TOUGH2 SIMULATION OF THE PUMPING TESTS AT KETZIN SITE: HETEROGENEITY EFFECTS AND MODEL CALIBRATION

Fei Chen, Quanlin Zhou, Jens Birkholzer

Lawrence Berkeley National Laboratory
One Cyclotron Road
Berkeley, CA, 94720, USA
e-mail: fei.chen@lbl.gov

Bernd Wiese, Ben Norden, Thomas Kempka

GFZ German Research Centre for Geosciences
Telegrafenberg
14473 Potsdam, Germany

ABSTRACT

The Stuttgart Formation used for CO_2 injection at the Ketzin pilot site in Germany is highly heterogeneous. The characterization data, including 3D seismic amplitude image, the regional geology data, and the core measurements and geophysical logs of the wells, show a lithologically heterogeneous formation composed of permeable sandstone channels of varying thickness and length embedded in less permeable mudstones. At the storage site, most of the sandstone channels are located in the upper 20 m of the formation, with only a few sparsely distributed sandstone channels in the lower part of the about 70-80 m thick formation. Due to the low channel thicknesses, the explicit spatial pattern of these channels could not be obtained from the 3D amplitude image. Heterogeneity has a large effect on the pressure propagation measured during a suite of pumping tests conducted in 2007-2008 and also impacts strongly the CO_2 arrival times observed during the ongoing CO_2 injection experiment. To understand the varying effects of heterogeneity at the Ketzin pilot site and calibrate the spatial variability of permeability and porosity using the field monitoring data, we developed a TOUGH2 model for modeling the hydraulic pumping tests. A geological model calibrated against downhole pressure of two wells and the CO_2 arrival times was used in the simulations discussed here. Our modeling results show that the simulated pressure responses to the pumping tests were significantly different in magnitude from the measured data. A systematic increase or decrease of permeability fails to improve the matches to the pressure data in all observation wells. Further work is needed on the calibration of the geological model against the pumping test results using inverse modeling approaches.

INTRODUCTION

The Ketzin pilot site is the first pilot test site for onshore CO_2 injection into a natural saline aquifer in Europe (Martens et al., 2012; Würdemann et al., 2010). It is located in the eastern part of a double anticline (Ketzin-Roskow anticline) in Northern Germany. Food grade supercritical CO_2 has been injected into the Upper Triassic Stuttgart Formation situated between 630 and 710m below the ground surface. The Stuttgart Formation is lithologically highly heterogeneous. Site characterization shows the formation is composed of highly permeable sandy channels of varying width and length alternated with the facies of low-permeability mudstone (Förster et al., 2006). The width of the channel belts ranges from several tens to hundreds of meters involving stacked sub-channels (Förster et al., 2006; Norden and Frykman, 2013). The spatial distribution of the permeable channels is difficult to predict (Frykman et al., 2006; Norden and Frykman, 2013). For the injection site, the log and core data show that the majority of the permeable channels are located in the top 20 m of the formation with only a few sparsely distributed in the bottom 60-m layer (Norden et al., 2010; Norden and Frykman, 2013). Above the Stuttgart Formation are layers of claystone, silty claystone and anhydrite. They have an average thickness of about 180 m, and provide an excellent seal for the saline aquifer (Förster et al., 2006).

Subsurface heterogeneity has a large effect on pressure propagation and fluid flow. The data obtained from the CO_2 injection and hydraulic tests, in return, can provide us information for better understanding of the heterogeneous storage formation. The CO_2 injection test at the Ketzin pilot site shows that CO_2 arrived at one of the observation wells (Ktzi 200) that is 50 m apart from the injection well (Ktzi 201) after 21.7 days, while it took 271 days to reach the other observation well (Ktzi 202) which is 112 m away from the injection well (Liebscher et al., 2013). First 3D simulations were applied to calibrate the geological model against the CO_2 arrival times as discussed in Kempka et al. (2010). The model was in good agreement with the first arrival time but failed to capture the one at the second observation well (Ktzi 202). The revision of the Norden and Frykman (2013) model undertaken using 3D seismic repeat besides other monitoring data is addressed in Kempka et al. (2013).

A suite of hydraulic pumping tests were conducted in the three wells between September 2007 and January 2008. Due to the multiple other objectives to be served, the pumping events were not optimized for the hydraulic tests (Wiese et al., 2010). For example, with the intention to remove all the fluids from the borehole, packers were not used in the pumping tests. The pumping rates were adjusted between 1.1 m^3/h and 1.8 m^3/h, based on the allowable drawdown (Wiese et al., 2010). Pressure in the pumping well was measured at locations close to the pump and the bottom-hole screen, while the pressures in the observation wells were measured about 5-15 m below the water table. The pumping test results were interpreted using analytical solutions by Wiese et al. (2010). They found that the effective permeability of the 20-m permeable zone is about one order of magnitude lower than the mean permeability of the core samples, a phenomenon has not been found in previous literature (Wiese et al., 2010). Simulations of the pumping tests with attempts to calibrate the geological model with these data were not carried out yet.

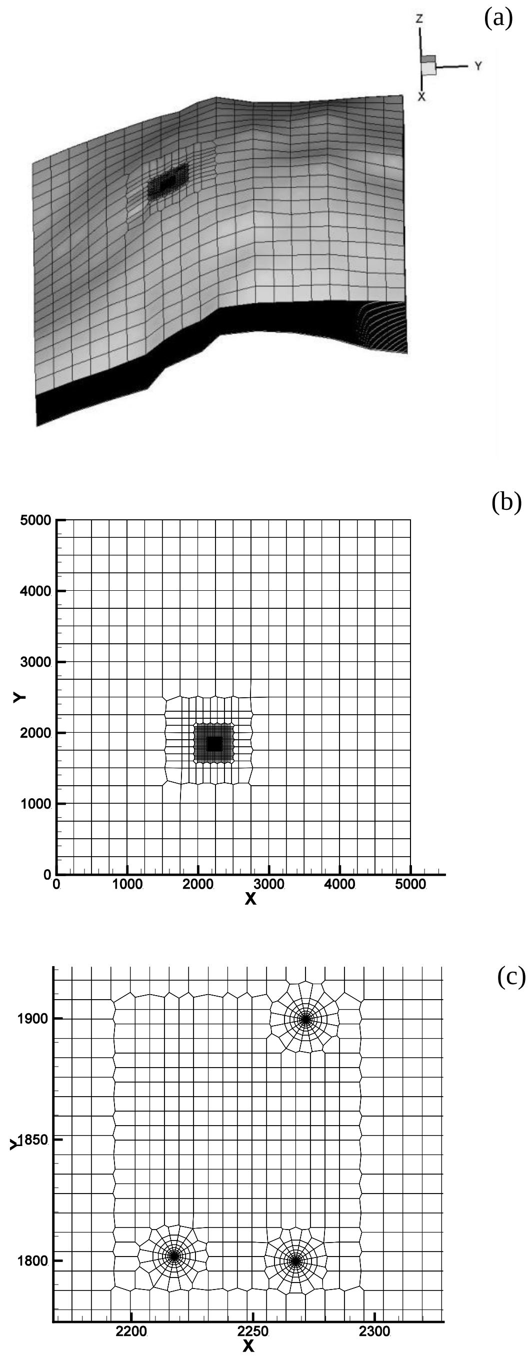

Figure 1 Generated mesh for the 5 km× 5 km model domain (a) in 3D view, (b) in plane view, (c) near the wells

To understand the varying effects of heterogeneity at the Ketzin site and calibrate the spatial variability of permeability and porosity using the field monitoring data, we developed a TOUGH2 model for the hydraulic pumping tests. The initial geological model of the

Stuttgart Formation at the Ketzin pilot site as introduced by Norden and Frykman (2013), revised as described in Kempka et al. (2013) and calibrated against downhole pressures as well as CO_2 arrival times by Kempka and Kühn (2013) is applied for the simulations in the present study. We then compare the simulation results with the measurement data.

(a)

(b)

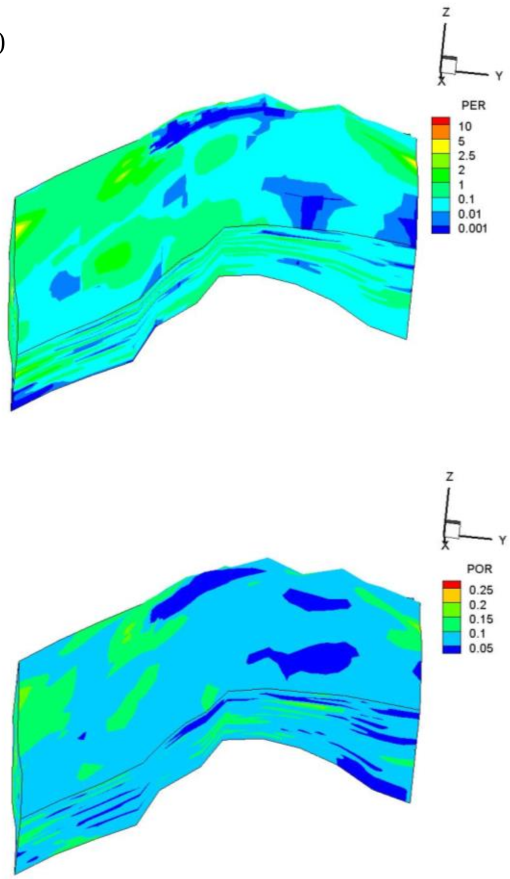

Figure 2 Permeability (a) and porosity (b) distributions used in the model

MODEL DEVELOPMENT

A geological model was generated using a geostatistical approach, based on a collection of measurement data including seismic profiles, stratigraphic and lithological information from boreholes, and CO_2 arrival time (Kempka et al., 2013; Norden and Frykman, 2013). The permeability and porosity distributions used for our model are interpolated from the geological model using the inverse-distance approach.

(a)

(b)

(c)

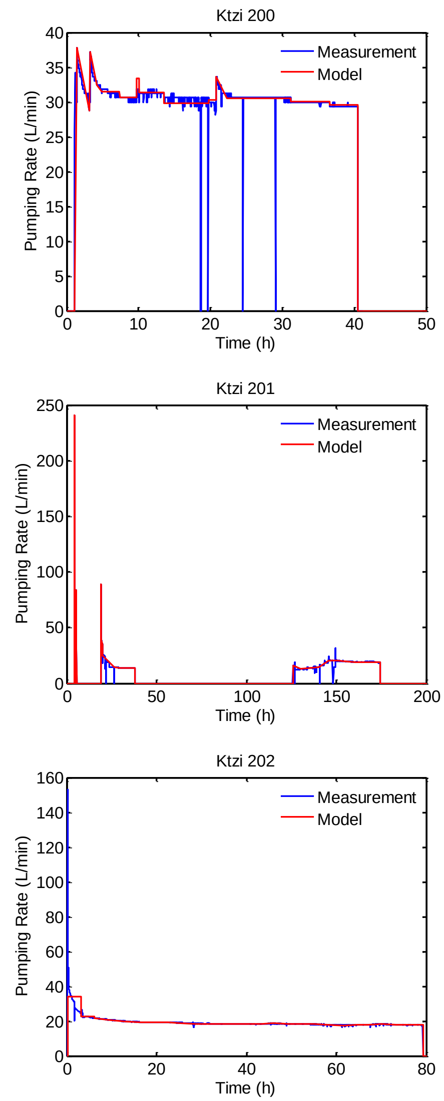

Figure 3 Pumping rates at the wells (a) Ktzi 200, (b) Ktzi 201, (c) Ktzi 202.

We created a three-dimensional grid (Figure 1) using WinGridder (Pan, 2007). The mesh covers an area of 5000 m × 5000 m with the elevation of layers and thickness varying to represent the anticline structure of the Stuttgart Formation. The area away from the wells is discretized by relatively coarse and regularly spaced meshes (250 m ×250 m). The mesh sizes gradually decrease to 4 m × 4 m as it gets close to the wells. Radially symmetric meshes are used to represent the well geometry (Figure 1c). The formation is uniformly discretized in the vertical direction by 74 layers, with the thickness of each layer proportional to the varying thickness of the formation.

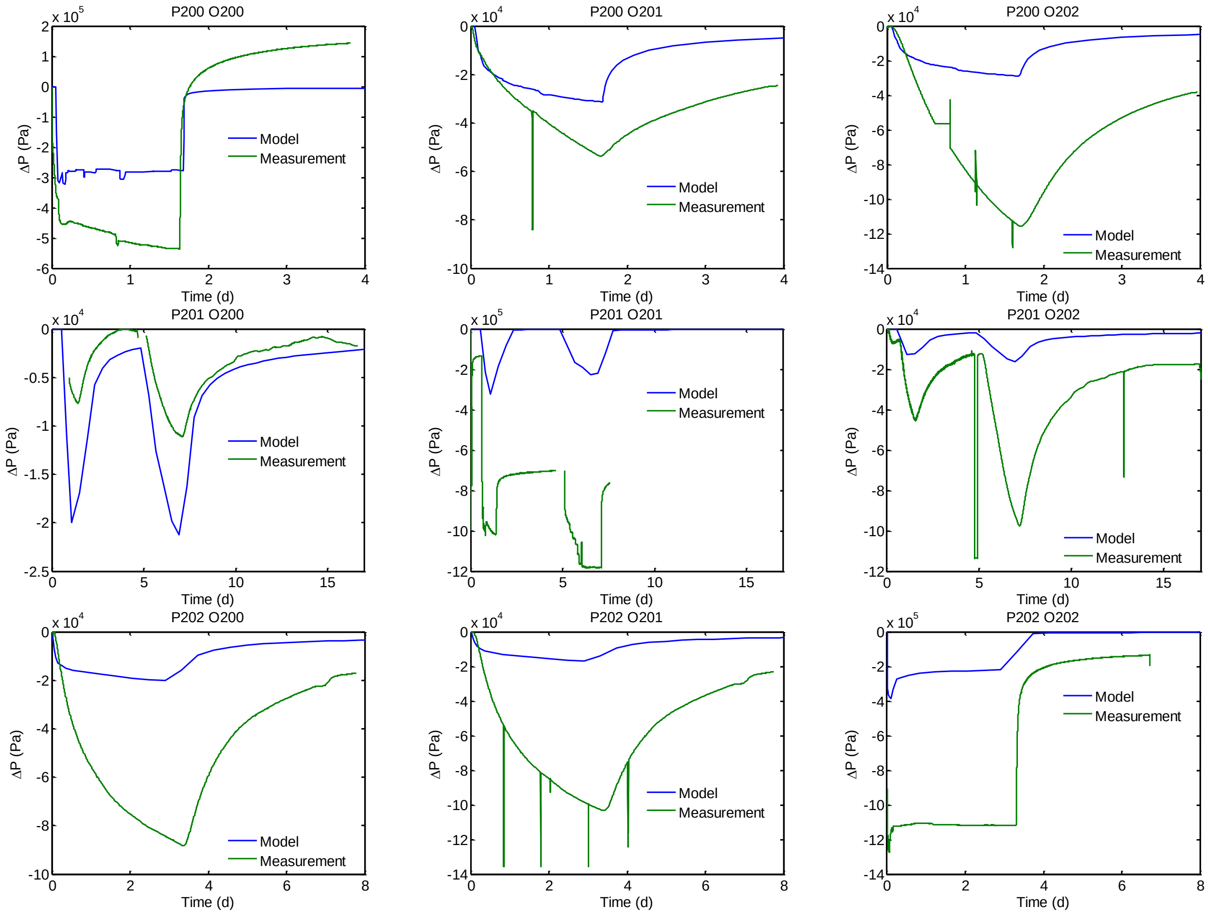

Figure 4 Pressure responses over time based on the geological model introduced in Norden and Frykman (2013) and Kempka et al. (2013)

We use the parallel version of the TOUGH2 code (TOUGH2-MP) (Zhang et al., 2008) with the fluid property module ECO2N (Pruess, 2005) to run the simulation. To simulate the vertical well, the permeability of the well elements is assigned with 4.98×10^{-8} m^2, which is equivalent to the permeability of a pipe with a diameter of 0.12 m. Time-dependent pumping rates are parameterized to fit the actual rates in the operation (Figure 3). No-flow boundary conditions are applied to the top and bottom of the model domain and the lateral boundaries are in fixed condition. The fluid is initially in equilibrium with the hydrostatic pressure. The salt concentration is 0.22 (wt/wt) and the temperature is 34 °C. We do not consider a CO_2 component in the pumping test simulation.

RESULTS

The simulated pressure changes are compared to the measured data (Figure 4). The pressure simulated with the model shows a similar pattern as a response to the pumping, though mismatch exists in the magnitude of pressure responses. There is no systematic trend on the differences between the model and the measurement data. When water is pumped in Ktzi 200 and Ktzi 202, the simulated pressure changes in the corresponding observation wells are less than the measured ones. When pumping in Ktzi 201, the model overestimates the response at Ktzi 200 but underestimates at Ktzi 202. The drawdown caused by a pumping event is affected by the spatial distribution of the hydraulic properties (e.g. permeability). For the well pairs having less pressure changes than the measured data, it is likely the permeability near these wells is

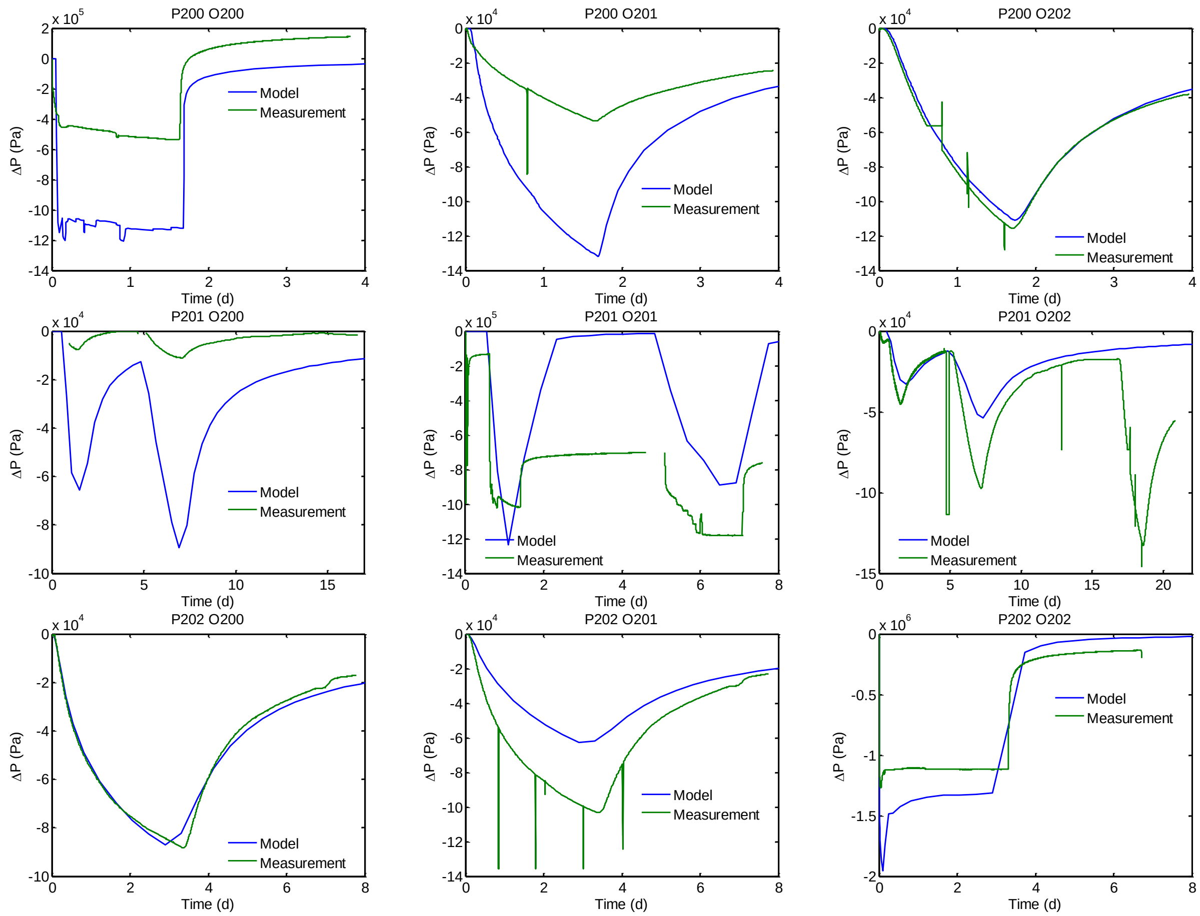

Figure 5 Pressure responses over time with decreased permeability

overestimated in the geological model. On the contrary, for those having larger pressure responses, it is likely the permeability around the region which is underestimated.

The pressure data in the pumping wells are difficult to interpret because many factors contribute to the final results. One of these factors is caused by density difference between brine and the fluid in the borehole. When water is pumped from the pumping wells, the fluid in the borehole is replaced by the brine from the saline aquifer. This density effect can be large. For a 400-m well, if we assume the well is initially filled with freshwater, the maximum pressure difference caused by the density effects can reach up to 6×10^5 Pa. As we mentioned before, the pumping tests serve multiple goals and were not optimized for hydraulic testing. It was reported that technical fluid that has a density close to freshwater was injected into the wellbore before the pumping tests (Wiese et al., 2010). We do not correct the effects caused by brine replacement in this study, but the data corrections are under way (Otto, 2013) to better interpret the pressure data in the pumping wells.

A further simulation is conducted by decreasing the permeability of the system by a factor of 10. It appears that a systematic decrease of the permeability by a factor of 10 improves the match in pressure in Ktzi 202/Pumping at Ktzi 200, Ktzi 202/Pumping at Ktzi 201, and Ktzi 200 and Ktzi 201/Pumping at Ktzi 202. However, the decrease of permeability causes mismatch in other wells such as Ktzi 200/Pumping at Ktzi 201 and Ktzi 201/Pumping at Ktzi 200.

CONCLUSIONS

We developed a numerical model to simulate a suite of pumping tests conducted at the Ketzin CO_2 storage pilot site, using the revised geological reservoir model of the Stuttgart

Formation. Compared to the measured data, the model shows similar patterns but a different magnitude of pressure changes as a response to the pumping regime. A systemic increase or decrease of permeability fails to improve the match for all observation wells, suggesting that the permeability and porosity distributions in the geological model do not well represent the local heterogeneity near the wells. Further work is required to calibrate the geological model against the pumping tests data using inverse modeling approaches.

ACKNOWLEDGMENT

This NRAP-ARRA work was funded by the Assistant Secretary for Fossil Energy, Office of Sequestration, Hydrogen, and Clean Coal Fuels, National Energy Technology Laboratory, of the US Department of Energy, under Contract No. DE-AC02-05CH11231. The GFZ involvement was conducted within the CO_2CARE project, funded by the European Commission under the Seventh Framework Programme; financial support by the European Commission and by the industrial partners Shell, Statoil, TOTAL, Veolia, RWE, and Vattenfall is gratefully acknowledged.

REFERENCES

Förster, A.; Norden, B.; Zinck-Jorgensen, K.; Frykman, P.; Kulenkampff, J.; Spangenberg, E.; Erzinger, J.; Zimmer, M.; Kopp, J.; Borm, G.; Juhlin, C.; Cosma, C.; Hurter, S. Baseline characterization of the CO2SINK geological storage site at Ketzin, Germany. Environmental Geosciences 2006, 13 (3), 145-161.

Frykman, P.; Zink-Jørgensen, K.; Bech, N.; Norden, B.; Förster, A.; Larsen, M. Site characterization of fluvial, incised-valley deposits. In Proceedings, CO2SC Symposium, Lawrence Berkeley National Laboratory, Berkeley, CA, March 20-22,2006.

Kempka, T., Class, H., Görke, U.J., Norden, B., Kolditz, O., Kühn, M., Walter, L., Wang, W., Zehner. B. (2013) A dynamic flow simulation code intercomparison based on the revised static model of the Ketzin pilot site. Energy Procedia (EGU GA 2013, in press).

Kempka, T., Kühn, M. Numerical simulations of CO_2 arrival times and reservoir pressure coincide with observations from the Ketzin pilot site, Germany. Environmental Earth Sciences 2013 (in press), doi:10.1007/s12665-013-2614-6.

Kempka, T.; Kühn, M.; Class, H.; Frykman, P.; Kopp, A.; Nielsen, C.M.; Probst, P. Modelling of CO_2 arrival time at Ketzin – Part I. International Journal of Greenhouse Gas Control 2010, 4 (6), 1007-1015.

Liebscher, A., Möller, F., Bannach, A., Köhler, S., Wiebach, J., Schmidt-Hattenberger, C., Weiner, M., Pretschner, C., Ebert, K., Zemke, J.. Injection operation and operational pressure–temperature monitoring at the CO_2 storage pilot site Ketzin, Germany - Design, results, recommendations. International Journal of Greenhouse Gas Control 2013, 15, 163-173.

Norden B, Frykman P (2013) Geological modeling of the Stuttgart Formation at Ketzin, Germany. Int J Greenh Gas Control (in press) doi: 10.1016/j.ijggc.2013.04.019.

Norden, B.; Förster, A.; Vu-Hoang, D.; Marcelis, F.; Springer, N.; Le Nir, I. Lithological and Petrophysical Core-Log Interpretation in CO2SINK, the European CO_2 Onshore Research Storage and Verification Project. SPE Res Eval & Eng 2010, 13 (2), 179-192.

Martens, S., Kempka, T., Liebscher, A., Lüth, S., Möller, F., Myrttinen, A., Norden, B., Schmidt-Hattenberger, C., Zimmer, M., Kühn, M., The Ketzin Group. Europe's longest-operating on-shore CO_2 storage site at Ketzin, Germany: a progress report after three years of injection. Environmental Earth Sciences 2012, 67, 323–334.

Otto, C., Hydraulische Characterisierung der Stuttgart Formation mittels Auswertung von Crosshole-Pumpversuchen und inverser Modellierung, Diploma Thesis, University of Potsdam, 2013

Pan, L. User information document for: WINGRIDDER version 3.0; 10024-UID-3.0-00; Lawrence Berkeley National Laboratory: Berkeley, CA, 2007.

Pruess, K. ECO2N: A TOUGH2 Fluid Property Module for Mixtures of Water, NaCl, and CO_2; LBNL-57952; Lawrence Berkeley National Laboratory: Berkeley, CA, 2005.

Wiese, B.; Böhner, J.; Enachescu, C.; Würdemann, H.; Zimmermann, G. Hydraulic characterisation of the Stuttgart formation at the pilot test site for CO_2 storage, Ketzin, Germany.

International Journal of Greenhouse Gas Control 2010, 4 (6), 960-971.
Würdemann, H., Möller, F., Kühn, M., Heidug, W., Christensen, N.-P., Borm, G., Schilling, F.-R., CO_2SINK Group. CO_2SINK—from site characterization and risk assessment to monitoring and verification: One year of operational experience with the field laboratory for CO_2 storage at Ketzin, Germany. International Journal of Greenhouse Gas Control 2010, 4, 938–951.
Zhang, K.; Wu, Y.; Pruess, K. User's Guide for TOUGH2-MP - A Massively Parallel Version of the TOUGH2 Code; LBNL-315E; Lawrence Berkeley National Laboratory: Berkeley, CA, 2008