Dear Path,

Thank you for your efforts in handling the review for our manuscript "Modeling fluid-driven fault slip dynamics with shear-induced dilation and compaction". We are submitting the revised version of this manuscript for your consideration.

The two reviewers provided thorough reviews, which have led us to make useful improvements to this manuscript. We have accepted most of the reviewers' recommendations and have revised the manuscript accordingly. Below we address each comment (our responses are colored **blue**), and where applicable, we include the changes applied within the manuscript.

In response to the reviewers' comments, we substantially expanded the Methodology section. Minor revisions were made to the Introduction and Results. The Discussion was expanded to address the reviewers' points, adding extra paragraphs to the relevant subsections. Figure and Table captions were updated to improve clarity.

See below for more detailed responses to each reviewers' comments. We also include the pdf of the new version, and a pdf with the changes highlighted. Please let us know if you have any questions on the revised version. We look forward to your assessment of the manuscript's suitability for publication in Seismica.

Sincerely,

Betti Hegyi, Luca Dal Zilio, Whitney Behr, Taras Gerya

Reviewer A:

The authors present results from numerical simulations of earthquakes using a recently introduced poromechanical model of the fault zone. The model emphasizes changes in fault strength from changes in pore pressure, in contrast to changes in strength from changes in friction coefficient (the classical mechanism for explaining earthquakes). While most of the model ingredients were introduced in prior publications by the group, this study provides a much broader exploration of parameter space, especially a comparison of the interplay between dilatancy and compaction. The model predicts substantial changes in pore pressure (which should be testable by measurements in laboratory and field experiments). I find the work interesting, though I personally feel that the authors attribute too many earthquake/slip-related phenomena to fluid pressure changes, and that experimental/field data can falsify or at least temper some of the claims in the manuscript. That said, I am supportive of publishing the study, perhaps with a few more caveats (if the authors agree with my assessment), as I feel that this study nicely highlights and quantitatively investigates some processes that most likely contribute to fault strength evolution in earthquakes. Below are specific suggestions that I encourage the authors to address:

We thank the reviewer for the constructive criticism and helpful comments. Some more discussion is added to support the feasibility of fluid pressurisation by shear-induced compaction as requested by the reviewer.

1. Line 17. It was unclear to me, at least early in the manuscript before the equations were introduced, why the authors use the term “(de)compaction” instead of just saying “dilatation.” This could be addressed by clearly defining, early in the manuscript, what is meant by compaction, decompaction, and dilatation.

The abstract has a limited length, however, we add a clearer explanation to the corresponding paragraph in the methods.
We add the following in paragraph starting in line 160:
“Within this framework, fault slip behavior is governed by the following mechanisms: (1) visco-plastic compaction, which represents irreversible deformation controlled by the effective (visco-plastic) compaction viscosity. During yielding, compaction localizes through a decrease in the effective compaction viscosity (eta^phi), driven by a reduction in the visco-plastic shear viscosity (eta_{plastic}), which lowers the resistance of the pore space to volumetric compaction (Eqs. 9 and 10). (2) Poro-elastic (de)compaction, which allows the reversible elastic opening or closure of the pore space in response to pore pressure variations, modulated by the Biot-Willis and Skempton coefficients. (3) Dilatancy corresponds to shear induced creation of pore space during plastic deformation (e.g. by grains rotation), which reduces pore pressure and increases effective normal stress. During transient slip, the poro-elastic component therefore evolves inversely to dilatancy, acting elastically to balance the inelastic pore-space opening.”

2. Line 21. The authors use the term “solitary” but they provide no evidence that the pressure features have properties that define solitary waves. I doubt that the solution features have the properties of solitary waves.

In the context of dynamic rupture and poromechanical coupling, solitary waves refer to nonlinear, self-reinforcing pressure perturbations that maintain their localized shape and amplitude as they propagate through a medium. Such behavior can arise when nonlinear compaction-decompaction dynamics of the porous skeleton interact with dispersive effects associated with pore-fluid diffusion and elastic coupling. The balance between these two processes prevents diffusive spreading and produces coherent traveling pressure fronts.

This mechanism is not speculative: in Dal Zilio *et al.* (2022), we demonstrated numerically that pressure perturbations generated within a deforming poromechanical fault zone indeed retain their amplitude and shape over propagation distances comparable to the domain scale, exhibiting precisely the characteristics of solitary waves. In the present work, we employ the same governing equations and constitutive formulations, so the emergence of such solitary-like pressure structures is a consistent and reproducible feature of our model.

The following sentences are now added from line 279, within the results section:
(2) The co-seismic phase, characterized by a developing shear instability and the propagation of seismic events as solitary fluid pressure waves on the timescale of milliseconds to seconds, while the slip rate on the fault accelerates from cm yr−1 to m s−1. The term solitary waves here refer to nonlinear, self-reinforcing fluid pressure perturbations, that maintain their localized shape and amplitude as they propagate through the medium. Such behavior can arise when nonlinear compaction-decompaction dynamics of the porous skeleton interact with dispersive effects associated with pore-fluid pressure diffusion and elastic coupling. The balance between these two processes prevents diffusive spreading and produces coherent travelling fluid pressure fronts, a mechanism also described in Dal Zilio et al. 2022.

3. Line 77. I struggled at first with this introductory discussion of dilation and compaction. Line 68 states that a fault can experience with dilation or compaction, which I agree with, but line 77 states that both processes can occur simultaneously, which I don't understand. Later it became clear that the authors are referring to two different terms in the governing equations, but the net effect of those two terms is either dilation or compaction but not both.

Thank you, the original sentence in line 77 "These two processes in nature should therefore compete and can counteract each other (Fig. 1)" is now modified to "*These two processes in nature should therefore compete and can counteract each other (Fig. 1),* ***resulting in either net compaction or dilation.***"

4. Line 105. I was expecting to see a complete set of governing equations but only some equations are summarized here. For example, Hooke's law and the yield criterion relating stresses and strains was only mentioned briefly in words but not in equations. This could be ok, but the authors should be clearer at the start that they will only present some of the governing equations, not all of them. That said, I do strongly recommend writing the equations that are used to define and calculate slip and slip velocity and fault shear stress, as these are essential for understanding the effective rheology of the fault zone. I think slip velocity is defined as the spatial integral over the fault zone of the total shear strain rate?

Yes, we are happy to provide more detail. We expanded the Methodology section, with multiple additional equations: the definitions of Biot-Willis and Skempton coefficients, drained compressibility, effective compaction viscosity, porosity-dependent permeability.

5. Line 114. I think beta_d is the drained compressibility, not drained bulk modulus.

Yes, the reviewer is correct, that is the drained compressibility, we corrected this.

6. Line 115. Please provide more explanation of how eta^phi, the compaction viscosity, is calculated. This is of fundamental importance to understanding the compaction behavior of the fault as well as to experimentally verify the theoretical model. If I understand correctly, this compaction viscosity is not a constant parameter but something that is determined from the shear yield condition? What are typical values? Are those consistent with experiments? I think the model is set up so that compaction occurs primarily only when the fault is actively slipping, so that eta^phi is small. Does this mean that eta^phi should be regarded as a function of slip velocity? This would be a useful connection to make.

Eta^phi is now defined in 2.1 Governing equations (previously it was defined in 2.3 Treatment of dilatancy) with all other additional equations.

The effective visco-plastic compaction viscosity is defined as
Eta^phi = 2m/(1+m) * eta_(plastic)/phi
with eta_(plastic) being the effective visco-plastic shear viscosity of the solid matrix, m is a geometrical factor (=1). The shear viscosity is given by

Eta_(plastic) = sigma_II / (2*eps˙''(plastic))

This formulation follows Yarushina and Podlachikov (2015). Eta^phi is determined from the changes in the visco-plastic shear viscosity (shear resistance) of the solid matrix. As plastic yielding initiates and strain rate increases, eta_(plastic) decreases, which leads to a reduction in eta^phi, and to the promotion of visco-plastic compaction. Therefore, compaction is primarily activated during periods of active deformation, with a direct dependence on slip velocity, which correlates positively with visco-plastic strain rate inside the actively slipping fault. The changes in eta^phi thus emerge from the coupled decrease in both shear and compaction resistance with increasing slip velocity. In nature, volumetric compaction can arise from grain crushing, microcracks, and related processes that are activated during shear. This provides a physical basis for scaling compaction viscosity with visco-plastic shear viscosity. Also, some laboratory experiments (e.g. Proctor et al., 2020; Aretusini et al., 2021) and theoretical studies (e.g., Iverson, 2005; Goren et al., 2010) support shear induced compaction thereby providing support to our simplified scaling model for visco-plastic compaction viscosity.

7. Line 115. Is dot{epsilon}_{II,plastic} the square root of the second invariant? Or the second invariant, as stated?

It is the square root of the second invariant. In geodynamical modeling, this quantity is however often named as the second invariant.

8. Equation (5). What does the prime on dot{epsilon} mean? This was not defined (and maybe is a typo).

The prime means deviatoric (rather than total) strain rate, which is now defined.

9. Line 143. It is strange to say that something decreased by 0%. Why not just say that it remained unchanged?

It's approximately a 40% decrease, this was a typo, and was corrected.

10. Line 158. If I understand correctly, dilatancy (i.e., plastic strain rate) is directly proportional to slip velocity (if slip velocity is calculated by integrating shear strain rate over the fault zone). If so, this dilatancy model has much stronger dependence on slip velocity than the commonly used Segall & Rice dilatancy model, which was based on Marone's experiments, where there is only dependence on log(velocity). Please comment on this, as the model seems in contradiction with at least some experiments.

Yes, the dilatancy model used in this paper has a strong dependence on slip velocity. We chose this simplified dilatancy model in order to derive and explore first-order effects of dilatancy by increasing the complexity (coming from fluid-related terms) of the models in every step. We agree with the reviewer that the dilatancy model is rather simple, and in our future research more complex dilatancy models will be implemented, however, right now these complex models are beyond the scope of this paper.

In line 203 we add the following after this sentence: "*To simplify our models, we assume a constant dilatancy coefficient, which captures the maximum stabilizing effect of dilatancy without accounting for its specific evolution over time or strain.* ***The dilatancy model here depends solely on plastic strain rate, and therefore scales with slip velocity.***"

11. Line 187. I don't understand how there can be pressure diffusion in the incompressible limit. Isn't specific storage zero in this case, so that even with finite permeability, the diffusivity is infinite? Or maybe I am misunderstanding what is meant by incompressible. In any case, it would be quite useful to provide a formula for hydraulic diffusivity in terms of the model parameters. The authors report permeability but really what is of interest in many of their experiments is the diffusivity (specifically, the diffusion time across the fault zone width as compared to other timescales).

We thank the reviewer for this important clarification. We add the following explanation to line 227 (Step 3): "*Similarly to the previous step, we assume unit Biot and Skempton coefficients (α = 1, B = 1), which removes elastic storage due to solid and fluid compressibility, but does not eliminate pressure diffusion. This is because pressure diffusion in our model is governed by Darcy flow driven by pore-pressure gradients, and remains finite as long as permeability (k) and fluid viscosity (μ) are finite. In this limit, the storage term becomes dominated by porosity changes associated with (de)compaction, rather than by elastic compressibility.*"

12. Line 199. The authors explain in Fig. 3 that their 2D model is a horizontal cross-section of a vertical, strike-slip fault. But then they discuss the two fault dimensions as horizontal and vertical. But really there are two horizontal dimensions, along strike and fault normal. Please consider revising the terminology to avoid confusion.

Thank you for the suggestion, now the sentence in line 244 is modified to: "*...and has a size of* ***120 km in the along strike direction*** *and 30 km* ***in in the fault-normal direction****, with an initial grid resolution of 500 m in both directions*"

13. Line 206. I have not heard the term "differential pressure." In poromechanics, the term "effective stress" or "effective pressure" is more commonly used. In any case, it would be best to pick one term or the other and use it consistently.

Thank you, we corrected everything to effective pressure (it can only be found in this line and in Table 1).

14. Line 212. What is "free slip"? There should be only one boundary condition for the fluid equation, which is impermeable, right?

Yes, the boundary condition for the fluid is impermeable, we added this to the manuscript in line 259.

15. Table 1, line 524, and elsewhere. I was confused about the fault zone width and what is actually represents. There are two important scales: the width of the localized shear zone that accommodates slip, and the width of the fault damage zone through which fluid is transported. The authors should distinguish between these.

Our fault width parameter corresponds to the width of the localised shear zone, however, because of computational reasons this width is defined more in the scale of a damage zone (~250 or 500 m). We discuss this in 2.5 Model setup and boundary conditions:

The 2D model setup is a simplified version of a natural strike-slip fault zone (Fig. 3a). The modeled fault width represents the numerically resolved shear zone in which deformation and slip localize. For computational reasons, this width is defined at the scale of a fault *damage zone in nature (250-500 m). The fluid is allowed to flow both inside and outside of this zone.*

16. Table 1. I don't think Vch was defined, at least not before or when first referencing Table 1 in the text.

Thank you, this was a mistake. Vch is the characteristic velocity, we corrected the table from V* to Vch.

17. Line 256. I don't think fluids are ever fully expelled from that fault. Perhaps the authors meant that pressure inside and outside the fault equilibrates? But the fault certainly remains fluid-saturated with nonzero porosity, right?

The fluids are never fully expelled, however, the constant increase in fluid pressure due to the low permeability chosen in the models, which in turn results in the slow decrease of the effective pressure along the fault, until the fluid pressure isn't high enough for an event to start. However, yes, the fluids remain in the fault zone.

The sentence in line 309 has been modified to: *"However, the fluid pressure always increases due to the chosen low permeability, which in turn results in the decrease of the effective pressure along the fault. This means that the fluids in the fault cannot depressurize efficiently, which causes a transition from regular earthquakes to slow slip events, and ultimately, to aseismic creep in the later stages of the model run."*

18. Line 268. I can understand the choice of 1% porosity as the lower bound, but porosity can exceed 5% in many rocks. Perhaps the authors could justify the 1-5% range of porosity with some references?

Thank you, we added the references "Peacock et al 2011, Tewksbury-Christle and Behr, 2021" at the end of this sentence.

19. Line 281. It would be useful to provide estimates of hydraulic diffusion time across the fault zone width to justify claims like the one in this sentence. Also, providing diffusion times will also help the reader understand if the computational limitation of a large fault zone width is expected to affect model predictions. Or perhaps it might be preferable to select an artificially large diffusivity so that the hydraulic diffusion time across the fault zone is within a realistic range?

We thank the reviewer for this suggestion. Hydraulic diffusion time can be estimated by the following relationship:

$T\_d \sim L^2/D\_h$

Where T_d is the diffusion time, L is the characteristic length scale (fault zone width), and D_h is the hydraulic diffusivity and it is calculated as

D_h = k/eta_f/beta*

with k as permeability, eta_f as fluid viscosity, and beta* as storage capacity [defined below at reviewer comment 22]. Using the typical values from our study: k=2E-19 m^2, eta_fluid = 1E-3 Pas, and beta* = 8E-12 Pa^{-1}. This yields a hydraulic diffusivity in the magnitude of D_h

= 2.6E-3 m^2/s. Using L=250 m, the hydraulic diffusion timescale is T_d ~ 2E7 seconds, or about 230 days. This is much longer than the duration of events (which is in the magnitude of milliseconds to seconds), but shorter than the recurrence interval of events (which can be 50 years-200 years). This means that the pore pressure is trapped during rupture, but relaxes between events, allowing the recurrence of instabilities.
However, the recovery of the effective pressure after an event is also related to the length scale of the surrounding material (km scale), for which diffusion time would be more than 10^2 years, preventing full interseismic recovery and promoting a transition to aseismic creep.

20. Line 286. The range of parameter values that produces earthquakes is quite narrow. Given this, do the authors feel confident that the proposed mechanism for earthquake instabilities is broadly applicable in the real world?

We agree that the range of parameters producing recurring fast events is relatively narrow. There are multiple reasons for this. First, the chosen model parameters are held constant in space and time. Additionally, the Biot-Willis and Skempton coefficients strongly regulate the slip response of the fault, which depend on the solid and fluid compressibilities,that are also held constant in all models. Dal Zilio et al. 2022 showed that varying fluid compressibility alone can broaden the range of conditions under which seismic and aseismic slip occur. Therefore, we interpret the narrow range of recurring fast events observed here as a consequence of the chosen model parameters (and the model limitations). We do not consider this narrow instability range to be a limitation on the applicability of fluid-driven slip mechanisms in nature, which we view as a complementary approach to classical rate-and-state friction models.

In Section 4.1 (Discussion) we add the following:
“The relatively narrow parameter range producing recurring fast slip events in the narrow fault width case reflects the simplifications in our model formulation, in which material properties (e.g. porosity and permeability) are held constant in space and time. However, variations in these parameters as well as in fluid compressibility can broaden the instability regime (Dal Zilio et al., 2022), suggesting that fluid-driven instabilities may dominate over a wider range of natural conditions than captured by the models in this study.”

21. Line 293. Please explain what area is being referred to in “total slip per unit area.”

We kept the shear modulus constant as the fault width parameter was changed, so widening the fault zone means an increase in the area over which strain is distributed. For a given stress drop, this implies a smaller average slip displacement on each unit area of the fault surface.
In line 346 we modify this sentence as follows:

“Additionally, since the shear modulus was not changed with fault width change, the total slip per unit area is smaller in case of a wider fault, and the strain is distributed over a larger area, ***as the increase in the fault width means an increase in the area over which strain is distributed.***

22. Line 393. Define “storage capacity” and provide an expression in terms of model parameters.

We add the following equation and explanation to the text in line 449 to define the storage capacity beta*.
We find it important to address here that beta* storage capacity is a local storage property, whereas the total pore volume scales with fault thickness. Because of this, numerically wide faults contain more pore volume, which affects pressure transients.
We address this scaling effect in the Appendix, by testing the convergence of parameters with and without the scaling law. Porosity is not scaled in these tests, as it represents a physical property rather than a numerical one. With grid refinement/non-uniform grid resolution the artificial pore volume could be reduced.

"*Fault zone width influences the storage capacity of the system and controls the magnitude of pore pressure changes during deformation (Faulkner et al., 2010; Cappa, 2011).* ***Here the storage capacity beta* is defined as***

Beta* = phi(beta_fluid-beta_solid)+(beta_drained-beta_solid)

Thus, an increase in porosity implies an increase in local storage capacity. Additionally, porosity also influences permeability (Eq.11), and therefore the effective pressure distribution within the fault zone. Although beta* is a material property independent of fault width, a wider fault implies that the pore pressure changes generated by compaction are distributed over a larger volume. In addition, wider faults have a larger total pore volume and enhance permeability pathways, promoting more efficient pressure diffusion. These effects together lead to the absence of recurring fast events in all wide fault models."

23. Line 416. Is it appropriate to compare the dilatancy parameter D in the current model with the Segall & Rice (1995) dilatancy parameter, given that the dependence of dilatancy on slip velocity is completely different? Please explain and justify.

We thank the reviewer for raising this important point. The comparison to the dilatancy parameter of Segall & Rice (1995) is intended to provide an order-of-magnitude reference rather than to imply an identical functional dependence. In our formulation, the dilatacy parameter D is a constant that linearly couples the plastic shear strain rate to volumetric dilatancy, namely it quantifies the proportional increase in pore volume (or porosity) associated with inelastic deformation of the fault gouge. In contrast, Segall & Rice (1995) defined their dilatancy parameter ε within a rate- and state-dependent framework, where dilatancy evolves dynamically with slip velocity and state variables through the evolution of pore pressure.

Despite these conceptual differences, both parameters describe the same underlying physical process, that is, an increase in pore space (and corresponding pore-pressure reduction) associated with shear deformation. The dimensional scaling of D in our model can therefore be related to the effective dilatancy response obtained from Segall & Rice (1995) under steady-state conditions, where dilatancy is approximately proportional to the imposed strain rate. We have clarified this distinction in the revised manuscript and now explicitly state that the comparison is made to illustrate the physical range of plausible dilatancy magnitudes, not the specific rate dependence.

We add the following clarification in the Discussion - 4.2 Role of Dilation to line 484:

“Although the dilatancy parameter in our model differs in formulation from the rate-and-state dilatancy parameter of Segall & Rice (1995), the comparison is still applicable here as an order-of-magnitude reference. In our formulation, dilatancy is a constant coefficient linking plastic shear strain rate to volumetric expansion, whereas Segall and Rice (1995) describes dilatancy as a dynamically evolving process within a rate-and-state dependent framework. Both approaches nevertheless represent the same physical mechanism of shear-induced pore-space creation and associated pore-pressure reduction. Recent work further suggests that porosity and compaction state may directly influence fault strength, providing an additional way by which dilatancy and compaction can stabilize or weaken slip (Sarma et al., 2025).”

-Eric Dunham

Recommendation: Revisions Required

Reviewer B:

The manuscript "Modeling fluid-driven fault slip dynamics with shear-induced dilation and compaction" by Hegyi et al. presents a numerical model designed to investigate seismic cycles on an idealized strike-slip fault under fluid-saturated conditions. The model is grounded in fundamental physical principles (conservation of momentum and mass) and couples fault and fluid dynamics, accounting for the effects of fault dilatancy, fluid flow, and compressibility. The simulations yield a broad spectrum of slip behaviors, including cyclic and transient slip events, fast and slow slip, and aseismic slip.
However, the manuscript lacks crucial information regarding the description of the model, its purpose and applicability, and its relation to existing models of fault mechanics. These omissions limit my ability to fully evaluate and appreciate the presented results. I recommend that the authors address the following points before the manuscript can be considered for publication:

We thank the reviewer for the feedback. The model description has been extended.

1) The physical mechanism driving fault slip is insufficiently explained. From my understanding, slip events are triggered by effective stress reduction due to rapid pore-fluid pressurization. Such pressurization is provided by “visco-plastic compaction” of the fault and the embedded pore space, presumably described by the first right-hand-side term in Eqs. (2) and (4). The mechanism may be summarized briefly, but it should be explained more clearly rather than relying solely on references to the authors’ earlier work.

We expanded the Methodology section. Now it includes more explanation regarding the terms, and the set of governing equations is now supplemented by the definition of multiple parameters. The explanation for the physical mechanism driving fault slip is added. The reviewer’s interpretation is indeed correct: fault strength decrease is related to fluid pressurization driven by visco-plastic compaction of pore space during the fault slip.

2) The origin and evolution of fault compaction are not explained at all. It is suggested that the fault begins compacting prior to slip events, with compaction accelerating during slip. Do the fault and pore space subsequently decompact, so that net compaction is zero over cyclic slip events, or is there a long-term trend? Since the boundary conditions preserve volume, how is the compaction balanced? Which processes cause this compaction, and what physical quantities control it? Equations (4) and (8) suggest a mechanical origin, governed by effective stress and porosity, rather than being directly induced by slip. Moreover, the form of the compaction term differs from that of the shear-induced dilatancy term in Eq. (4). This requires clarification.

We thank the reviewer for this constructive comment, and we address this in the expanded Methodology section. In our formulation, compaction and decompaction arise from two distinct but coupled mechanisms: visco-plastic compaction of the solid skeleton and poro-elastic (de)compaction of the pore-fluid phase. These two terms, expressed in Eqs. (2) and (4), are mechanically coupled through the evolution of effective stress and porosity and act in competition with one another. Visco-plastic compaction occurs when the total pressure (Pt) exceeds the pore pressure (Pf), leading to irreversible reduction of pore space as the solid matrix yields. This process is governed by the visco-plastic compaction viscosity and controlled by the effective stress state. In contrast, poro-elastic (de)compaction represents the reversible volumetric response of the fluid–solid system to rapid pore pressure changes if fluid cannot diffuse fast enough, pressure increases and partially offsets the solid compaction. These processes are regulated by the drained compressibility, Biot-Willis, and Skempton coefficients. Because of the imposed boundary conditions, total volume is conserved: local compaction within the fault zone is balanced by fluid diffusion and by elastic expansion of the surrounding medium. The dilatancy term, on the other hand, represents a distinct mechanism – shear-induced inelastic increase in porosity controlled by the plastic strain rate. While both compaction and dilatancy affect porosity evolution, they operate under different mechanical drivers (pressure vs. shear) and have opposite signs. Their interplay determines whether the net response of the fault zone is compactive or dilatant. The long-term trend of the fault in the case of zero dilatancy is indeed net compaction, which should slowly decrease fault porosity with time. This long-term evolution of porosity is neglected in our relatively short-term models.

3) The model produces strong compaction and fluid pressurization, driving effective stress to near-zero values (Fig. 8). In contrast, laboratory and field observations indicate that seismogenic faults typically dilate on slip, leading to pore pressure drop and the effective stress buildup (dilatancy hardening) [e.g., the following references taken from the manuscript Brantut, 2020; Samuelson et al., 2009; Marone et al., 1990; Lockner and Byerlee, 1994; and many others]. Recent laboratory studies even indicate evaporation of the in-fault pore fluid due to its depressurization as a result of the fault dilatancy [Brantut, 2020]. Significant pore pressure changes require (“undrained”) conditions controlled by hydraulic parameters and dilatancy rate, as investigated e.g. by Parez et al., J. Geophys. Res. Solid Earth 128 (2023). Such conditions, under which dilatancy hardening stabilizes fault slip, should be compared to the stability region derived in the present simulations. The latter work also shows that pore-fluid depressurization can slow down dilatancy. In contrast, the present simulations show compaction and pressurization accelerating at slip initiation, leading to a rapid drop in effective stress (Figs. 7–8). Although the model incorporates dilatancy (last term in Eq. 4), its

effect appears delayed until significant plastic strain accumulates, and thus it cannot offset the preceding pressurization. This likely explains why the results are not very sensitive to the presence of dilatancy. The authors should discuss this issue and, importantly, specify under which geological or experimental conditions such strong compaction and near-complete fluidization of the fault are realistic. This would help readers to understand the applicability of the model.

We appreciate this detailed and insightful comment. The reviewer is correct that many laboratory and field studies show dilatancy-induced pore-pressure reduction during fault slip. However, the conditions represented in our simulations differ from these classical dilatancy-hardening regimes. Our models specifically explore the transient evolution of a fluid-saturated fault zone subjected to mechanically activated compaction mechanisms, which can dominate under particular pressure–strain-rate conditions. In our formulation, visco-plastic compaction arises from time-dependent inelastic collapse of the pore space when the total pressure exceeds the pore pressure. This process is controlled by the effective stress, the visco-plastic compaction viscosity, and the drained compressibility. In low-permeability, or fluid-rich environments, such as the deeper seismogenic or transition zones, this compaction can outpace the shear-induced dilatancy, leading to transient pore-pressure buildup and near-fluidization at slip initiation. We added several references advocating shear-induced compaction on the basis of experimental results (e.g. Proctor et al., 2020; Aretusini et al., 2021) and theoretical studies (e.g., Iverson, 2005; Goren et al., 2010).

The dilatancy term included in Eq. (4) is active but, as the reviewer notes, its effect emerges only once plastic shear strain has accumulated. This behavior reflects the microphysical distinction between the two processes: compaction is pressure-driven and instantaneous with loading, whereas dilatancy is strain-driven and evolves progressively with shear deformation. Consequently, in our simulations the dilatancy term cannot fully offset the early-stage pressurization, which explains the delayed onset of effective stress recovery.

We have clarified in the revised manuscript that the modeled regime corresponds to compaction-dominated, fluid-rich fault zones, potentially representative of deep subduction-interface segments or low-permeability, clay- or gouge-filled faults, where transient fluid pressurization is expected (e.g., Segall & Rice, 1995; Brantut et al., 2020).

We added the following paragraph in 4.4. Implication for natural fault zones:

"*In this context, the deformation regime in our models differs from the shallow, well-drained fault behavior commonly inferred from laboratory experiments. The simulations here show a compaction dominated, fluid-rich regime in which pressure-driven deformation can promote transient pore-pressure build-up and reduced effective stress at slip initiation. These conditions may be relevant at low-permeability conditions, for example at clay-rich faults, where fluid diffusion is limited and fluid pressurization is expected. Several authors* advocated *shear-induced compaction on the basis of experimental results (e.g. Proctor et al., 2020; Aretusini et al., 2021) and theoretical studies (e.g., Iverson, 2005; Goren et al., 2010).*"

4) What occurs in the model when effective pressure becomes negative? Does rupture acquire a mode I component? What is the focal mechanism for simulated ruptures?

In our simulations, effective pressure does not become negative, and therefore no tensile opening (mode I) failure occurs. The governing equations and constitutive formulation ensure that pore pressure remains below the total normal stress, maintaining a positive effective stress throughout the rupture evolution. Most importantly, the viscoplastic compaction term becomes zero when the difference between the fluid and total pressure approaches zero. Consequently, slip proceeds purely in shear (mode II) along the fault plane. We have verified this by monitoring the evolution of both total and pore pressures in all simulations. Even in cases of near-fluidization, the effective normal stress approaches, but never crosses zero. The resulting focal mechanism is therefore dominantly double-couple, consistent with shear rupture.

We added a short explanation at the end of 2.4 Model setup and boundary conditions: *“Notably, the model formulation ensures that pore pressure never exceeds the total normal stress, such that the effective normal stress remains positive throughout the rupture evolution. Slip therefore proceeds in shear (mode II) along the fault plane.”*

5) Table 1 lists the material parameters used in the model, but it is unclear whether they are identical for the fault material and the surrounding host rock. If so, what distinguishes the fault behavior? Is it a specific rheology? Do Eqs. (5–6) apply only to the fault zone? If yes, why is the surrounding medium described as poro-visco-elasto-PLASTIC (e.g., Fig. 3 caption)? Are Eqs. (1–4) solved across the entire domain in Fig. 3b? Which constitutive relations govern the host rock, e.g. to calculate its stress tensor σ_i□? Some constitutive relations appear missing — for example, solid viscosity \eta^s does not appear in any equation throughout the manuscript, neighter do compressibilities beta^s and beta^f. It is also not clear which variables are solved for in Eqs. (1–4).

The specific material parameters used in the model for the fault and the host rock are clarified. The fault behavior is distinguished by the differences in viscosity, density, solid and fluid compressibility and rate-strengthening exponent gamma - as shown in Table 1, and Figure 3. The gamma setup forces the nucleation of events to the fault zone and makes it not possible for the events to propagate into the surrounding region around the fault.The governing equations are solved in the whole domain, including the equations for stress, however, the plasticity model is solved only for the fault. Equations 1-4 are solved for the solid vx,vy velocities, the Darcy vxD,vyD velocities, and the total and fluid pressures.

We added the following sentences in 2.1 after introducing the governing equations: *“Equations 1,2,3,4 are solved across the entire model domain (Fig. 3b). The primary solved variables are the solid velocity components (vsx,vsy), the Darcy fluid velocity components (vxD,vyD), the total pressure (Pt), and the fluid pressure (Pf).”*

6) The numerical fault is strongly rate-strengthening, given the low value of $\gamma = 0.027$ in Eq. (5). Under constant effective stress, slip would therefore remain stable, I suppose. Seismic slip in the model arises only because rising pore pressure (Eq. 6) weakens the fault. In contrast, traditional stability analyses [Segall & Rice, 1995; Rudnicki & Chen, 1988] predict that (a) intrinsic slip- or rate-weakening is required for instability, and (b) low effective stress

(high P^f) tends to favor aseismic slip. A qualitative comparison of stability conditions in the present model versus the classical framework and a discussion of their discrepancies would be beneficial.

We partly analysed the fault stability condition by introducing critical dilation, which compensates shear-induced compaction. It is rather difficult to directly compare the traditional RSF model with the pore fluid pressurisation model as formalisms for state parameter evolution of RSF and pore fluid pressure evolution of our poro-visco-elasto-plastic model are very different. The detailed analyses would therefore rather require a separate paper.

We have added the following paragraph to Discussion 4.3 Comparison to rate and state friction models:
"Classical RSF models predict seismic instability at rate- or slip-weakening regimes, whereas velocity-strengthening faults are expected to exhibit stable slip under constant effective stress (Rudnicki and Chen, 1988, Segall and Rice 1995). Reduced effective normal stress due to elevated pore pressure is commonly associated with aseismic behavior in these models. Consistent with these results, our simulations exhibit creep behavior under high pore pressure conditions (e.g. Fig. 5). However, a key distinction in our framework is that effective stress is not prescribed, but evolves dynamically throughout the model run, due to hydro-mechanical coupling. Consequently, pore fluid pressure increases weaken the fault, enabling dynamic slip even for intrinsically rate-strengthening rheologies."

As a minor but related remark, "visco-plastic" compaction (dilatancy) may enhance (diminish) the fault strength [see, e.g., Sarma et al., J. Geophys. Res. Solid Earth 130 (2025)]. This effect could potentially be incorporated by adding a porosity-dependent or compaction-dependent factor to the constitutive law (Eqs. 5-6), without the need to introduce state variables.

We agree with the reviewer that these effects could in principle be incorporated by making the strength depend directly on porosity or compaction and added a sentence on that with the reference to Sarma et al. (2025) within the discussion section 4.2 Role of dilation.
Dilatancy can, in fact, stabilise the otherwise unstable fault (figure 6); however, in our case the dilatancy coefficients need to be very high in order to stabilise the fault. In our study we chose to represent dilatancy and visco-plastic compaction in separate terms, which allows us to distinguish the contributions of the compaction and dilatancy to the pore pressure evolution, which controls the slip mode. If the two factors would be combined into one term, it would obscure which process dominates the evolution at a given time, and for this reason, we track both mechanisms separately.

7) The manuscript does not sufficiently position its contribution within the broader literature. How does the present model differ from previous works? Is the originality in the constitutive law? While most seismic-cycle models rely on rate-and-state friction, other constitutive laws have also been used [e.g. Chen & Niemeijer, J. Geophys. Res. Solid Earth 122 (2017); Ohnaka, Earth Planet Sp 56 (2004); Shimamoto & Noda, J. Geophys. Res. Solid Earth 119 (2014)]. Fluid-induced seismicity models often employ Mohr–Coulomb or Drucker–Prager failure criteria [e.g., Miller, Geofluids 15 (2015); Zhai et al., PNAS 116 (2019)]. Or is the

novelty of the model in incorporating solid-fluid interactions? Full hydro-mechanical coupling, including dilatancy and compressibility effects, have been addressed in [e.g., Ciardo & Lecampion, J. Geophys. Res. Solid Earth 124 (2019); Parez et al., J. Geophys. Res. Solid Earth 128 (2023)].

The discussion section "4.3. Comparison to rate and state friction models" to position our paper within the broader literature has been extended, and we added multiple references from the publications to which the reviewer is referring. We are aware of the existing body of work on frictional and hydro-mechanical fault models, including the studies cited by the reviewer. However, this paper does not replicate or marginally extend those approaches, it redefines the modelling framework.

Our model is not based on rate-and-state friction, nor on simplified failure criteria. Slip and rupture emerge directly from the governing continuum equations that couple solid deformation, fluid pressure evolution, and porosity change. The constitutive formulation combines visco-plastic compaction, poro-elastic (de)compaction, and shear-induced dilatancy in a fully compressible, two-phase medium. These are not add-on terms to an existing friction law but the physical origins of fault weakening and slip in our model.

Unlike previous formulations that prescribe fault behavior, our system produces it self-consistently. This is the novelty. The model unifies deformation, fluid transport, and failure without relying on ad hoc friction parameters or predefined instability criteria. We have revised the introduction to make this distinction explicit and to state clearly that the contribution lies in providing a physics-based, continuum framework for fluid-controlled fault slip—something that existing rate-and-state or partially coupled models do not achieve.

We also added the following sentence at the last paragraph of the Introduction: "*In the models presented in this paper, fault slip emerges self-consistently from the coupled evolution of solid deformation and fluid pressure evolution.*"

Taken together, the description of the model, its assumptions, and its applicability are currently insufficient to allow a meaningful evaluation of the results. The model may potentially provide valuable insights into fault dynamics under fluid-pressurized conditions, but without clarification of the above points, its significance and relevance to the readership remain unclear.

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Dear Path,

Thank you for your efforts in handling all rounds of reviews for our manuscript titled "Modeling fluid-driven fault slip dynamics with shear-induced dilation and compaction". We are submitting the third round revisions of this manuscript for your consideration.

The reviewer provided a comment for this round, about adding estimates and a plot of the values of the compaction viscosity to improve the manuscript. We have accepted this recommendation and have revised the manuscript accordingly. We added a plot on the evolution of this parameter to the appendix with a short description. Below we address this comment (our responses are colored **blue**).

See below our detailed response. We include the pdfs of the new version of the manuscript, and one with the changes highlighted. Please let us know if you have any questions on the revised version. We look forward to your assessment of the manuscript's suitability for publication in Seismica.

Sincerely,

Betti Hegyi, Luca Dal Zilio, Whitney Behr, Taras Gerya

Reviewer A:

I encourage the authors to provide estimates of the bulk viscosity (which I understand is not a fixed material property) like I did in my previous review, and explain how it varies with slip velocity, shear zone width, etc. I believe this is essential information for readers that will help them evaluate the proposed mechanism. The estimates and dependencies on parameters and variables could be complemented with exact numerical values of eta_phi from the situation (e.g., a plot of eta_phi at some point on the fault as a function of time). Furthermore, providing these specific quantitative predictions of the model will help experimentalists design experiments to validate or falsify the proposed mechanism. The current description is helpful, but still qualitative, and I doubt that readers will understand from that description that eta_phi varies over 10 or more orders of magnitude.

Recommendation: Accept Submission

We thank the reviewer for his comments and suggestions through all rounds of reviews, which helped to significantly improve the manuscript.

We added a plot in the appendix showing the evolution of the compaction viscosity in time in the middle of the fault through multiple seismic cycles.