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Interactive comment on "Anisotropic transport and frictional properties of simulated clay-rich fault gouges" *by* Elisenda Bakker and Johannes H. P. de Bresser

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Interactive comment on "Anisotropic transport and frictional properties of simulated clay-rich fault gouges" by Elisenda Bakker and Johannes H. P. de Bresser Anonymous Referee #2 Received and published: 26 February 2021

In this paper, the authors describe a series of direct shear experiments conducted on simulated gouge materials made of crushed Opalinius Claystone. They aim at investigating the mechanical behavior and gas conductivity evolution of caprock penetrating faults. The paper is well organized and written in a clear manner. We appreciate this

comment on the organization and clarity of the paper.

However, the authors fail to convey the originality of their work and the relevance to real application in my opinion. Moreover, some of the interpretation of the results are not very convincing.

1. Other authors in the literature have already looked at the behavior of clay-rich fault gouge varying the amount of clay content, the normal pressure, etc. and performed permeability tests during the experiments. As stated in the present paper, the results obtained in these previous studies (e.g. Crawford et al. 2008 or Zhang et al., 1999) are similar to the ones obtained here. Therefore, it is not clear the new information brought by this study. The originality of the paper lies in the use of a fault gouge during deformation experiments prepared from a natural rock that is directly relevant when studying faults in caprocks of reservoirs. Many caprocks of (former) hydrocarbon reservoirs that are now considered for CO2 storage are clay-rich, hence the choice of the natural Opalinus Claystone as our source material. Previous studies used mainly artificially composed mixtures: Crawford et al. (2008), for example, made synthetic mixtures of fine-grained quartz and kaolinite, Zhang et al. (1999) used pure quartz, feldspar and muscovite gouges. The latter authors also made granitic gouge from natural Westerly granite, but that is not a rock type widely relevant as reservoir caprock. Moreover, our Opalinus claystone not only is a mixture of quartz and clay, but also contains a substantial amount ($\sim$17%) carbonates. Previously tested mixtures only contained trace amounts of carbonate (e.g., Rutter and Mecklenburg, 2017). Finally, we investigated the characteristics of the fault gouge during and after shear under conditions relevant for CCS. Our results thus are complementary to results obtained in previous studies on fault gouges studied because of their role in the behaviour of major lithospheric faults such as the San Andreas fault (e.g. SAFOD project).

2. The mechanical behavior of clays is strongly dependent on the presence of water, and it is likely that a fault zone will be saturated in natural conditions. Therefore, the influence of water on the results obtained here and how it should modify what would

happen in the field should be addressed by the authors. Undoubtedly, water is important in natural fault zones. But our study has to be seen in the context of CCS and the possibility that a fault becomes flooded with CO2 gas, as would be the case in a leakage scenario, resulting in drying out the fault gouge. Two aspects are important. First, previous permeability studies [e.g. Faulkner and Rutter, 2000] carried out with both water (wet) and argon (dry) have shown that water permeability values are consistently lower than argon gas permeability values. Secondly, wet fault gouges have been found to show lower friction coefficients than dry gouges (e.g. Morrow et al, 2000; Moore and Lockner, 2004). Shear tests with measurement of argon gas permeability, as carried out in our study, thus help determining the upper limit of the fault gouge permeability/frictional strength and trends with increasing shear displacement and increasing normal stress (which is related to/representing an increasing depth). That being said, we can add to the manuscript that the influence of water on the results presented by us is that the permeability during increasing shear displacement is likely to become very low, close to impermeability and thus to cause a fault to act as a barrier to flow.

3. The authors used an interesting setup to induce flows across or along the experiments. However, the way the samples are prepared should not lead to any anisotropy for the permeability (compressed powder of fine particles). Therefore, the anisotropy they have observed (especially for the initial permeability) appears more as an artefact of the experiment, coming from flow path across the gouge that is more subjected to heterogeneities compared to the flow along the gouge. It makes the comparison with the anisotropy of fault zones not very justified. The natural rock used to prepare the gouges from is a claystone with a high percentage, close to 47%, of platy minerals (phyllosilicates). During the preparation of the fault gouge layer, the pre-pressing perpendicular to the (future) shear plane, at normal stress below 6 MPa, will already cause the platy minerals to rotate to an orientation perpendicular to the maximum stress, hence towards parallelism with the shear/fault plane. This will be further enhanced during testing at normal stresses of 10 MPa and higher. As a result, an initial perme-

ability anisotropy develops prior to shear. Such anisotropy has also been observed in other studies, such as that of Zhang et al. (1999) on pure muscovite gouges. These authors found an order of magnitude difference in permeability parallel and perpendicular to the experimental fault plane before actual shearing. This was attributed to progressive alignment of the basal planes of muscovite to the plane of the fault. Although our samples are not 100% clay, our close to 50% volume of platy minerals is high enough to result in a measurable anisotropy. The development of a planar fabric is well known from natural fault gouges containing clay (e.g. Faulkner and Rutter, 2000 and references therein). Hence, the permeability anisotropy in our samples is not an unwelcome artefact of our experiments; on the contrary, it makes comparison of experiments with nature more meaningful.

4. A mature fault zone presenting a gouge is supposed to have accommodated a large amount of displacements and reach the “critical state” (as defined in the soil mechanics community). At this stage, the material does not change its volume when sheared, so the volume variation observed here and affecting the permeability in the first millimetres of the experiment would presumably not be observed. The largest decrease in permeability indeed takes place roughly the first 2 mm of shearing. The gradual change in permeability continues during further shearing beyond 2 mm, though less substantial. We have not been able to measure volume changes so cannot relate permeability changes to volume changes during specific parts of the progressive shearing. It is known though from other studies (e.g. Faulkner and Rutter, 2000) that permeability changes occur without further compaction or with only very minor dilatation. We thus consider the changes in permeability in our experiments, and in particular the systematic difference between along fault and across fault, as related to the progressive development of an internal foliation with increasing shear displacement. This is directly relevant to the broad aim of this paper, obtaining improved insight into the evolution of faults in clay-rich caprocks.

5. The fact that the fault zone as a conduit along its shearing direction is mostly due to

the damage zone that you are not studying. It is true that our study does not include the damage zone, which of course is due to the character of the experimental set-up, with a gouge layer between two stainless steel pistons. This is not different from several previous studies with comparable set-ups. So our results are of importance for the fault core, and then it depends on the architecture of the fault zone as a whole to what extent differences between fault core and damage zone control overall permeability. Cain et al (1996) present a conceptual model of the permeability structure in fault zones, with end members defined by the relative percentage of core (localized conduit vs. localized barrier) and of the relative percentage of the damage zone (distributed conduit vs. combined conduit-barrier). In case you have a low damage zone with a low to high fault core width, a fault can act as a localised conduit or as a localised barrier. Our results are relevant for these architectures.

6. The interpretation of the evolution of friction with normal stress should be elaborated. The decrease of the friction with increasing effective normal stress is attributed to be an effect of the cohesion, whereas this effect has been extensively studied in Rock mechanics and is related to the change in volumetric behavior. Several models like Hoek-Brown or Cam-clay have been specifically developed to describe this effect. Stick slip coming from slip weakening. To our knowledge, the effect of cohesion the reviewer is referring to is more widely studied and know from experiments under low normal stress (kPa range to a maximum of $\sim$4 MPa), so in soil mechanics, than it is known from (friction) experiments on rock materials at normal stresses in the MPa range. At steady state sliding at such normal stresses, in principle no volume change will be expected, and the effect of cohesion (absolute value low relative to the normal stress) will be limited. We have looked into the Hoek-Brown-PAC and Cam-Clay models. The Hoek-Brown-PAC model provides a representation for yielding that accounts for the changing failure condition. The modified Cam-Clay model is an incremental hardening/softening elastoplastic model. We will refer to these models in the revised manuscript, with special attention to the implied volumetric effects. However, we are limited by the fact that our experimental set up did not allow monitoring of volume changes.

7. The observation of stick-slips events during the experiments presented here are quite interesting as the material is velocity-strengthening, but the possible explanation to explain this behavior are not convincing. Argument 1 seem quite difficult to verify and does not seem very likely. Arguments 2 and 3 (lines 405-415) mention some mechanisms that would induce some slip-weakening. If there was any slip weakening it should be observed on the mechanical response of the material. Moreover, slip weakening leads to a single instability (or stress drop) and cannot create repetitive stick-slip events. The stick slip events that we observed are relatively small anomalies, as also indicated by reviewer 1 (see reviewer's comment l.397-415). We did not observe the events in all samples, and have not systematically investigated them. For that reason, we can only speculate what the explanation is for the events. We decided to include a short description of the events since we do not want to ignore the observations, though not really the focus of our work. We will follow the suggestion of referee 1 who indicates the anomalies should not be discussed at great depth.

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