Authors' Responses to Reviewer's Comments

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Title: Hybrid implicit–explicit XFEM simulation of injection-induced seismicity: resolving multi-scale rupture nucleation and dynamics

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We thank the reviewers for their constructive and insightful comments and have revised the manuscript accordingly. We have marked changes made in the revised manuscript in **blue-colored** text, and describe the steps taken to address the reviewers' comments point by point below.
We hope that the revisions have improved the manuscript's contribution to the field and meet the reviewers' expectations. We are grateful for the opportunity to revise our work and look forward to the continued consideration of our manuscript for publication in GMD.

Response to Reviewer #1

Reviewer#1: The authors propose an implicit-explicit (IMEX) time-integration scheme to resolve different timescales in a fully coupled hydromechanical finite element model. The results look promising, especially because of the potential speedup of calculations. However, many details and definitions are missing, therefore improvements are needed before publication. Overall, I thus recommend major modifications of the manuscript before resubmission.

We sincerely thank the reviewer for carefully evaluating the revised manuscript and for identifying the remaining points requiring clarification. We have addressed all comments and further revised the manuscript accordingly.

Comment #1: The definitions of σ is still missing, and as it is now the names for the test functions are even more confusing for me, please either call them v and q or $\delta \boldsymbol{u}$ and δp.

Response: We have now explicitly defined $\boldsymbol{\sigma}'$ as the effective stress tensor and $\boldsymbol{t}$ as the traction vector acting on the fault interface. We have also revised the notation for the test functions to ensure consistent use throughout the weak formulation.

Comment #2: Eq. (5) was not derived in more detail, please explain how you get there from (2).

Response: As mentioned in the text, Eq. (2) is multiplied by the pressure test function ψ and integrated over Ω. Applying integration by parts to the divergence term gives the domain-gradient terms and the corresponding boundary-flux terms. The latter are separated into the prescribed hydraulic Neumann boundary Γ_w and the internal fault interface Γ_d, where the matrix–fault exchange flux appears.

Comment #3: The fix is fine in general but please remove the "discontinuous" since the domain itself is not discontinuous.

Response: Agreed. We have removed the word "discontinuous," since the fault domain itself is not discontinuous; rather, discontinuities may occur in the associated solution fields.

Comment #4: Can you give a reference for the appearance of w^2?

Response: We have also clarified the origin of the aperture-dependent terms arising from the lower-dimensional integration and added the corresponding reference to Khoei (2015).

Comment #5: Should there not be a term like (n + 1) $\zeta^n - n\zeta^{n-1}$?.

Response: The superscripts n and $n+1$ denote time-step indices rather than mathematical powers; therefore, the previous-step slip variable is constant during the local Newton iteration and the additional term suggested in the comment does not arise.

Comment #6: Please add some part of your answer from your response letter here.

Response: We have added further explanation in the manuscript.

Comment #7: Please write explicitly that this formula only holds for a one-dimensional fault since in your work everything else looks as if it also holds in higher dimensions.

Response: We have clarified that, in the present two-dimensional model, the fault is represented as a one-dimensional interface with a single tangential slip direction; therefore, V in Eq. (19) is a scalar slip speed. For a higher-dimensional fault surface, the tangential slip velocity would generally be vector-valued and V entering the rate-and-state law would correspond to its magnitude.

Comment #8: It should be "denotes the number"

Response: Corrected.

Comment #9: I did not understand your response here since in line 283 neither C or D are defined, furthermore C is also not defined before or after (34).

Response: We now explicitly define D as the global damping matrix. We also define the elastic constitutive matrix appearing in the stiffness matrix and distinguish it from the hydro-mechanical inertial-coupling matrix introduced later in Eq. (37), thereby removing the ambiguity in the notation.

Comment #10: The word order in the new part is not correct, it should be "where $\mathrm{m} = [1 \quad 1 \quad 0]^T$ is the Voigt representation".

Response: Corrected.

Comment #11: There is still K_T and k_T in (50) and (51).

Response: Corrected.

Comment #12: But the term in (63) is quadratic and not cubic, please fix or explain that.

Response: Equation (63), $k_f = \frac{w^2}{12}$, defines the intrinsic fault permeability and is therefore quadratic in aperture. The cubic dependence refers instead to the lower-dimensional hydraulic transmissivity, since multiplying the permeability by the aperture gives $wk_f = \frac{w^2}{12}$. We have revised the text to clearly distinguish the quadratic permeability relation from the cubic-law transmissivity.

Comment #13: Going through your appendices I realized that the figures there should be called B1, B2, ..., C1, C2,... and not all starting with an A.

Response: We have corrected the appendix figure numbering and all corresponding in-text references so that figures are numbered according to their respective appendices (e.g., B1 and C1–C3), rather than continuing with the "A" prefix.

Response to Reviewer #2

Reviewer#2: We thank the reviewer for the detailed assessment. We respectfully disagree that the present study requires simulations containing tens or hundreds of millions of elements in order to establish the contribution of the proposed method. The objective of this work is not to demonstrate an HPC implementation or formal parallel scalability, but to assess a hybrid implicit–explicit time-integration strategy under controlled and directly comparable conditions. The manuscript includes verification of the hydromechanical, frictional, and elastodynamic components, mesh-sensitivity analysis over five resolutions, sensitivity studies of the principal numerical parameters, and direct CPU-time comparisons against the fully implicit reference formulation. We therefore consider the presented numerical evidence sufficient to support the methodological conclusions of the study within its stated scope.

Comment #1: The governing equations do not represent the full dynamic Biot formulation; therefore, the simulations should not be described as "fully coupled poroelastodynamic."

Response: We clarify that the formulation is fully coupled in the sense that the displacement and pore-pressure fields are solved simultaneously within a monolithic hydromechanical system, while inertia is retained in the solid momentum equation. We already explicitly state in Sect. 2.1 that the formulation is not the full two-field dynamic Biot model and does not include relative fluid inertia, added-mass effects, or tortuosity. Therefore, the terminology is intended to describe the coupling between poroelastic deformation and elastodynamic solid response, not to claim a complete dynamic Biot formulation.

Moreover, in the literature, the term fully coupled poroelastodynamic is not always restricted to the full dynamic Biot formulation and has also been used for coupled formulations retaining solid inertia while neglecting fluid inertia.

Comment #2: The simulations are too small to demonstrate computational efficiency or scalability, and therefore the statements regarding computational efficiency and potential for larger-scale simulations are not supported.

Response: We distinguish computational efficiency for the problem considered from formal parallel or asymptotic scalability. The manuscript does not present a high-performance-computing scalability study. Instead, computational efficiency is quantified by direct CPU-time comparisons between the hybrid and fully implicit formulations for identical meshes, constitutive models, tolerances, and physical conditions. Under these controlled comparisons, the hybrid strategy reduces CPU time by approximately 58–71%, while preserving the principal fault-response metrics. We therefore consider the relative efficiency comparison well supported. We agree, however, that extrapolation to substantially larger systems would require dedicated scaling studies, and we have ensured that the manuscript does not present the current results as a formal demonstration of scalability.

Comment #3: Existing 2D and 3D studies use hundreds of millions of cells, whereas the present 200×200–255×255 meshes are too small to demonstrate the proposed approach.

Response: We consider direct comparison based solely on element count to be inappropriate in this context. Computational cost depends strongly on the governing equations, discretization, nonlinear constitutive laws, number of degrees of freedom per element, coupling strategy, and solver architecture. The present simulations involve coupled hydromechanics, XFEM enrichment, frictional contact, rate-and-state constitutive updates, adaptive time stepping, and nonlinear Newton iterations. Consequently, the number of cells alone is not a meaningful measure for comparison with voxel-based or GPU-based simulations solving different mathematical problems. The objective of the present study is to evaluate the proposed time-integration strategy under controlled conditions, rather than to demonstrate an HPC implementation.

Comment #4: Comparing 200×200 and 255×255 meshes does not establish mesh convergence; the resolution should be systematically doubled.

Response: We agree that the current analysis should not be interpreted as a formal asymptotic mesh-convergence study. However, the assessment is not based only on the 200×200 and 255×255 meshes: five mesh resolutions ranging from 100×100 to 255×255 were investigated. Across this range, the peak slip-rate variation from the course to the finest mesh is approximately 6.99%, with progressively smaller changes at the finer resolutions. The purpose of this analysis is therefore to demonstrate limited mesh sensitivity within the resolution range relevant to the present simulations, rather than to establish a formal convergence order. We have adjusted the wording accordingly.

Comment #5: A systematic scalability analysis should not be considered beyond the scope because a new computational approach is presented.

Response: We disagree that a large-scale HPC scalability study is required to establish the contribution of the present work. The methodological objective is to assess whether switching between implicit and explicit time integration can reduce the computational cost associated with resolving widely separated temporal scales in injection-induced fault reactivation. This is evaluated through controlled comparisons against the corresponding fully implicit formulation, including sensitivity to the switching criterion, time-step size, mesh resolution, and treatment of the slip tangent operator. Parallel scalability, preconditioner scalability, and very-large-scale three-dimensional performance constitute separate numerical questions that require different solver implementations and computational studies. These extensions are therefore identified as future work rather than prerequisites for assessing the proposed time-integration methodology.

Comment #6: The wave-propagation component is not validated; comparison against an analytical solution and convergence rates are required.

Response: We clarify that the elastodynamic component is verified using the SCEC/USGS TPV205-2D dynamic rupture benchmark, an established community benchmark specifically designed for verification of dynamic rupture solvers. The purpose of this benchmark is to assess

the explicit elastodynamic rupture component independently of the rate-and-state formulation. In addition, the manuscript compares acceleration, velocity, displacement, rupture propagation, and wave-arrival characteristics between the fully implicit and hybrid formulations. An additional analytical wave-propagation benchmark and convergence-rate study would certainly provide further verification, but we do not consider it necessary for establishing the numerical consistency of the specific solver-switching methodology investigated here.