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Interactive Comment

Interactive comment on "Effective damage zone volume of fault zones and initial salinity distribution determine intensity of shallow aquifer salinization in geological underground utilization" *by* M. Langer et al.

M. Langer et al.

etillner@gfz-potsdam.de

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The authors would like to thank the three anonymous referees for the careful reading of our manuscript. We deeply appreciate all the valuable comments and suggestions, which helped us a lot to improve the quality of the paper. We have responded to all comments made and will consider them in our revised manuscript.

On behalf of all co-authors, Elena Tillner

Answers to comments of anonymous Referee #1

General comments:

RC: Results are similar to the paper findings in Tillner et al. (2013) / Injection of water instead of CO2

AC: Some paper findings are indeed similar to the findings presented in Tillner et al. (2013), however, in the present study we investigated also the long-term effects of brine displacement processes, which were not considered in Tillner et al. (2013). In Tillner et al. (2013), the simulation ends with the injection stop. In the present study, we investigated also the duration of pressure reduction until initial conditions and thus, duration of mass flow into the shallower aquifers as well as density driven backflow of displaced brine and showed that brine flow can occur until well after the injection stop (> 1,000 years). We further determined the depth in the fault zones from which brine is displaced into the shallow aquifer and thereby demonstrated that salinization of shallow aquifers does not necessarily need to occur in geological underground utilization. Brine migrates only from the upper part in the fault up to a maximum depth of 300 m into the shallow aquifer. We thereby showed that the initial salinity distribution is pre-determined for the degree of upper aquifer salinization. To confirm these results we have performed two extra simulations considering a linear salinity gradient in addition to the scenarios with sharp salt-/freshwater interface. The additional results will be presented discussed in the manuscript.

The reason why we did not use CO2 injection will be explained more clearly in the manuscript. In the respective industrial project, it was planned to inject CO2 into the Lower Mesozoic formations at the top of an anticline structure located at a distance of about 4.5 km from the nearest fault zone (Fuerstenwalde-Guben fault zone). We used the same injection well location in the present study, however, since we are focusing also on the long-term effect of brine displacement, it is likely that without topographic variations and structural trapping below an e.g. anticline, CO2 reaches the fault zone

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after a couple of years. This would make our simplified model more complicated as intended, so we decided to inject brine. We are aware of CO2 compressibility effects and that the displaced volume of brine might be smaller when injecting CO2, however we believe that compressibility effects are negligible in the long-term after the injection stop when pressure comes to equilibrium, as also demonstrated by Nicot (2008).

Specific comments:

RC (Page 5704, Line 19-20): the sentence: ”only to retardation in brine displacement up to a factor of five and three, respectively” is not clear. Please, clarify the term “retardation”.

AC: The term retardation will be deleted. We will restructure the sentence to clarify what happens if reservoir boundaries are closed and the effective damage zone volume of faults is small: “If reservoir boundaries are closed, the fluid mass that migrates upward into the shallow aquifer corresponds to the mass of injected fluid since flow persists until pressure conditions prior to injection are re-established. In that case, a small effective damage zone volume only extends the duration of brine mass flow because pressure dissipation occurs over a smaller area.”

RC (Page 5705, Line 13): Reference IPCC, 2005. And, ten years after ?

AC: Birkholzer et al. (2015) recently published a review article on CO2 migration and pressure evolution in deep saline aquifers and summarized the knowledge gained over the past ten years after publication of the IPCC report. We have added this reference to the manuscript, in addition to two other more recent publications focussing on CO2 storage in saline aquifers (GCCSI, 2014; Michael et al., 2010).

RC (Page 5705, Line 15-17): Please, give a reference.

AC: e.g. Kempka and Kühn (2015), Nicot et al. (2013), Tillner et al. (2013), Walter et al. (2013), Walter et al. (2012), Birkholzer et al., (2011), Celia et al. (2011), Birkholzer et al. (2009), Nicot (2008). We will add the reference to the manuscript.

RC (Page 5709, Line 20): You assumed that the caprocks are impermeable, but is it realistic?

AC: In a previous study, Kühn and Kempka (2015) investigated the impact of CO2 storage in saline aquifers by upward brine migration through a sequence of caprocks and showed that saltwater does not reach into the groundwater resources through intact caprocks with a permeability of at least 10-17 m2. In the present study, the caprock above the storage formation mainly consists of marine evaporates such as anhydrite and halite. An intact anhydrite or halite is most likely characterized by permeabilities lower than 10-17 m2, preventing salinization of overlying units according to the authors mentioned above. From our point of view, brine migration through the caprock sequence is rather unlikely due to the lithology on site and we therefore defined the caprocks as impermeable. This will be explained clearer now in the manuscript.

RC (Page 5710, Line 12-14): I understand that for grid regularity you neglected the dip angle. But, I think it would be very interesting to test the effect of the fault inclination in order to project the results of simulations as a generalization of the whole site.

AC: In TOUGH2, it is of advantage that the line connecting the centres of two neighbouring elements is normal to their interface. A mesh with non-orthogonal connections (neighbouring elements at dipping fault), produces errors during pressure calculation as demonstrated by e.g. Croucher and O'Sullivan (2013). Thus, for grid regularity we decided to neglect the dip angle, which is not an extreme simplification since all faults in our model are characterized by a relatively steep inclination between 67.8° and 74.3° in average. However, further research is underway to extend the assumptions made by the implementation of heterogeneous fault zones with spatial variations in porosity and permeability and related non-uniform architecture and fault inclination.

RC (Page 5711, Line 22-25): As conclusion, you specified that the initial salinity distribution is one of the most important condition. Nevertheless, your simulations are realized with an abrupt transition between freshwater and brine.

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AC: As suggested by the referee, we have performed two additional simulations considering a linear salinity gradient in addition to the scenarios with sharp salt-/freshwater interface. The additional simulations confirm our results and will be discussed in the manuscript.

RC (Page 5712, Line 5-8): As mentioned previously, I suggest multi-phase flow simulations as all recent papers.

AC: see above (answer to second general comment).

RC (Page 5712, Line 23-25): Please describe formulae and add reference accordingly. Table 2: Please, can you justify the applied porosity for your faults. Please, give reference.

AC: We will add references and formulae to the manuscript. In a conservative approach, we assumed that hydraulic properties of the fault damage zones are in between those of the Rupelian basal sands and the Detfurth Formation to promote upward brine displacement instead of across fault flow.

RC (Page 5716, Line 19): "pressurization of ca." ?

AC: The exact value is 1.2 bar. We will add this information to the manuscript or delete "circa".

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