28th May 2020

Dear Editor,

Thank you for your helpful comments on our manuscript entitled “Characteristics of earthquake ruptures and dynamic off-fault deformation on propagating faults” [Paper se-2020-16]. We are grateful for the constructive and thoughtful comments made by the reviewers. We have addressed their questions, which are quoted below in blue. Text in red indicates text added to the new version of the manuscript. We also provide a PDF version of the revised manuscript in which we highlighted the changes in red (deleted) and blue (added). All line numbers in the letter below refer to the tracked-changes document. We hope that our revised manuscript has clarified the questions raised by the reviewers and made the paper stronger.

Best regards,
Simon Preuss (on behalf of all co-authors)

Reviewer 1 - Michele Cooke

A. The assumption of lateral propagation of strike-slip faults does not consider how crustal faults might form by the upward propagation and/or linkage of early fault segments. Experiments of strike-slip fault evolution show upward propagation with the formation of an early set of echelon faults that link to form a through-going strike-slip fault (e.g., Tchalenko, 1970; Hatem et al., JSG 2017). We don’t have reason to believe that crustal strike-slip faults would initiate differently from experiment observations. The text uses results of Perrin et al. (2016) that faults are most mature along their centers to justify lateral propagation. Lateral variation in fault maturity don’t preclude early upward propagation that would produce echelon segments that may link earlier along some portions of the fault than others. Unlike the quasi-2D simulations in this paper, the base of 3D laboratory experiments distributes shear within the suprajacent material in a manner analogous to crustal systems where mid crustal deformation drives upper crustal faulting. I’m not saying that the investigation of lateral propagation of strike-slip faults within this paper is unreasonable. This is a great first step towards understanding the complex evolution of strike-slip faults but may be only part of the story. To strengthen the implications of the paper, the introduction and discussion of the manuscript should include consideration of the 3D context of these strike-slip faults. How might the findings differ if strike-slip faults initiate with upward propagation followed by linkage?

We thank the reviewer for this thoughtful comment and for pointing out differences between 2D and 3D experiments. Indeed, our 2D (map view) and 2.5D simulations cannot model upward propagation of fault segments. However, there are other scenarios for fault strike-slip formation that are mechanically viable, such as those demonstrated in our paper and supported by field observations and other lab experiments. Both scenarios are not exclusive: it is very possible that the initiation of a fault is driven from below by the process the reviewer describes, but, as shown here and elsewhere, the subsequent lateral growth does not need to be driven from below.

We have followed a common practice in 2D numerical modeling of fault growth/branching or rupture propagation in strike-slip faults to simulate map view experiments (e.g. Kame et al., 1999; Poliakov et al., 2002; Rice et al., 2005; Meyer et al., 2017; Herrendörfer et al., 2018; Preuss et al., 2019). With our approach we are focusing on a very important part of the problem: the lateral growth stage.

To strengthen and clarify the scope of the paper we add the following to the introduction (line 31) :

Analogue experiments have shown that strike-slip faults can initiate by upward propagation and linkage of an early set of echelon faults to form a through-going fault (e.g. Tchalenko, 1970; Hatem et al., 2017). Further growth towards a through-going strike-slip fault generally occurs due to lateral propagation and the structural fault complexity usually increases towards the younger portions at the fault tip (Perrin et al., 2016a; Cappa et al., 2014).

And we add to the existing text (black italic) in the discussion section (line 688) :

This approximation does not actually account for the third dimension and neglects parameter variations with depth as well as a possible change of the fault dip angle with depth. In this study faults are always vertical in a plane-strain sense, cutting through the entire upper crustal layer. This implies that faults in our models can not initiate at depth and link from an early set of echelon faults that propagate upwards as shown by analogue experiments. *Further, the simulations exclude a temperature-dependent rheology that would imply rheology changes with depth.*

B. The conclusions that the strike-slip faults grow predominantly in the aseismic period of the earthquake cycle is based on the assessment that the rate weakening results, with their fast coseismic growth, are unreasonable.

We emphasize that all four reference models have predominantly aseismically growing faults. This was stated at various points in the old version of the manuscript already. The longest seismically grown fault segment in the rate weakening model measures 12.3 km (line 313) and the rest of the newly formed fault (i.e. ~30 km for fault RW2) was produced aseismically. Moreover, the rate weakening model does not have faster and more coseismic growth than the other models. We add that the rate weakening results are not per se considered unreasonable. Our results in section 3.1 show that a bulk rheology with constant rate-sensitivity (including the rate weakening model) favors a faster fault growth of up to 77 km/yr in contrast to more realistic fault growth rates of ~1.8 km/yr in model RT.

To clarify our findings we add to line 483 (beginning of discussion):

Our results suggest that all four reference models have predominantly aseismically growing faults. A bulk rheology with constant rate-sensitivity favors a faster fault growth. In contrast, the heterogeneities introduced by a weakening of the RSF parameters L and b slow down the

faulting process due to the absorption of energy by the weakening mechanism. As a consequence, the faults in the model RT that transition from rate-strengthening to rate-weakening can extend in alternating seismic and aseismic growth periods. Only if the region ahead of the fault tip has experienced distinct plastic strain and *L* and *b* are altered to create a rate-weakening fault earthquakes can propagate on there. Otherwise, dynamic rupturing is hindered in the intact bulk, where *L* is still high and *b* is still low and rate-strengthening, respectively. This contrast of large *L* and low *b* in the bulk rock results in intermittent seismic and aseismic growth sequences. We think this behaviour reflects the natural growth of crustal faults better than constant values of *L* and *b*, which lead to rapid fault propagation after singular earthquakes.
Furthermore, evolution of *L* and *b* with strain was observed in laboratory studies (e.g. Beeler et al., 1996; Scuderi et al., 2017; Marone and Kilgore, 1993).
The differences between the two end-member bulk rheologies have major implications on the dynamics and geometry of fault evolution, which are discussed in this section.

We furthermore add to line 553:
However, in general fault growth predominantly occurs through aseismic deformation in all four reference models, independent of the type of bulk rheological behaviour. That is because a seismic rupture only reaches the current fault tip if this part of the fault is already highly localized. This is solely the case in the first earthquake when the entire fault trace coincides with the predefined, weak, mature fault.

We furthermore add to line 260:
The models with constant rate-sensitivity (models RS, RN, and RW) have fast fault growth rates of up to 77 km/yr that are much faster than in model RT. Despite this major difference, all reference models have in common that fault growth during the earthquakes contributes only a small portion to the total formed fault length FL (Fig. [3b]).

We do have evidence that faults can link during earthquake rupture along previously unmapped segments. This process of quick coseismic linkage could look a lot like the results of the rate weakening models that propagate towards the edges of the model. If the models had a second fault segment, perhaps the rate weakening models would showing linkage of the segments in a very reasonable way. For this reason, perhaps the rate weakening rheology may be overlooked should not be considered completely unreasonable.
We agree that fault linkage can occur during earthquake rupture along previously unmapped segments. We did show this in Figure 9 for model HPT. Adding to that we explained in the previous comment that we do not per se consider the rate weakening rheology as unreasonable.
We are currently running models of a natural earthquake example in which we predefine several unlinked segments that are supposed to link on the long-term (Preuss et al., 2020, EGU General Assembly 2020 presentation: link). However, fault linkage is a complex

process that needs further investigation and is not among the main aspects of this paper, which is already long. We refer to the last two sentences of our manuscript:
With our work we provide the basis for simulations and analyses of complex evolving fault networks subject to long-term and short-term dynamics. The approach we presented has potential to be applied to a more realistic fault map in a future study.

C. This question is related to the comment of B. Rate neutral and rate weakening are rheologies that we expect in the crust. In this study, they are excluded because the models do not produce more than one earthquake. What model parameters could be altered (for example, in a future study) to get more than one earthquake cycle for the rate neutral and rate weakening models?
We are not sure if rate neutral and rate weakening are the most realistic rheologies we can expect in the crust. Laboratory observations show that RSF parameters *(a-b)* and *L* weaken with plastic strain (Beeler et al., 1996; Scuderi et al., 2017; Marone and Kilgore, 1993). This behavior suggests that a crustal bulk rheology with no rate-sensitivity (like constant rate-neutral or constant rate-weakening) is less likely. We conducted up to ~1000 experiments with different parameter setups but were unable to get to more than one earthquake or distinctly slower fault growth rates in any of those models with no rate-sensitivity.
In contrast a rate sensitivity as observed in laboratory studies is incorporated in model RT, which produces the most realistic fault growth rates and earthquake sequences rather than single earthquakes. Thus, we consider model RT the most realistic model and the rate-transitioning rheology the most likely crustal behaviour.
In a future study we suggest to test the following to get more than one earthquake cycle for the rate neutral and rate weakening models:

- Substantially larger model box with mesh refinement close to the fault
- Strongly misaligned initital fault
- Higher value of background pressure
- Higher initial bulk state variable
- Higher cohesion potentially in combination with strain weakening of cohesion

D. Some parameters seem a bit outside of expected crustal ranges. The width of the plastic yielding fan seems large.
We emphasize that observations distinguish between outer and inner damage zones. The "outer damage zone" (Perrin et al., 2016) is much bigger than the "inner damage zone" (Savage and Brodsky, 2011). In our study we furthermore find that the initial orientation of the fault and various parameter(-combinations) alter the width of the plastic yielding fan severely:
In section 3.3 and particularly in Figure 8 we show that the width of the plastic yielding fan depends on the initial orientation of the fault in the surrounding stress field. The large fan width results from the misorientation of the predefined fault. Thus the initial fault orientation

relative to the regional stress is a crucial parameter. A corollary is the possibility to distinguish between optimally oriented and severely misoriented faults by assessing the extent of coseismic off-fault damage.
In section 4.4 we comment on this particularity of our findings. For example we write in line 582:
Our findings regarding the time-dependent optimality of the fault angle have implications for nature and for future dynamic rupture modeling studies. Active fault strands in nature that are surrounded by severe localized or diffuse damage zones, possibly extending far into the host rock, are strongly misaligned with the interseismic far-field stress field. This misalignment may be increased dynamically during seismic rupturing. This means that individual fault traces may reflect the local geology, structure or stress state rather than the prevailing far-field, long-term stress field and this effect would vary from segment to segment randomizing the fault pattern (Moore and Byerlee, 1989). This explains the complex nature of inter-branched crustal fault systems.

We add the following to the new version of the manuscript (line 669):
The width of the plastic fan in our models is larger than that seen in observations from Savage and Brodsky (2011). This difference is related to the non-optimally oriented fault of the reference model, which was discussed in section 4.4 and which is compared to an optimally oriented fault with a significantly lower width of the plastic yielding fan in figure 8. Furthermore, the plane strain assumption in our 2.5-D model assumes a constant thickness of the seismogenic fault with depth-constant rate-weakening behavior, which favours a larger width of the plastic yielding fan generated during earthquakes if it is compared to a natural fault which typically has alternating rate-weakening and rate-strengthening patches. Additionally, in our model the width of the fan is controlled by several parameters, of which the thickness of the elastic layer T on top of the visco-elastic half-space has the greatest impact. Higher values of $(a - b)$ as well as high and low initial bulk host rock state variable values θhr decrease the fan width significantly.

The static frictional strength of the faults of 0.6 is high when we consider that crustal faults have fluids.
We agree with the reviewer on this point. However, we assume a typical pore fluid pressure ratio of $\lambda \sim 0.67$ that increases the background pressure to a lithostatic pressure of $PBlith = 60.6 MPa$ (line 221). Alternatively, the pore fluid pressure could be included to calculate an effective friction coefficient of 0.6 * (1 - 0.67) = 0.2 at shallower depths This difference in perspectives reflects procedures in different communities. The geodynamics community usually defines an effective friction coefficient by multiplying the fluid pressure ratio with friction, whereas the seismicity community leaves the friction coefficient untouched and works with effective stress or pressure (stress minus fluid pressure). In addition, due to the low initial state on the predefined fault the effective friction coefficient on this fault drops to values around $\mu \sim 0.4$ as the fault is ruptured.

The 20 km choice for maximum fault zone width for the heuristic fault zone thickness, needs stronger substantiation.

We add to line 180:

The upper fault width limit Wmax is defined as the width of inelastic interseismic deformation obtained from fault-parallel GPS and InSAR data. We get a first order estimate of this quantity by measuring the half width of the fault-parallel velocity approaching the far-field plate velocity asymptotically. Wmax can vary significantly between ~ 2 km (Jolivet et al., 2013) and ~ 100 km (Jolivet et al., 2015; Lindsey and Fialko, 2016) in natural faults and depends on the crustal material and thickness, the rate of deformation and the size of the respective fault zone. Consequently, we set Wmax = 20 km as an averaged proxy for the fault width in the interseismic phase. The relation 12 can be interpreted as a heuristic fix to the problem of grid-size-dependent localization in continuum models with RSF.

E. Something to consider in the discussion of the paper is the role of nearby faults on the 'bending' of fault traces. While fault strike may bend in response to changing slip conditions, most crustal faults develop within a complex system where they might interact with nearby faults. Slip on a nearby fault (such as the Garlock fault near the San Andreas) may in many cases have larger impact on the bending of faults than difference in aseismic and coseismic lateral propagation.

This is very right and we agree with the reviewer on these points. Indeed, they were addressed in our manuscript already. Especially in section 3.4, in which we introduce model HPT, we noticed and mentioned fault bending and interaction (line 462):

In the following we analyze several indications of fault and rupture interactions due to stress changes that are typically ignored in seismic cycle models. They include: (1) Rupture arrest when two sub-parallel ruptures get too close to one another. This can be observed for fault HPT001, which stops growing because the stresses on the extensional side of the subsequently forming branch HPT01 increase, get dominant and limit the compressional side stresses of HPT001. As a consequence, only extensional stresses remain at the tip of HPT001, such that the fault gets thinner on its compressional side (Fig. [9c,b]). This leads to (2) a stop in fault growth and fault abandoning. ***Further, fault bending (3) is observed as fault HPT02 approaches HPT0001 and the former starts to bend due to local interactions of stresses. After bending, both faults intersect (4), which causes HPT02 to terminate*** *(5). All together, this behavior is well visible in the video of the HPT simulation, 19 Mb. Consequently, new interjacent branches can stop if their extensional side stress field interacts with the compressional side stress field of another rupture. This is the case when the branches of two subparallel ruptures get close to one another. In this process, the fault on the extensional side is likely to continue extending. This line of reasoning applies for a dextral fault system and is reasonable since the evolving fault structure as a total has an extensional character, which means that an extensional stress state is predominant and the extensional fault's side is favored.*

We have summarized our findings and have discussed them in section 4.5 (line 608):

The single main fault rupture in this model excites 10 dynamic secondary ruptures on the extensional side bulk that can arrest, bend, converge, intersect and get abandoned. This

complexity is linked to variations of the normal stress during and between earthquake sequences, which affect the evolving fault pattern. That behavior highlights the importance to include a varying normal stress in earthquake cycle models instead of assuming a constant normal stress. ...
An interesting feature in model HPT is the main fault replacement (or jump). This is reflected in the singular growth and slip activity of the outermost fault branch HPT0001 at the end of the simulation. In the dynamically altered stress field this outermost fault branch is most favorably oriented. A main fault jump was reported in southern California where the San Gabriel fault was originally the main strand of the San Andreas fault, but was replaced at about 4 Ma (Moore and Byerlee, 1991). Faults that are unfavorably oriented for large amounts of slip will be replaced by progressively better oriented faults (Moore and Byerlee, 1989). Fault branch interaction occurs also on the long-term when the stress fields of approaching fault strands start to interfere (manifest in a seismically initiated incipient connection between RT1 and RT2 at x~140 km in Fig. 3). Seemingly, the fault system intends to increase its efficiency by decreasing the fault complexity on the long-term due to fault interaction which can lead to abandoning of abundant fault strands. This is another indication, apart from the previously discussed one, that the fault optimizes its growth efficiency and aims at reaching a steady state on the long-term in which seismic and aseismic growth preferentially happen in the same direction.

Additionally, immature faults may develop bends in their earliest stages when neighboring segments that are not colinear link up to form a single fault surface (Hatem et al., JSG 2017).
We have reported this behavior in the submitted version of the manuscript, already (line 362):
Additionally, faults RT1 and RT2 interact with each other. Fault RT2 starts to bend towards RT1 at 360 years. This behavior is not recorded in the other reference models. Visible is also a seismically initiated connection between RT1 and RT2 at x=130 km that starts at 355 years.

F. The manuscript strives to address a wide range of conditions/questions. I wonder if some parts of the manuscript, such as the HPT models, might be best served as supplemental material.
We would not want to exclude or shift a part that answered the remarks of reviewer 1 posed under previous point **E**.

Specific comments

The paper is very well written. I have a few specific comments that may strengthen the writing in places.

Throughout the manuscript (eg. Line 102, 298 and many others): 'Fault extension' reads a bit odd since extension is a strain term. The text might be clearer with use of 'fault propagation'.
We changed that everywhere.

Line 40 (and there abouts): The use of Riedel terminology for splay fractures strikes me as a bit odd because we typically refer to Riedels as the early formed echelon fault segments. The fractures within the damage zone are more commonly called splay cracks. You may find papers by Cooke (JGR 1997) and Willemse and Pollard (1998) helpful because they show the range of orientation of splay fractures that can develop with different conditions on the fault.
We agree. We changed the respective paragraph and added the reference to Cooke (1997).

Line 51: Define SCEC.
We defined it in the new version of the manuscript.

Line 213: Mixing strain (extensional) and stress (compressional) term. Make these both either strain or stress.
We did not find the term "stress" between lines 211-216. What is the reviewer referring to?

Line 252: spelling of strengthening
We changed that.

Line 253: 'This results' is ambiguous. This what? Being more clear will help the reader. Line 254: Better than what?
We changed that to (line 496):
This contrast of large *L* and low *b* in the bulk rock results in intermittent seismic and aseismic growth sequences. We think this behaviour reflects the natural growth of crustal faults better than constant values of *L* and *b*, which lead to rapid fault propagation after singular earthquakes. This difference has major implications on the dynamics and geometry of fault evolution, as discussed in the next section.

Line 399 and throughout: I'm not a fan of the acronym OOF for optimally oriented fault model. Why not just spell it out since you already have a lot of acronyms and only use OOF for one section of the paper?
The term OOF is now spelled out in the new version of the manuscript.

Line 497: This is just one paper, for which there is a rich literature. Add e.g. and some more citations.
We added (line 525):
Stress analysis of a crack loaded in mode II explains the formation of tensile fractures at the crack tip (e.g. King and Sammis, 1992; Cooke, 1997; Poliakov et al., 2002; Rice et al., 2005).

Line 540: Another interesting study is a quasi-static dynamic model of Savage and Cooke (JSG 2010). That study differs from the ones citated in that it does not limit damage development along pre-existing mesh. So, the results of Savage and Cooke (JSG 2010) might be interesting to compare to your new model results.
We added (line 572):
The value of the slip-weakening distance was shown to regulate between more continuous along-strike damage and concentrated fracturing at fault tips (Savage and Cooke, 2010).

Line 573-574: This is an interesting result. I believe that this finding confirms results of Jiang and Lapusta – it could be helpful to cite their work here.
Jiang and Lapusta (2016, 2017) use a depth dependent effective normal stress. However, our models feature, on top of a spatially varying effective normal stress (in our case effective pressure), a temporal variation of the effective normal stress (effective pressure). To make it more clear we add to line 609:
This complexity is linked to spatial and temporal variations of the normal stress during and between earthquake sequences, which affect the evolving fault pattern. That behavior highlights the importance to include both spatially and temporally varying normal stress in earthquake cycle models instead of assuming a constant normal stress or only assuming a depth dependent normal stress.

Line 583: There is a rich literature on the development of new faults that are more efficient. Add e.g to this reference.
Thanks, we added that.

Line 594: Cooke (JGR 1997) show that changes in friction distribution near fault tips alters the stress concentration and the angle of the splay crack. The change in friction arises in the transition between mature fault with static friction to immature fault with higher friction. Could this process be contributing to your observation of changing splay angle?
A change in the splay angle occurs due to earthquakes (as discussed in section 4.2) and consequently due to differences between aseismic and seismic fault growth (as discussed in section 4.3). Both depend on the optimality of the pre-existing fault angle (as discussed in section 4.4) and are influenced by fault branch interactions (as discussed in section 4.5). As shown in Preuss et al. (2019) the local friction coefficient at the tip of an aseismically and a seismically growing fault differ substantially, which leads to different fault orientations. So yes, the transition between a mature fault with a given friction to an immature fault with a different (possibly higher) friction is contributing to the observation of changing splay angles. This finding is extensively mentioned throughout the manuscript and in Preuss et al. (2019). Hence, we do believe a further explanation or interpretation is not needed in section 4.6.

Line 602: Add Cooke (JGR 1997) to this reference list as it is very much related to these other good papers.
Thanks, we added that.

Line 628: The width of the plastic fan in the models is larger than that seen in Savage and Brodsky (2011).
We agree and refer to our answer of the reviewers remark **D** in which we discuss that the size of the plastic off-fault fan is a result of a misorientation of the predefined fault in the

reference models. As shown in Figure 8, an optimal oriented fault results in a severe decrease of the plastic fan. To make this clearer we add to line 669:

The width of the plastic fan in our models is larger than that seen in observations from Savage and Brodsky (2011). This difference stems from the non-optimally oriented fault of the reference model, which was discussed under 4.4 and which is compared to an optimally oriented fault with significantly lower off fault yielding in figure 8. Additionally, in our model the width of the fan is controlled by several parameters, of which the thickness of the elastic layer T on top of the visco-elastic half-space has the greatest impact. Too high values of $(a - b)$ and too high and too low initial bulk host rock state variable values θ_{hr} decrease the fan width significantly.