June 30, 2008, the injection facility has been operating safely and reliably. By the end of September 2011, approximately 53,000 tonnes of CO_2 had been injected via the well Ktzi 201 (Fig. 3). The injection facility at Ketzin is designed to allow for injection rates ranging from 0 to 78 tonnes per day. The average injection rate since the start is ~1,350 tonnes CO_2 per month (45 tonnes per day).

Two kinds of CO_2 have been injected: the primary source is food grade CO_2 (purity >99.9 %) that occurs as a by-product of hydrogen production, delivered by Linde AG. Up to the end of September 2011, a total amount of 51,500 tonnes of food grade CO_2 had been injected. Furthermore, 1,515 tonnes CO_2 (purity >99.7 %) from the oxyfuel pilot plant Schwarze Pumpe (Vattenfall) were injected within a trial period from May 4, 2011 to June 13, 2011. The experiment with CO_2 from Schwarze Pumpe was the first one worldwide where technical CO_2 captured at a power plant was injected. Gaseous tracers were added

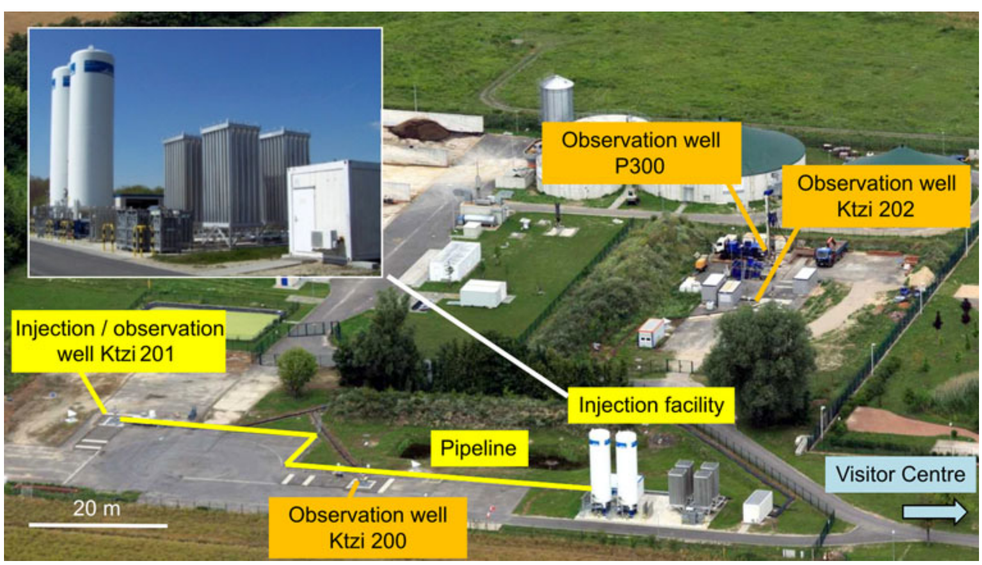


Fig. 2 An aerial view of the Ketzin pilot site displaying the injection facility with two storage tanks and ambient air heaters, pipeline to the injection well (Ktzi 201) and the observation wells (Ktzi 200, Ktzi 202, P300). Drilling rig is located on observation well P300 (July 2011)

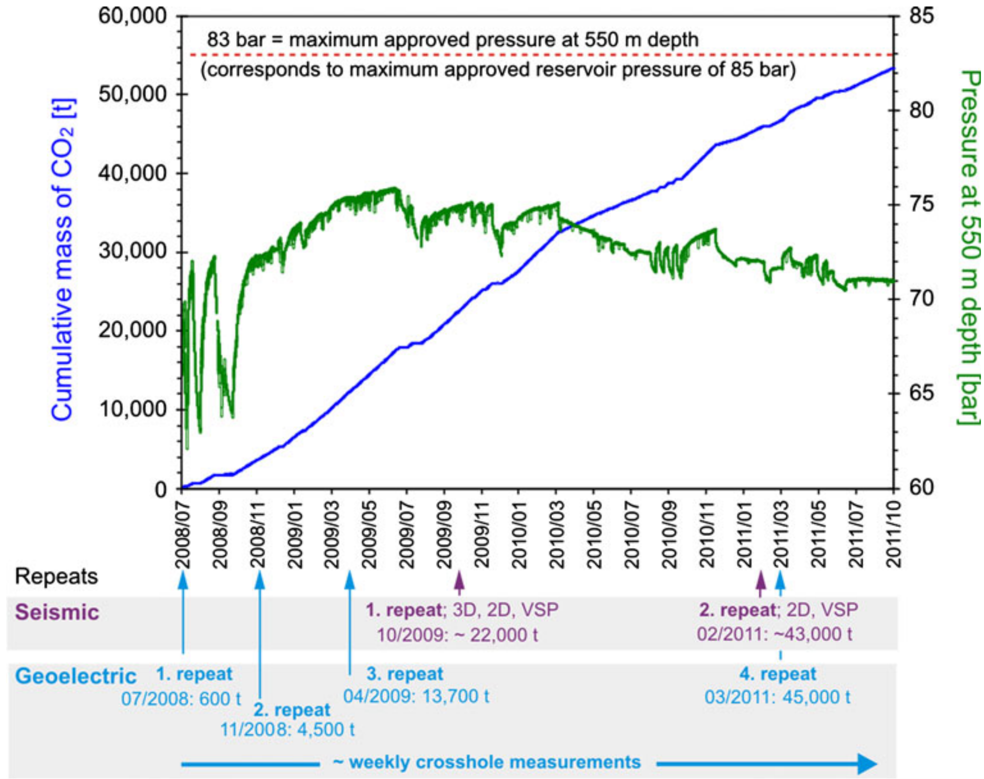


Fig. 3 Evolution of downhole pressure at 550 m depth (well Ktzi 201) and cumulative mass of injected CO_2. Lower part shows timing of accompanying seismic and geoelectric repeat surveys. Seismic baseline surveys were conducted in 2005 (2D/3D) and 2007 (VSP). Geoelectric baseline surveys were carried out in October 2007 (surface-downhole/1. baseline), in April 2008 (surface-downhole/2. baseline) and on June 21, 2008 (crosshole)

directly before and after the CO_2 batch from Schwarze Pumpe in order to better track CO_2 migration (see "Borehole monitoring").

The evolution of the injection pressure conditions is continuously monitored by pressure sensors at the wellhead and within the injection well Ktzi 201. For technical reasons, the within-well sensor is installed at a depth of 550 m directly above the end of the injection tubing. Measured pressure at this depth is extrapolated to the injection depth of 630 m with the commercially available software ASPEN Plus applying a Peng–Robinson equation of state. Numerical wellbore simulations show that only the weight column of the CO_2 contributes to this pressure extrapolation. For the prevailing in-well pressure–temperature and, thus, CO_2 density conditions this weight column transforms into an additional pressure of 2 bar that has to be added to the measured pressure at 550 m depth. This calculated 2 bar value is also consistent with the observed injection wellhead pressure of about 60 bar. With a mean downhole pressure of about 74 bar at 550 m depth (see below) the overall pressure gradient within the injection tubing is about 2.1 bar/80 m. Fig. 3 depicts the results of the downhole pressure monitoring with the increasing amount of CO_2 injected and the timing of the accompanying geophysical surveys (see "Geophysical monitoring"). After the start of injection on June 30, 2008, pressure increased from initially 60.4 bar to a maximum of 76 bar in June 2009. From late summer 2009 until spring 2010 pressure has stabilized between ~74 and 76 bar. By spring 2010, the overall mean injection rate was lowered (see change in overall slope of cumulative mass curve by March 2010 in Fig. 3) and pressure smoothly decreased and again stabilizes between ~71 and 72 bar. This positive correlation between injection rate and reservoir pressure is also shown on the short term for shut-in phases, which are generally accompanied by an almost instantaneous decrease in reservoir pressure.

Maximum reservoir pressure as defined in the approved licensing documents for the Mining Authority (LBGR-Landesamt für Bergbau, Geologie und Rohstoffe/State Office for Mining, Geology and Natural Resources Brandenburg) is 85 bar at 630 m depth, which transforms into 83 bar at 550 m depth, i.e. installation depth of the pressure sensor. Monitoring shows that within 39 months of operation, the downhole pressure has always been significantly below the maximum approved pressure.

Monitoring

The interdisciplinary monitoring concept at the Ketzin pilot site is one of the most comprehensive programs worldwide applied to geological storage of CO_2 and integrates different geophysical, geochemical and microbial methods with different objectives and timely and spatial resolution (Giese et al. 2009). Permanent monitoring techniques are applied and repeat surveys are conducted for a comprehensive characterization of the reservoir processes and joint interpretations.

In this contribution, we focus on the seismic and geoelectric methods, wire-line pressure–temperature monitoring in the wells and the gas geochemical monitoring. For further details on microbiological and additional wellbore monitoring the reader is kindly referred to Freifeld et al. (2009), Morozova et al. (2010, 2011), Henninges et al. (2011) and Liebscher et al. (2012).

Geophysical monitoring

Seismic monitoring

Surface and surface-downhole seismic measurements are applied to test and optimize the resolution of different methods and to visualize the CO_2 plume. The seismic monitoring is spearheaded by time-lapse 3D surveys, carried out in 2005 (baseline) and 2009 (first repeat) as denoted in Fig. 3. The CO_2 signature could be detected by an increased reflectivity at the top of the target reservoir, by a change in the attenuation behavior and by a reduced propagation velocity within the reservoir (Lüth et al. 2011). After about 15 months of injection (~22,000 tonnes), the CO_2 plume was concentrated around the injection well Ktzi 201 with a lateral extent of approximately 300–400 m and a thickness of about 5–20 m.

Quantifying the CO_2 imaged by the 3D seismic data is still challenging due to the relatively small CO_2 amount, the heterogeneous reservoir and the limited information on CO_2 saturation. Based on the integration of borehole measurements (Pulsed Neutron Gamma Logging), petrophysical lab experiments and core analyses, a quantitative analysis of the CO_2 contained in the area of the seismic time-lapse amplitude anomaly was performed. The mass distribution of the imaged CO_2 can be compared to the history-matched reservoir simulations (see "Dynamic modeling") indicating a general consistency of the simulation with the monitoring results and qualitatively showing the existence of a detection threshold for the seismic monitoring which is not imaging the more distant parts of the CO_2 plume away from the injection point. A more detailed analysis of the detection threshold is currently underway.

An analysis of the variations of seismic amplitudes from the reservoir with the source-receiver offset (AVO-amplitude versus offset) enables a direct quantitative petrophysical interpretation of seismic time-lapse data. The AVO analysis results in a quantification of the zero-offset reflection coefficient of a given reflector, and, using petrophysical models, this can be converted, in time-lapse mode, to the saturation of CO_2 at the respective location (Ivanova et al. 2011; Yang et al. 2011; see Fig. 4). The AVO analysis revealed qualitatively a lower CO_2 saturation at the distant monitoring well Ktzi 202 than at the injection well Ktzi 201, with some uncertainties concerning the actual saturation but being consistent with borehole logging results and reservoir simulations.

Alternatives to the high logistical and financial efforts of frequent 3D time-lapse surveys are of particular interest for the long-term monitoring of a storage reservoir. At Ketzin,

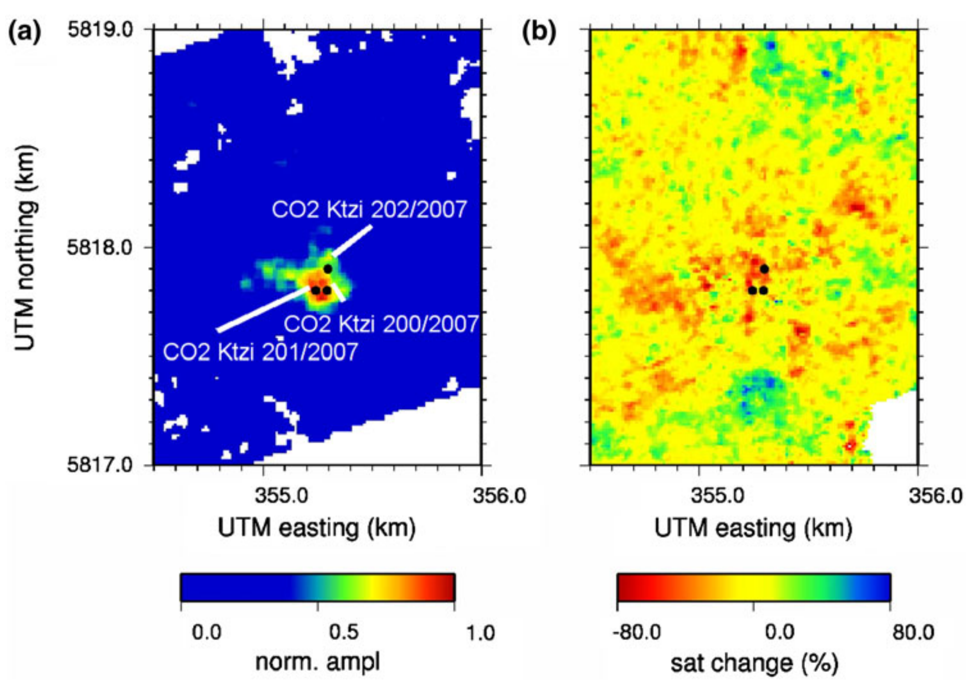


Fig. 4 Results from seismic monitoring at the Ketzin pilot site. **a** Normalized time-lapse amplitude variations for the baseline (2005) and first repeat survey (2009) indicating the lateral extent of the CO_2 plume after injecting approximately 22,000 tonnes. For reference, the positions of the injection well Ktzi 201 and the monitoring wells Ktzi 200 and 202 are indicated. **b** Change in water saturation for the Stuttgart formation, derived from AVO-analysis of the 4D seismic data. A negative change in water saturation correlates with CO_2 replacing brine in the Stuttgart formation. The results are still preliminary, showing strong scatter and artifacts at locations where no CO_2 has been detected by amplitude variations

the 3D surveys are therefore complemented by pseudo 3D surveys with an acquisition geometry restricted to profiles oriented in a star-like manner around the injection site. The second repeat survey of this type of pseudo 3D surveys was acquired in February 2011. Although the 3D subsurface coverage was extremely heterogeneous, it was possible to detect a CO_2 related signature at the depth level of the Stuttgart Formation in the second repeat survey data. This showed a larger lateral extent than the first repeat survey, acquired in September 2009. However, the imaged plume extent image by the pseudo 3D survey was considerably smaller than the one imaged by the first full 3D repeat, acquired in autumn 2009, indicating that at the given site conditions of Ketzin, alternative pseudo 3D surveys are only able to detect the CO_2 where a sufficiently high subsurface coverage is achieved.

Geoelectric monitoring

Since completion of the three Ketzin wells Ktzi 200, Ktzi 201 and Ktzi 202 geoelectrical surveys on different temporal and spatial scales have been conducted in order to monitor the CO_2 migration in the target reservoir. The specific geoelectrical concept combines surface and downhole measurements by deployment of the permanent vertical electrical resistivity array (VERA) installed in the three wells Ktzi 200, Ktzi 201 and Ktzi 202 (Kiessling et al. 2010). The VERA system comprises 15 steel electrodes with a spacing of about 10 m that have been installed in each of three wells at depths between ~590 m and 750 m. For surface to downhole measurements 16 surface dipoles with dipole length of 150 m are placed on two concentric circles around the injection well with radii of 800 m and 1500 m, respectively, and combined with potential dipoles in all three wells from the VERA system (Kiessling et al. 2010).

Comprehensive field datasets were acquired and evaluated according to the electrical resistivity tomography (ERT) method. The large-scale surface-downhole surveys were carried out in 10/2007 and 04/2008 (baseline measurements) as well as in 07/2008, 11/2008, 04/2009 and 03/2011 (repeat measurements) as denoted in Fig. 3. The crosshole measurements, which cover the near-wellbore area have been carried out on an almost weekly basis until to date. The ERT is shown to be sensitive to resistivity changes caused by the migration of the CO_2 within the originally brine-filled reservoir (Schmidt-Hattenberger et al. 2011).

In Fig. 5 we observe a relatively stable CO_2 signature over time in the near wellbore area, which indicates that the actual CO_2 plume expansion occurs outside the imaging plane of the VERA system. For further evaluation of additional saturation related effects combined investigations with fluid-flow modeling are foreseen for the near future.

Due to infrastructure near the pilot site a considerable level of anthropogenic noise is infiltrated into the gathered

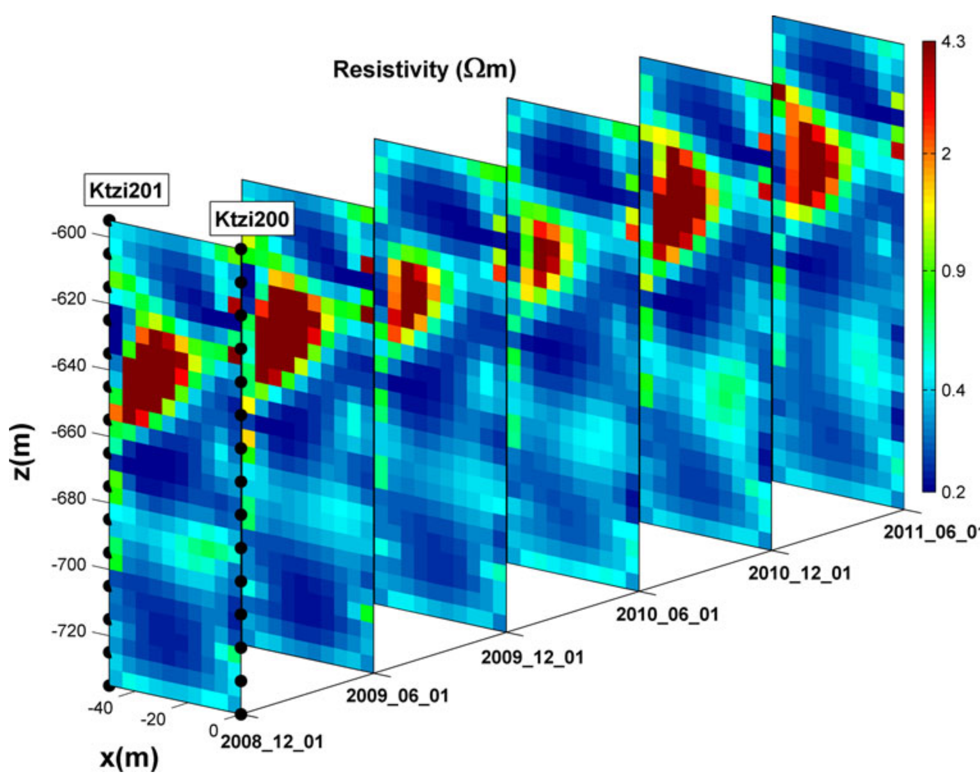


Fig. 5 Results from geoelectric monitoring at the Ketzin pilot site. A time-lapse sequence from field data (December 2008 to June 2011) of the permanently installed vertical electrical resistivity array (electrodes are depicted as *black dots*) shows a significant resistivity increase at the reservoir level (630–650 m) since the beginning of the CO_2 injection in June 2008. Data are shown for the observation plane between wells Ktzi 201 and Ktzi 200

raw data. Therefore, thoroughly data quality assessment and efficient pre-processing routines are prerequisites to establish consolidated datasets of apparent resistivities for the inversion procedure. For the large-scale surface-downhole surveys, a selective stacking approach was applied to the acquired voltage time series. For the cross-hole data, a workflow was developed, which considers the short signal cycles as well as the large number of measured electrode configurations. The procedure is based on merging electrode combinations of the same type, averaging their signals, and finding an appropriate interpolation for the temporal evolution of the resulting apparent resistivities.

In addition, a more detailed evaluation of the pre-inversion data provided important findings as e.g. the influence of well completion onto the permanent electrode array performance, and the increasing degradation process of individual electrodes during the array's life cycle under the present subsurface conditions. A quantitative estimation of CO_2 saturation based on the inverted 2D and 3D resistivity distributions and corresponding petrophysical results is currently underway. This final analysis is an important key feature to develop the ERT surveys towards a meaningful tool within a reservoir-monitoring program.

In general, the results from the Ketzin geoelectrical monitoring concept contribute to the detection of the CO_2 plume extension. The pre-processed and inverted field datasets could clearly indicate a CO_2-related resistivity signature in the reservoir zone.

Borehole monitoring

During March 2011, the wells Ktzi 200, 201 and 202 were again inspected by a comprehensive wellbore logging campaign. Pressure–temperature measurements in the two observation wells Ktzi 200 and 202 confirmed the findings of previous logging campaigns (see Henninges et al. 2011).

Both observation wells are characterized by a complex interplay between different CO_2 fluid states (Fig. 6). Down to about 620 m (Ktzi 200) and 600 m (Ktzi 202), two-phase fluid conditions prevail in both observation wells with coexisting vapour and liquid CO_2. Down to about 413 m (Ktzi 200) and 403 m (Ktzi 202) vapour CO_2 dominates with liquid CO_2 droplets condensing within the well. Below this depth, liquid CO_2 dominates that boils off bubbles of CO_2 vapour. Below the two-phase fluid conditions, single phase CO_2 partly at supercritical pressure and temperature conditions prevails down to the brine table at 643 (Ktzi 200) and 650 m (Ktzi 202). Camera inspections of the observation wells Ktzi 200 and 202 proved the results from the pressure–temperature measurements and gave no hints to any corrosion of the innermost casings.

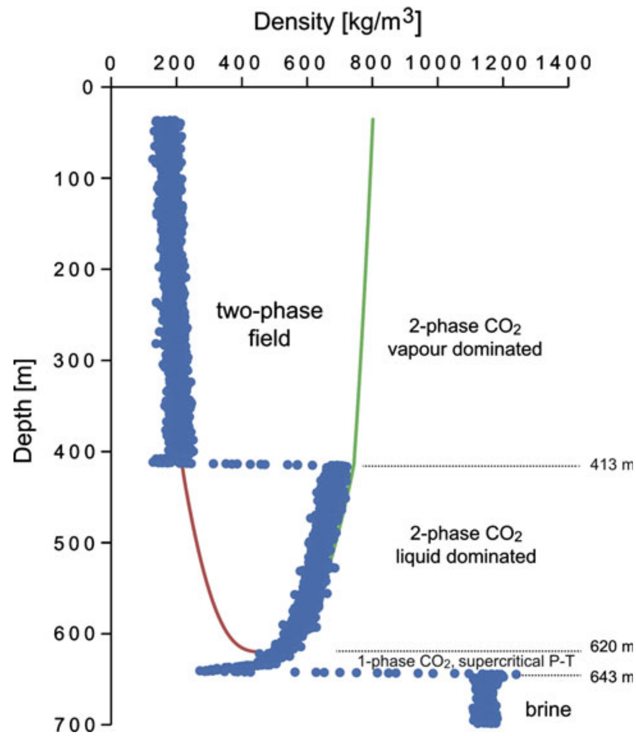


Fig. 6 Density-depth conditions within observation well Ktzi 200 as measured during logging campaign from March 2011. Effective density has been calculated based on measured pressure gradients at each depth and liquid–vapor phase relation has been calculated based on measured temperature and the equation of state from Span and Wagner (1996)

Gas geochemical monitoring

Long-term surface monitoring

A comprehensive surface monitoring network has been established at the Ketzin pilot site since 2005 in order to identify and monitor upward migration of CO_2 with potential leakage to the surface. This network consists of 20 sampling locations for soil CO_2 gas flux, soil moisture, and temperature measurements distributed across a study area of approximately 2 km × 2 km (Zimmer et al. 2011). To gain long-term data on natural background CO_2 flux, its temporal and spatial variations and impacts of potential CO_2 leakage measurements are conducted once a month and already started in 2005.

Since the start of injection in 2008, no change in soil CO_2 gas flux could be detected in comparison to the pre-injection baseline (2005–2007). Mean CO_2 flux as averaged over all sampling locations ranged from 2.4 to 3.5 μmol/m^2 per second for the pre-injection period and from 2.2 to 2.5 μmol/m^2 per second after the start of injection (Zimmer et al. 2011). The spatial variability of soil CO_2 gas flux is 1.0 to 4.5 μmol/m^2 per second among all 20 sampling locations reflecting different organic carbon and nitrate contents, both serving as nutrients for bacterial life in the soil. The data show that soil temperature is the key factor controlling the biogenic CO_2 production and subsequently the CO_2 flux rate. The observed spatial variability of soil CO_2 gas flux transforms into a natural background soil CO_2 gas flux of 1,400–6,300 t/km^2 per year at Ketzin and places an upper limit on biogenic CO_2 emissions apart from leakage. Thus, these values also provide a rough estimate of the lower leakage detection limit of the soil CO_2 gas flux measurements at Ketzin (Liebscher et al. 2012).

In March 2011, the surface monitoring network was expanded by the installation of eight permanent stations with automated soil gas samplers in direct vicinity of the injection and monitoring wells. At these eight locations, CO_2 gas flux, soil moisture and temperature are measured on an hourly basis. Evaluation and comparison with the available long-term data are currently underway.

Borehole monitoring

Gas–chemical and isotope investigations in Ketzin are direct methods to gain chemical and physicochemical information on processes in the storage reservoir. In particular, the comparison between CO_2 samples collected at the injection wellhead Ktzi 201 prior to injection and CO_2 samples collected at observation well Ktzi 200, i.e. after traveling 50 m through the storage reservoir, provide benchmark data such as gas migration velocity and changes in composition.

In connection with the trial with CO_2 from Schwarze Pumpe, gas tracer tests with krypton (Kr) and sulphur hexafluoride (SF_6) were performed to further track the CO_2 from the different sources (Linde and Schwarze Pumpe). On May 3 and 4, 2011, before the injection of CO_2 from Schwarze Pumpe started, 6.5 m^3 (STP) gaseous SF_6 and Kr were added through a valve into the injection well Ktzi 201. This was followed by 54 m^3 (STP) nitrogen (N_2) to pressurize the borehole and to force the tracers into the formation. Subsequently, the injection was restarted with CO_2 from Schwarze Pumpe on May 4, 2011. On June 15, 2011, after the injection of CO_2 from Schwarze Pumpe was finished, 7.98 m^3 (STP) SF_6 were pumped into the injection well to mark the change back to food-grade CO_2 from Linde. Samples were collected periodically at the well head of the Ktzi 201 and continuously in the observation well Ktzi 200 at 640 m depth using an especially installed 1/4″ stainless steel riser tube. Incidentally, these two different CO_2 sources also exposed different stable carbon isotope composition, thus providing ideal conditions for mass balance and mixing calculations.

Significant changes in the gas composition and amount between CO_2 from Linde and Schwarze Pumpe have neither been detected at the injection well head Ktzi 201 nor in the observation well Ktzi 200. The gas generally consists of pure CO_2 with traces of N_2, He and CH_4 during the whole test period. The arrival of the CO_2 from Schwarze Pumpe in well Ktzi 200 was verified by the detection of the gas tracer mixture (Kr and SF_6) after 15 days on May 18, 2011 and its end by the arrival of the second SF_6 tracer after 34 days on July 19, 2011. The longer retention time of the second tracer in the storage formation is likely due to a reduction in the CO_2 injection rate.

The δ^{13}C of dissolved inorganic carbon (DIC) has proven to effectively trace the migration of the injected CO_2 at the Ketzin pilot site (Myrttinen et al. 2010). The δ^{13}C CO_2 isotopic composition of gas samples, collected at the wellhead of Ktzi 201 and from the observation well Ktzi 200 with the riser tube, has been analyzed since April 2011. A change in the ^{13}C/^{12}C composition of the CO_2 during the temporary use of CO_2 from Schwarze Pumpe was detected (Fig. 7). The mean δ^{13}C CO_2 increased from −28.3 ‰ (Linde) to −26 ‰ (Schwarze Pumpe). The point of time of the isotopic change corresponds well with the arrival of the tracers at the observation well Ktzi 200, which also signals the arrival of the CO_2 from Schwarze Pumpe.

These results show that gas chemical measurements combined with tracer gas tests and isotope investigations are suitable methods for identifying CO_2 from different sources and for tracing the distribution velocity, fate and behavior of injected CO_2 in the storage reservoir. They lay foundations for further work and comparison between conservative gas tracers (Kr and SF_6) and the naturally already present label in the injected CO_2.

Modeling and simulations

Static and dynamic modeling tasks were undertaken in order to implement a history-matched reservoir model of the Stuttgart formation at the Ketzin pilot site for prediction of reservoir behavior.

Static modeling

As discussed in Kempka et al. (2010) a history match of reservoir pressure and CO_2 arrival times in both observation wells Ktzi 201 and Ktzi 202 was not feasible applying the initial static model developed by Frykman et al. (2009) in dynamic simulations. This model was based on 3D seismic investigations (Juhlin et al. 2007) interpreted and depth-converted in 2008. Data updates being available from consecutive monitoring at the Ketzin pilot site allowed for a revision of the static model of the Stuttgart formation. This revision aimed at geological modeling of

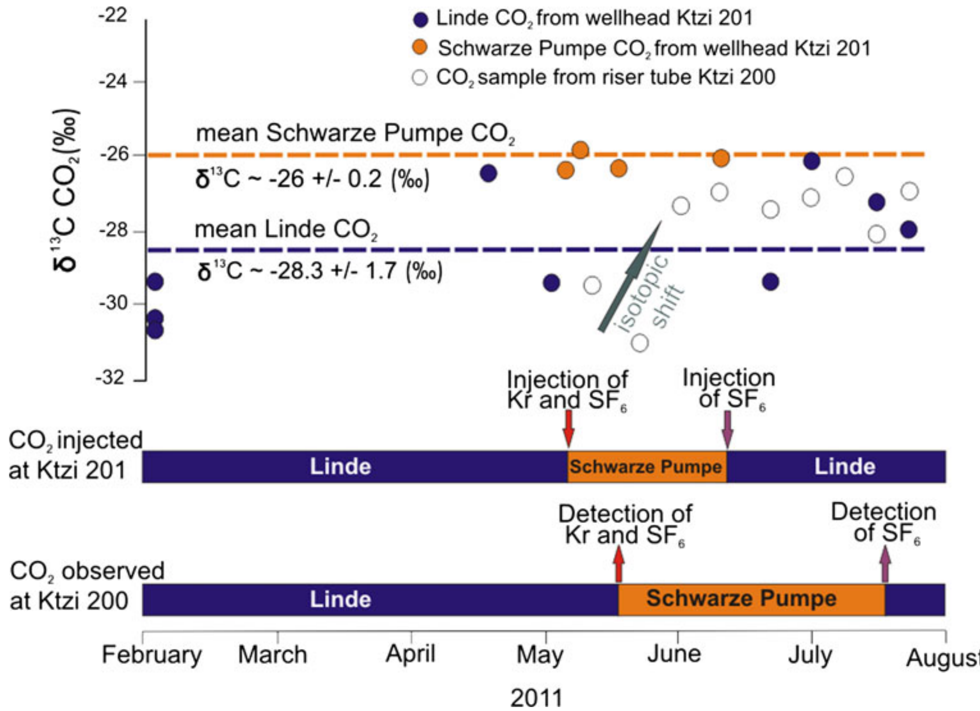


Fig. 7 CO_2 injection and detection of the gas tracers Kr and SF_6 together with the $\delta^{13}C$ CO_2 isotope data from Ketzin. Pre- and post-injection of SF_6 and Kr bracket CO_2 from Schwarze Pumpe

the fluvial facies bodies within the floodplain facies and distribution of the petrophysical properties. Fault zones identified by seismic surveys are not implemented in the present model, but will be in future releases.

The Stuttgart formation was divided into three zones for facies modeling. The upper zone (A) represents the uppermost 25 m of the formation, where the highest CO_2 mass is present. This zone was discretized with a vertical resolution of 0.25 m. The middle zone (B) with a thickness of 25 m has a vertical discretization of 0.5 m, while the lower zone (C) is vertically discretized by 1.0 m. The horizontal grid spacing (10 m $\times$ 10 m) is uniform for all zones. Facies modeling considered the expected regional trend of the channel distribution. In addition, the results of Kazemeini et al. (2009) were included for zone A and used as a trend (probability) map for the presence of channel facies. Furthermore, the results of the repeat 3D seismic survey from 2009 were applied to define areas of high sand content in a deterministic way. As further input, the sand–clay content was re-evaluated based on borehole records of wells of the broader Ketzin area. The floodplain facies is more dominant in the revised model in zone A compared to the previous model. Thus, the overall share of the channel systems is decreased in the revised model version.

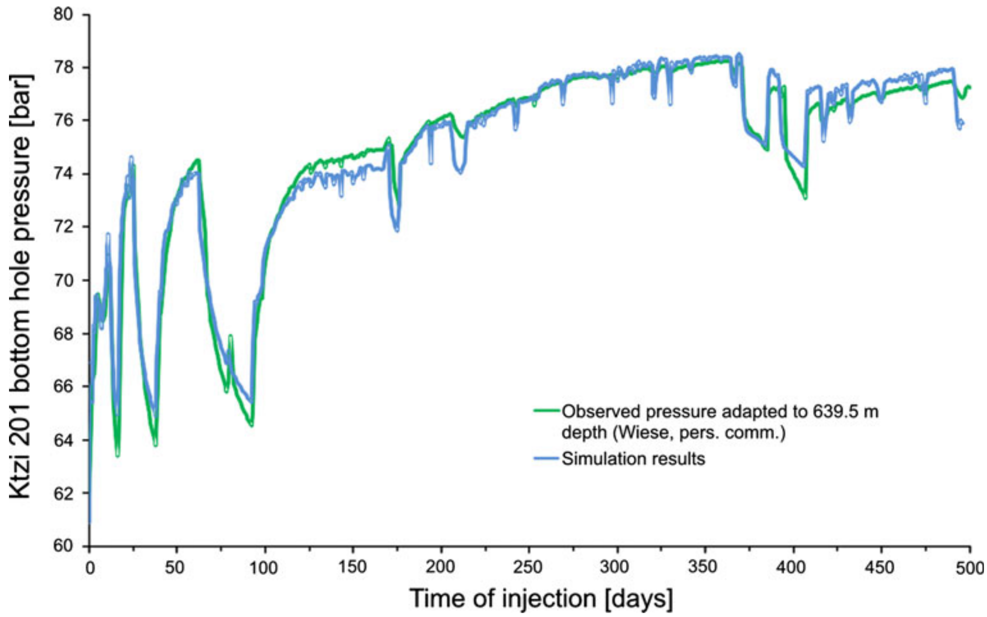
Petrophysical modeling of the two facies types (sand channel and floodplain) was undertaken by an integrated interpretation of borehole logging and laboratory data (Norden et al. 2010) extended by literature data for the Stuttgart formation (Wolfgramm et al. 2008). These data sets allowed for a re-evaluation of the porosity distribution curves (variograms) of the respective facies. Porosity was modeled using the sequential Gaussian simulation provided by the Petrel software package (Schlumberger 2010), taking into account the 3D seismic attribute map developed by Kazemeini et al. (2009) after scaling it to represent a trend map for porosity distribution.

Dynamic modeling

Numerical simulations were carried out using the revised static model of the Stuttgart formation while taking into account the discretization, initial and boundary conditions as well as injection rates as described by Kempka et al. (2010). The aim of these simulations was the verification of the revised static model with regard to the reservoir pressure determined in the injection well Ktzi 201 and the first CO_2 arrival in the observation wells Ktzi 200 and Ktzi 202 as described in Würdemann et al. (2010). Using the Eclipse 100 reservoir simulator (Schlumberger 2009), a successful match of monitored data was achieved where the deviation of arrival times is below 10 % with calculated times of 23 days for the well Ktzi 200 (21 days observed) and 258 days for the well Ktzi 202 (271 days observed). Furthermore, a good agreement of calculated and monitored reservoir pressure was achieved by the simulations as illustrated in Fig. 8.

A comparison of CO_2 plume thickness using the CO_2 plume distribution calculated and scaled based on the time-lapse amplitude analysis of the 3D seismic repeat results ($\sim$22 kt CO_2 injected) is plotted in Fig. 9. The areas with

Fig. 8 Comparison of observed and calculated bottom hole pressure in the injection well Ktzi 201



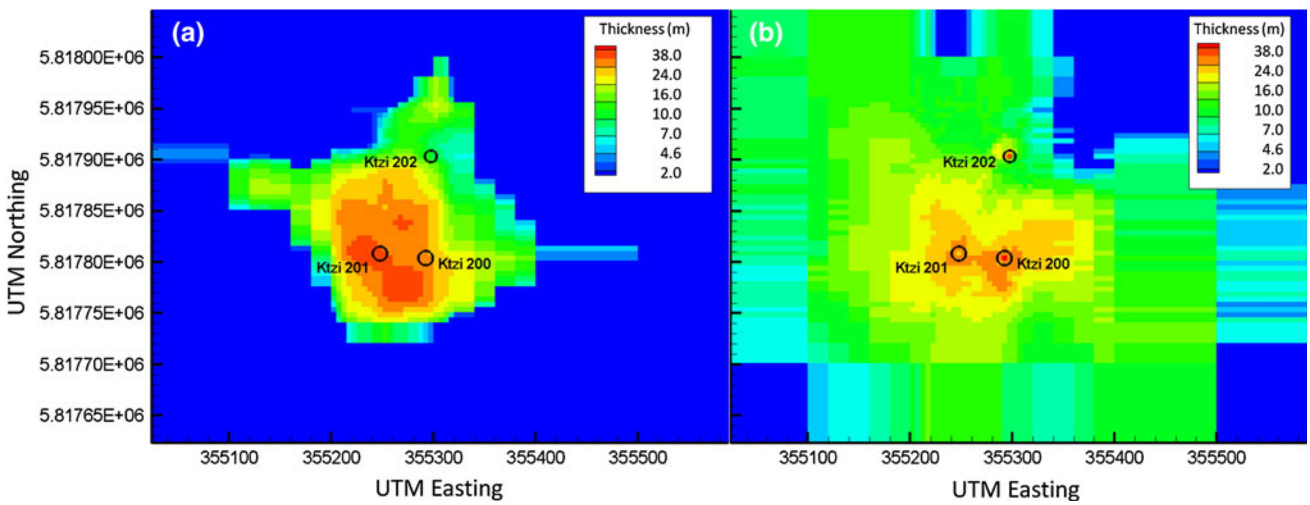


Fig. 9 CO_2 plume thickness scaled to dynamic model grid from **a** time-lapse amplitude analysis for the 3D seismic repeat (acquired during September to November 2009 after injection of 22 to 25 kt CO_2), **b** dynamic modeling

high concentrations of CO_2 (plume thickness >16 m) are in remarkably good agreement. The plume thickness in the near well area is very close with regard to the extension and location of CO_2 accumulation spots. This behavior is supported by the spatial decrease in thickness followed by a northward increase in the north of the well Ktzi 202. However, matching quality is significantly decreasing where CO_2 plume thickness is below 7 m indicating a potential limitation of the site-specific 3D seismic resolution.

A revision of the dynamic modeling grid is scheduled to allow for a more realistic representation of the CO_2 plume extent calculated in the numerical simulations. Since the present dynamic model and gridding were initially intended for history matching of arrival times and reservoir pressure only, the large-volume grid elements surrounding the near well area do not allow for an exact estimation of the CO_2 plume extent.

Communication and public outreach

Public perception is a main aspect of the Ketzin project. Since the start, a key premise of all communication activities is to ensure an open and transparent dialog with the general public, especially the local community. This concept is reflected by a large and positive national and international resonance in the media and continuous visitor groups to the pilot site (800 visitors in 2011).

Information about the activities and experiences gained at the Ketzin pilot site are made available through multiple communication types. The visitor center on site is the most important contact point and a corner stone for close collaboration with stakeholders and dissemination of knowledge. In spring 2011, the center was expanded and renovated in order to host larger visitor groups and permanent exhibits (e.g. posters, core samples, physical models) that can be used to visually illustrate the concept of CO_2 storage. In addition, interested groups, especially the local community, were invited by GFZ to attend an open day on site in May 2011. The event was well received and carried out in close cooperation with people from the nearby city of Ketzin/Havel, for example, with the involvement of the Mayor, the local fire brigade and other service providers. The project status and progress are also covered in videos and brochures, with attention drawn to the project website (www.co2ketzin.de) where more general and scientific information is available.

Conclusion and future work

The Ketzin project represents the longest-operating on-shore CO_2 storage site in Europe and successfully demonstrates CO_2 storage in a saline aquifer. After three years of injection, the results can be summarized as follows:

1. Since the start of the CO_2 injection in June 2008, the operation has been running reliably and safely.
2. Downhole pressure data prove correlation between the injection rate and the reservoir pressure and indicates the presence of an overall dynamic equilibrium within the reservoir.
3. The extensive geochemical and geophysical monitoring program is capable of detecting CO_2 on different scales and gives no indication for any leakage.
4. Numerical simulations (history matching) are in good agreement with the monitoring results.

The fundamental regulatory principles surrounding future site closure, transfer of responsibility to the competent authority and post-closure obligations are set out in the EU Directive on CO_2 Geological Storage (EU 2009). Although the Ketzin pilot site is still in the operational phase it is interesting to note that the three items (2) to (4) mentioned above also refer to the following three minimum criteria as defined in Article 18 for transfer of responsibility:

- Site is evolving towards a situation of long-term stability.
- No detectable leakage.
- Observed behavior of the injected CO_2 conforms to the modeled behavior.

These conditions define satisfactory for long-term site performance at a high-level. However, the EU Directive does not give any technical criteria based on real site performance data, which can demonstrate that a storage site meets the three requirements. In order to close this gap, the Ketzin pilot site is part of the portfolio of nine international sites within the European project CO_2CARE (2011–2013). Main objectives of CO_2CARE are the development of site abandonment procedures and technologies, which guarantee the fulfillment of these criteria as well as so called dry runs or virtual implementations of the abandonment process at real storage sites.

The Ketzin pilot site is a research and development project and limited by legal regulations to a maximum amount of stored CO_2 of <100,000 tonnes. Injection is scheduled to last until 2013. Following the success of the Ketzin project to date, drilling of another $\sim$800 m deep observation well (Ktzi 203) on the existing injection site is planned for 2012. Cores retrieved from the Stuttgart Formation will provide the unique opportunity for research to be conducted with samples that have been exposed in situ to the CO_2 for a period of about 4 years. In addition, the seismic monitoring will be complemented by the next 3D survey repeat measurement in 2012/13.

Acknowledgments The authors would like to thank the interdisciplinary team working on the Ketzin project and all partners for their continued support and significant contributions. The research described in this paper is funded by the European Commission (Sixth and Seventh Framework Program), two German ministries—the Federal Ministry of Economics and Technology and the Federal Ministry of Education and Research—and industry. Funding from the Federal Ministry of Education and Research within the GEOTECHNOLOGIEN Program (GEOTECH-1831) and industry partners enables the on-going research project CO_2MAN (www.co2ketzin.de). We also thank Mary Lavin–Zimmer and two anonymous reviewers for their constructive comments on this manuscript.

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