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Hydrology and Earth System Sciences
Discussions

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.

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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 #2

Major comments:

RC: It is assumed that faults hydraulically connect reservoir layers separated by confining layers. However, the fault zone architecture is very complex and can act either as a barrier to flow or as a conduit (Caine et al., 1996). Actually, the permeability considered for this numerical study is reasonable for the fracture zone of a typical reservoir layer, with a more permeable fracture zone (Cappa and Rutqvist, 2011), but without the low permeable core. This distribution gives rise to a low permeability perpendicular to the fault (horizontal permeability) and a high permeability parallel to the fault (vertical permeability). However, in multilayer systems like the one considered in this study, with alternating layers of reservoir-caprock, the permeability within the caprock layers is usually of lower permeability than that of the surrounding rock due to clay smearing (e.g. Crawford et al., 2008; Egholm et al., 2008). Thus, the vertical permeability of faults is very heterogeneous (Vilarrasa and Carrera, 2015). Apart from including a discussion on this point, explaining the complexity of faults, it should be acknowledged that due to the high complexity of faults, this assumption will only be valid for certain faults.

AC: We agree with the referee that the assumptions made in our study are only valid for certain faults. A lower fault permeability than that of the surrounding rock due to clay smearing was not considered since our simulations should trigger upward brine migration into the shallow aquifer. In a conservative approach, we investigated one possible fault end-member and assumed that hydraulic properties of the fault damage zones are in between those of the Rupelian basal sands and the Detfurth Formation. Brine migration across the faults is indeed possible since no impermeable fault core was considered, however, by application of a higher fault than reservoir permeability, brine migration occurs almost solely upward into the overlying formations and is negligible in horizontal direction across the faults (in Detfurth and Muschelkalk formations). 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. Nonetheless, we will explain our assumptions more detailed in the manuscript and include a discussion on the high complexity of faults as recommended by the referee.

RC: The analytical solution of leakage through a fault proposed by Zeidouni (2012) should be cited either in the Introduction or the Discussion.

AC: The publication of Zeidouni (2012) will be integrated into the discussion chapter.

RC (Page 4, lines 5-8): the radius of influence is in fact proportional to the square root of the hydraulic diffusivity. AC: We will be considered this comment in our manuscript.

RC: Grid is very coarse, but it is justified.

RC: Instead of injecting CO2, an equivalent volume of water is injected. CO2 density is calculated from the initial pressure and temperature conditions. However, the high injected flow rate induces a significant overpressure (see Figure 6). Since CO2 is very compressible, CO2 density will increase and thus the displaced volume of brine will be smaller. Thus, CO2 compressibility effects should not be neglected.

AC: 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 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).

RC (Page 21, lines 6-9): accounting for the storage coefficient would induce a delay in pressure buildup evolution. So for a given time, overpressure would be slightly lower, leading to just a “slight” less intense brine displacement. It should be emphasized that this effect will be small.

AC: Since our simulations should show the greatest possible effect on brine displacement, pore compressibility was neglected. However, it is true indeed that pressure build-up will be delayed when considering the storage coefficient. As commented by the referee, we will emphasize that this might lead to less intense brine displacement at the early stage of injection.

RC: Some discussion on attenuation or mitigation measures to minimize salinization of freshwater aquifers should be done.

AC: We will discuss attenuation or mitigation measures for minimizing salinization of freshwater aquifers as suggested by the referee. In this context, some reference considering e.g. simultaneous CO2 injection and brine production from the storage reservoir for pressure reduction will be added to the manuscript as well (Kempka et al., 2014; Tillner et al., 2013; Court et al., 2012; Bergmo et al., 2011; Buscheck et al., 2011).

RC: Why don’t you simulate the three interlayered reservoirs that will probably dampen brine displacement?

AC: We agree that two, three or more interlayered reservoirs that are hydraulically connected to the fault zones would further reduce brine displacement into the uppermost unit. However, the effect that we wanted to demonstrate is already apparent when considering only one overlying reservoir. Nevertheless, a more complex model will be considered in future investigations.

RC (Page 26, lines 11-16): nothing is said in the manuscript about the hydro-mechanical couplings that may affect fault stability, so it cannot be a conclusion. However, this is a very important aspect, and should be included in the discussion. A recent paper of Rinaldi et al. (2015), in which modeling of fault stability of a 3D fault is done, should be cited as well.

AC: This is true. We will include a discussion on the impact of CO2 injection and pressure build on the mechanical integrity of faults. Recent papers such as e.g. Rinaldi et al. (2015), Kempka et al. (2014), Tillner et al. (2014) and Cappa and Rutqvist (2009) will be cited as well.

RC (Figure 3): The legend should be corrected because the results of this Figure correspond to a model with closed boundary conditions, so instead of B_O, should be B_C.

AC: Figure 3 will be corrected as commented by referee.

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