

Dear authors,

I would like to thank you for all the work you put into addressing the reviewers' comments. I'd like to give you a final opportunity to address the minor comments from this last round of reviews before the manuscript is published.

Best regards,

Juliane Dannberg

Dear Dr. Dannberg, Dear reviewers,

Thank you for your constructive feedback. We have carefully considered comments from the reviewer, and have revised the manuscript.

Best regards,

Yury Alkhimenkov, Lyudmila Khakimova and Yury Podladchikov

Response to Reviewer 1: Our comments are provided in blue. Text modifications are provided in green.

The authors have made a commendable effort to focus their manuscript on converged simulations.

Thank you for your positive feedback.

Figure 8 shows that the amplitudes of stress drops overall decrease with increasing loading strain. For instance, they are clearly very small after a strain of 1.2 %, and quite large before a strain of 0.4%. To show this more clearly, I recommend plotting the logarithm of stress drop amplitudes as a function of loading strain.

We agree with the reviewer and have add a figure of stress drop amplitudes as a function of loading strain.

Figure 9 shows a histogram of stress drop for the whole simulation. I recommend plotting also the histogram of the later portion of the simulation after a loading strain of 1.2 %. Is it almost symmetric? Is it approximately log-normal?

We added a figure (histogram of the later portion of the simulation after a loading strain of 1.2 %.). No, it is not log-normal.

Based on that, you can discuss whether the asymmetry of the current histogram (noted in Line 418) arises from the fact that stress drops become smaller with increasing loading strain.

In this study, we report only the results of a single converges simulation with the same boundary conditions. As can be seen the stress drops become smaller. But in reality boundary conditions are not the same but changing, therefore, for evolving boundary

conditions the stress drops may not become smaller (but even become larger). To mentions this in the manuscript, we need to present another study, therefore, it is not discussed in the manuscript.

Minor comments (line numbers refer to the pdf with tracked changes):

1. Lines 6-7, "Finer temporal and spatial discretization leads to sharper stress drops and lower minimum stress values": Clarify that this statement holds for simulations that have not converged yet. Once convergence is reached, by definition, results no longer depend on discretization refinement.

We added more details.

for simulations that have not converged yet

2. Line 22: the word "triggering" should be replaced through the whole paper, for the reason explained in minor comment #1 of my previous review

We agree with the reviewer. We replaced triggering.

nucleation

3. Lines 36-37, "Recent studies ...": I would modify this sentence as "Numerical studies have suggested that plasticity plays a crucial role in earthquake rupture, particularly through off-fault plasticity mechanisms (e.g., Andrews (1976, 2005))". In fact, such studies are not recent, the first one is 50 years old.

We agree with the reviewer. We modified the sentence.

Numerical studies have suggested that plasticity plays a crucial role in earthquake rupture, particularly through off-fault plasticity mechanisms

4. Lines 39, "earliest studies": add "earliest 3-D studies" and move this sentence to Line 47, before "Another significant advancement ..."

We agree with the reviewer. We modified and moved the sentence.

\cite{ma2008physical, ma2010inelastic} conducted some of the earliest 3D studies on dynamic rupture with plasticity.

5. Line 62-63: You can add that an important goal is to achieve convergence of the numerical results and then focus on high-resolution (converged) simulations.

We agree with the reviewer. We have added a sentence.

An important goal is to ensure convergence of the numerical results, after which we focus on high-resolution, converged simulations.

6. Lines 72-73, "We propose a physics-based explanation for spontaneous stress drops": The stress drops in your simulations are produced by the known process of structural softening. Thus this item is not a "novelty of the present study". 7. Lines 74-75, "We do not prescribe any pre-existing faults; instead, new faults emerge spontaneously from the stress field": This is a feature of multiple previous modeling works too, thus not a "novelty of the present study".

We agree with the reviewer. Our main contribution that we explore the physics proposed in (a few) previous studies with very high spatial and temporal resolution, that was not possible before, that's why we can analyze histograms and have many faults. We modified the text and removed "novelties":

The distinct features of this study among other recent HPC simulations are:

...

2. We systematically investigate a previously proposed physics-based explanation for spontaneous stress drops using convergence-controlled, high-resolution GPU simulations, thereby extending the accessible resolution and fidelity of the theory. \\

3. We allow faults to emerge spontaneously from the evolving stress field, as it was done in a few previous studies. Our higher spatial/temporal resolution and GPU throughput produce a much larger population of emergent faults, enabling analyses that were previously intractable. \\

8. Line 83: replace "1..3" by "1,2,3"

We agree with the reviewer. We modified the sentence.

1,2,3

9. Equation 5: v_k might need a superscript "eb"

We agree that some explanation is needed, therefore, we modified two equations in the text.

10. Equation 15: plus sign is repeated

We agree with the reviewer. We modified the formula.

11. Section 3.1: I understand that during simulations you switch between explicit solver (during fast deformation periods) and accelerated-pseudo-transient solver (during slow quasi-static deformation periods). Explain the criterion used for switching. Discuss whether the choices made in the switching criterion (for instance, threshold values) affect the statistics of small stress drop events.

APT solver is in fact a wave propagation solver. We simply add visualization of wave propagation for a displacement caused by a single stress drop. This visualization does not affect the quasi-static simulation.

The quasi-static equations are solved with the accelerated pseudo transient method (described below), while the dynamic wave-propagation is only visualized to illustrate the transient fields and does not affect the quasi-static evolution.

12. Line 227: define “N”

We agree with the reviewer. We modified the sentence.

(N is the number of grid cells in x-dimension)

13. Legend of figure 2a: define “n_x” (or did you mean N?)

We modified the figure. It should be N.

14. Lines 445-446, “the prevalence of small events and the presence of occasional larger ones are qualitatively consistent with the Gutenberg–Richter relationship”: This statement conflates stress drop and earthquake magnitude. In natural earthquakes, stress drops are quite independent of magnitude. The Gutenberg-Richter relation pertains to magnitudes, not to stress drops.

We agree with the reviewer. We modified the sentence.

Gutenberg–Richter-like

15. Line 508, “low-resolution simulations, where the regularization length scale becomes comparable to or larger than the grid resolution”: but this holds instead for high-resolution simulations, which have shear band thickness larger than the grid size. Clarify.

In large resolution simulation, with correct regularization, shear band thickens is a about several grid cells (e.g., 10-30). As we show in figure 2, resolution does play a key role.

16. There is dissonance between sections 6.2 and 6.2. The former emphasizes the importance of regularization to obtain well-resolved results, while the latter argues that similar results are obtained with and without regularization. Clarify.

Regularization is important for convergence of the results. But without regularization the results are similar --- same number of stress drops, approximately the same magnitudes.

17. Lines 524-525, “In 3D the stress and strain fields exhibit additional complexity, including the development of intersecting or branching shear bands”: This features are also present in 2D, thus they are not an “additional complexity”.

We agree with reviewer and removed this sentence.

18. Line 536, “quasi-periodic pattern”: If you really mean quasi-periodicity, you should document it by computing the Coefficient of Variation (COV) of interevent times (the time intervals between stress drops). COV is defined as the standard deviation divided by the mean value. A small COV indicates quasi-periodic behavior.

We agree with reviewer and modified this sentence. The pattern of stress drops does not correspond to log-normal or normal distributions. This is a property of “hard” turbulence. But we do not mention it in the main text since it requires a specific study, focused on this property.

The pattern of stress drops does not correspond to log-normal or normal distributions.

19. Line 594: Are you suggesting that “subsequent stress drops” are not due to structural softening, but to a different mechanism? Clarify.

We clarified this in the text.

In this study, we investigated stress drops and earthquake-like behavior in idealized elasto-plastic media using two-dimensional numerical simulations. The first stress drop occurs following the onset of strain localization, a process driven by structural softening \citep{vermeer1990orientation, le2013strain, sabet2019structural}. This structural softening mechanism, which received relatively little attention until recently \citep{sabet2019structural}, is explored here as a cause of spontaneous strain localization in an ideal plasticity model with a constant friction coefficient. Subsequent stress drops are associated with transitions between quasi-static loading intervals, during which the system moves from one equilibrium state to another due to the inability of strain localization to continue growing in the same direction. This behavior is consistent with fault offset theories developed by \cite{forsyth1992finite, buck1993effect} and validated by \cite{lavier1999self}. \cite{forsyth1992finite} emphasized that Anderson’s theory for faulting applies strictly to infinitesimal displacements. The initial orientation of a fault corresponds to the orientation that minimizes the regional stress required for slip initiation. However, \cite{forsyth1992finite} demonstrated that the additional horizontal stress necessary to maintain slip along the same fault increases linearly with accumulated displacement. Consequently, after only a few hundred meters of slip on a typical fault, it becomes mechanically more favorable to nucleate a new fault than to continue slip on the pre-existing one. Switching from sliding along an active fault to nucleation of a new fault is a fundamental cause of sudden stress drops and a potential mechanism for earthquake cycles.

20. There are several typos. They can be fixed by running a spell/grammar checking tool.

We would like to thank the reviewer again for valuable comments, which helped us improve the quality of the manuscript.

Sincerely,
Yury Alkhimenkov, Lyudmila Khakimova and Yury Podladchikov