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Fault reactivation and ground surface uplift assessment at a prospective German CO_2 storage site

Lina Röhmann[a,b]*, Elena Tillner[a], Fabien Magri[a], Michael Kühn[a,b], Thomas Kempka[a]

[a]*GFZ German Research Centre for Geosciences, Section 5.3 – Hydrogeology, Telegrafenberg, 14473 Potsdam, Germany*
[b]*University of Potsdam, Institute of Earth- and Environmental Science, Karl-Liebknecht-Straße 24-25, 14467 Potsdam, Germany*

Abstract

The present study assesses potential geomechanical impacts of pore pressure increase induced by CO_2 injection at a prospective CO_2 storage site located in the Middle Bunter sequence in Eastern Germany. A 3D supraregional-scale structural geological model was implemented in one-way coupled hydro-mechanical simulations to assess caprock and fault integrity. Simulation results show a maximum ground uplift of 0.021 m at the end of CO_2 injection, while shear failure observed at the simulated time steps does not achieve a significant density in the entire model. Consequently, reservoir, caprock and fault integrity are not compromised at any time of CO_2 injection operation.

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Keywords: CO_2 storage; caprock and fault integrity; geomechanical modelling; pressure perturbation

1. Introduction

A promising option for reducing anthropogenic greenhouse gas emissions into the atmosphere includes the technology of carbon capture and storage (CCS) in deep sedimentary formations acting as geological reservoirs [1]. Geological storage of carbon dioxide (CO_2) in deep saline aquifers offers hereby the greatest potential compared to other options such as storage in depleted hydrocarbon reservoirs or deep unmineable coal seams [1-2]. Based on the recent scientific research, studies of operating CO_2 injection

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* Corresponding author. Tel.: +49-331-288-28669; fax: +49-331-288-1529.
E-mail address: roehmann@gfz-potsdam.de.

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sites report a significant importance to geomechanics due to changes in pore pressure as a result of the imposed injection pressure [3]. Hence, large-scale pressure build-up impacts on the geomechanical rock and fault behaviour resulting in stress changes, and therefore altering the integrity of reservoir and caprock as well as possibly leading to reactivation of existing faults by shear failure. These geomechanical effects must be carefully assessed in order to determine inherent risks that may pose potential health, security or environmental hazards.

Previous research includes studies as for example the work of Rutqvist et al. [4] investigating the geomechanical response due to subsurface pressure increase as a result of CO_2 injection within the enhanced gas recovery project at the In Salah storage site, Algeria. Furthermore, that study includes the suggestion that ground deformation can be linked to the volumetric expansion of the CO_2 injection zone due to related pore compressibility [4]. A related study from 2008 conducts a synthetic case about potential tensile and shear failure related to CO_2 injection into a multi-barrier system [5]. Another study presents a geomechanical assessment as a significant method to observe the impact of pressure disturbance associated with large-scale CO_2 storage which could lead to potential triggering of notable seismic events, affecting the geomechanical behaviour of reservoir, caprock and surrounding fault systems, and thereby endanger the long-term integrity of a CO_2 storage site [6]. Orlic [7] focuses on the possible mechanical impacts of CO_2 injection, and thus stress alteration within the reservoir with regard to seal and well integrity as well as fault stability and concludes that these issues can be addressed by numerical modelling. All these studies show that the use of geomechanical analyses can indicate the suitability of prospective CO_2 storage sites, and thereby support recommendation for overall safe and secure operational constraints.

Here, we present a geomechanical assessment in terms of possible fault and seal integrity and ground surface uplift related to CO_2 injection and associated pore pressure changes. This required a 100 km x 100 km supraregional-scale 3D geological model of a prospective CO_2 storage site which was then implemented in the geomechanical simulator FLAC^{3D} [8]. We summarise the build-up of the 3D geological model with the Petrel software package [9] and the geomechanical model implementation. Concluding, we present and evaluate the results of the geomechanical analysis and potential impacts.

2. The prospective CO_2 storage site – location and geology

In Germany, geological storage of CO_2 received large attention in the past decade which led to the installation of the pilot project in Ketzin, about 25 km west of Berlin which commenced injection of CO_2 in 2008 and is still operating [10]. In general, the geology of northern Germany offers the potential to include several storage sites within the sedimentary formations of the North German Basin (NGB) which is part of the Southern Permian Basin [11].

Within the scope of this study, a prospective German CO_2 storage site located in the Northeast German Basin (NEGB) was investigated. The NEGB is a sub-basin of the NGB and on account of that presents potential storage horizons for CO_2 injection. The Mesozoic anticline structure Beeskow-Birkholz (in the following only referred to as Beeskow), about 60 km southeast of Berlin in the East of the State of Brandenburg (Fig. 1, left), is located within the NEGB. Because of the location and the main characteristics, Beeskow was selected as a prospective CO_2 storage site [12-13]. The anticline lies above the corresponding Upper Permian (Zechstein) salt pillow and its longitudinal axis is NW-SE oriented with a maximum length and width of about 20 km and 5 km, respectively. The Beeskow salt pillow evolved initially from the regional tectonic pattern during the Mesozoic (starting in the Keuper, Upper Triassic) and subsequent post-depositional salt tectonics and followed basin inversion that started during transition of Lower to Upper Cretaceous [14-15]. Due to consequential uplift and erosion there is a depositional gap of Cretaceous to Tertiary sediments that indicate that the Beeskow anticline is succeeded from Triassic

(Bunter and Keuper) to Jurassic (Lias) to Tertiary deposits, including the Rupelian clay which is the main regional seal (separating deep saline waters from shallow groundwater), to Quaternary deposits [14].

The regional fault systems generally divide the succession of basin sediments of the NEGB into blocks [16]. Thereby, the Beeskow anticline lies within the Mittenwalde block that is delineated by the fault systems Fuerstenwalde-Guben (about 5 km east of the anticline, dipping southwest) and Lausitzer Abbruch fault zone (dipping northeast) which are both NW-SE oriented [16]. In SW-NE orientation the Mittenwalde block is bordered by the continued Potsdam fault zone (dipping southeast) in the North and the Tauer fault zone (dipping northwest) in the South [16] (Fig.1, right). All fault systems are constituted mostly of normal faults, except of the Fuerstenwalde-Guben fault zone which features reverse faults in some parts [16].

The prospective storage horizon is the Middle Bunter which is subdivided (from bottom to top) into the Volpriehausen, Detfurth and Hardegsen sequences. In detail, the Volpriehausen and the Detfurth sequences represent the prospective storage horizons that each consist of a basal sandstone, constituting the storage formation, that is succeeded by an alternation of sandstone and silt-sandy parts [12-13]. The Detfurth Formation was selected as prospective storage horizon and has an effective thickness of 23 m and a reservoir top at a depth of about 1,080 m at the chosen CO_2 injection well location [12-13]. Accordingly, it was also selected for this study as injection formation. Due to public opposition and lack of a national regulation the industrial storage project was suspended in 2011. Previous studies analysing this area of interest include the work of Tillner et al. [17] that assessed brine migration through fault zones as a result of CO_2 injection. Analysis of geomechanical aspects such as seal and fault integrity was not yet conducted on a supraregional-scale model. However, in this issue, Magri et al. [18] conducted hydro-mechanical simulations over an area of 42 km x 42 km. It was concluded that a larger model is required to rule out boundary effects on the calculated stress field. For this reason, results of pressure distribution based on reservoir simulations on CO_2 injection from Tillner et al. [17] are integrated into our geomechanical simulations to observe any stress changes and related geomechanical effects.

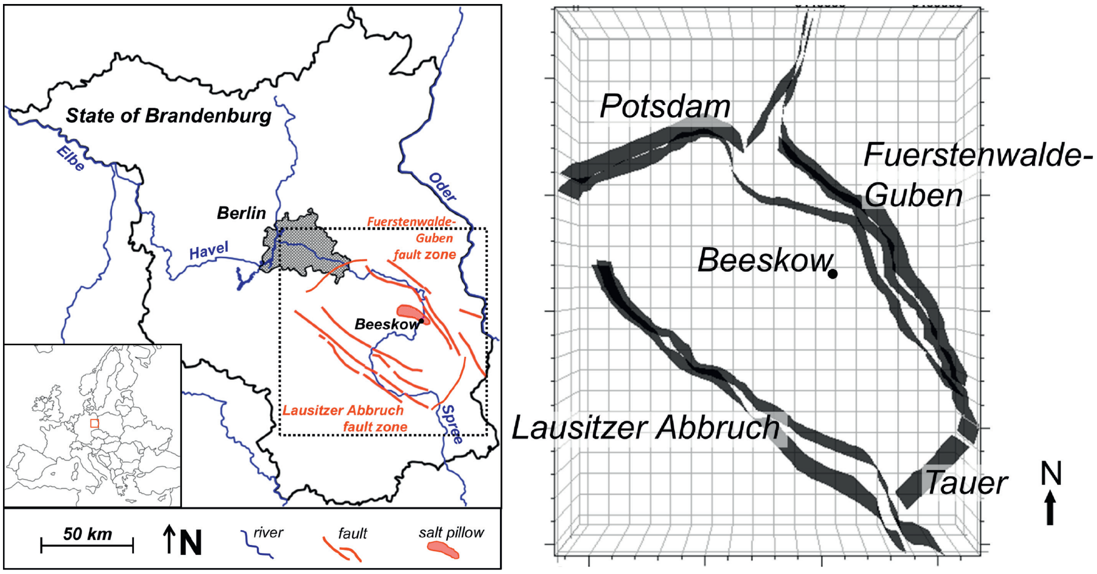

Fig. 1. (left) Location of the study area Beeskow-Birkholz indicated by dashed rectangle. Main fault zones are shown as well as the anticline structure that presents the prospective CO_2 storage site (modified after [17]); (right) All integrated faults displayed in the Petrel software package that build up the fault systems Lausitzer Abbruch, Potsdam, Fuerstenwalde-Guben and Tauer

3. Pre-processing

3.1. Structural geological model

The modelled area which is situated in the East of the State of Brandenburg has an areal extent of 100 km x 100 km. It is approximately centred at the CO_2 storage site Beeskow. The Petrel software package [9] was used to build-up the 3D structural geological model. In a first step, depth contour lines of the Middle Bunter, Keuper and Lias were digitised based on the online cartography GeotIS (Geothermal Information System) [19]. From these input data the major fault systems were also adapted. Based on additional literature data further horizons (topography, Zechstein salt, Zechstein rock, Rotliegend and the basement) were added [14; 20-21]. This was performed in order to extend the model, and thereby mitigate boundary effects in the geomechanical simulations. The digitalisation of the stratigraphic contour and major fault lines led to a preliminary model which was then correlated and adjusted in terms of stratigraphy and depth for each unit. Furthermore, a thickness correction was applied and additional borehole data and profile lines from GeotIS were adopted for corrections.

The final 3D geological model comprises eight layers (Fig. 2, left). From bottom to top (at a basal depth of 5,000 m) the basement is succeeded by the Rotliegend, Zechstein rock (transition), Zechstein salt, Middle Bunter (Triassic), Keuper (Triassic), Lias (Jurassic) and Quaternary. In total there are nine faults in the final structural geological model, which define four regional fault systems. The included fault systems are the Fuerstenwalde-Guben in the East, the Tauer fault in the South, the Lausitzer Abbruch system in the West and the Potsdam fault system in the North (Fig. 2, left).

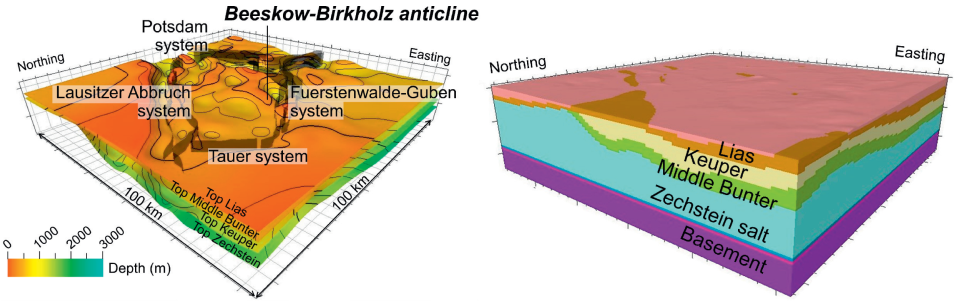

Fig. 2. (left) 3D geological structural model of the Beeskow site with geological layers and the major fault zones. Fault zone 1 displays the Fuerstenwalde-Guben, fault zone 2 the Lausitzer Abbruch and fault zone 3 the Potsdam fault system [16]; (right) 3D model generated in the Petrel software package which was subsequently exported into FLAC^{3D}

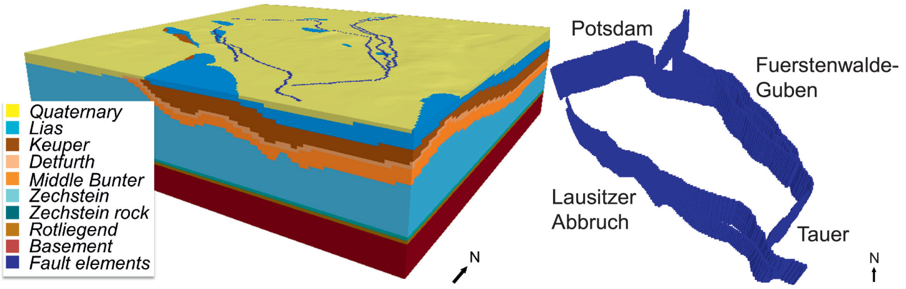

Fig. 3. (left) Geomechanical model displayed in FLAC^{3D}; (right) Elements of the mechanical grid that are cut by a fault plane are defined as ubiquitous joints elements

3.2. Gridding process

In order to implement the 3D geological model into the geomechanical simulator FLAC^{3D} it is necessary to discretise the geological model in respect to the general grid convergence criteria of FLAC^{3D}. For this reason the model was initially gridded in the Petrel software package with a lateral discretisation of 400 m x 400 m and about 130 m in vertical direction. This resulted in a total of 2.5 million elements ($n_x = 250$, $n_y = 250$, $n_z = 40$). The elements were then assigned to zone properties in order to upscale the geological units to the geomechanical grid ensuring maintenance of grid convergence criteria in FLAC^{3D}. The resulting zone model includes all relevant geological information (Fig. 2, right). After export of the grid from the Petrel software package, it is converted and implemented to the geomechanical simulator FLAC^{3D} (Fig. 3, left). Additionally, the storage formation (Detfurth Formation) was vertically and horizontally refined resulting in 339,169 additional elements. This refinement was undertaken to account for the CO_2 storage reservoir thickness of about 23 m.

3.3. Fault model

According to our implemented workflow we proceeded with the fault modelling using the Petrel software package. We started to integrate the fault model in the geological model, but excluded the faults from the gridding process since geometrical gridding of the fault planes was undertaken using the software Rhinoceros 5 [22]. All faults were then imported as geometry into FLAC^{3D}. In order to integrate the faults into our 3D geomechanical model we used the ubiquitous joints approach. The ubiquitous joints resemble weak zones within the model effective for all elements of the grid cut by a fault (Fig. 3, right). The dip angle and dip direction for the ubiquitous joints were assigned to each element cut by a fault according to the values at the respective fault plane location.

3.4. Geomechanical model parameterisation

After implementation of the grid to the geomechanical simulator the resulting geomechanical model was parameterised using the Mohr-Coulomb constitutive law. Mechanical properties that were assigned include Young's modulus (E), Poisson coefficient (ν), friction angle (φ), cohesion (τ_0) and tension (T_0) as well as density (ρ) which were taken from literature data [23-26] (cf. Table 1).

Table 1. Geomechanical properties assigned to the integrated formations of the geomechanical grid [23-26]

Period	Age	Elasticity modulus E (*GPa*)	Poisson coefficient ν	Friction angle φ (°)	Cohesion τ_0 (*MPa*)	Tension T_0 (*MPa*)	Density ρ (*kg/m³*)
Quaternary		2.6	0.47	29.5	0	0	2,100
Jurassic	Lias	4.0	0.42	25.0	5	5	2,350
Triassic	Keuper	8.5	0.34	27.0	5	5	2,500
	Middle Bunter	27.7	0.26	25.0	5	5	2,453
Permian	Zechstein salt	30.0	0.30	27.0	0	0	2,060
	Zechstein rock	51.8	0.29	30.0	5	5	2,629
	Rotliegend	15.0	0.25	30.0	5	5	2,501
Carboniferous	Basement	40.1	0.19	30.0	5	5	2,698

As for the fault model, the ubiquitous joints were also populated with layer-specific mechanical properties including cohesion, friction and dilation angle [23]. Thereby, the faults were modelled as cohesionless to consider a worst case scenario of possible shear failure. The friction and dilation angles of the ubiquitous joints were assigned after Ouellet et al. [23] given with 20° for the friction angle and 10° for the dilation angle.

4. Geomechanical simulations

4.1. Initialisation

In order to run simulations the geomechanical model was initialised with the assigned mechanical properties and gravitational load applied. Initial pore pressure was applied using a pore pressure gradient which was consequently adjusted to the adopted initial pore pressure at depth of the reservoir top (a pore pressure of about 10 MPa at 1,080 m depth [17]). In addition, displacements normal to the axial directions were not allowed at the model boundaries except at the model top. The equilibrated model state is used from there as initial stress field for all simulations discussed in the present study.

4.2. Simulation

A one-way coupling concept was implemented using the spatial distribution of pressure perturbation interpreted from dynamic flow simulations carried out by Tillner et al. [17] to realize the hydro-mechanical one-way coupling. Thereto, radial pressure distribution was fitted using polynomial functions according to the radii given in Table 2, and subsequently integrated into the geomechanical model. The time frame for the dynamic simulations is 20 years of CO_2 injection. Pressure changes after 10 days and 20 years were considered in the mechanical time steps (Table 2). The maximum pore pressure is reached after 10 days, while the maximum spatial pressure perturbation is encountered after 20 years. Therefore, both time steps were selected for the simulation. Moreover, the simulation was undertaken with a scenario of faults closed for hydraulic flow limiting pressure perturbation to the area enclosed by the four fault blocks (cf. Fig. 1, right).

Table 2. Downhole pressure for selected geomechanical time steps derived from dynamic flow simulations [17]

Time after injection	Downhole pressure (*MPa*)	Radius of pressure perturbation (*m*)
Initial	10.0	-
10 days	19.4	3,500
7,300 days (20 years)	17.9	35,000

5. Results and discussion

The simulation was conducted for an injection period of 20 years. Thereby, a maximum vertical displacement of 0.0042 m (uplift) was observed at the ground surface after 10 days of CO_2 injection. Comparatively, maximum vertical displacement reached 0.012 m at the top of the Detfurth Formation. Evidentially, vertical displacement increases after the maximum pore pressure is achieved at 10 days of injection resulting in 0.021 m at ground surface and 0.025 m at the reservoir top (Fig. 4). However, the radius of the pressure perturbation has a considerable greater extent of 35,000 m after 20 years compared to that of 3,500 m after 10 days of injection. The changes in effective stresses (σ_e) show that due to the injection induced pore pressure (p_t) increase the resulting effective principal stresses decrease at the injection depth of about 1,080 m (Fig. 5). As a consequence, maximum shear stress is reduced by the decrease of the mean stress explaining that shear failure is almost absent in the storage formation and its caprock. Analysis of the stress state of the caprock, reservoir and faults show a scarce occurrence of shear and the absence of tensile failure. Thereby, shear failure in the caprock (Keuper) does only occur at the early stage of injection (maximum pressure increase in the reservoir) with an insignificantly low density of affected elements. No additional failure in the caprock is observed at the last time step (maximum spatial pressure perturbation in the reservoir). Failure within the injection horizon (Detfurth Formation) does not occur in the vicinity of the Beeskow anticline, but in between the adjacent faults (Fuerstenwalde-Guben fault system) (Fig. 6 (top left) and 6 (top right)). The elements of the faults are also affected by shear failure, whereas its greatest density is mostly apparent below the injection horizon (Fig. 6 (bottom left) and 6 (bottom right)). Besides, failure is only scattered in the remaining parts of the distributed faults not indicating the occurrence of a consistent slip plane. At the faults close to the injection well at the Beeskow anticline only few ubiquitous joints elements are affected by shear failure, but failure also occurs within the matrix of these elements. Consequently, fault reactivation cannot be expected at any time of CO_2 injection considering the applied parameterisation.

Within the present study supraregional geomechanical impacts of CO_2 injection into the Beeskow anticline were investigated with a fixed data set, whereby the simulation results indicate that neither reservoir and caprock nor fault integrity are compromised. This is supported by a regional-scale sensitivity analysis carried out by Magri et al. [18], whereas both models show similar displacement patterns and vertical displacements at the top of the Detfurth Formation of about 0.009 m to 0.012 m for the maximum pore pressure after 10 days. A comparison for the maximum simulation time of 20 years is not reasonable, since the faults were assumed to be closed for fluid flow in the present study. Consequently, the calculated vertical displacements are almost twice as high here compared to Magri et al. [18]. Nevertheless, 3D seismic data for the study area is required for an extensive structural geological assessment. Consequently, we considered the documented main faults penetrating all relevant formations above the Zechstein, whereas assigned fault properties consider a worst case scenario.

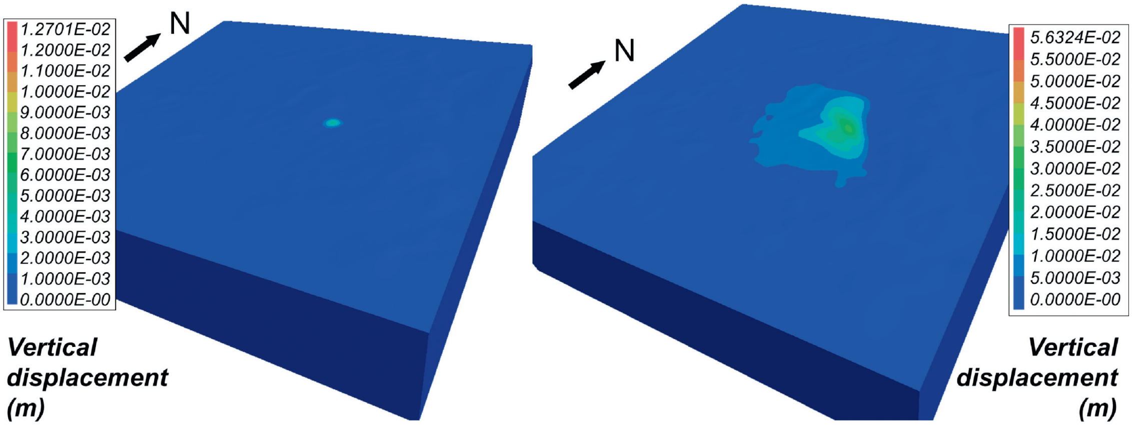

Fig. 4. (left) Distribution of vertical displacement after 10 days of CO_2 injection. The greatest vertical displacement at ground surface is at the injection well location; (right) Distribution of vertical displacement after 20 years of CO_2 injection. The greatest vertical displacement at ground surface is at the injection well location (vertical exaggeration: 5)

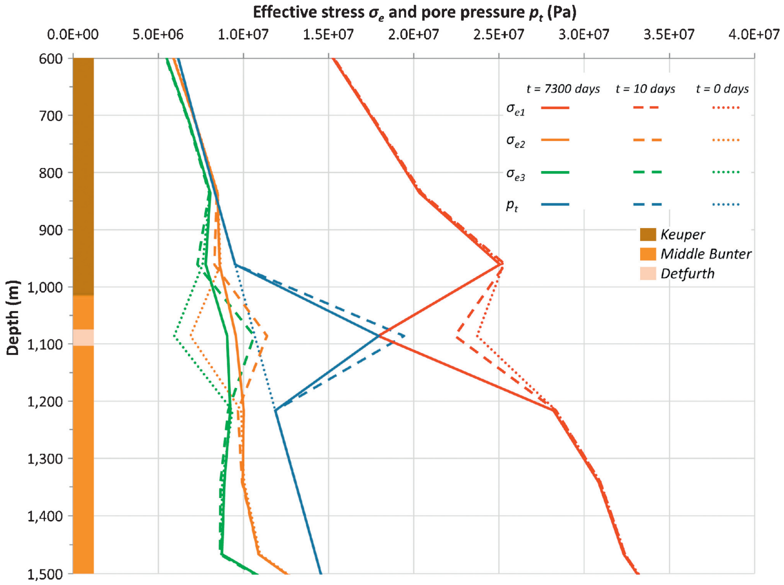

Fig. 5. Effective stress (σ_e) and pore pressure changes (p_t) are shown for the time steps 0 days, 10 days and 7300 days (20 years) plotted against depth

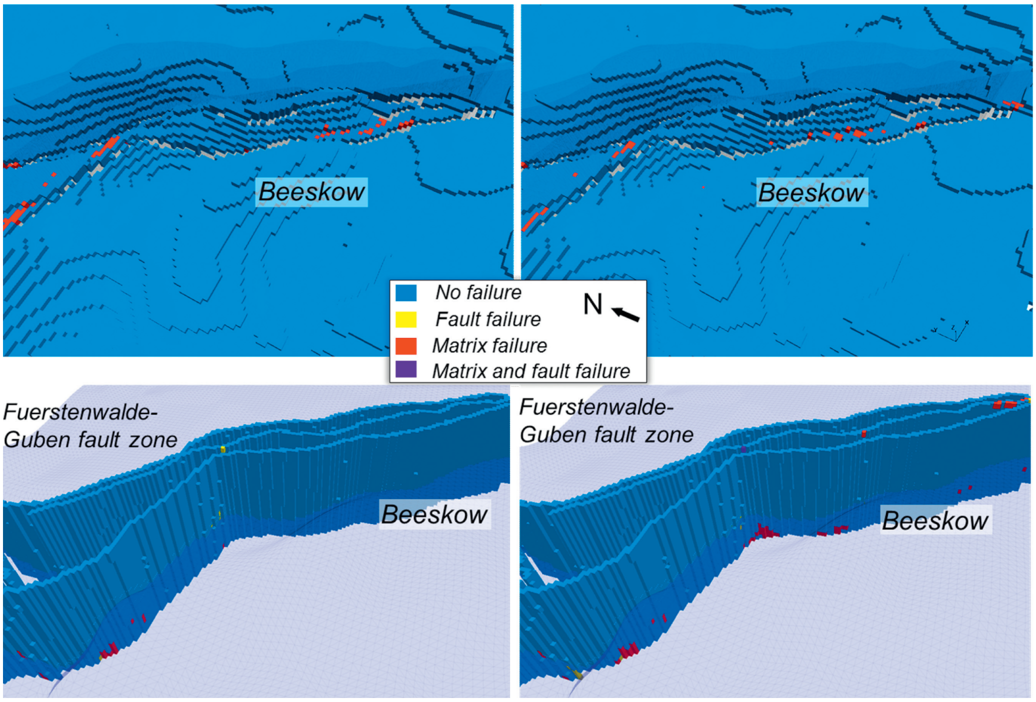

Fig. 6. (top left) The state of the injection formation after 10 days (top right) and 20 years after CO_2 injection; (bottom left) State of the distributed faults with the injection horizon indicated after 10 days (bottom right) and after 20 years of CO_2 injection (only shear failure is observed; vertical exaggeration is 5)

6. Conclusions

A prospective CO_2 storage site located in the NEGB (Beeskow anticline, which lies in the East of the State of Brandenburg, Germany) was selected for the assessment of potential geomechanical impacts resulting from pore pressure increase. For the purpose of the present study a 100 km x 100 km 3D supraregional-scale structural geological model was set up integrating available literature data. This 3D geological model comprises eight horizons and includes the storage horizon Middle Bunter (Detfurth Formation). Subsequently, the 3D geological model was transferred to the geomechanical simulator and populated with mechanical properties. Then, a one-way coupling concept was implemented using the results of published dynamic fluid flow simulations. Geomechanical simulations were carried out for 20 years of CO_2 injection. Simulation results show a maximum vertical displacement (uplift) of 0.0041 m at the ground surface after 10 days (maximum pore pressure) and 0.021 m after 20 years (maximum spatial pore pressure perturbation) of CO_2 injection. Matrix and ubiquitous joints elements shear failure at both simulated time steps does not achieve a significant density in the entire model. Consequently, reservoir, caprock and fault integrity are not compromised at any time of CO_2 injection operation. This is also supported by a regional-scale sensitivity analysis [18].

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