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Interactive comment on “Potential influence of overpressurized gas on the induced seismicity in the St. Gallen deep geothermal project (Switzerland)” *by* Dominik Zbinden et al.

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Summary and evaluation by the reviewer

In the manuscript entitled “Potential influence of overpressurized gas on the induced seismicity in the St. Gallen deep geothermal project (Switzerland)”, the authors conducted a detailed study on induced earthquakes in a geothermal project during which gas kick occurred. After a comprehensive introduction on observation data, the authors set up a hydro-mechanical numerical model to compute the stress perturbations caused by operations in different stages, e.g. injection test, acid stimulations, and gas kick and well control. The modeling results support the hypothesis in that unexpected gas kick induced earthquakes with magnitudes up to ML 3.5. Overall the manuscript is well written and I can easily follow the logic. I think the manuscript can be accepted after minor revisions.

We are glad that the reviewer found our paper interesting and are grateful for the comments, which helped to improve the manuscript. Please find our detailed reply to each comment below.

(1) Reviewer comments (2) Author response (3) Changes in the manuscript

Detailed Comments:

(1) In the Introduction the authors list a number of anthropogenic activities that may induce earthquakes. One type of activity, which has direct connection and may benefit from the results of this study, is large underground gas storage (UGS) where cyclic injection and extraction of natural gas is conducted. UGSes have been built globally, with notable examples with large capacity in China. It has been recently reported that the injection and extraction of natural gas in a large UGS may induce earthquakes (Zhou et al., 2019; Jiang et al., 2020).

Zhou, P., H. Yang, B. Wang, and J. Zhuang (2019), Seismological investigations of induced earthquakes near the Hutubi underground gas storage facility, J. Geophys. Res., doi:10.1029/2019JB017360

Jiang, G., X. Qiao, X. Wang, R. Lu, L. Liu, H. Yang, Y. Su, L. Song, B. Wang, and T.F. Wong (2020), GPS observed horizontal ground extension at the Hutubi (China) underground gas storage facility and its application to geomechanical modeling for induced seismicity, Earth Plane. Sci. Lett., 530, https://doi.org/10.1016/j.epsl.2019.115943

(2) In the introduction, we now mention UGS as an additional industrial application that can induce earthquakes.

(3) “Anthropogenic earthquakes have been observed related to water impoundment, mining, geothermal power production, hydrocarbon extraction, hydraulic fracturing for

shale gas extraction, CO2 sequestration, wastewater injection, and cyclic injection and extraction operations at underground gas storage (UGS) sites (Ellsworth, 2013; Grigoli et al., 2017; Foulger et al., 2018)."

(1) Indeed the Hutubi UGS was bounded by different faults, which now seal the reservoir. The reported findings in this study have implications on potential changes on fault permeability by smaller earthquakes and thus causing gas flow/leakage from the reservoir or repository. This can be added in discussion and help expand the horizon.

(2) We thank the reviewer for the abovementioned papers, which are now cited in the manuscript. Additionally, we briefly discuss the implications of fault seal permeability changes for UGS sites, in particular for the HUGS, where the seals of the bounding faults could be breached due to the induced seismicity and thus cause gas leakage.

(3) "Such permeability changes in sealing faults due to induced seismicity can have implications for other geo-energy applications, such as CO2 sequestration and UGS. For instance, the large Hutubi underground gas storage (HUGS) facility in northwestern China is bound by multiple faults sealing the reservoir (Jiang et al., 2020). These seals may be damaged by small induced earthquakes reported in the field (Zhou et al., 2019), which could cause gas leakage."

(1) Is that necessary to add another fracture zone to explain those deeper earthquakes? If using fully coupled poroelastic model, poroelastic stress perturbation would be sufficient to induce earthquakes that were 300 m away. Even for injection of gas, poroelastic stress changes are sufficiently large to induce earthquakes (e.g. Jiang et al., 2020). The argument in lines 385 to 392 seems to draw a conclusion based on the horizontal fracture zone (Fig. 8d&e). While the earthquakes are probably too small to derive focal mechanisms, Coulomb failure stress is quite sensitive to receiver fault geometry. So I do not think the justification here is very convincing. Indeed it is quite common to observe induced earthquakes beneath the injection or extraction zone, depending on fault orientation.

(2) Lines 385 to 392 discuss a possible alternative scenario without a fracture zone, which has been investigated in one of our previous studies (Zbinden et al., 2020). Based on a fully physics-based hydro-mechanical model, we concluded that a hydraulic connection between the fault and the injection well is a more plausible scenario for the St. Gallen case, because stress changes purely governed by poroelasticity were too small to induce the seismicity. Note that the magnitude of poroelastic stress changes not only depends on the distance between the fault and the well, but also on the total injected fluid volumes, which were rather low at St. Gallen. We agree with the reviewer that adding a second fracture zone to explain the three deeper events induced during the injection test is unnecessary, because (i) it does not affect any of our conclusions, and (ii) Diehl et al. (2017) argued that the location of the deeper events is most probably an artifact caused by a local vp/vs velocity anomaly and thus these seismic events would be located at shallower depth. This would allow to explain all the relocated events induced by the injection test with only one fracture zone. Since our paper is already relatively long, we decided to completely remove the scenario with a second hydraulic connection (including Fig. 8) from the paper. We then changed the manuscript as follows:

(3) In Section 3: "The second hydraulic connection could then explain the fast seismic response to the stimulations in the lower part of the fault. However, despite these observations, Diehl et al. (2017) proposed that the vertical offset of this cluster is a location artifact, which can be explained by the presence of a local vp/vs velocity anomaly. For this reason, we choose to perform the numerical simulations with only one hydraulic connection."

In Section 5.1: "The three deeper events could be explained by a second fracture zone connecting the well with the reactivated fault at greater depth. However, as mentioned in Sect. 3, the location of the deeper events is most probably an artifact (Diehl et al., 2017), which would allow to explain all the induced events with only one fracture zone."

(1) In the model the fault core is set as 5 m wide low permeability zone. According to

observations of exhumed faults, most crustal faults have fault cores in cm scale, where earthquake slip is concentrated. Such 5 m scale is limited by the model, or is intended to set in such a scale? What is the effect of such scale, for example, if you decrease it by one order?

(2) The thickness of 5 m corresponds to the width of the fault core elements. However, we do not think that fault core thickness is a crucial parameter in our model. Firstly, for the initialization of the gas plume, the fault seal is not only a hydraulic seal (i.e., very low permeability), for which the thickness would have an effect, but also a membrane seal (e.g., Yielding et al., 1997) due to the high capillary entry pressure adopted in the fault core. Hence, the fault seal could maintain a similar overpressure of the gas reservoir even with a smaller thickness. Secondly, we would indeed expect some influence of fault core thickness on the strength of the gas kick, because reducing the thickness would result in a higher pressure gradient between the two reservoir compartments, which would cause more fluid flow across the fault after the seal has been breached. However, according to Darcy's law, this would be equivalent to increasing the permeability of the breached fault seal (which would also result in more flow). This is exactly what we did in Fig. 10, where we show the effect of the permeability of the breached fault seal on the pressure and gas saturation change at the fracture-well and fracture-fault intersections. Decreasing the fault core thickness by one order would thus correspond to the scenario with a breached fault seal permeability of 10-14 m2. We now explain this equivalency in the manuscript in Section 5.2:

Yielding, G., Freeman, B., and Needham, D. T. (1997). Quantitative fault seal prediction. AAPG Bulletin, 81(6), 897-917.

(3) "Note that according to Darcy's law, an increase (decrease) in permeability of the breached fault core would correspond to a decrease (increase) in thickness of the fault core, since in both cases the fluid flow across the fault would be equally affected."

Additional reply to the last reviewer comment:

Although fault core thickness can vary over a wide range, we agree with the reviewer that individual fault cores are usually thinner than 1 m (e.g., Shipton et al., 2006). However, faults may contain multiple narrow cores (e.g., Faulkner, 2010) so that the sealing part of the fault can be thicker. Such approximations are often used in numerical modeling studies, where fault seals with thicknesses up to several meters have been adopted (e.g., Rinaldi et al., 2014; Jiang et al., 2020). Furthermore, we do not explicitly calculate fault slip for individual earthquakes. Therefore, from a mechanical modeling perspective, the thickness of the fault core is not important here. Nevertheless, even if fault slip is taken into account, it was shown that the finite-thickness approach leads to similar results compared to using a zero-thickness interface approach for the fault (Cappa and Rutqvist, 2011).

Cappa, F., and Rutqvist, J. (2011). Modeling of coupled deformation and permeability evolution during fault reactivation induced by deep underground injection of CO2. International Journal of Greenhouse Gas Control, 5(2), 336-346. https://doi.org/10.1016/j.ijggc.2010.08.005

Faulkner, D. R., Jackson, C. A. L., Lunn, R. J., Schlische, R. W., Shipton, Z. K., Wibberley, C. A. J., and Withjack, M. O. (2010). A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. Journal of Structural Geology, 32(11), 1557-1575. https://doi.org/10.1016/j.jsg.2010.06.009

Rinaldi, A. P., Rutqvist, J., and Cappa, F. (2014). Geomechanical effects on CO2 leakage through fault zones during large-scale underground injection. International Journal of Greenhouse Gas Control, 20, 117-131. https://doi.org/10.1016/j.ijggc.2013.11.001

Shipton, Z.K., Soden, A.M., Kirkpatrick, J.D., Bright, A.M., and Lunn, R.J (2016). How thick is a fault? Fault displacement-thickness scaling revisited. In Abercrombie, R. (Eds) Earthquakes: Radiated Energy and the Physics of Faulting, pp. 193-198. AGU.

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