Joint Research Project CO_2MAN (CO_2MAN Reservoir Management): Continuation of Research and Development Work for CO_2 Storage at the Ketzin Pilot Site

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Abstract The joint project CO_2MAN (CO_2 Reservoir Management) was a scientific programme accompanying geological CO_2 storage at the Ketzin pilot site in the German Federal State of Brandenburg. The project which was funded by the German Federal Ministry of Education and Research (BMBF) from 1 September 2010 to 31 December 2013 enclosed six scientific institutions and seven industry partners. The Ketzin pilot site is the longest-operating on-shore CO_2 storage site in Europe. In advance of the CO_2MAN project, CO_2 injection had already started in June 2008 and storage operation had been accompanied by one of the world's most extensive scientific research and development programmes. The CO_2MAN project took advantage of this unique potential of the site in order to answer further technical and scientific questions on CO_2 storage and to inform about this highly debated technology. The CO_2MAN project demonstrates safe geological CO_2 storage at the Ketzin site on a pilot scale.

1 Introduction

CO_2MAN which stands for CO_2 Reservoir Management was a scientific programme accompanying geological CO_2 storage at the Ketzin pilot site. Within the framework of CO_2MAN a total of six German scientific institutions and seven

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industry partners from Norway, Austria and Germany participated (Fig. 1). The joint project was coordinated by the GFZ German Research Centre for Geosciences in close cooperation with all partners.

The Ketzin pilot site for geological storage of CO_2 is located about 25 km west of Berlin in the German Federal State of Brandenburg (Fig. 2). It is the longest operating European on-shore CO_2 storage pilot site and provides an in situ laboratory for CO_2 storage in a saline aquifer of the Northeast German Basin. Injection of CO_2 at Ketzin started on 30 June 2008 and was accompanied by one of the most comprehensive scientific research and development (R&D) programmes worldwide with key objectives being R&D on injection operation, monitoring and modelling. The first results that had been achieved at the pilot site Ketzin were promising (Schilling et al. 2009a; Würdemann et al. 2010). However, for a final assessment of the technology further investigations were necessary (Stroink et al. 2009). Hence the aim of the CO_2MAN project was to take advantage of the unique potential and the infrastructure of the Ketzin pilot site and to continue CO_2 injection and the R&D activities with a dedicated public outreach programme. The key objectives of the joint research project were:

- to monitor the migration of the injected CO_2, to determine the sensitivity of individual monitoring methods and to test and develop geophysical monitoring concepts for CO_2 storage sites,
- to characterize and quantify CO_2-induced interactions between fluid, rock and microbial community in the storage system,
- to validate tools for static modelling and dynamic simulations for the Ketzin pilot site, and
- to inform the public, stakeholders, decision makers and regulatory authorities about CO_2 storage.

Fig. 1 CO_2MAN partners from academia and industry. The consortium includes GFZ German Centre Research for Geosciences (coordinator) in Potsdam, Friedrich-Alexander University of Erlangen-Nürnberg, University of Stuttgart (Department of Hydromechanics and Modelling of Hydrosystems (LH2)), University of Leipzig and the Helmholtz Centre for Environmental Research -UFZ in Leipzig. Industry partners are Dillinger Hüttenwerke, OMV, RWE, Saarstahl, Statoil, Vattenfall and VGS

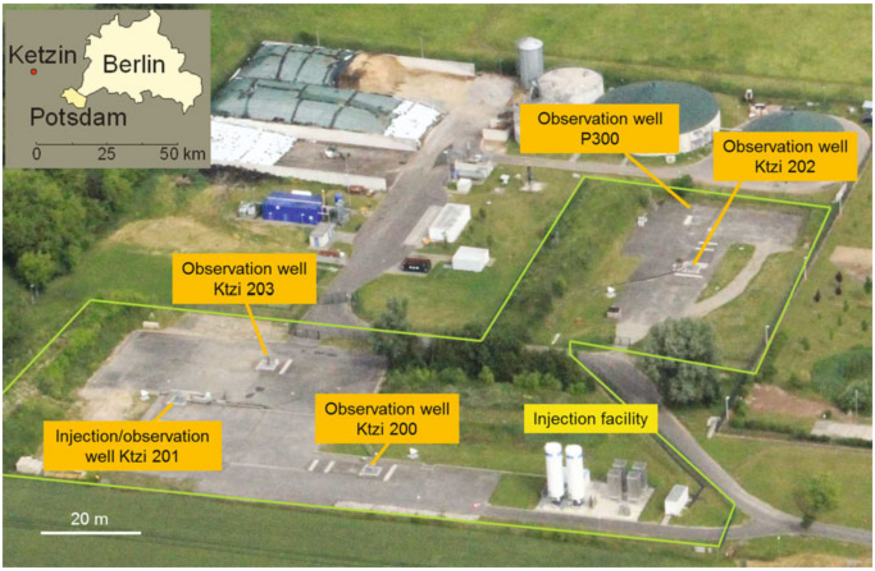

Fig. 2 Geographic location of the Ketzin pilot site in the Federal State of Brandenburg and aerial picture of the site with its research infrastructure in June 2013

The core of the project consisted of the four work packages "Research Infrastructure", "Geophysical Monitoring", "Reservoir Processes" and "Modelling and Simulations". Each work package comprised three to five sub-projects (Fig. 3). The work packages were complemented by the activities "Data Management", "Information Centre Ketzin" and "Project Management". This contribution comprises an overview of the work carried out and the results obtained under the joint research project CO_2MAN.

2 Research Infrastructure at the Ketzin Pilot Site

The Ketzin project on CO_2 storage was initiated by the GFZ German Research Centre for Geosciences in 2004 (Würdemann et al. 2010). Hence, there was already a certain research infrastructure available at the pilot site and the CO_2 injection was on-going since June 2008 when the CO_2MAN joint project started in September 2010. The infrastructure consisted of an injection facility (Fig. 4) with two intermediate CO_2 storage tanks and four large ambient air heaters as well as the injection/observation well Ktzi 201 and the pure observation wells Ktzi 200 and 202. In the course of the CO_2MAN project the CO_2 injection was continued until the end of August 2013 and two additional monitoring wells were drilled.

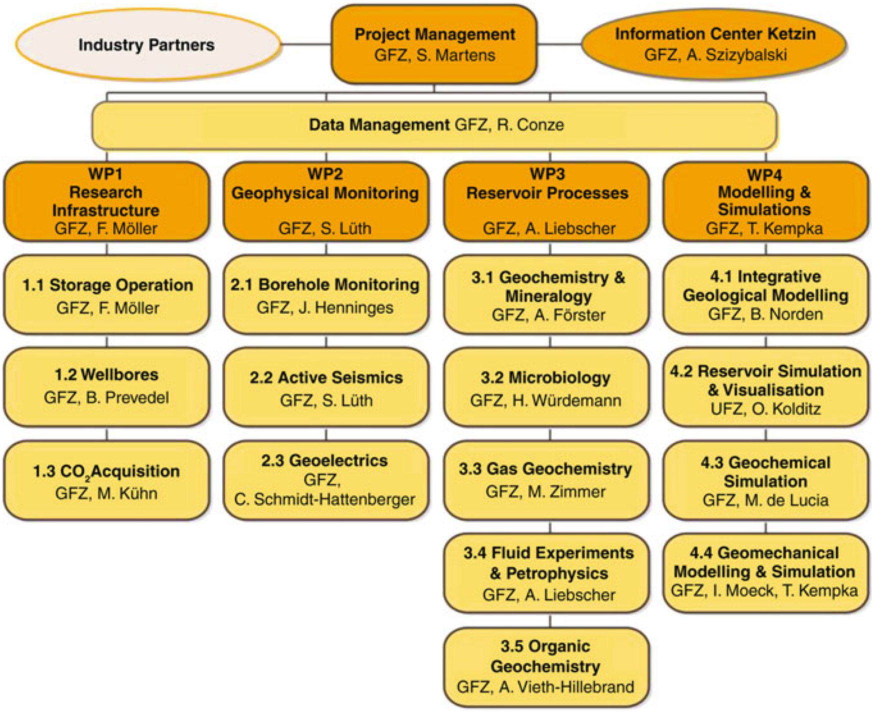

Fig. 3 Organization chart of the joint project CO_2MAN, showing the different work packages, sub-projects and respective lead scientists

2.1 Storage Operation

Injection of CO_2 at the Ketzin pilot site started already prior to the CO_2MAN project on 30 June 2008 and ended on 29 August 2013. The CO_2 was delivered by road tankers in a liquid state and stored at about −18 °C and 21 bars in the two intermediate storage tanks on site (Fig. 4). Prior to injection the pressure was raised by plunger pumps to the necessary injection pressure and the CO_2 was heated by ambient air heaters and an electrical heater. Then the CO_2 was transported via a pipeline of about 100 m length to the injection well Ktzi 201. A total amount of 67 kt of CO_2 was safely injected over the more than 5 years period. Thereof, 29,337 t were injected within the CO_2MAN project (Fig. 5). During most of the time food-grade CO_2 (purity > 99.9 vol%) was used with monthly injection rates between 1,000 and 2,300 t. From May to June 2011, 1,515 t of CO_2 captured from the Vattenfall Schwarze Pumpe oxyfuel pilot plant (purity > 99.7 vol%) were used.

CO_2 injection was accompanied by a comprehensive operational pressure-temperature monitoring programme (Liebscher et al. 2013). Due to CO_2 injection the reservoir pressure increased to about 76–79 bars already after eighth months of injection (Fig. 5). After this initial increase the reservoir pressure slightly decreased

Fig. 4 Injection facility at Ketzin with two intermediate CO_2 storage tanks (*left*) and ambient air heaters (*middle*) before decommissioning in December 2013

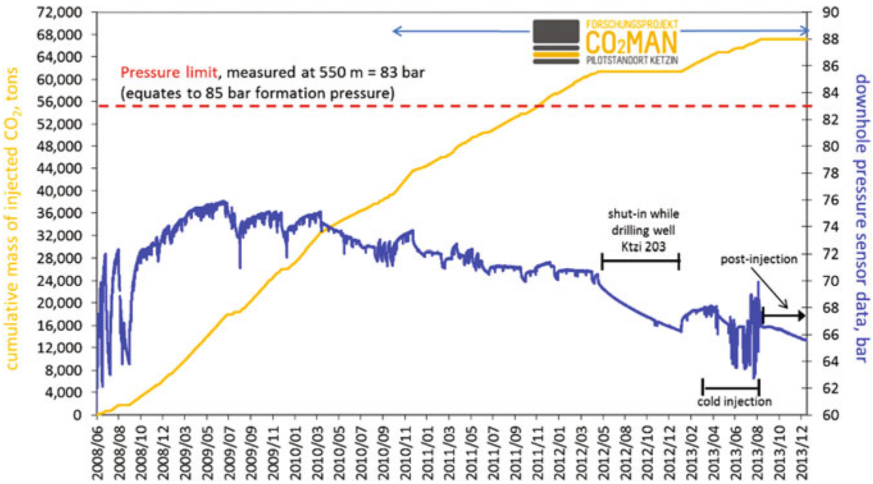

Fig. 5 Overall injection history at the Ketzin pilot site showing cumulative mass of injected CO_2 (*orange*) and measured pressure at 550 m depth in well Ktzi 201 (*blue*) from June 2008 to December 2013. The reservoir pressure at 630 m is about 2 bars higher than the measured pressure at 550 m. The *red line* refers to the maximum permitted pressure of 85 bars at reservoir depth (=83 bars at 550 m) given by the Mining Authority

and stabilized between about 72 and 75 bars reflecting a stable injection regime (Liebscher et al. 2013). Between March and July 2013, the injection temperature was lowered stepwise down to 10 °C to demonstrate the feasibility of a "cold injection" process, i.e. without pre-heating the CO_2. Despite high dynamics of the measured pressure within the injection well Ktzi 201 (Fig. 5), the entire injection process ran smoothly and the experiment could be carried out successfully.

Longer shut-in phases, e.g. during drilling of the Ktzi 203 well, and the beginning of the post-injection phase at the end of August 2013 were characterized by a continuous decrease of the reservoir pressure. The maximum approved reservoir pressure as defined by the Mining Authority is 85 bars at 630 m depth, which transforms into 83 bars at 550 m depth, i.e. installation depth of the pressure sensor in well Ktzi 201. During the entire storage operation the reservoir pressure was always well below this maximum approved value. The injection facility was dismantled in December 2013 whereas post-injection monitoring continues.

During the CO_2MAN project the four deep wells at Ketzin were inspected by comprehensive wellbore logging campaigns on an annual basis. Logging included magnetic measurements, saturation measurements using pulsed neutron gamma (PNG) logging and borehole inspections with a video camera to enable visual inspection. Based on the results of the logging campaign and the video material the good condition of the wells could be repeatedly confirmed. Fluid samples from the wells were gained during all logging campaigns and used for further investigations on reservoir processes (compare Sect. 4).

The storage operation at Ketzin is carried out under the framework of the German Mining Law. The injection phase was realized with well trained personnel from the gas storage industry and monitored, in addition to the scientific investigations, by two consulting engineering companies. The consultants reported to the mining authority independently from the GFZ on a regular basis. This constellation proved to be successful in the way that over more than 5 years of injection no health, safety or environmental issues occurred. The safe storage of CO_2 at Ketzin was only possible due to a close and trustful cooperation between the storage operator, the consultants, the mining authority and of course all scientific personnel. This also ensured that all scientific experiments within CO_2MAN could be carried out while at the same time all legal requirements were met.

2.2 Drilling and Well Abandonment

Prior to the start of the CO_2MAN project three wells (Ktzi 200, Ktzi 202, Ktzi 202) had already been drilled at Ketzin in 2007 and were completed with a smart casing concept (Prevedel et al. 2009). To meet the scientific needs of the CO_2MAN project two additional monitoring wells (P300, Ktzi 203) were drilled in 2011 and 2012.

The well P300 was drilled in summer 2011 to 446 m depth into the lowermost aquifer (Exter Formation) above the cap rock of the CO_2 storage reservoir (Fig. 6) to allow for above-zone monitoring in the indicator horizon. The geological succession

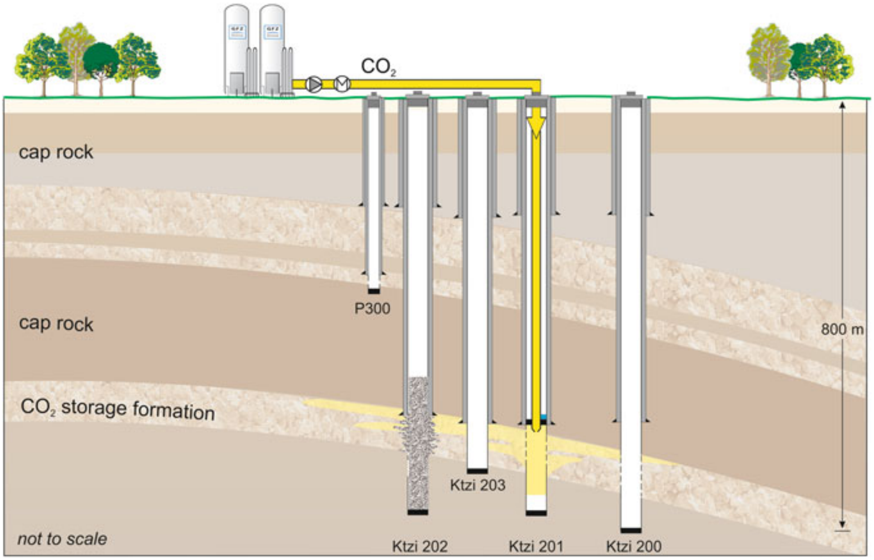

Fig. 6 Schematic vertical profile of the Ketzin pilot site showing its four deep wells (Ktzi 200 to Ktzi 203) and one shallow observation well (P300). Both wells P300 and Ktzi 203 were drilled in the course of the CO_2MAN project. A plug cementation was carried out in the lower part of the observation well Ktzi 202 in autumn 2013

encountered at well P300 (Martens et al. 2013) was very similar to the geology observed at the other Ketzin boreholes (Förster et al. 2009). 40.9 m of best quality cores could be retrieved, allowing a detailed analysis of the mineralogy and geochemical properties of the Exter Formation. The well was completed with a combined high resolution pressure and temperature sensor at 418 m depth, a level sensor at 21 m and a non-cemented monitoring string with a U-tube fluid sampling system to allow for pressure and fluid monitoring of the indicator horizon (compare Sect. 3.4).

In August and September 2012, the well Ktzi 203 was drilled about 25 m apart from the injection well Ktzi 201 (Fig. 2) to 701 m depth to gain cores of the cap rock and reservoir sandstones that were in contact with the injected CO_2 for more than 4 years. This well was planned and drilled in accordance with a slim-hole concept and recovered 90 m of cores. The well showed a geological profile very similar to the Ktzi 201 borehole. At the top of the storage (Stuttgart) formation the approximately 18-m thick reservoir sandstone is present. At final depth the reservoir section was cased and cemented with fiber glass casing pipe for testing the applicability of corrosion resistant composite pipe material for future storage operation and abandonment steps. The well Ktzi 203 was completed with a combined 3.5″ steel/fiber glass production casing with two distributed temperature sensing (DTS) cables and two pressure-temperature sensors on the outside at 305 and 610 m depth. Subsequent wireline logging runs in the Ktzi 203 well revealed an obstruction inside the 3.5″ production casing at 557 m that required a work-over operation in order to remove this section which was blocked by cement. This operation was conducted in April/May 2013 and freed the inside of the casing so that logging tools and a perforation gun could reach the CO_2 injection horizons and finally connect the well to the reservoir.

As the begin of a staged well abandonment at the Ketzin pilot site, a plug cementation in the form of a partial abandonment of well Ktzi 202 (Fig. 6) was carried out in autumn 2013. As this well was a monitoring borehole since 2007 it was entirely filled with CO_2 under elevated pressure. In order to start the abandonment the well had to be pressure killed by injecting NaCl brine from the surface into the wellhead and such pushing the CO_2 back into the storage formation. By that means a brine filled and secured borehole situation could be established and the wellhead could be safely removed and replaced by a blow-out preventer for the subsequent plug cementing work in the reservoir section. A special CO_2 resistant cement (EverCrete) was chosen which will be partly core-drilled and analyzed in the course of the follow-up project COMPLETE in 2015.

3 Monitoring of the Ketzin Pilot Site

R&D on monitoring of the Ketzin pilot site was one of the key objectives of the CO_2MAN project. Already in advance of this joint research project, a comprehensive monitoring concept which combined operational, geophysical, geochemical and microbiological monitoring techniques had been tested and established at the pilot site (Würdemann et al. 2010).

In the framework of CO_2MAN, geophysical techniques including borehole monitoring, active seismic and geoelectric methods were continued in order to further monitor the migration of the injected CO_2 on different scales. Gas geochemical monitoring focused on CO_2 soil flux measurements at the surface and fluid sampling from the wells via permanently installed capillary riser tubes and a U-tube system.

3.1 Borehole Monitoring

The migration of the injected CO_2 close to the boreholes was monitored using a combination of different well logging techniques. The temperature distribution along the deep boreholes was continuously recorded with permanently installed distributed temperature sensing (DTS) cables. The saturation conditions within the CO_2 storage horizon and the cap rock were investigated using pulsed neutron-gamma (PNG) logging. Furthermore, the heat-pulse method was tested for monitoring of saturation changes. Here the formation thermal conductivity is determined based on temperature changes under the influence of a controlled heat source. For this purpose, a combined opto-electric sensor-heater cable was installed behind casing in the new observation well Ktzi 203.

After filling up with CO_2 the temperature conditions in the deep observation wells are controlled by a heat-pipe process (Henninges et al. 2011). Temperature changes are caused by phase transitions during evaporation and condensation of CO_2, and characteristic temperature gradients are established in the two-phase zone. The pressure evolution along the borehole depends on the composition and the phase distribution within the fluid column (Loizzo et al. 2013).

For the Ktzi 203 well, in situ thermal conductivities were calculated by numerical inversion of the data acquired during heat-pulse measurements. The thermal conductivity profiles show a good correlation with lithological changes, with values ranging between 1 and 4.5 $Wm^{-1}K^{-1}$. They display similar characteristics as the profiles previously determined for the other wells (Freifeld et al. 2009). Within the storage horizon, changes of thermal conductivity in the order of 20–30 % could be observed between different measurements, but the results show a high sensitivity against external thermal influences.

PNG logs were acquired within all deep wells in about annual intervals and saturation conditions were calculated by comparison of the data with previously recorded baseline and repeat measurements (Fig. 7). The highest CO_2 saturations

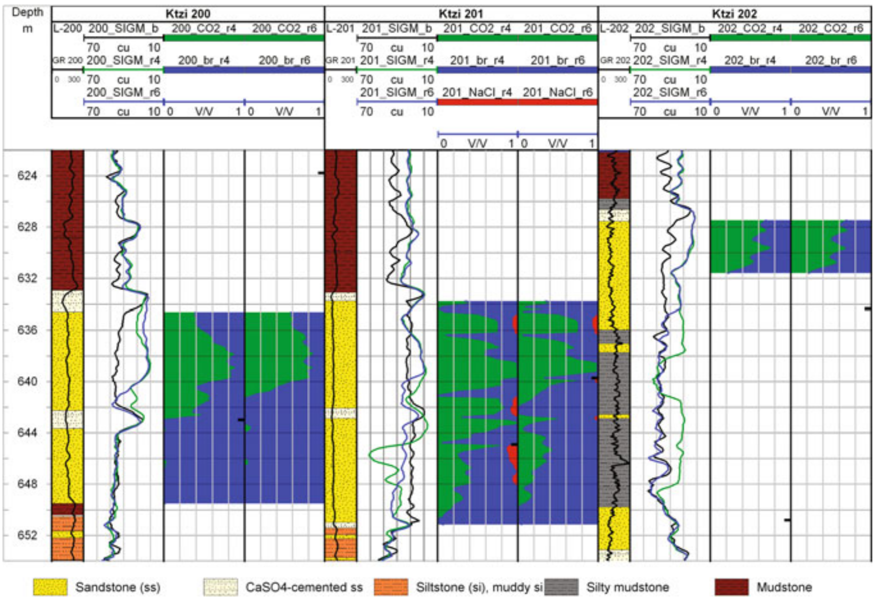

Fig. 7 PNG logging data and calculated CO_2, brine (br) and halite (NaCl) saturations in the wells Ktzi 200 (*left*), Ktzi 201 (*middle*) and Ktzi 202 (*right*). SIGM: measured macroscopic formation capture cross-section; b: baseline (June 2008), r4: repeat 4 (March 2011), r6: repeat 6 (October 2012). The positions of the brine levels within the wells are indicated with *black* markers. Lithology after Förster et al. (2010)

occur at the injection well Ktzi 201, with average values of 68 %, and up to 100 % locally. At the observation wells CO_2 saturations are lower, with average values of > 60 % at well Ktzi 200, and a further decrease towards well Ktzi 202 (averages < 60 %). A new PNG saturation model for CO_2 and NaCl brine was developed which besides displacement also accounts for evaporation and precipitation processes (Baumann 2013; Baumann et al. 2014). Based on this model and the PNG measurements salt precipitation at the CO_2-brine contact in the Ktzi 201 near-well area could be shown for the first time.

Within the cap rock, no indications for accumulation of CO_2 in shallower aquifers were observed. This is important evidence that no significant migration of CO_2 along the boreholes is occurring. The calculated saturations were used as input parameters for estimates of the CO_2 mass contained within the storage horizon based on seismic data (Ivanova et al. 2012; see below) and for evaluation of electrical resistivity tomography data (Bergmann et al. 2012; see below). The established fiber-optic sensor cable network also exhibits favorable properties for seismic surveys using the newly emerging method of distributed acoustic sensing DAS (Daley et al. 2013).

3.2 Seismics

The main task of seismic monitoring at the Ketzin pilot site is to image the lateral and vertical propagation of the injected CO_2 in the reservoir. To this end, high-resolution vertical seismic profiling (VSP), star-profile surveys close to the injection location (Ivandic et al. 2012) and large scale 3D surface seismic surveys (Ivanova et al. 2012, 2013) were repeated providing time-lapse observations at various scales. Additionally, the emerging technology applying a fiber optic cable as a seismic (acoustic) receiver array DAS was investigated on site (Daley et al. 2013). As all four deep wells on the site are equipped with a fiber optic cable, conditions are ideal for a simultaneous four-well acquisition of multi-offset DAS-VSP data.

The VSP and star-profile surveys, acquired in February 2011, revealed a clear CO_2 related amplitude signature at the top of the storage formation. Due to the limited spatial aperture of these measurements the CO_2 signature was restricted to the close vicinity of the injection well and showed only a part of the complete CO_2 signature imaged by the previous and subsequent full 3D repeat surveys. An analysis of time-lapse amplitude variations in the vertical direction showed clearly that no CO_2 signature was detected above the top of the storage (Stuttgart) formation indicating there is no leakage detected by high resolution reflection seismic surveys. It could also be shown that the sparse acquisition geometry, concentrating on seven profiles ("star") in the area close to the injection site, is able to detect the CO_2 in the reservoir. However, the time-lapse data are characterized by a smaller degree of repeatability than are the time-lapse data of the full 3D repeat measurements (Ivandic et al. 2012).

The second 3D repeat survey was acquired in autumn 2012 after 61 kt CO_2 injected in the storage formation. The data were time-lapse processed and amplitude variations were extracted for the top of the Stuttgart Formation. The lateral distribution of time-lapse amplitudes at the top of the Stuttgart Formation shows a high degree of anisotropic propagation and confirms several features of propagation detected by the first repeat survey (2009) which is shown in Fig. 8. After the injection of 61 kt the CO_2 could be imaged with a west-east extension of about 700 m in autumn 2012 (Fig. 8, right).

For seismic reservoir monitoring, the use of fiber optic cables is currently discussed as an emerging technology with considerable potential of replacing conventional wireline-based seismic acquisition in boreholes and also in surface applications (Parker et al. 2014). In May 2013, a simultaneous DAS-VSP survey was acquired using 23 vibro points and acquiring the seismic wave field along the fiber optic cable deployed in four wells and with a spatial sampling of 1 m. The survey was performed within 4 days. The acquired DAS-VSP shot gathers show clear onsets of the downgoing compressional wave and of reflected upgoing waves. The data acquired in this survey are the basis for a high-resolution 3D imaging of the reservoir layer between the injection and monitoring wells of the Ketzin pilot site.

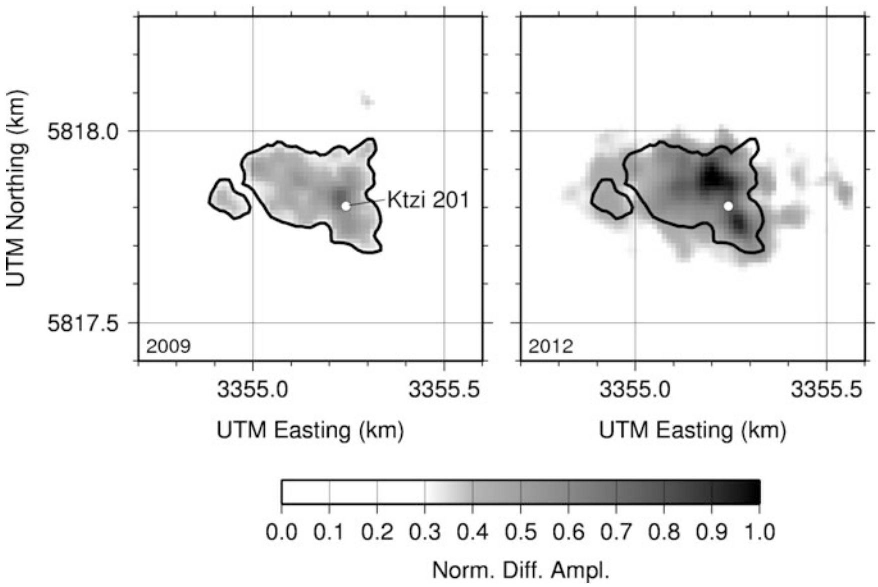

Fig. 8 Map displaying the normalized time-lapse amplitudes at the top of the Stuttgart Formation for the first 3D repeat survey in 2009 (*left*) and the second repeat survey in 2012 (*right*). Time-lapse amplitudes exceeding a background noise level of 0.3 are displayed in *grey-scales*. The location of the injection well (Ktzi 201) is indicated by a *white circle*. For the comparison of the lateral extents of the CO_2 in 2009 and 2012, the contour of the 2009 image (*black line*) has been projected onto the 2012 image

3.3 Geoelectrics

The geoelectrical monitoring programme at Ketzin comprised direct current (DC) geoelectric measurements in three different setups: (1) surface-to-surface, (2) surface-to-downhole and (3) crosshole data acquisition. The first two setups were performed as dipole-dipole measurements on two crossed profiles (length ~4.8 km each of them) and two sparsely settled rings with radii of 0.8 km and 1.5 km, respectively. In addition, the setups (2) and (3) made use of 45 electrodes permanently installed in the wells Ktzi 200, Ktzi 201 and Ktzi 202 (Fig. 9).

At a detection level of about ~600 t of injected CO_2 the geoelectric measurements indicated relevant subsurface resistivity changes associated with the

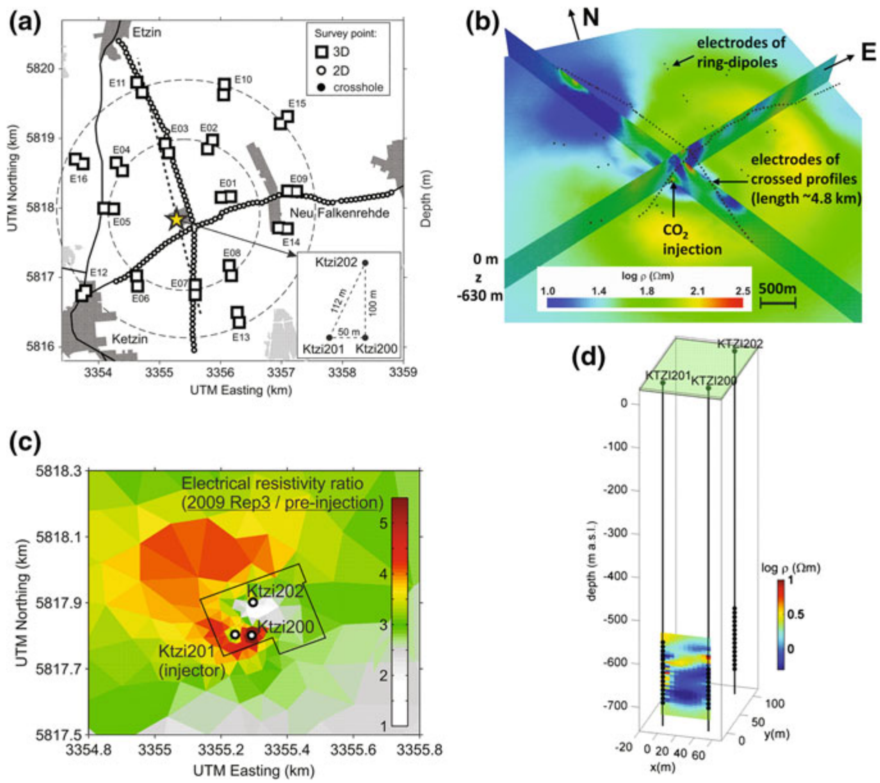

Fig. 9 **a** Schematic of the DC geoelectric measurement concept at the Ketzin pilot site. Large-scale surveys were acquired in 2008, 2009, 2011 and 2012. Weekly-measured crosshole surveys were conducted in the wells Ktzi 200, Ktzi 201 and Ktzi 202 (see inlay for the borehole distances). The major results are: **b** 3D resistivity distribution from inversion of the crossed profiles and the surface-downhole survey in 2011, **c** Resistivity change (repeat 3/2009 vs. baseline) from constrained inversion of surface-downhole data (modified after Bergmann et al. 2014), and **d** Corresponding crosshole results in the major observation plane Ktzi 200–Ktzi 201

migration of CO_2 in a depth of about 630 m. The measured resistivity contrast was in consistency with laboratory measurements on Ketzin sandstone core samples, where Archie fluid substitution revealed a resistivity increase of a factor of about 3 (Kiessling et al. 2010). The permanent downhole electrode array was the subject of engineering developments, such as modular system components, automated optimization of data pre-processing and remote-controlled data acquisition in order to achieve the operational requirements of CO_2 storage sites. From the weekly-measured crosshole data (Schmidt-Hattenberger et al. 2012) and the periodically measured large-scale surface-downhole surveys (Bergmann et al. 2012) consistent time-lapse images of the CO_2 plume migration were derived which correlated fairly well with other monitoring results obtained from seismic surveys, borehole logging and geochemical data.

As a promising tool of geophysical data integration, a structurally constrained inversion approach was applied that incorporates seismic structural information as a priori information into the resistivity inversion (Bergmann et al. 2014). The resulting time-lapse resistivity signature of the constrained inversion was found to collocate clearer with the time-lapse signature from the repeated 3D seismic investigations. The asymmetrical extension of this signature indicates preferential CO_2 migration towards the northwest direction which was also in good agreement with the results from the seismic interpretation.

3.4 Gas Geochemistry

Long-term background data on the natural spatial and timely CO_2 distribution and variability are indispensable for a reliable monitoring and the detection of a potential leakage. In order to obtain this information for the Ketzin pilot site, gas-chemical and isotope investigations have been performed since 2005. Up to now, no indication of any CO_2 leakage has been detected with this comprehensive gas monitoring network system.

The monitoring network comprises 20 sampling locations for soil gas flux, soil moisture and temperature measurements distributed across an area of approximately 2 km × 2 km around the pilot site. In March 2011, eight permanent automated soil gas samplers were added in the direct vicinity of the boreholes together with a meteorological station. Since the start of injection in 2008, no change in soil CO_2 gas flux could be detected as compared to the pre-injection baseline (Zimmer et al. 2011a; Martens et al. 2013). Mean CO_2 flux as averaged over all sampling locations ranged from 2.4 to 3.5 μmol/m^{2}s for the pre-injection period and from 2.2 to 2.5 μmol/m^{2}s after the start of injection (Zimmer et al. 2011a). The spatial variability of soil CO_2 gas flux is 1.0–4.5 μmol/m^{2}s for all sampling locations reflecting the 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.

A U-tube system in the shallow observation well P300 enables above-zone monitoring and the possible detection of a potential leakage through the first cap rock at an earliest possible stage. Formation water from well P300 was permanently sampled from a depth of 417 m (Exter Formation) and analyzed for dissolved cations, anions, gases and $^{12}C/^{13}C$ isotope ratio of CO_2 and revealed no impact of the injected CO_2 on the Exter Formation.

From March 2010 to October 2011 a riser tube was installed in well Ktzi 200 which allowed for continuous sampling and analyses of gas from 600 m depth. The measured gas composition was relatively constant with about 99 % CO_2 and traces of nitrogen, helium and methane. Two tracer tests were performed where both krypton and sulfur hexafluoride were added in the injection well Ktzi 201 in May and June 2011. Both gaseous tracers were detected in well Ktzi 200 after the injection of 608 and 701 t of CO_2, respectively, since the tracer test started. In October 2011 the riser tube was transferred to well Ktzi 202. The analyzed gas composition from 600 m depth showed constant values until the end of the measurements in October 2013 and consists of 99.5 % CO_2 with traces of nitrogen, helium and methane. Following the partial closure of the observation well Ktzi 202 in autumn 2013, a gas membrane sensor (Zimmer et al. 2011b) for real time observation of gas at depth was installed at 500 m (21 m above the cement head) to monitor the tightness of the cementation.

Since the beginning of the CO_2 injection in 2008, stable isotope measurements have been conducted for a detailed geochemical characterization of the reservoir and overlying formations, comprising $\delta^{13}C$ and $\delta^{18}O$ data of brine dissolved inorganic carbon (DIC) and H_2O (Nowak et al. 2013). Isotope measurements in connection with gas tracer tests were also carried out when CO_2 from the Schwarze Pumpe oxyfuel pilot plant was used for injection in May and June 2011 (Martens et al. 2012). The $\delta^{13}C$ of DIC proved to effectively trace the migration of the injected CO_2 at Ketzin (Myrttinen et al. 2010). When the $\delta^{13}C$ CO_2 isotopic composition of gas samples from the wellhead of Ktzi 201 and well Ktzi 200 were analyzed, a change in the $^{13}C/^{12}C$ composition of the CO_2 was detected during the temporary use of CO_2 from Schwarze Pumpe (Martens et al. 2012).

4 Fluid Experiments and Processes in the Storage Reservoir

In order to examine the potential interactions between injected CO_2, formation fluid, the storage system and its microbial community at the Ketzin pilot site, laboratory experiments and investigations of samples from the site were carried out. On the one hand, the processes occurring in the reservoir should be characterized and quantified. On the other hand measurements were taken to monitor these processes. The main focus was on the study of fluid, gas and rock samples from

Ketzin, especially from the newly drilled observation well Ktzi 203. The work on the natural samples was supplemented by experimental studies under defined laboratory conditions.

4.1 Fluid Experiments and Petrophysics

Geochemical experiments on the fractionation of Fe, Cu and Zn between CO_2 and formation fluid showed that CO_2 acts as a solvent for trace elements and mobilizes small but measurable amounts of Fe, Cu, Zn regardless of the CO_2 density. By CO_2 dissolved organic compounds act as potential complexing agents and increased the extraction ability for trace elements. In terms of long-term CO_2 storage, the potential consequences of these results include the precipitation of carbonate minerals in shallower, more distal regions of the aquifer and the transferal of metals to adjacent aquifer systems (Rempel et al. 2011).

Several batch experiments under in situ conditions have been performed using CO_2, formation fluid and rock samples from Ketzin wells (Ktzi 201, 202). Results neither show clear changes nor uniform trends over time (up to 40 months) with regard to porosity, pore-size distribution, capillary pressure or geomechanical parameters. Nuclear magnetic resonance (NMR) spectroscopy and mercury injection porosimetry (MIP) were used to characterize samples before and after experiments. For two core sets geomechanical parameters were determined before and after CO_2 treatment. Baseline measurements are consistent with porosity logging data of corresponding wells and show high variability due to the heterogeneous lithology of the Stuttgart Formation. This natural variability of the reservoir hampers the comparability of whole rock samples before and after the experiments. Nonetheless, several lines of evidence indicate that mineralogical-geochemical changes occur due to CO_2 exposure; but these are quantitatively subordinate. In conclusion, effects of injected CO_2 on the reservoir system integrity are minor (Fischer 2013; Fischer et al. 2013).

Porosity measurements on core samples recovered before the injection and the corresponding NMR log (Ktzi 201) compared with porosity measurements of approximately 100 cores of the newly drilled well Ktzi 203 (gained after about 4 years of CO_2 exposure) show that the impact of CO_2 injection on pore size related properties of reservoir and cap rocks is minor and within the natural variability (Fig. 10). The variation of the porosity estimated by different methods is generally low for the corresponding depths of the lithological sections. The mineralogical investigations on the samples show also no significant dissolution or precipitation of minerals and find only minor quantities (usually < 2 vol%) of various species of newly precipitated carbonates with three potential CO_3^{2-} sources: dolomite dissolution, reactions of injected CO_2 with the formation fluid, and the drill mud (Bock et al. 2013). The influence of the potash-containing drilling fluid of the well Ktzi 203 could be determined by porosity investigation on twin samples from inner and outer parts of the cores. Especially for porous outer core samples NMR core

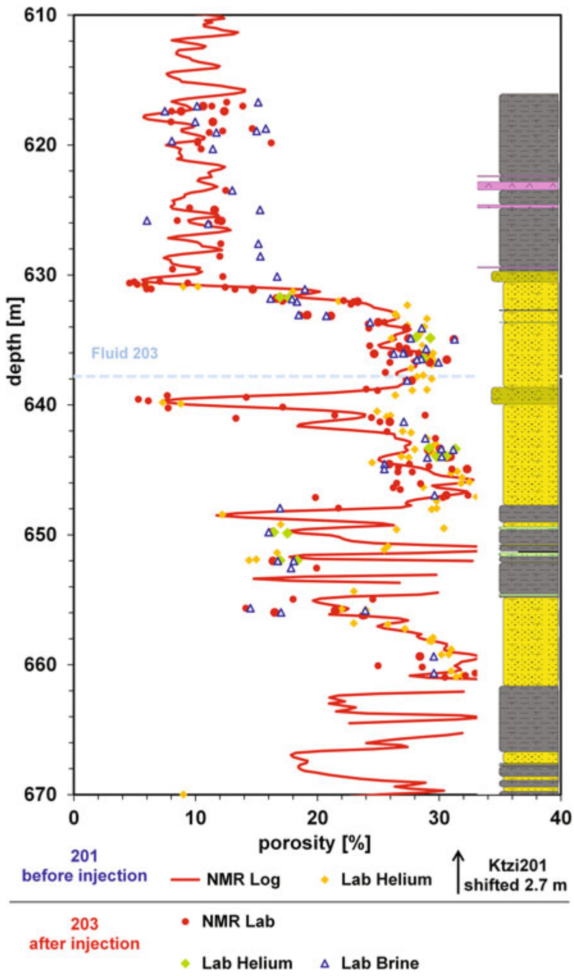

Fig. 10 Porosity—cross plot of neighboring wells with similar lithology: Ktzi 201 before the injection of CO_2 and Ktzi 203 after four years of injection with schematic lithology. Ktzi 201: porosity from NMR log and from Helium pycnometry reported by Norden et al. (2010). Depth was shifted by 2.7 m to correlate the cemented sandstone at 640 m. Ktzi 203: porosity from NMR, Helium pycnometry and brine saturation after Archimedes from laboratory measurements of cores

measurements show a reduced fraction of larger pores together with lower porosities and so only inner core samples were used for further investigation.

Comparison with data from the open hole logging (e.g. gamma ray, neutron-neutron, resistivity, sonic, PNG) of the neighboring wells show clear difference for corresponding units before and after the injection for the reservoir sandstone and no difference in the overlaying cap rock units, because methods are more sensitive to the CO_2 in the pore fluid and do not exhibit changes in the rock matrix, which affect the capacity, injectivity or integrity of the storage system.

Due to the heterogeneous character of the Stuttgart Formation it is difficult to estimate definite CO_2-induced changes from petrophysical measurements. However, given the only minor differences between rock samples from pre- and post-injection, it is reasonable to assume that the potential dissolution-precipitation processes appear to have no severe consequences on reservoir and cap rock integrity or on the injection behavior. This is also in line with the continuously recorded injection parameters which do not point to any changes in reservoir injectivity.

4.2 Microbiology

The microbial biocenosis was monitored in fluids taken from the deep wells of the Ketzin pilot site before and during the CO_2 injection. Drilling fluids, cleaning procedures and the CO_2 injection itself affected the microbial community of the fluids in its composition and abundance as detected by genetic fingerprinting (SSCP) and fluorescence in situ Hybridisation (FISH). Before CO_2 injection, up to 10^7 cells ml^{-1} with up to 40 % sulphate reducing bacteria (SRB) were enumerated in well fluids with DAPI staining (Morozova et al. 2010). The clean-up of wells prior to CO_2 injection reduced temporarily the total cell numbers by one order of magnitude, the numbers of SRB were below detection limit and the TOC declined from 600 to 20 mg l^{-1}. However, after 5 months of exposure to CO_2 cell numbers and the microbial activity increased again (Morozova et al. 2010). SRBs were quantified to 20 % of total cell numbers and remained at a high level until the third year of storage. Subsequent to the CO_2 exposure and during 5 years of monitoring the TOC concentration showed high variations between 1 and 160 mg l^{-1} in the injection and observation wells. Going along with decreasing TOC contents over the years also the cell numbers declined slowly. After 5 years, the SRB numbers were again below the detection limit in all wells.

The results indicate that the microbial community was able to adapt to the changes of the deep biosphere environmental conditions caused by the CO_2 injection and was mainly influenced by the availability of TOC strongly affected by technical procedures. Thus, a decrease in total cell numbers and the SRB numbers was first observed after 3 years of CO_2 exposure and corresponded to the decreasing concentrations of organic carbon in the well fluids. This long-term effect of organic carbon to the deep subsurface on the microbial biocenosis clearly emphasizes the need to limit the use of organic substances for drilling and maintenance procedures. Especially the high abundance of SRB in the first 3 years of CO_2 storage might pose a risk as SRB are known to be involved in microbial induced corrosion processes. The increase of iron concentrations after start of the CO_2 injection and arrival of the CO_2 at the observations wells was suspected to be a result of mobilization effects due to the injected CO_2 and/or of corrosion processes. However, in the Ketzin case, well inspections gave no indications for technical relevant corrosion effects to the casings.

The quantity and diversity of subsurface microorganisms differed significantly between fluid- and sediment-associated populations within the same formation, which is in accordance with other studies in deep aquifers (Fry et al. 1997; Hazen et al. 1991). Cell numbers enumerated in sandstone cores of the Stuttgart Formation

(Wandrey et al. 2010) were at least four orders of magnitude lower than in the well fluids collected via hydraulic testing and downhole sampling. In the reservoir sandstones, the concentration of low molecular weight organic acids like acetate and formate were below 0.1 % (Scherf et al. 2011). However, activity and numbers of microorganisms could be significantly increased if organic carbon is introduced by drilling procedures or mobilized and enriched by injected CO_2.

4.3 Organic Geochemistry

At typical CO_2 storage conditions, CO_2 is known as an excellent solvent for low to medium polar organic compounds (Hawthorne 1990) and extraction and mobilization of the organic matter present in the reservoir by the injected CO_2 is most likely. When studying storage of CO_2 in coal seams, the release of hydrocarbons from the coals has been investigated in more detail (Kolak and Burruss 2006). During and after CO_2 injection into a deep saline aquifer (Frio Formation, USA) a strong increase in DOC (dissolved organic carbon) as well as an increase in concentrations of formate, acetate and toluene has been observed in fluid samples (Kharaka et al. 2009). At the Ketzin pilot site, rock samples from the reservoir formation have been tested for the mobilization of different organic compounds during extraction with CO_2 at in situ reservoir conditions in lab experiments (Scherf et al. 2011).

Within the CO_2MAN project, the effects of injected CO_2 on the natural organic matter in reservoir and cap rock have been characterized using three different approaches: (i) characterization of natural organic matter in reservoir and cap rock samples prior and after the injection of CO_2; (ii) monitoring of changes in DOC in fluid samples from the wells Ktzi 200, 201 and 202 prior and during the injection of CO_2; (iii) monitoring of organic compounds being transported with the injected CO_2.

To characterize the quality and quantity of organic compounds that are transported with the injected CO_2, one riser tube (stainless steel, inner diameter 5 mm, total volume 12 l) installed in well Ktzi 202 was used for the continuous sampling of fluids from the reservoir horizon (compare Sect. 3.4). Fluids were produced from a depth of 600 m with a flow rate of 5 l/min. The produced gas was percolating through a gas washing bottle filled with distilled water or dichloromethane (DCM) over different times. In general, the amount of organic compounds increases with increasing washing times. This clearly shows that solubility is not limiting the extraction and that these compounds are not strongly degraded in the gas washing bottle. Variable yields of total DOC and of different aliphatic acids have been detected in the water samples over the monitoring period (Fig. 11). In all samples, yields of propionate, butyrate and valerate are very low whereas yields of acetate and formate are much higher. It seems as if the yields of individual organic acids are quite variable within our monitoring but that yields are not related to the duration of

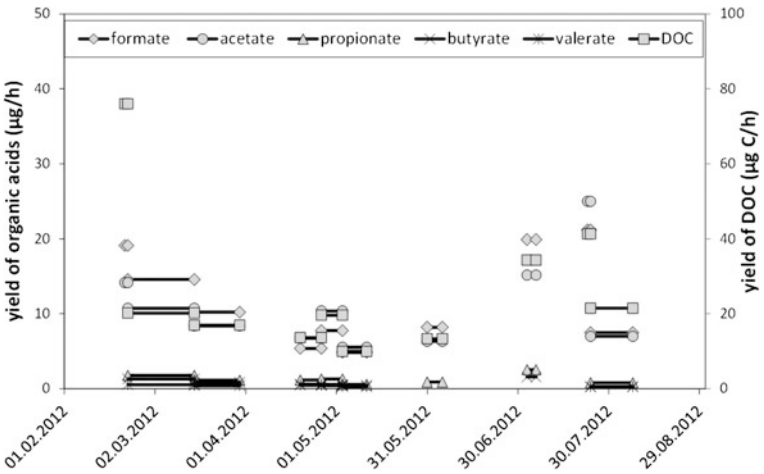

Fig. 11 Yields of LMW organic acids (in µg/h) and DOC (in µg C/h) washed out from produced gas into distilled water (well Ktzi 202; February–October 2012)

the washing experiment or to the observed decrease in distilled water volume in the gas washing bottle. Using size exclusion chromatography DOC was separated into different fractions. Dominant DOC-fractions were low molecular weight (LMW) acids (30–50 %) and LMW neutrals (40–60 %).

DCM extracts from the washing bottle contained a huge amount of phthalates. These esters are commonly used as plasticizers and are derived from the tube connection between riser tube and gas washing bottle. Composition of hydrocarbons (n-alkanes from nC_{14} to nC_{26}, hopanes and steranes) in all DCM extracts is comparable. In DCM extracts the distribution of hopanes is comparable to some technical additives that have been used in drilling and injection activities at Ketzin. Thus, it cannot be easily distinguished if the organic compounds detected in gas washing bottle extracts are derived from natural organic matter of reservoir, cap rock or formation fluids or from anthropogenic activities at the pilot site.

5 Modelling, Simulations and Data Management for the Ketzin Project

Sound geological models are a prerequisite to the sustainable and safe use of the subsurface. They consist of the structural geometry of geological bodies and their properties. Like for all models, appropriate simplifications of the in situ conditions are necessary to allow e.g. the simulation of complex dynamic processes. Depending on the purpose of the applied simulation, different models need to be considered, for example for the evaluation of the long- or short-term behavior of the CO_2 distribution in the subsurface or for the evaluation of rock-fluid interactions. In the course of the CO_2MAN project, the geological models of the Ketzin project including reservoir models of the storage formation and structural models of the wider area were updated. The static model was then used for further dynamic reservoir simulations taking into account hydrodynamics as well as geochemical and geomechanical processes.

5.1 Integrative Geological Modelling

For the Ketzin pilot site, like for many other sites worldwide, the challenge is to integrate a diversity of information of both local and regional origin as well as of different data types and formats and combine it for consistent models. Data available for the Ketzin project include reconnaissance data (e.g. regional geological maps, borehole reports, logging data, core data, hydraulic test data, seismic surveys from the 1960s and 1970s) and data collected during development and operation of the storage site. Important details are given for the first evaluation of open-hole logging data by Norden et al. (2010), for the first interpretation of the seismic data by Juhlin et al. (2007), Kazemeini et al. (2009) and Yordkayhun et al. (2009), and for the near-surface groundwater system by Norden (2011). The characterization of the storage formation is presented by Förster et al. (2009, 2010) and hydraulic and monitoring data is presented by Würdemann et al. (2010), Martens et al. (2012, 2013), Wiese et al. (2010) and Ivanova et al. (2012).

Data was integrated using the commercial software package Petrel. As neither the Ketzin seismic 3D data nor the borehole data is supplying sufficient information to resolve the internal structure of the complex fluviatile Stuttgart Formation in any detail and thus do not allow a deterministic modelling of the facies architecture and related properties of the reservoir, geostatistical approaches were used (Norden and Frykman 2013). The resulting geological models were step-wise adapted if necessary, guided by observations based on new drillings at the Ketzin site and based on the results of the monitoring. In return, the geological models supported the interpretation of the monitoring data (e.g. Bergmann et al. 2012, 2014; Chen et al. 2014).

The geological models of the Ketzin pilot site consist of reservoir models of the storage formation and structural models of the wider Ketzin area, including the overburden with its multi-barrier cap rock system. At the top of the anticlinal Ketzin structure, a Graben fault zone is present which is related to the updoming of the Roskow-Ketzin salt pillow (Fig. 12a). The faults of this graben extend from the Base Tertiary (see e.g. Juhlin et al. 2007) to the Buntsandstein and do most likely reach down to the Zechstein salt (although not resolved by the Ketzin 3D seismic data). These faults were not present at the time of deposition of the Stuttgart Formation. The shown petrophysical characterization of the Stuttgart Formation is one possible scenario taken into account the general geological setting and the existing borehole data (facies, porosity, permeability etc.; Fig. 12b). Based on such a scenario, dynamic simulations were performed to model the distribution of CO_2 in the reservoir (e.g. Kempka et al. 2010; Kempka and Kühn 2013).

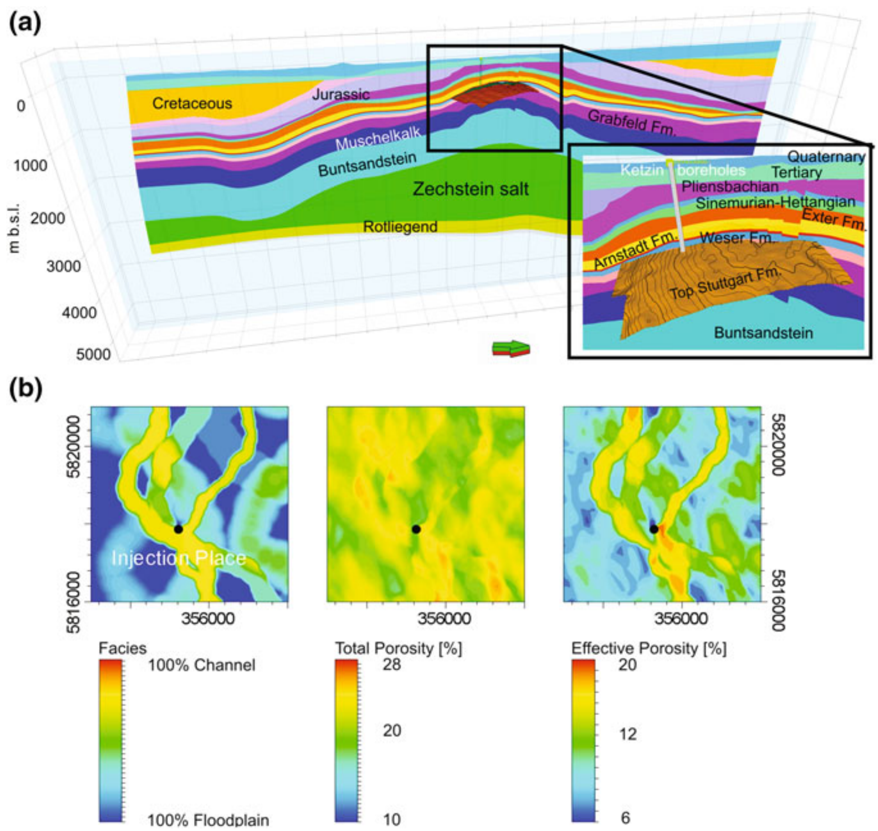

Fig. 12 **a** Regional S–N section of the Ketzin pilot site. Length of profile approx. 40 km. The inlet map shows the Top Stuttgart surface. Drilling paths and offsets along faults could be recognized. Exaggeration is 3-fold. **b** Average facies and porosity maps of the uppermost 20 m of one realization of the Stuttgart facies model. Plotted are mean facies distribution (*left*), average total porosity (*middle*), and effective porosity (*right*). The location of the Ketzin pilot site is indicated by a *black dot*. The size of the reservoir model is 5 km × 5 km (Figure adapted from Norden and Frykman 2013)

5.2 Reservoir Simulations

Numerical multi-phase flow simulations were already carried out in the planning phase of the Ketzin project by different modelling groups to account for sustainable injection rates in terms of reservoir pressure elevation and expected CO_2 arrival times at the two observation wells Ktzi 200 and Ktzi 202. A prediction of CO_2 arrival times at both observation wells was undertaken in advance of the start of injection in June 2008. While the numerical simulators applied showed relatively small differences in simulation results, all numerical modelling groups were only able to match the CO_2 arrival time at the Ktzi 201 well, while that predicted for the Ktzi 202 well was underestimated by a factor of three (Kempka et al. 2010).

Integration of new monitoring data becoming available with the increasing amount of monitoring activities and campaigns at the Ketzin pilot site with time allowed us for revisions of the geological model (Norden and Frykman 2013; Kempka et al. 2013a) resulting in an excellent agreement of the simulation results with the CO_2 arrival times at both wells and of downhole pressures determined at the Ktzi 201 and Ktzi 202 wells (Kempka and Kühn 2013). Using the resulting calibrated (history-matched) numerical models, we were able to predict the Ktzi 201 downhole pressure for more than 1 year of operation (January 2012 onwards) including an injection stop of about 6 months with low deviations only (Class pers. comm.).

Furthermore, we were able to carry out long-term predictions on reservoir stabilization by means of development of CO_2 trapping mechanism contribution illustrated in Fig. 13 (Kempka et al. 2013b). Thereto, innovative hydro-chemical coupling concepts as discussed by Klein et al. (2013) were employed to account for long-term mineral trapping at reservoir scale for the Ketzin pilot site. Our simulation results show that at a simulation time of 16,000 years almost all CO_2 is dissolved in the formation fluid (0.2 % remaining residually trapped in gaseous state), while 11.7–30.9 % precipitate as siderite and dolomite depending on the assumptions underlying the hydro-chemical simulation model (compare Sect. 5.3).

The numerical reservoir simulation results were coupled to hydro-mechanical simulations to account for mechanical system integrity (compare Sect. 5.4).

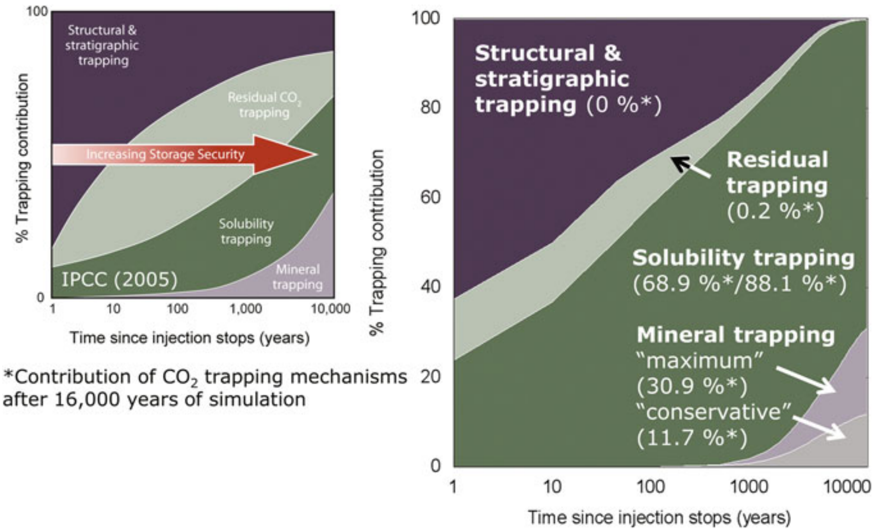

Fig. 13 *Left* General CO_2 trapping mechanisms in geological formations (IPCC 2005). *Right* simulated trapping mechanisms of CO_2 for the Ketzin pilot site

5.3 Geochemical Simulations

The quantification of water-rock interactions in reservoir and cap rock triggered by the injection of CO_2 at the Ketzin pilot site was carried out by means of batch geochemical models and coupled reactive transport simulations based on the available characterization of the Stuttgart formation and the pristine formation fluids (Förster et al. 2006, 2010; Norden et al. 2010 for the mineralogical analyses on core samples and Würdemann et al. 2010 for fluid analyses).

3D reactive transport models on computationally affordable coarse grid predict that mineral trapping of CO_2 at the Ketzin pilot site will be dominated by siderite, dolomite and magnesite, with only transient appearance of calcite (Fig. 14). Significant precipitation in the reservoir will start only about 500 years after injection stop and is expected to continue for at least 10,000 years (the considered simulation time). Clay minerals such as illite and chlorite and anhydritic rock cement will be dissolved by the CO_2-charged fluids. The net predicted result is a negligible loss of porosity, since the largest predicted change in mineral volume amounts to only about 3,000 cm^3/m^3 of rock (=0.3 vol%). However due to the spatially quite large extent of the reservoir affected by chemical reactions due to the CO_2 migration, up to 40 % of the total injected carbon is predicted to be minerally trapped after 10,000 years. However this result could be overestimated due to the coarse grids used for the simulations and consequent poor matching of observation data and migration pattern of CO_2 in the reservoir. Thereto, a novel one-way coupling strategy for multiphase hydrodynamics and chemistry has been developed (Klein et al. 2013) and validated for the Ketzin pilot site. Through this strategy it is possible to consider much larger, heterogeneous grids for multiphase flow and more

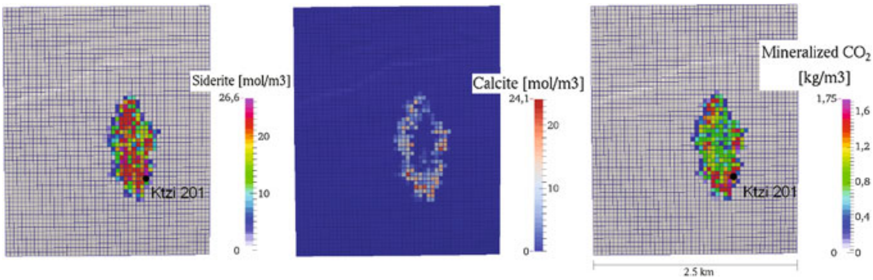

Fig. 14 Top view of 3D reactive transport models 2,200 years after injection stop at Ketzin. The size of the model is 2.5 km × 3.5 km. The injection well Ktzi 201 is marked by a *black dot*. Depicted are the main CO_2 sink minerals, the iron carbonate siderite (*left*), the transient appearance of calcium carbonate calcite (*middle*) and the overall amount of carbon-bearing precipitates in reservoir (*right*). Coarseness of the grid, boundary conditions and spatial heterogeneity of porosity and permeability are in these reactive simulations simplified due to constraint on the number of grid elements allowable for the computationally expensive coupled simulations. This is reflected in differences in the migration pattern of the CO_2 in comparison with seismic monitoring and non-reactive modeling and therefore in the distribution of mineralization

complex chemistry without the oversimplifications necessary for the fully-coupled simulations. The resulting error is acceptable, mainly arising from the assumptions about the minimum CO_2 gas saturation and dissolved CO_2 concentration that can be considered geochemically active. It was confirmed by extensive validation that choosing reasonable cut-offs for these quantities achieves good matching with fully-coupled simulations. This method contributed to the evaluation of the mineral trapping potential using the history matched simulations of Kempka and Kühn (2013) and predicted that between 11.7 and 30.9 % (following a conservative or optimistic cut-off choice, respectively) of the injected CO_2 will be mineralized after 16,000 years (Kempka et al. 2013b). 1D reaction-diffusion models of dissolved CO_2 into the first layers of mudstone cap rock predict that CO_2 would penetrate for about 5 m in the cap rock after 500 years. The models show an overall tendency of loss of porosity through newly precipitated carbonates and thus highlight the self-healing potential of the covering horizon.

The results of 3D coupled reactive transport models point towards a long-term stabilization of the reservoir at the Ketzin pilot site, with no significant mineral alteration during the operational time.

5.4 Geomechanical Modelling and Simulation

Mechanical system integrity taking into account reservoir rock, cap rock and fault integrity was assessed by hydro-mechanical simulations for the Ketzin pilot site (Kempka et al. 2014). For that purpose, history matched reservoir simulations (Kempka and Kühn 2013) were considered as a basis for our one-way hydro-mechanical model simulations. Thereto, a 40 km × 40 km × 5 km hydro-mechanical model with twelve lithological units and 24 discrete major faults was implemented based on a previously elaborated 3D structural geological model considering 2D/3D seismic and well log data as well as available geological maps. The mechanical model was discretized by about 1.4 million elements with sizes of 50–800 m in horizontal and 20–160 m in vertical direction. A refinement of the lateral grid discretization was carried out to capture hydro-mechanical processes in the near-well area.

An initial stress regime with a maximum horizontal stress azimuth of 150° ± 5° and a magnitude of $S_{Hmax} = S_{hmin} = 0.85\ S_v$ (normal faulting stress regime), with S_{Hmax} representing the maximum horizontal stress, S_{hmin} the minimum horizontal stress and S_v the vertical stress, was assigned to the hydro-mechanical simulation model in agreement with the interpretation of sonic logs from the Ktzi 201 well (Sinha et al. 2010). Hereby, S_v was determined from the gravitational load of the overburden using numerical simulations.

Mechanical model parameterization followed the data on the Northeast German Basin given by Ouellet et al. (2010), Nagelhout and Roest (1997) and Kopf (1965). The Mohr-Coulomb plasticity model was applied for the rock matrix and the FLAC3D ubiquitous joint model (Itasca 2012) for fault representation. Thereto, an element-wise representation of fault geometries by means of dip direction angle and

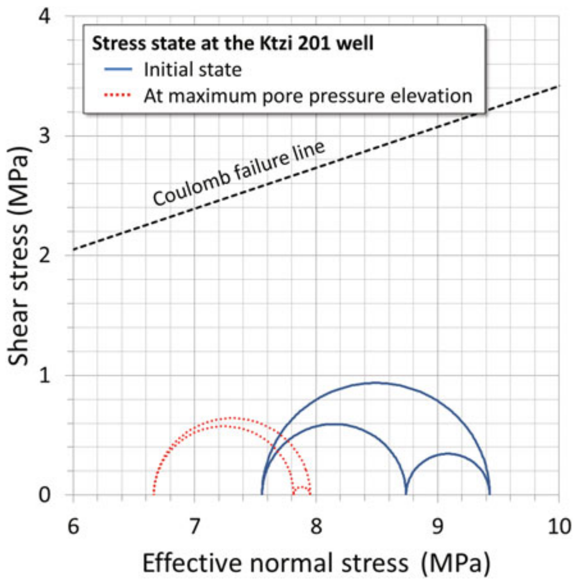

Fig. 15 Initial stress state (*blue*) and state at maximum pore pressure elevation (*red*) at most upper element of storage formation at injection well Ktzi 201 based on numerical hydro-mechanical simulations

dip angle was taken into account to allow for a detailed fault analysis. After running the hydro-mechanical model to a mechanical equilibrium, spatial pore pressure distributions calculated for 14 different time steps by the numerical reservoir simulations (compare Sect. 5.2) were integrated as coupling parameter into the hydro-mechanical simulations.

Simulation results show maximum vertical displacements of about 6 mm at the reservoir top and about 4 mm at the ground surface in March 2010 with a maximum vertical displacement radius of up to 3 km. Both are in good agreement with the hydro-mechanical simulations carried out by Ouellet et al. (2010) considering the first 500 days of CO_2 injection only. Neither shear nor tensile failure is observed at any time step in the rock matrix and ubiquitous joints elements (representing the faults) in the hydro-mechanical model due to the limited increase in pore pressure resulting from the CO_2 injection (Fig. 15). The reservoir and coupled numerical simulation results, therefore, suggest safe and reliable CO_2 storage operation at the Ketzin pilot site.

5.5 Data Management

Comprehensive understanding of subsurface processes of CO_2 storage at the Ketzin pilot site requires reliable geological interpretation and modelling at multiple scales which only become possible by a careful integration of results derived from drilling and different monitoring approaches (Behrends and Conze 2012). Thus, the integrative compilation of geological, operational and scientific monitoring data which had started with the CO_2SINK project was continued and extended in the CO_2MAN project.

Since the first wells for research purposes were drilled at Ketzin in 2007, a data entry system was provided during the acquisition phase of geological field data and continuously extended throughout the subsequent projects. Hence, this system was also used when the wells P300 and Ktzi 203 were drilled in 2011 and 2012, respectively.

A web-based data management system (DMS) contributes to a close cooperation among scientists from different disciplines. The main functions of the DMS implemented for the CO_2MAN project were:

- *Information*: Dissemination of project management material (planning documents, internal reports, conference abstracts, papers etc.) and new science data sets.
- *Archiving*: Provision of metadata-, long-term storage-, reporting- and downloading-services; integration of published data with new unpublished working data sets and legacy data sets from predecessor projects and external partners.
- *Collaboration*: Exchange platform to internal data sets, benchmarking, quality and version control of data sets and models.

The data management system was implemented using a secured web-based platform. Target audiences were all members of the project consortium. Science data sets stored in the system comprise e.g. basic geological data, technical drilling data, down-hole measurements, monitoring time series along the injection history up to geological models of the storage formation. The software development project had to deal with heterogeneous data sets of diverse origin, different scales and data file formats. It is required to extend the workflow of curating science data to later project phases. All these services can be continuously used and will be further developed during the follow up project COMPLETE.

6 Public Outreach

For the Ketzin project, public outreach was a key element from the very beginning and already started in 2005 to ensure an open and transparent dialogue with all stakeholders (Schilling et al. 2009b). During the course of the project, it turned out to be important to provide up-to-date information and keep the dialogue with the public (Martens et al. 2013). Thus, public relations were also a central component of the CO_2MAN project. In order to inform the general public about the background of CO_2 storage and the research results from Ketzin manifold information material was developed and disseminated using various communication tools (Szizybalski et al. 2014).

The main contact point is the information centre at the Ketzin pilot site where a visitor service is offered on a weekly basis. With the expansion of the centre in

2011 larger visitor groups could be welcomed and more permanent exhibits presented. About 2,140 people from Germany and abroad visited the pilot site throughout the CO_2MAN project phase whereof most were students and scientists ($\sim$50 %) and the general public ($\sim$25 %).

Since 2011, an annual open house day was held at the pilot site (Fig. 16). At these events, visitors can inform themselves about the research activities during guided tours and presentations and talk to scientists (Martens et al. 2013). The open day is carried out in close cooperation with the city of Ketzin as we also include the local fire brigade and the local retail, e.g. musicians, bakery, and the Ketzin tourist information. At the annual “Long Night for the Sciences” in Berlin and Potsdam the Ketzin project is also presented already since 2007. For educational activities it is important to provide comprehensible information materials and experiments, for example, demonstrating the presence of CO_2 in everyday life or the concept of CO_2 trapping mechanism. Therefore, five mobile experiments were added as information tools and used, for example, during school visits.

The initial Ketzin project website, which was developed during the CO_2SINK project, was superseded by the public website http://www.co2ketzin.de in 2011. Besides background information on the Ketzin project, the history of the pilot site, the objectives and current status of CO_2MAN were presented in both German and English. In addition, a bilingual Ketzin brochure was regularly updated according to the current status of the project and also made available on the website. The information material was complemented by a film entitled “The geological storage of CO_2” made up of seven short segments (Hübner et al. 2013) funded by the CLEAN project also including an overview of the Ketzin pilot site. A further short film which was produced within the CO_2MAN project documents the drilling activities at Ketzin in 2011 and 2012. These short films are available on the public website, on DVD and are also shown during visits at schools.

Our public outreach activities are reflected by a mainly positive media resonance and a wide public acceptance for the research activities at Ketzin, allowing the research on CO_2 storage, e.g. large-scale seismic measurements, to be conducted without severe restrictions.

Fig. 16 Annual open house day at the Ketzin pilot site (*left*: June 2012; *right*: June 2013)

7 Conclusion

The Ketzin project is one of the world's most significant sites for investigating CO_2 storage on a pilot scale. In the course of the CO_2MAN project, two new boreholes could be drilled at the site and the CO_2 injection was continued and finally ceased after the injection of a total amount of 67 kt of CO_2 on 29 August 2013. The accompanying scientific activities in the work packages "Research Infrastructure", "Geophysical Monitoring", "Reservoir Processes" and "Modelling and Simulations" as well as in the fields of data management, public outreach and project management were completed as planned and afforded a rich learning experience. The results obtained in the joint research project show that:

- the geological storage of CO_2 at the Ketzin pilot site runs safely and reliably,
- a meaningful, site-specific combination of geochemical and geophysical monitoring techniques is able to detect even small amounts of CO_2 and to image its spatial distribution,
- fluid-rock interactions induced by the injected CO_2 have no significant effects at the Ketzin pilot site and do not affect the integrity of the reservoir and cap rocks,
- numerical simulations are able to predict timely and spatial behavior of the injected CO_2 and to provide prognosis on the long-term behavior of the storage formation
- a targeted communication and dissemination programme is able to establish a wide public acceptance for research activities like the Ketzin project and to overcome critical public perception even for highly debated technologies.

Although the CO_2 injection at Ketzin ceased in August 2013 and the CO_2MAN project ended in December 2013, R&D activities on CO_2 storage are still underway in order to address and close the entire life cycle of a storage site. Hence post-injection monitoring and well abandonment are the main focus of the on-going post-injection phase and part of the COMPLETE project which has started in January 2014.

Acknowledgments The authors thank all participants of the CO_2MAN project who made the Ketzin project a success. We would also like to acknowledge the German Federal Ministry of Education and Research (BMBF—Grant numbers 03G0760A to F), Dillinger Hüttenwerke, OMV, RWE, Saarstahl, Statoil and Vattenfall for funding as well as the site owner VGS and the Projektträger Jülich for their continuous support.

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