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Interactive comment on "The physics of fault friction: Insights from experiments on simulated gouges at low shearing velocities" *by* Berend A. Verberne et al.

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SEE SUPPLEMENT FOR OUR REPLIES IN RED

Anonymous Referee #2 Received and published: 12 August 2020

General comments: This paper summarizes experimental, microstructural, microphysical, and numerical modeling studies of the frictional behavior of simulated gouge conducted at Utrecht University (UU) in the past two or so decades. Although the paper does not have any new results, except some of the modeling results only presented in the recent international conference, it includes the basic information on the experi-

mental setup and results, microphysical model, and numerical modeling of earthquake cycles using their friction model (CNS model). The paper is based on many previous papers presented by UU group and hence it is very well written. Therefore, I recommend publication only after the following minor comments shown below. We thank the reviewer for his thoughtful comments, which have helped to improve the quality of the ms.

Quality of figures: As mentioned in the reviewer 1, overall quality of figures is too low. Some of the words can't be read. Hence it should be improved. Yes, point taken. We now apply a consistent style between the figures, and ensured a high resolution (300 DPI) upon exporting the figures to JPEG format. We are confident that this will constitute the high figure quality needed for publication. See also our response to the first comment by Reviewer 1.

The difference in the frictional properties. Line 258-inset of Fig. 5b: I assume that the authors try to mention the similarity of temperature dependences between calcite (Fig. 5) and qtz-phyllosilicate mixture (Fig. 4a) gouges. However, their variations as a function of temperature are different. In particular, calcite gouges show a wide region of negative v dependence with sharp peaks at 500 C. Can you elaborate more on the difference? Because as shown in later, the CNS model offers fault friction law based on microphysics supported by those experiments. If the authors can illuminate tho difference in terms of rock and mineral physics aspects, this will give a more generalized view on the microphysics of fault friction. I assume that is a point the CNS model aims. This is a good point raised by the reviewer. Taking the CNS model in mind, the shape of the temperature sensitivity of v-dependence (i.e., plotted in Fig. 4a and Fig. 5b) is expected to be dominantly controlled by the rate of intergranular creep. In the case of calcite, intergranular creep occurs by water-assisted diffusive mass transfer at low temperatures (T<150°C) (Verberne et al., 2014a,b; Chen et al., 2015a,b; Chen & Spiers, 2016), and by dislocation- / diffusion-mediated plasticity at higher temperatures (Verberne et al., 2015; Chen et al., in review). In the case of qtz-pyllosilicate gouges, the intergranular creep mechanisms are more difficult to constrain, and the modelling is more complex (Den Hartog and Spiers, 2014; Niemeijer, 2018). As pointed out in section 7, one of the key remaining challenges is to quantitatively underpin the relevant creep processes in polymineralic gouges, and their incorporation into the CNS model. This remains subject of future study. Instead of comparing Fig. 4a with Fig. 5b, as mentioned by the reviewer, in fact we wanted to highlight the similarity in the shape of the (a-b) vs T curve with the derivative of the curves in Fig. 4b (sketched in the inset to Fig. 5b), that is, the inherent prediction from the Den Hartog and Spiers' (2013) model. We realize that this may have been confusing. To address this we now more specifically mention the comparison between Fig. 4b and Fig5b-inset (lines 263-266).

Robustness of the CNS mode. As repeatedly mentioned in the paper, CNS model is based on microphysics supported by experimental results. In that sense, the CNS model provides a transparent origin of the constitutive parameters. However, as shown in Fig. 9 and Chapter 7 (Remaining challenges), the CNS model has a significant shortcoming on that it can only reproduce slow slip or earthquakes with limited coseismic displacement. Hence, I guess that the authors should avoid bold statements on the robustness of the model (e.g., lines 25, 361, 468, and so on). OK, point taken. When the reviewer mentions that 'the CNS model can only reproduce slow slip or earthquakes with limited coseismic displacement', we assume that he/she is referring to the incorporation of dynamic weakening processes at co-seismic slip rates, or lack thereof. This is indeed the case in its present form (see Section 5), however, the first steps to a unified model are already under way (poster by Chen et al. at GeoProc international conference, 2019). To address the reviewers' comment, we have rephrased statements on the robustness of the CNS model. We included notes that refer to the challenges ahead (see lines 25-26, 371-374, 468-469).

Lines 169-170: "The maximum rotation or shear displacement that can be achieved is limited by the water cooling and pore fluid systems, ". What does that mean? It is better to elaborate more on the experimental detail for readers outside of the field. The

water cooling and pore fluid systems include connections (i.e., hoses and tubing) to external reservoirs. These connections must be able to accommodate rotation of the vessel. Smart designs have helped to accommodate rotation such that very large sample displacements can be achieved (>100 mm). Following the reviewers' suggestion, we rephrased line 176-177 in accordance with the above.

Line 240 and Fig. 4: Need a more detailed explanation of the Fig. 4 (in particular 4c). For example, explanations on the differences in color and meaning of peaks in dash-lines are needed. OK. We have improved the overall quality of Figure 4 (see reply to first comment), including readability of Fig. 4c. We rewrote the caption to ensure that all abbreviations, symbols, colours, etc used are explained (applies to all figures), and we included a description on the meaning of the peaks in Fig. 4c.

Line 250: "an important role for the presence of (pressurized) pore water (Fig. 5a-insets) But how can we understand the importance of ((pressurized) pore water) from Fig. 5a? The data shown in Fig5a are from experiments on simulated calcite gouge carried out under the same effective normal stress and temperature conditions, one lab-dry and the other using a pore fluid pressure of demineralized water of 10 MPa. The inset highlights a part of the slide-hold-slide sequence in the test, demonstrating a marked difference in healing behaviour (i.e., note $\Delta\mu$r). We acknowledge that this was not sufficiently clear in the original ms, and we thank the reviewer for pointing this out. To address this, we now refer to Fig. 5a-inset at the appropriate location in the text, including a note on $\Delta\mu$r (see line 260-261). Furthermore, we have clarified the text within, and caption to, Figure 4, to better indicate the dry vs. wet experiment.

References NOT cited in the revised ms: Chen, J., Verberne, B. A., and Niemeijer, A. R. Flow-to-friction transition in simulated calcite gouge: Experiments and microphysical modelling. Under review for publication in J. Geophys. Res, preprint available on ESSOAr, 25 April,

Please also note the supplement to this comment:

https://se.copernicus.org/preprints/se-2020-85/se-2020-85-AC2-supplement.pdf

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