Govindan, R., Babaei, M., Korre, A., Shi, J.-Q., Durucan, S., Norden, B., Kempka, T. (2014): CO2 Storage Uncertainty and Risk Assessment for the Post-closure Period at the Ketzin Pilot Site in Germany. - *Energy Procedia*, *63*, p. 4758-4765.

DOI: http://doi.org/10.1016/j.egypro.2014.11.506

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 63 (2014) 4758 – 4765

Energy Procedia

GHGT-12

CO_2 storage uncertainty and risk assessment for the post-closure period at the Ketzin pilot site in Germany

Rajesh Govindan[a], Masoud Babaei[a], Anna Korre[a]*, Ji-Quan Shi[a], Sevket Durucan[a], Ben Norden[b], Thomas Kempka[b]

[a]Department of Earth Science and Engineering, Royal School of Mines, Imperial College London, London SW7 2BP, United Kingdom
[b] GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

Abstract

Comprehensive knowledge gained through the application of a unique and multidisciplinary monitoring program at the Ketzin pilot site has been largely integrated into the development of a site-specific static geological model. Although dynamic modelling results have demonstrated good conformity with the field observations thus far, the long-term fate of CO_2 remains uncertain. This is due to the lack of sufficient data regarding the geological characteristics of the far-field region in the reservoir. In this paper, the authors describe a methodology to quantify these uncertainties in order to perform a site-specific risk assessment for the post-closure period.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: Ketzin pilot site; saline aquifers; CO_2 storage; post-closure; risk assessment.

1. Introduction

The Ketzin pilot site for CO_2 storage is located about 25 km west of Berlin in the State of Brandenburg, in North Germany. It lies in the eastern part of a double anticlinal structure, known as the Ketzin-Roskow anticline, of the Northeast German Basin (NEGB). Under the framework of the CO_2SINK project, one combined injection-observation well (Ktzi 201) and two observation wells (Ktzi 200 and Ktzi 202) were drilled into the upper Triassic

* Corresponding author. Tel.: +44 -20-7594-7372; Fax: +44-20-7594-7444
E-mail address: a.korre@imperial.ac.uk

Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.506

Stuttgart reservoir formation at Ketzin in 2007. The exploration data acquired from these wells enabled a detailed geological characterisation of the near-field region in the reservoir [1]. Based on the analyses of the log and core data, the Ketzin reservoir is a heterogeneous fluvial system consisting of several metres of sandstone channel units of good reservoir quality, alternated by floodplain mudstones and siltstones of poor quality. From June 2008 to August 2013, slightly more than 67 kt of CO_2 have been safely injected into the channel units at an approximate depth interval of 630 m to 650 m. After 5 years of successful operation, the injection was terminated at the Ketzin pilot site on 29th August 2013 [2].

Comprehensive studies, which included detailed data acquisition and analysis, modelling, and verification, were carried out since the development of the Ketzin pilot site in 2004. A unique and multidisciplinary monitoring program was implemented and operated at the site using time-lapse seismic imaging, cross-hole electrical resistivity measurements, borehole temperature and pressure profiling, and microbiological techniques [3, 4]. The monitoring data acquired has been largely integrated into the development of a 3D geological model of the storage reservoir through history matching in order to reflect the high complexity of the geological setting in the fluviatile Stuttgart Formation [5, 6].

Research efforts were further undertaken to focus on the reservoir and risk management for the post-closure period at the Ketzin site [7]. The history matched model was implemented in the long-term numerical simulations to assess the CO_2 trapping mechanisms in the reservoir, namely structural, residual, dissolution, and mineral trapping, during the post-closure period. The forecast of the plume behaviour is that it will migrate to the top of the anticline and essentially become structurally trapped along the bounding fault network. It is also estimated that, after 16,000 years, approximately 98 % of the plume will eventually dissolve into the formation water, hence contributing towards the long-term stabilisation of the site [7].

Although the general trend of plume migration during the injection period has been history matched in the near-field region of the geological model, it is recognised that there remains uncertainty in the fluvial channels distribution in the far-field region, which in turn leads to uncertainty in the long-term fate of CO_2. On this basis, the following were the objectives of the research described in this paper:

- Model and quantify the uncertainties of the plume behaviour in the far-field region of the storage reservoir.
- Carry out a risk assessment based on the modelling results for the post-injection period.
- Consider the implications of uncertainty and risk assessment in developing appropriate monitoring plans.

In order to meet these objectives, the team at Imperial College developed a methodology to carry out the uncertainty analysis and risk assessment for the post-closure period at the Ketzin pilot site using the datasets provided by GFZ during the CO_2CARE project.

2. Available data

The 3D model has a lateral size of 5 km × 5 km and an average thickness of 74 m, and includes seven major faults [5]. The structural model contains: three lateral discretisation zones – an inner zone of size 150 m × 200 m containing 5 m × 5 m grid blocks; an intermediate zone of size 3.5 km × 1.5 km, based on the envisaged plume size after a simulation time of 3.5 years, containing 50 m × 50 m grid blocks; and an outer zone of size 5 km × 5 km containing 100 m × 100 m grid blocks; and three vertical discretisation zones, namely (from the top to bottom) - Zone A: of about 24 m thickness, containing grid blocks with 0.5 m thickness, in order to account for buoyancy effects (gravity override) of CO_2 in a multiphase system; Zone B: of about 12 m thickness, containing grid blocks with 2 m thickness; and Zone C: of about 36 m thickness, containing grid blocks with 6 m thickness. Fig. 1a illustrates the zones of discretisation in the structural grid. As shown, the seven major bounding faults, with throws of 10 m to 20 m, at the top of the anticline are represented in the model. Additionally, locations of the injection and observation wells were also provided (Fig. 1b).

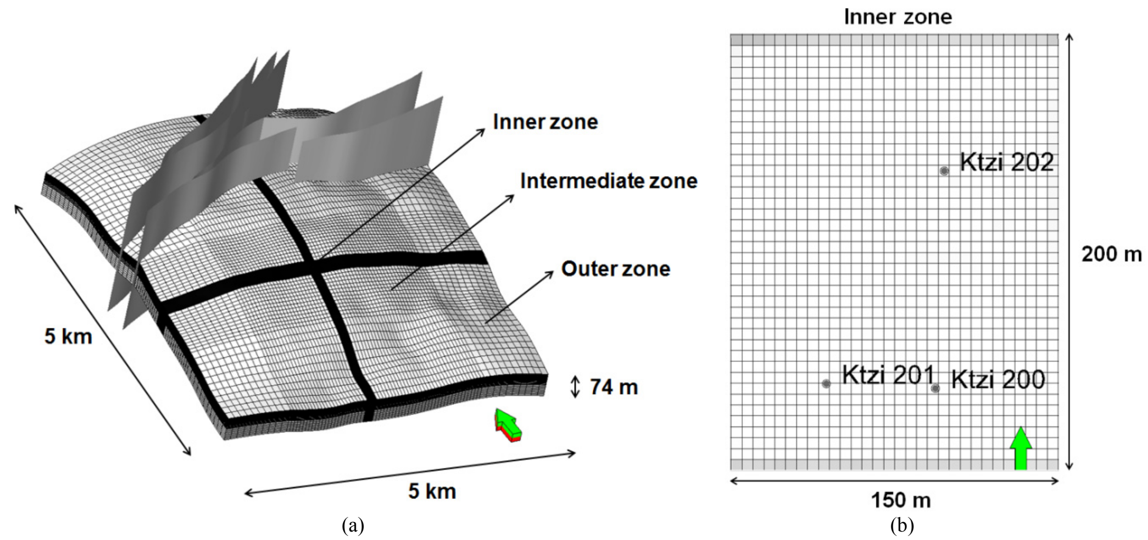


Fig. 1. (a) The structural model; (b) The location of the injection well (Ktzi 201) and observation wells (Ktzi 200 and Ktzi 202) inside the inner zone [5].

The geological model consists of populated facies and petrophysical properties. The facies model is a complex binary distribution, representing the depositional environment inside the Stuttgart Formation in Ketzin, *i.e.* siltstones and mudstones deposited on a flood plain, in which sandstones of the channel facies are incised. The construction of the model was based on the observed basin-wide characteristics of the Stuttgart Formation as well as site-specific point and spatial data, as discussed in more detail by Norden and Frykman [6]. The model was later updated using a revised interpretation of the seismic surveys and available monitoring data [8]. The updated facies model is illustrated in Fig 2a. The porosity values were populated geostatistically using Sequential Gaussian Simulation (SGS). The porosity estimation is based on separate variogram functions for the channel and floodplain facies, determined using the petrophysical core and log data available from the site [1]. Permeability was estimated using deterministic and empirical porosity-permeability relationships for the different facies types [8]. The permeability distribution was further calibrated by Kempka and Kühn [5] to carry out the history matching for well bottomhole pressures (BHPs) and plume arrival times at the two other observation wells.

In order to meet the objectives of history matching, the dynamic reservoir simulation model was setup using the following parameters [5,9]:

- Initial permeability anisotropy was assumed as Kv/Kh = 1/3, while the final permeability anisotropy was determined by history matching the observation and simulation data using near-field and far-field multipliers in the permeability distribution;
- Initial pressure is 62 bar at a depth of 639.5 m in the injection well Ktzi 201, and the temperature was considered to be constant at 34 °C in the entire reservoir;
- Brine salinity was set at 0.22 kg NaCl per kg of brine;
- Residual water saturation was set at S_{wr} = 0.15 and residual gas saturation S_{gr} = 0.05 as determined from laboratory experiments;
- Relative permeabilities and capillary pressure were derived from flow-through experiments on core samples from the Stuttgart Formation, as illustrated in Fig 2b;
- A permeability multiplier of 10,000 was applied to the boundary grid blocks to take care of boundary pressure effects in the model; and
- As there is no indication of low horizontal fault permeability based on the hydraulic tests that were undertaken [10] and unpublished operational data of the previous gas storage operations at Ketzin, all seven faults implemented in the reservoir model were assumed to be horizontally conductive, with no vertical transmissibility.

The CO_2 injection data, namely rates and well BHPs from June 2008 to August 2013 were also available. Since the top of the reservoir is located at about 80 m below the pressure and temperature sensors installed in the wells, a pressure correction was applied for the comparison between the observed and simulated pressures [5].

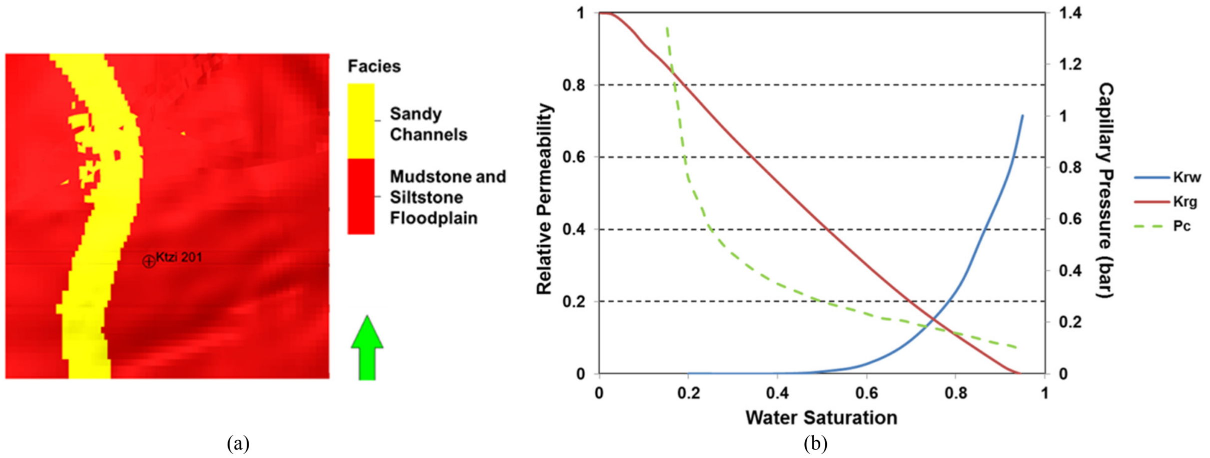


Fig. 2. Modelling data applied in the present study: (a) top layer of the facies model; (b) relative permeability curves for water and CO_2, and capillary pressure data [5].

3. Methodology

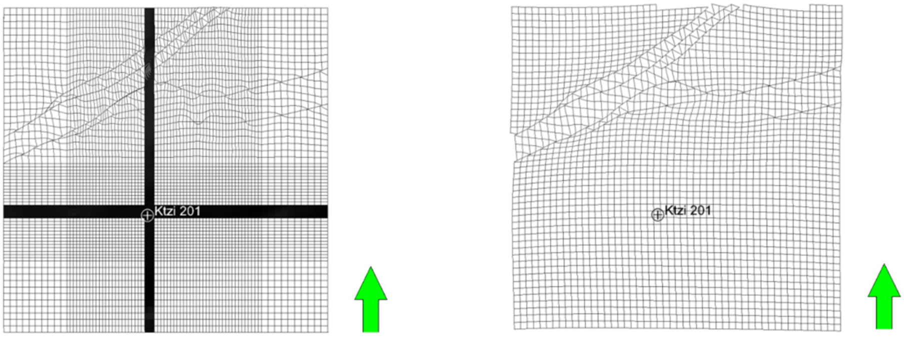
3.1. Dynamic reservoir model and history matching a detailed near-field model

In the research described here, the flow model was set up in Schlumberger's ECLIPSE 300 (E300) software using the static geological model and the dynamic reservoir parameters. The compositional flow simulation of CO_2 storage in a saline aquifer, enabled by the CO2STORE option, was carried out by implementing a quasi-isothermal, multi-phase, and multi-component algorithm, wherein the mutual solubilities of CO_2 and brine are considered. Simulations were carried out for 1,500 years, comprising the CO_2 injection and post-injection periods. The simulated BHPs for wells Ktzi 201, Ktzi 200, and Ktzi 202 were compared with the observed pressure measurements for the injection period (Fig 4a). Despite the small discrepancies in the order of a few bars, and since the focus of this research is not history matching, it was assumed that the reasonable match between the observed and simulated pressures is sufficient for conducting the uncertainty analysis and risk assessment. Moreover, the combined effect of buoyancy, topography, and the fluvial channel system drives most of the simulated CO_2 plume away from the near-field region within 50 years and the plume reaches the fault network at the top of the anticline, located approximately 1.5 km to the North from the injection well Ktzi 201, as also noted in the previous modelling studies [7].

3.2. Setup and validation of a workable upscaled model

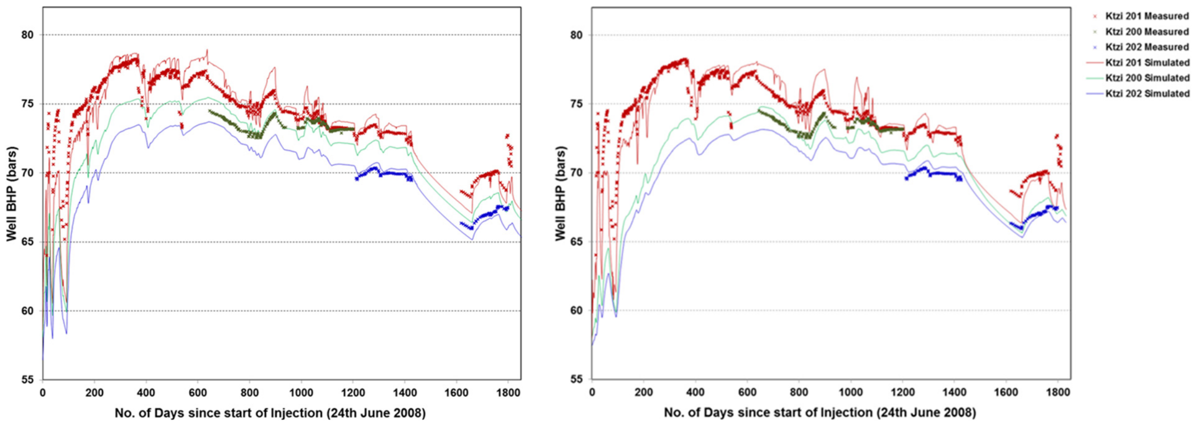
The computations for CO_2 injection and post-injection simulations using the fine grid model take over 2 days with a workstation running on an eight core Intel® Xeon processor at 2.4GHz and 64 GB RAM. This is due to the fine scale gridding of the static geological model, containing 648,420 grid blocks, and the complexity of the model property attributions. Due to the long simulation time, it was found necessary to perform grid upscaling. The static model was uniformly upscaled in the horizontal direction with grid block resolution of 100 m × 100 m, as illustrated in Fig. 3, while the vertical zonation and resolution were maintained as before. The number of grid blocks was reduced to 156,060 after upscaling. The petrophysical properties were subsequently upscaled to the new grid using arithmetic and harmonic volume averaging for the porosity and permeability distributions, respectively.

After the upscaled static geological model was implemented in E300, it was observed that the simulation time reduced significantly to less than 12 hours. The observations based on the BHPs comparison (Fig. 4b) and plume behaviour during the CO_2 injection and post-injection periods are quite similar to those of the original model. The simulated plume migration indicates a preferential N-NW trending pattern in the near-field region of the upscaled model at the end of injection in 2013, which is generally in agreement with the results from the 4D seismic image analysis [11] and previous numerical simulations [5].



(a) (b)

Fig. 3. Grid upscaling: (a) the initial structural grid [5]; (b) the upscaled grid with uniform 100 m×100 m grid blocks in the horizontal direction.



(a) (b)

Fig. 4. Comparison of measured (dotted lines) and simulated (solid lines) well BHPs for (a) the original model; and (b) the upscaled model.

3.3. Far-field geological uncertainty modelling

In order to carry out the geological uncertainty modelling, it was firstly important to identify the boundary between the near-field and far-field regions in the model. In the near-field region, the distribution of the fluvial channel system and its properties are known with relatively high confidence. On the other hand, the knowledge about the channel and floodplain attributes in the far-field region is only based on a general interpretation of the depositional environment within the wider (regional) extent of the Stuttgart Formation [6], and hence remains uncertain. It was assumed that the prediction of the plume migration until the year 2012 using the dynamic modelling in E300 is consistent with the 4D seismic data [11]. Thus, the extent of the simulated plume in 2012 was used to define that boundary (Fig. 5a).

The geological uncertainties in the far-field region were represented by multiple stochastic realisations of the fluvial channels system that honour the near-field data using the stochastic object modelling approach [12]. The coefficient of variation (CV) statistics estimated for the simulated mass of CO_2 and its arrival time at the top of the anticline suggest that thirty realisations would be sufficient for risk assessment. Two examples of the stochastic realisations that were generated are illustrated in Figs. 5b and 5c.

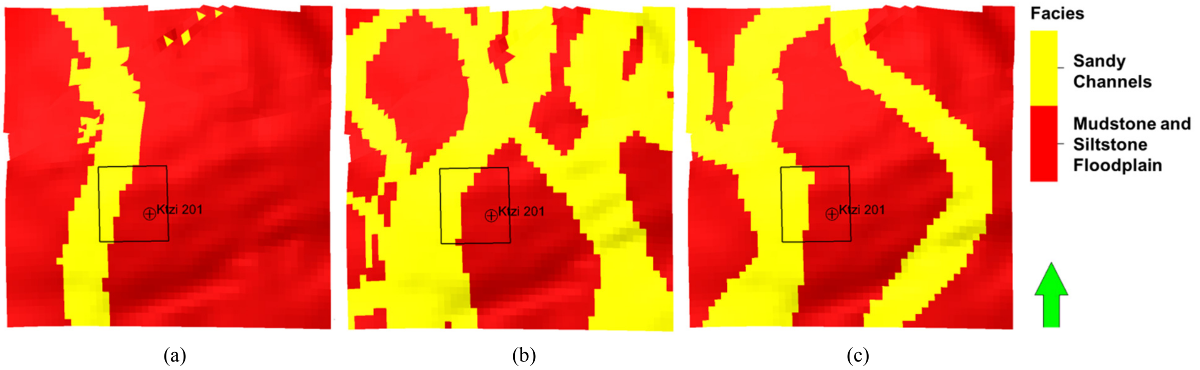


Fig. 5. (a) The near-field region boundary superimposed on the top layer of the facies model; (b) and (c) examples of the stochastic realisations of fluvial channel distributions in the far-field region for the top layer of the model.

3.4. Quantifying far-field uncertainty in plume behaviour

To assess the uncertainty in plume behaviour in the far-field region, it was decided to divide the model into regions of interest, based on the assumption that the CO_2 plume could act as either a mobile or a stationary source of potential leakage in different regions of the reservoir. This was carried out by implementing thirty stochastic realisations in E300 to simulate CO_2 saturation distributions for a period of five years of CO_2 injection and 1,495 years of post-injection. The results were summarised as probability maps that give an indication of the most likely plume locations in the reservoir at different periods. It is observed that the simulated CO_2 plume has swept through only a limited area of the reservoir model. Based on the probability values of the plume distribution after 1,500 years, when it stabilises at the top of the anticline, the grid blocks within the total sweep area were classified into two regions of interest, namely the transient and non-transient regions, as illustrated in Fig. 6.

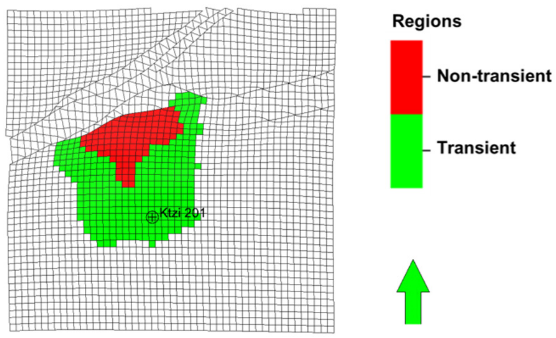


Fig. 6. Total sweep area of the CO_2 plume comprising of transient (in green) and non-transient (in red) regions.

Quantification of the uncertainty in plume behaviour in the transient and non-transient regions was then carried out by assessing the following variables:

- arrival time - the time it takes for the CO_2 plume to arrive at the non-transient region;
- residence time - the duration of time the CO_2 plume resides in the transient and non-transient regions; and
- amount of CO_2 - the maximum amount (mass) of CO_2 plume available in the transient and non-transient regions.

4. Results and discussion

To carry out the risk assessment, it was decided to split the CO_2 plume distribution into fractions, namely the free CO_2 in the gaseous phase, the dissolved CO_2 in the aqueous phase, and the residually trapped CO_2 in the gaseous phase, as illustrated by the probability maps in Fig. 7. The results for the simulated plume distribution after 1,500 years suggest there is a high likelihood that the free-phase CO_2 will accumulate at the top of the anticline, along the faults, which is coherent with the results of previous long-term studies [7]. However, for the Ketzin project there is no indication for high fault slip and dilation tendencies, thereby significantly reducing the potential leakage through the faults [13]. Moreover, the growing footprint of the dissolved CO_2 fraction, which generally tends to be larger than the footprint of the free-phase fraction, also gives a reassurance that dissolution is likely to play an important role in reducing the leakage risks with time. On the other hand, it is observed that the residual trapping mechanism is less likely to play an important role in further risk reduction since the faults impede the migration of free-phase CO_2.

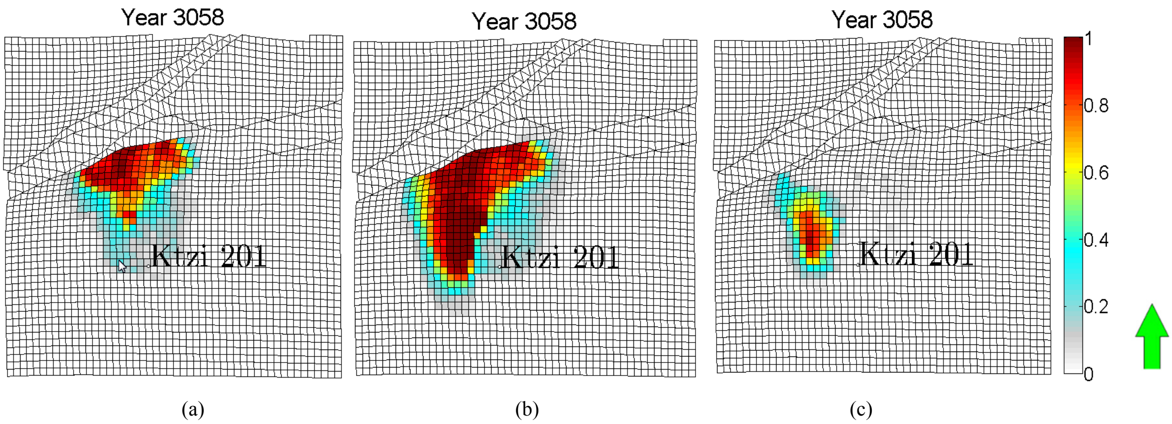


Fig. 7. Probability maps of the simulated CO_2 plume distribution in the top layer after 1,500 years for the (a) free; (b) dissolved and (c) residually trapped CO_2.

Furthermore, in the transient region, the plume is continuously moving with time. The potential risk associated with this region is the leakage through the fractures in the caprock. This is considered to be a short to medium-term risk. To assess this risk, the uncertainties in arrival time, residence time, and the mass of CO_2 were estimated. The free-phase CO_2 has a large average residence time of 185 years in the transient region, with a very large uncertainty, as indicated in Table 1. In the non-transient region, the plume is nearly stationary and the associated potential risk is identified as the leakage through the fault network at the top of the anticline. This is a medium to long-term risk, however, it also depends on the rate of CO_2 dissolution in the formation brine and mineralisation trapping mechanisms. Based on the results in Table 1, there exists significant uncertainty in the arrival time of 7 years.

Table 1. Results of uncertainty quantification for the transient and non-transient regions.

Uncertainty quantification for regions	Arrival time (years)			Residence time (years)			Mass of free-phase CO_2 (tonnes)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Transient	0	0	0	74	185	>500	19,700	30,000	38,000
Non-transient	3	6	10	>500	>500	>500	6,900	10,750	13,500

5. Conclusions

With due consideration of the post-closure phase at the Ketzin pilot site, a detailed uncertainty analysis and risk assessment was carried out. It is forecasted that the free-phase CO_2 would propagate up dip the Ketzin anticline and is likely to settle against the fault network, since further advancement would be impeded by the large throw of the faults. It is shown that the migration of the plume in the far-field region of the Ketzin reservoir is driven by a combination of factors, namely the buoyancy effects, reservoir topography, reservoir heterogeneity of the high permeable fluvial channels, and the diffusion process inside the low permeable floodplain sediments. This is clearly demonstrated by the results presented in this paper using probability maps of the CO_2 plume distribution in the reservoir at different times. For the purpose of a risk management, the results of the uncertainty quantification suggest that:

- the large uncertainties in the plume residence time and sealing characteristics of the caprock are important considerations in the transient region;
- in the non-transient region, an average mass of 10,000 tonnes of free-phase CO_2 may be available long-term at the top of the anticline; and
- during the post-injection period, dissolution in brine is more likely to reduce potential CO_2 leakage risks than residual trapping.

In addition, any monitoring data acquired during the post-closure period can be used to calibrate the current far-field geological models, thereby offering the opportunity to reduce uncertainties in the parameters considered in this work.

Acknowledgements

Research reported in this paper was conducted with funding from the European Commission FP7 project CO_2CARE, Grant Agreement No: 256625, and also co-financed by an industrial consortium consisting of Statoil, Shell, TOTAL, RWE, Vattenfall, and Veolia. The ECLIPSE 300 software used in this study is kindly provided by Schlumberger.

References

[1] Norden B, Förster A, Vu-Hang D, Marcelis F, Springer N, Le Nir I. Lithological and petrophysical core-log interpretation in CO_2SINK, the European CO_2 onshore research storage and verification project. SPE Reservoir Evaluation and Engineering 2010; 13:179-192.
[2] Martens S, Moeller F, Streibel M, Liebscher A, and the Ketzin Group. Completion of five years of safe CO_2 injection and transition to the post-closure phase at the Ketzin pilot site. Energy Procedia 2014; in press.
[3] Giese R, Henninges J, Lüth S, Morozova D, Schmidt-Hattenberger C, Würdemann H, Zimmer M, Cosma CG, Juhlin C, CO_2SINK Group. Monitoring at the CO_2SINK site: a concept integrating geophysics, geochemistry and microbiology. Energy Procedia 2009; 1:2251-2259.
[4] Juhlin C, Giese R, Zinck-Jørgensen K, Cosma C, Kazemeini H, Juhojuntti N, Lüth S, Norden B, Förster A. 3D baseline seismics at Ketzin, Germany: the CO_2SINK project. Geophysics 2007; 72(5):B121-B132.
[5] 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; 70:3675-3685.
[6] Norden B, Frykman P. Geological modelling of the Triassic Stuttgart Formation at the Ketzin CO_2 storage site, Germany. International Journal of Greenhouse Gas Control 2013; 19:756-774.
[7] Kempka T, Klein E, De Lucia M, Tillner E, Kühn M. Assessment of Long-term CO_2 Trapping Mechanisms at the Ketzin Pilot Site (Germany) by Coupled Numerical Modelling. Energy Procedia 2013; 37:5419-5426.
[8] Kempka T, Class H, Görke U-J, Norden B, Kolditz O, Kühn M, Walter L, Wang W, Zehner B. A Dynamic Flow Simulation Code Intercomparison based on the Revised Static Model of the Ketzin Pilot Site. Energy Procedia 2013; 40: 418-427.
[9] Kempka T, Kühn M, Class H, Frykman P, Kopp A, Nielsen CM, Probst P. Modelling of CO_2 arrival time at Ketzin–Part I. International Journal of Greenhouse Gas Control 2010; 4(6):1007-1015.
[10] 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.
[11] Ivanova A, Juhlin C, Lengler U, Bergmann P, Lüth S, Kempka T. Impact of temperature on CO_2 storage at the Ketzin site based on fluid flow simulations and seismic data. International Journal of Greenhouse Gas Control 2013; 19:775-784.
[12] Deutsch CV, Wang L. Hierarchical object-based stochastic modelling of fluvial reservoirs. Mathematical Geology 1996; 28(7):857-880.
[13] Kempka T, De Lucia M, Kühn M. Geomechanical integrity verification and mineral trapping quantification for the Ketzin CO2 storage pilot site by coupled numerical simulations. Energy Procedia 2014, in press.