Response Letter

Manuscript 1603, "Forecasting 3D Rupture Dynamics of the Alto Tiberina Low-Angle Normal Fault, Italy" by M. Marchandon, A.-A. Gabriel, L. Chiaraluce, E. Tinti, E. Casarotti & J. Biemiller

We thank the Handling Editor Marlon Ramos, one anonymous reviewer, and the internal USGS reviewer Ruth Harris for their thoughtful and constructive comments.
We have revised the manuscript to better clarify the role of non-planar fault geometry in dynamic rupture nucleation on the Alto Tiberina Low-Angle Normal Fault (LANF). In addition we have expanded the discussion on the implications of adopting a strong velocity weakening friction law. To improve clarity, we also added further explanations and relevant references in the text, revised Figures 1 and 2, and added a new supplementary figure (Figure S2).

Below, we respond point-by-point to all reviewers' questions and comments. We use black font for the reviewer's comment, while our responses are in blue font. In our responses, extracts from the paper are noted in *italic blue font* with modifications highlighted in ***bold.***

We hope that the revised manuscript meets the expectations of the Editor and can now be considered suitable for publication in the journal.

Mathilde Marchandon on behalf of all co-authors

Reviewer 1: Handling Editor (Marlon Ramos)

General Comments

1) I concur with anonymous reviewer #1 that as written, the abstract/introduction might suggest that this study has solved a universal problem in Andersonian fault theory regarding fault dip angle, normal fault formation, and earthquake potential. The impact of a nonplanar fault geometry (variable dip angle) plays an underappreciated role on rupture dynamics and the authors show that even small changes to the relative prestress ratio (Ro) or other on-fault initial conditions could lead to drastically different fault dynamics or final (static) fault deformation.

We fully agree that the non-planarity of the Alto Tiberina Fault plays a key role in enabling large ruptures on the ATF. This point was already highlighted in the discussion (section 5.1 "*Importance of the ATF geometry and scenario limitations*") and in the conclusion (L458-459 in the initial version of the manuscript), where we state: "*We show that the geometry of the ATF is of critical importance, as dynamic ruptures can nucleate only at favorably oriented, steeper parts of the faults (dip ≥~30°).*"

To ensure the crucial role of the ATF morphology is more prominent, we have now emphasized it further in the abstract, introduction and conclusion. We note that Seismica requests short abstracts of 200 words.

Abstract

The seismic potential of active low-angle normal faults (LANFs, < 30° dip) remains enigmatic under Andersonian faulting theory, which predicts that normal faults dipping less than 30° should be inactive. The Alto Tiberina fault (ATF) in the northern Apennines, a partly creeping 17°-dipping LANF, has ~~***hosted***~~ ***not been associated with*** *any historical earthquakes but could potentially* ~~***produce***~~ ***generate earthquakes up to*** *Mw~7* ~~***events***~~*. We investigate the mechanical preconditions and dynamic plausibility of large ATF earthquakes using 3D dynamic rupture and seismic wave propagation simulations constrained by multidisciplinary data from the Alto Tiberina Near Fault Observatory (TABOO-NFO). Our models incorporate the complex,* ***non-planar*** *ATF fault geometry, including hanging wall secondary faults and a recent geodetic coupling model. We show that potential large earthquakes* ***(up to Mw~7.4)*** *are mechanically viable under Andersonian extensional stress conditions if the ATF is statically relatively weak (μ_s=0.37). Large earthquakes* ***only*** *nucleate on favorably oriented, steeper fault sections (dip>30°), and remain confined to the coupled portion, limiting earthquake magnitude. These ruptures may dynamically trigger an intersecting synthetic branch but are unlikely to affect more distant antithetic faults. Jointly integrating fault geometry and geodetic coupling is crucial for forecasting dynamic rupture nucleation and propagation.*

Introduction L91-101:

Our dynamic rupture models incorporate multi-segment non-planar fault geometry constrained from seismic data, homogeneous and data-constrained heterogeneous initial stress distribution, the slip weakening friction law, friction coefficients consistent with the lithology of the area, and topography. In the different models, we investigate the favorable conditions (static fault strength, pre-stress level, nucleation location, ***fault non-planarity****) that enable rupture to propagate.* ***While our simulations show that potential large earthquakes (up to Mw ~7.4) are mechanically viable under Andersonian extensional stress conditions for a statically relatively weak ATF (μs = 0.37), they also reveal that the non-planarity of the ATF is of primary importance, as dynamic rupture simulations assuming a planar 17°-dipping fault fail to propagate. When the initial stresses are constrained by a coupling model, the rupture remains confined to the coupled parts of the fault, limiting the earthquake magnitude to Mw 6.7. We then discuss the scenarios limitations and potential avenues for future work.***

Conclusion L497-499:

We show that ~~***the geometry***~~ ***local heterogeneities in the geometry*** *of the ATF****, which result in a non-planar fault surface***~~***, is***~~ ***are*** *of critical importance, as dynamic ruptures can nucleate only at favorably oriented, steeper parts of the faults (dip ≥~30°).*

2) I would note that exploring the effect of dynamic triggering is one future direction that could be mentioned for a follow-up study. There is text discussing this possibility on lines 367 – 369.

Thank you for the note!

Specific comments

3) Line 90: Instead of *large*, did you mean *wide*?

We have deleted the information about the ATF dimension as it was already given in the introduction (see also comment n°1 of the USGS internal reviewer):

L103-104: The Alto Tiberina low-angle normal fault (ATF) is ~~**an ~17° east-dipping 70 km long and 40 km large low-angle normal fault**~~ located in the inner region of the Umbria-Marche Apennines, Central Italy (Figure 1).

4) Lines 92-93: Instead of "It is the easternmost, youngest, and only active fault of six subparallel east-dipping low-angle normal faults that have accommodated successfully (along with associated high-angle antithetic normal faults) the extension of the Northern Apennines as it migrated eastward." I suggest a slight revision of the sentence structure to improve flow:

"It is the easternmost, youngest, and only active fault of six subparallel east-dipping low-angle normal faults that have successfully accommodated (along with associated high-angle antithetic normal faults) extension of the Northern Apennines as it migrated eastward."

Thank you, we modified the sentence (L105).

5) Line 102: Suggest writing out the number seven.

Done (L115).

6) Line 184: Please cite the publication that allows one to calculate the critical radius for sustained dynamic rupture in 3D. I imagine this is Day et al., 2005 or Gallis et al., 2015 for a perfectly elastic medium.

We added the citations to Day et al., 2005 and Galis et al., 2015 (L274). Note that the nucleation procedure is now described in the section 3.5 "*Nucleation Procedure*" (see also comment n°5 of the USGS internal reviewer).

7) Line 206: consider the following re-wording:

"… and allows for the prescription of the magnitude of the deviatoric stresses."

This part has been modified to answer your comment n°8.

8) Line 210: A R_o ratio of 0.7 seems perfectly valid for a somewhat stressed fault in the reference model, but there may be confusion for the reader to distinguish R_o (estimated theoretically) from R (a function a variable shear and normal stresses due to non-planar fault geometry). I would suggest clarifying the assignment of Ro – for instance, this value is valid at the nucleation location or is simply the average assuming a constant stress field and simple fault geometry?

Thank you for your comment. We agree that distinguishing R_0 from R is important and deserves a clear explanation. We have revised the text in section 3.2 to avoid any potential confusion.

L215-229: *The relative pre-stress level R_0, the ratio of potential stress drop over breakdown strength drop (Aochi and Madariaga, 2003, Ulrich et al., 2019), describes the closeness to failure of a virtual**,** optimally-oriented fault* ~~***according to***~~ ***under*** *the Mohr–Coulomb theory.* ***When*** *R_0=1, an optimally-oriented fault is critically stressed (Aochi and Madariaga, 2003). R_0 is defined as:*

$$R_0 = \frac{\tau_0 - \mu_d \sigma_n'}{(\mu_s - \mu_d)\sigma_n'} \qquad (2)$$

Prescribing R_0 , ***mu_s, and mu_d****, allows for the calculation of the magnitude of the deviatoric stresses.* ***We assume μs=0.6 (and μd=0.1)****, therefore, in the assumed stress regime, an optimally oriented fault is a ~60°-dipping planar fault (striking in the SHmax direction). We use R_0=0.7 for the reference model and vary this value to evaluate its influence on the scenarios (Table 1 and Figure 4).* ***Since R_0 represents the background pre-stress level relative to fault strength of a virtual, optimally-oriented fault within the assumed stress field, it does not necessarily reflect the ratio of pre-stress level to fault strength on the geometrically complex modeled faults. Therefore,*** *for each tested model, we compute R* ***-*** *the relative pre-stress level resolved on the modeled faults* ***(using the μ_s distribution shown in Figure 2 and μ_d=0.1)****. Although* ~~***we load***~~ *the faults* ***are loaded*** *with a laterally homogeneous regional stress field (i.e., uniform orientation and amplitude of the principal stresses), the normal and shear stresses resolved on the* ~~***modeled***~~ ***non-planar*** *faults* ***surfaces*** *are* ~~***heterogeneous due to their non-planar geometry, resulting in a***~~ ***spatially variable, leading to*** *heterogeneous* ~~***relative pre-stress level***~~ ***values of*** *R (e.g. Figure 4 and Ulrich et al. 2019).*

9) Line 232: It might be nice to include the equation from Glehman et al., 2024 in the supplementary text S2 so a reader doesn't have to search multiple references.

We extended the explanations for the methodology used for the data-constrained model in supplementary text S2 (renamed "*Dynamic relaxation step* ***and data-constrained initial stress***"), but we want to underline that it is slightly different from Glehman et al, 2024 as we add the full stress tensor to a background regional stress tensor (computed with Ro=0) to obtain the data-constrained initial stress distribution (see section 3.3.2).

10) Line 238: Please justify the use of 1800 years. Was this level of strain accumulation time necessary to sustain dynamic rupture at the nucleation location chosen? The introduction mentions that "*no historical earthquake is known to have occurred on the ATF in the last 1000 years*," but this does not necessarily explain a T > 1000 years.

Thank you for your question. The value T=1800 years was chosen because it allows sufficient stress accumulation on the fault to enable successful rupture propagation without causing instantaneous failure. We explored values ranging from 1000 to 3000 years. Values lower than 1600 years do not lead to rupture propagation, T=1700 years leads to a Mw 6.1

earthquake, and values larger than 2000 years lead to instantaneous failure of large fault areas.

We have clarified the rationale for this choice in the main text:

L262-265: *We use T=1800 years****, corresponding to the stress accumulation time necessary for the rupture to propagate. We explore T in a range of 1000-3000 years. Values lower than 1600 years do not allow rupture to propagate, while T=1700 years results in a Mw 6.1 earthquake. For values greater than T=2000 years, unrealistic rupture occurs instantaneously across large fault areas.***

11) Line 248: 5 to five

Done (L268)

12) Line 260: Perhaps there is an extra o, but you meant to say the mesh comprises ~7 million unstructured cells?

Yes, it has been corrected (L288).

13) Line 299 – 300: I think you make a good point that small changes in the initial conditions for static friction or Ro can produce similar static results, but different dynamic results. I wonder if it might be easier to discuss (or at least mention) what the Ro value is (0.70) for the =0.3 scenario so a reader can appreciate how a 0.5 change can lead to different results.

We agree with the Reviewer and now we remind the reader what the R_0 value is for the μ_s=0.3 scenario as well as for the other scenarios discussed in this paragraph.

*L326-336: Interestingly, scenarios having the same moment magnitude and similar final slip distributions do not necessarily have the same dynamics. For example, the R_0=0.75 (**μ_s=0.37**, Figure 4a) and μ_s=0.30 scenarios (**R_0=0.70**, Figure 5a) both produce a Mw 7.4 earthquake with a very similar final slip distribution. However, the rupture speed is higher for the μ_s=0.30 scenario (mean rupture speed of 2202 m/s) than for the R_0=0.75 scenario (mean rupture speed of 1978 m/s). This is also shown by their respective moment rate release (Figure 6). The moment rate release of the μ_s=0.30 scenario (Figure 6b) is shorter (30~s) and displays two more pronounced and higher peaks (reaching $1x10^{19}$ Nm/s) than the R_0=0.75 scenario (Figure 6a, 35~s with highest peak of $0.85x10^{19}$ Nm/s). Similarly, the reference (**μ_s=0.37, R_0=0.7**), and μ_s=0.40 **(R_0=0.7)** scenarios both produce a Mw 7.3 event (Figures 4b and 5b, respectively) but the rupture of the latter lasts 85 s with 3 peaks in the moment rate (reaching ~$0.4x10^{\wedge 19}$Nm/s, Figure 6b) whereas the rupture of the reference model has a shorter duration (50 s) and a moment rate release with only two peaks reaching a higher amplitude (~$0.6x10^{19}$ Nm/s, Figure 6a).*

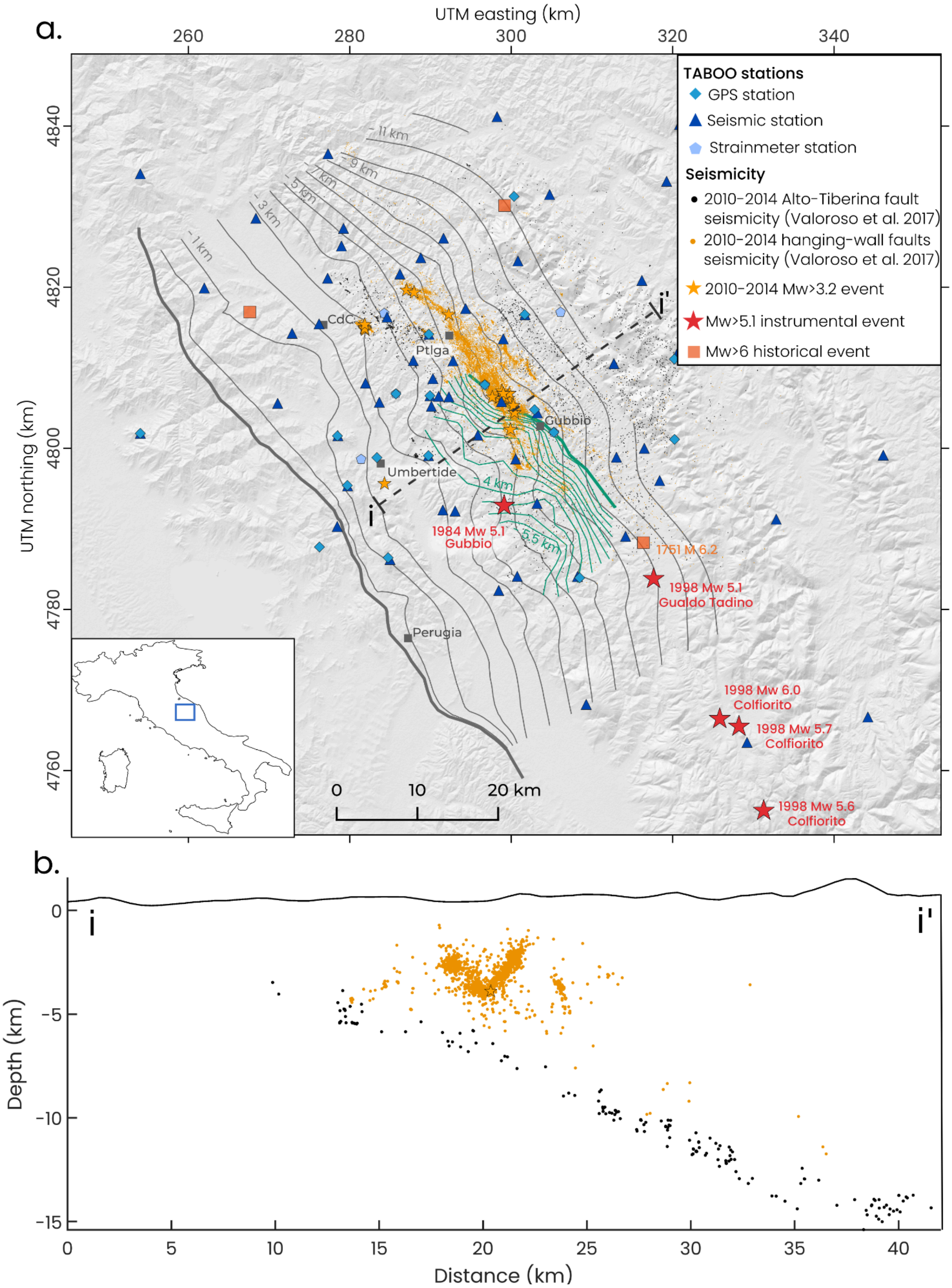
14) Line 384: Uncertainty from the geodetic coupling models for the main fault is definitely a source of uncertainty – as is the level of strain accumulation on the smaller faults (e.g., Gubbio, Umbertide, Pietralunga).

We agree and now mention the uncertainty related to the level of stress on the secondary faults too.

L414-420: *In particular, the southeast half of the fault is not well covered by GPS stations, and coupled portions of the fault could be undetected by the current GPS network (Anderlini et al. 2016).* ***Moreover, both the magnitude and spatial distribution of stress on secondary faults, such as those near Gubbio, Umbertide and Pietralunga remain poorly constrained. Higher stress amplitudes or different stress distributions could potentially facilitate rupture on these faults. In this study, we explore a range of plausible rupture scenarios, but we acknowledge that*** *assuming* ***different*** *frictional and elastic properties* ***or a different stress accumulation pattern*** *could lead to* ***significantly*** *different rupture behaviors.*

15) Figure 1: The 2010-2014 Mw > 3.2 seismicity are a little difficult to visually distinguish from the Mw > 5.1 instrumental events. Suggest changing the color of one of the stars.

Done. We have modified the color of the Mw> 5.1 instrumental events (Rebuttal Letter Figure 1).

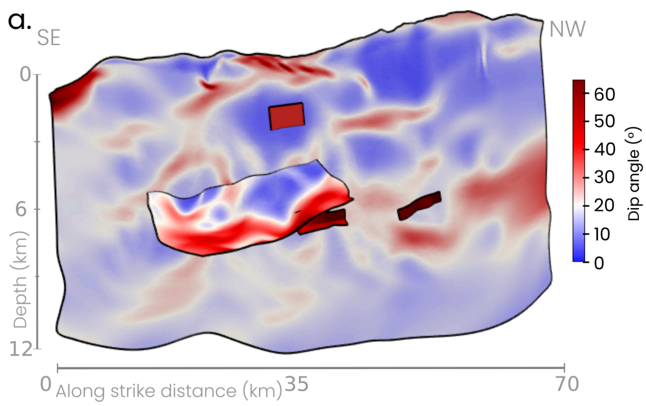


Rebuttal Letter Figure 1: Revised Figure 1.

16) Figure 2: To emphasize the shallower fault dip angle of the Alto Tiberina master fault, I would suggest having the colorscale go from 0 to 17 degrees on subplot (a). Alternatively, plot the colorscale discontinuously as is done for subplot (b) to show the levels of static

friction level. This may emphasize the truly shallow angles along-strike and along-dip of this fault.

Thank you for your comment. We have modified the colormap so that the low-angle areas of the fault (dip-angle < 20°) appear in bluish tones, while the steeper parts (dip angle > 20°) appear in reddish tones.



Rebuttal Letter Figure 2: Revised Figure 2a.

We modified the caption as follow:

Figure 2: 3D view of the modeled faults colored with (a) the dip angle and (b) the static friction coefficient used in our reference model. ***The colormap in panel (a) is chosen such that the low-angle areas of the fault (dip-angle < 20°) appear in bluish tones, while the steeper parts (dip angle > 20°) appear in reddish.***

Reviewer 2

1) The authors spend a lot of space describing the mystery of the Anderson fault theory's prediction of the potential of low-angle normal faults (LANFs) in the introduction. Under the Anderson fault theory, normal faults with a fault dip angle of < 30° have a low potential to host large earthquakes. However, the authors point out that the Alto Tiberina fault (ATF) in this study, a 17° low-angle normal fault with partial creep, still has the potential to produce a Mw 7 earthquake. This kind of description gives the illusion that the authors seem to have solved the insufficiency of the Anderson theory in predicting the potential of large earthquakes on LANFs. However, the numerical experiments in the paper show that the occurrence of an Mw 7 earthquake on this fault still requires the presence of a locally high-dip-angle (steep) fault (the NW direction of the ATF fault, at a depth of 6-10 km). The low-dip angle is still an effective factor in preventing sustainable dynamic rupture (Figures 4, 5, 7). In general, the authors are exploring how the low-angle-dip region of the fault is passively driven by the rupture occurring at a steeper region of the fault. Therefore, this is an effect of non-planar fault geometry. Other numerical experiments in this study show (Figure 7) that the fault cannot be sustained if nucleated at the low-dip-angle region, which is not surprising. Therefore, I suggest that the authors slightly modify the abstract and introduction to emphasize the non-planar geometry more, to show that the non-planar ATF cannot be simply explained by the idealized Anderson fault theory.

We fully agree with the Reviewer and the Associate Editor that the non-planarity of the Alto Tiberina Fault plays a key role in enabling large ruptures on the ATF. We refer the Reviewer to our answer to Associate Editor's comment n°1 on p.1 detailing our modified abstract, introduction and conclusion. We note that Seismica requires a short abstract of only 200 words.

We also note, that the importance of the ATF morphology was already reflected in the discussion (section 5.1 "*Importance of the ATF geometry and scenario limitations*") and in the conclusion (L458-459 in the initial version of the manuscript), where we state: "*We show that the geometry of the ATF is of critical importance, as dynamic ruptures can nucleate only at favorably oriented, steeper parts of the faults (dip ≥~30°).*" To ensure the crucial role of the ATF morphology is more prominent, we have now emphasized it further in the abstract, introduction, and conclusion.

2) Assessing the likelihood of full-rupture scenario earthquakes is crucial for seismic hazard studies in the region, so I was surprised that the authors did not explore the impact of dynamic weakening on large earthquake potential, especially since the authors are aware of this and point it out in the paper. From the authors' previous extensive series of papers, dynamic weakening of ruptures is crucial for seismic hazards and could also be important in this research. Indeed, the authors have shown in this study that full-fault rupture is possible if the fault is statically weak (mu_s=0.3-0.4). However, when the authors considered a kinematic coupling model, the rupture was confined to the coupled region, resulting in a much smaller earthquake magnitude (Mw 6.7). This situation might be very different if dynamic weakening was also considered. Whether the uncoupled and/or low-dip-angle region of the fault can effectively limit sustainable dynamic rupture under consideration of the dynamic weakening mechanism deserves careful study. This study would be much stronger if this was also considered.

We thank the reviewer for this insightful comment. We agree that severe dynamic weakening mechanisms are crucial in governing rupture propagation, particularly in cases where the fault is known to produce large earthquakes. However, our goal in this study is to explore under which physical conditions the ATF could potentially host large ruptures. For this reason, we adopted a simpler slip-weakening friction law which allows us to control the initial stress state and explicitly test the sensitivity of rupture to variations in static friction, pre-stress level, and fault geometry. We agree that exploring the impact of dynamic weakening would be an important step forward. However, such a modeling framework would require a completely new ensemble of models and it is therefore beyond the scope of this study.it.

We now better clarify this point in the revised manuscript (L450-462), where we expand the discussion on the limitations of neglecting dynamic weakening and acknowledge its relevance for future work.

However, it is important to ***note*** *that* ***our models do not incorporate*** *fast velocity weakening* ***rate-and-state friction (Ampuero and Ben-Zion, 2008, Noda et al. 2009) observed in laboratory experiments (e.g., di Toro et al., 2011; Kohli et al., 2011) and thought to account for physical weakening processes operating on natural faults at***

the high slip velocities typical of dynamic earthquake rupture (Rice, 2006). Incorporating such a frictional law facilitates the simulation of statically strong and dynamically weak faults, and enables a range of rupture complexities and fault interactions (Dunham et al. 2011; Taufiqurrahman, 2023; Palgunadi et al., 2024}. For example, in dynamic rupture simulations for the Mai'iu low angle normal fault, velocity-weakening friction law allowed rupture to propagate into a shallow velocity-strengthening portion of the fault (Biemiller et al. 2022). Similarly, fully dynamic seismic cycle simulations with rate-and-state friction laws show that ruptures can propagate through velocity-strengthening barriers under specific conditions (e.g. Kaneko et al., 2010). Additionally such friction laws allow faults to rupture at relatively low shear stress levels (e.g., Ulrich et al., 2019). Incorporating a strong velocity weakening friction law in simulations for the ATF would therefore be highly relevant. While this is beyond the scope of the present study, we consider this an important direction for future work.

3) Regarding the kinematic coupling model, I am curious about how the parameter T = 1800 year was selected, because this will affect the calculation of stress changes, which is likely to have an important impact on the dynamic rupture simulation. However, the authors did not explain how to select the value of T in the main text, nor did they use other values for testing.

Thank you for your question. The value T=1800 years was chosen because it allows sufficient stress accumulation on the fault to enable successful rupture propagation without causing instantaneous failure. We explored values ranging from 1000 to 3000 years. Values lower than 1600 years do not lead to rupture propagation, T=1700 years leads to a Mw 6.1 earthquake, and values larger than 2000 years lead to instantaneous failure of large fault areas.

We have clarified the rationale for this choice in the main text:

L262-265: *We use T=1800 years****, corresponding to the stress accumulation time necessary for the rupture to propagate. We explore T in a range of 1000-3000 years. Values lower than 1600 years do not allow rupture to propagate, while T=1700 years results in a Mw 6.1 earthquake. For values greater than T=2000 years, unrealistic rupture occurs instantaneously across large fault areas.***

USGS internal review (Ruth Harris)

Main comments:

1) One thing I am wondering about is if it would be possible to distill a bit of the text describing the tectonic setting, fault slip rates, dynamic rupture inputs, etc. Some of this material appears more than once, in neighboring sections of the manuscript.

Thank you for your comment. We carefully reviewed the manuscript and noticed some redundancies. We have revised the text for conciseness. The modifications are listed below:

- In section 2 "*The Alto Tiberina low angle normal fault*", we removed the information about the dimensions and dip angle of the Alto Tiberina fault as it was already given in the introduction.
- We have removed the paragraph discussing an alternative parametrization for the data-constrained model (initially located in the results section, L337-342 of the initial manuscript) as a similar discussion was also included in the discussion section (L450-462 of the revised manuscript; see also our answer to Reviewer 2's comment n°2).

2) I was a little confused about the mention of slip-rates on low-angle normal faults being faster than slip rates of regular-dip normal faults. If this is the case, then one might think that LANF's would produce more earthquakes, unless they're slipping aseismically?

We thank the reviewer for this comment. We agree that the observation that LANFs may slip faster than high-angle normal faults is intriguing. This apparent paradox may be explained by a combination of factors, including a dominant contribution of aseismic slip. Moreover, due to their low dip angle, LANFs tend to project a larger horizontal component of slip onto the surface, which can result in an apparently higher slip rate when inferred from geodetic data or geological markers of horizontal extension.

We modified the main text as follow:

L59-65 *Moreover, slip rate estimates for 49 active or inactive LANFs (Webber et al., 2018) suggest that these faults slip faster (mostly <10 mm/y but one third >10 mm/y) than their high-angle counterparts (Nicol et al., 2005, mostly <1 mm/y and no faster than 6 mm/y).* ***This observation may be explained by a combination of factors, including a dominant contribution of aseismic slip (e.g., Hreinsdottir & Bennett, 2009). Moreover, due to their shallow dip angle, LANFs are more efficient at accommodating horizontal deformation than regular normal faults, which can result in an apparently higher slip rate when inferred from geodetic data or geological markers of horizontal extension.***

3) The figures look really good overall. Please make sure that locations mentioned in the text also appear in a figure.

Thank you. We have checked and the locations mentioned in the text all appear in the figures.

4) Lines 139-146. There's suddenly mention of important information about the frictional properties. Should this information instead appear in the fault strength section?

We agree and we have moved this information into the fault strength section (L188-192).

5) Line 147. The method section. This would be a good place to mention friction as a separate section (it's one of the four "ingredients" for dynamic rupture simulations).

The friction law was originally described in Section 3.2 "*Fault Strength and Nucleation Procedure*". We have now separated the nucleation procedure into its own section and renamed Section 3.2 "*Fault Friction*". Additionally, the information on frictional properties previously included in Section 2 has been moved to this section (see comment n°4).

6) Figure 1 question – I'm wondering why the time period for some of the depicted seismicity is just 2010-2014.
Section 2. I'm wondering why the catalog is limited to the years 2010-2014.

At the time the study was conducted, the only published high-resolution seismicity catalogs available for the Alto Tiberina fault system covered the period from 2010 to 2014, with 2010 marking the start of the TABOO Near-Fault Observatory. Specifically, we used the catalog by Valoroso et al. (2017), which includes 40,000 events with a completeness magnitude M_C = 0.5 and a relative formal errors on the order of tens of meters, to constrain the location and non-planar geometry of the hanging-wall active faults included in our simulations (see also Section 3.1, Text S1, and Figure S1). Very recently, Poggiali et al (2025) published a new seismicity catalog covering a longer time period (2010-2023).This catalogue, however, does not modify the first order of geometrical evidence identified by Valoroso et al. 2017. We modified the main text and the caption of Figure 1 as follow:

L127-131: *In particular, the dense seismic network of TABOO records the seismicity of the Alto Tiberina fault system with a very low event detection threshold (down to M_L=-0.2) and completeness magnitude (M_c=~0.5), thus enabling the production of high-resolution earthquake catalogs that finely characterize the architecture of the Alto Tiberina fault system (Chiaraluce et al. 2007, Valoroso et al., 2017, Vuan et al. 2020, Essing and Poli, 2022, 2023,* ***Poggiali et al. 2025****)*

L172-174:***Very recently Poggiali et al. (2025) have generated another high-resolution catalogue covering a longer time span, from 2010 to 2023. This catalogue, however, does not modify the first order of geometrical evidence identified by Valoroso et al. 2017.***

Caption of Figure 1:
The black and orange dots show the 2010-2014 Alto-Tiberina and hanging wall faults seismicity, respectively (Valoroso et al., 2017). ***Note that, at the time this study was conducted, high-resolution catalogs published for the ATF fault system did not cover longer time periods.***

7) Section 3.5. I'm thinking that the frequency resolution might not represent the actual resolution, because a 1D velocity model is being used, not a more realistic 3D velocity model (unless in this region the rock layers happen to consist of horizontal bedding).

We agree and now acknowledge in the main text that the use of a 1D velocity model may limit the realism of our synthetics.

L286-288 *The mesh resolution inside and outside the high-resolution box can resolve frequencies of at least 1~Hz and 0.25~Hz, respectively.* ***However, we note that the use of a 1D velocity model may limit the realism of the simulated ground motions.***

8) Section 4. Please cite a general reference for the significance of nucleation location – many papers over the years have mentioned that it was important, so there are many references to choose from.

We agree and have modified the beginning of Section 4.1.3 to acknowledge previous studies regarding the significance of nucleation location.

L338-341 ***Previous dynamic rupture studies have shown that the nucleation location can impact on the rupture extent, slip distribution, and earthquake size (e.g. Aochi and Ulrich, 2015; Kyriakopoulos et al., 2019; Ramos et al., 2021; Yu et al., 2023, Chan et al. 2023). In this section,*** *we* ***therefore*** ~~*also*~~ *test the impact of the nucleation location* ***on the rupture scenarios.***

9) Section 5. – the Discussion section: I'm thinking that the Coulomb stress change calculations should be in the Results sections instead?

We agree and have moved the Coulomb stress change analysis to the result section 4.3 (L.370).

10) Acknowledgements section: Please add the USGS trade names disclaimer statement.

Done.

Supplementary comments from the PDF file

Note that minor comments such as grammatical suggestions are not listed below but have been taken into account in the revised version of the manuscript.

11) L45 "longer recurrence intervals" would need to explain why this is the case though - e.g., do all LANF's have lower slip rates?

This statement is based on the work of Wernicke (1995) that uses simple mechanical considerations to show that low angle normal faults accommodate a given rate of horizontal extension with fewer but larger earthquakes, compared to steeper normal faults. Based on the fact that the average stress drop is proportional to $\frac{D}{\sqrt{A}}$ with D the average slip D and A the slip area, Wernicke (1995) shows that D is proportional to $1/sin(\theta)$ with θ the fault dip angle (assuming $\sqrt{A} = h/sin(\theta)$ with h the seismogenic layer thickness). For a given rate of horizontal extension, Wernicke (1995) further shows that the frequency of events per fault R is proportional to $tan(\theta)$: LANFs are geometrically more efficient at accommodating horizontal extension than steeper normal faults, thus less frequent earthquakes are needed.

We modified the text as follows:

L44-49: The scarcity of large LANF earthquakes in the instrumental record may be due to ***potentially*** *longer recurrence intervals compared to steeper-dipping normal faults.* ***Using simple mechanical considerations,* Wernicke (1995) *shows that the average slip*** D ***and recurrence interval*** R ***is proportional to*** $1/sin(\theta)$ ***and*** $1/tan(\theta)$, ***respectively, with*** θ

***the dip angle). This suggests that for a given rate of horizontal extension, LANFs accommodate the deformation with fewer but larger earthquakes compared to steeper normal faults*, which** *aligns with neotectonic studies […].*

12) L56: “Moreover, slip rate estimates for 49 active or inactive LANFs (Webber et al., 2018) suggest that these faults slip faster (mostly <10 mm/y but one third >10 mm/y) than their high-angle counterparts (Nicol et al., 2005, mostly <1 mm/y and no faster than 6 mm/y).”

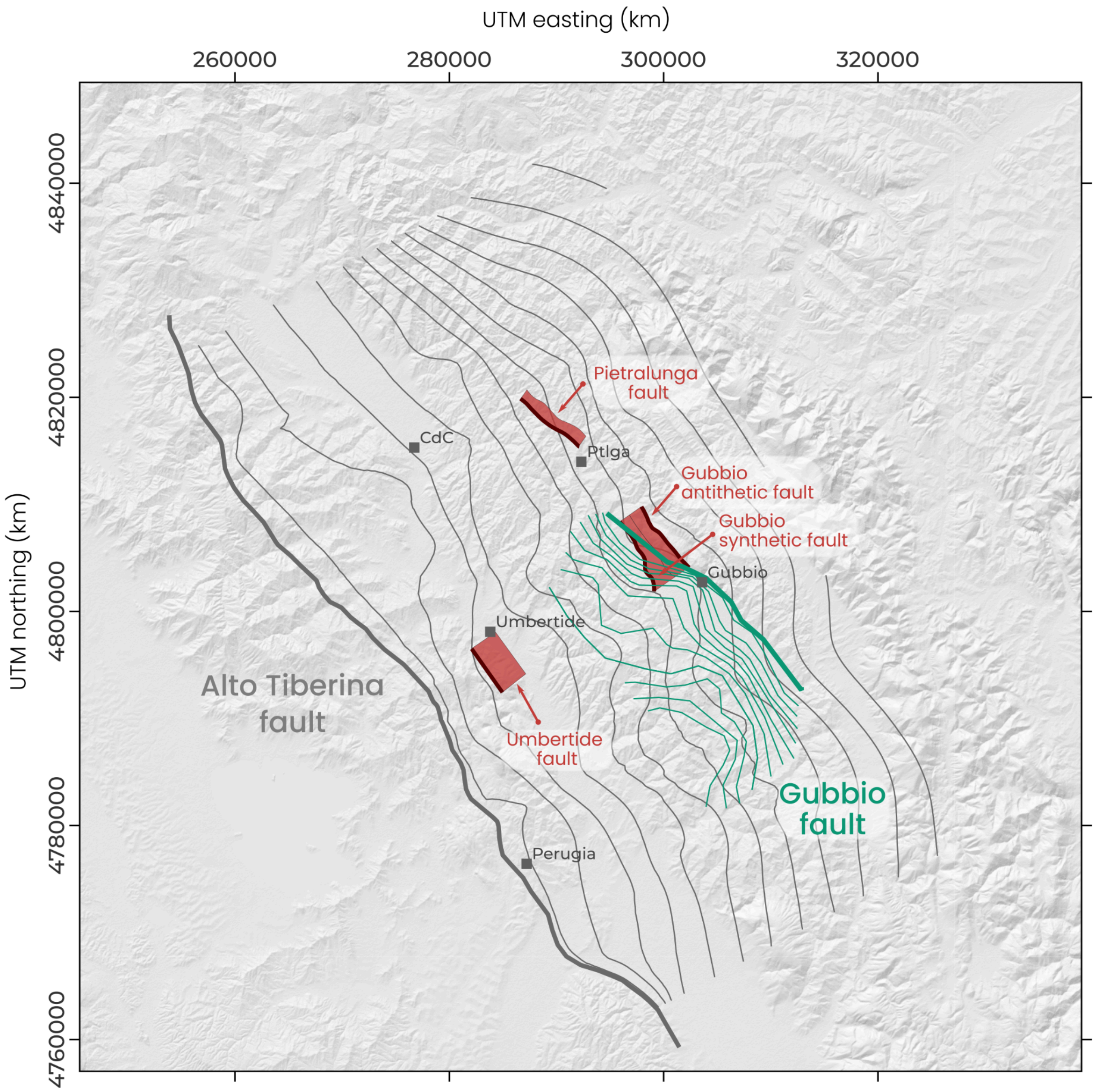
This is interesting information. One would think that if LANF's have higher slip rates than regular NF's, then LANF's should have EQ's more often, unless LANF's primarily slip aseismically. I'm wondering though about the inclusion of the word "inactive" here. Inactive would mean that they're not slipping now?

We thank the reviewer for this comment. We agree that the observation that LANFs may slip faster than high-angle normal faults is intriguing. This apparent paradox may be explained by a combination of factors, including a dominant contribution of aseismic slip. Moreover, due to their low dip angle, LANFs tend to project a larger horizontal component of slip onto the surface, which can result in an apparently higher slip rate when inferred from geodetic data or geological markers of horizontal extension. We modified the text L59-65 (see also our answer to your comment n°2).

Webber et al. (2018) divide the LANFs they used in their compilation in three groups: *inactive LANFs*, *potential active LANFs*, and *confirmed active LANFs*. “Inactive” means they do not participate in accommodating the deformation anymore, neither aseismically, nor seismically.

13) Figure 2: I'm wondering where these fault surfaces are located relative to the fault structures shown in FIgure 1. Or maybe this is revealed in figures in the supplement?

We have added a new figure (Figure S2) in supplements showing a map view of the secondary fault locations:



Rebuttal Letter Figure 3: New Figure S2.

We refer to this figure L172:
*[...] we use the seismicity catalog of Valoroso et al. (2017) to constrain the non-planar geometry of three of the secondary faults (Pietralunga, Gubbio synthetic, and Gubbio antithetic faults, supplementary text S1 and Figure**s** S1 **and S2**)*

14) L178 please add a reference here for the clay-rich gouge material

This sentence is no longer in the manuscript as we move the information regarding the ATF fault friction (along with the appropriate references) from section 2 to method section 3.2 where this sentence was (see comments n°4 and 5, above).

15) L217. Is this depth range chosen from the locations of the microseismicity, or from another data set?

The depth range is based on microseismicity. It is now clarified in the main text:

L231-232 *This depth range is consistent with the depth limit of the microseismicity in the Alto Tiberina area (Valoroso et al. 2017).*

16) T=1800 years. Why this value?

Thank you for your question. The value T=1800 years was chosen because it allows sufficient stress accumulation on the fault to enable successful rupture propagation without causing instantaneous failure. We explored values ranging from 1000 to 3000 years. Values lower than 1600 years do not lead to rupture propagation, T=1700 years leads to a Mw 6.1 earthquake, and values larger than 2000 years lead to instantaneous failure of large fault areas.

We have clarified the rationale for this choice in the main text:

L262-265: *We use T=1800 years****, corresponding to the stress accumulation time necessary for the rupture to propagate. We explore T in a range of 1000-3000 years. Values lower than 1600 years do not allow rupture to propagate, while T=1700 years results in a Mw 6.1 earthquake. For values greater than T=2000 years, unrealistic rupture occurs instantaneously across large fault areas.***

17) L.241 does the fact that the ATF is partly creeping affect the other faults in the model?

In the data-constrained simulation, only the ATF initial stress distribution is constrained from the coupling model. The initial stress distribution on the other faults is identical to the homogeneous reference model. We add a sentence to stress this point.

L257-261 *Note that the kinematic coupling model of Anderlini et al. (2016) includes only the ATF. Therefore, in our heterogeneous simulations, only the initial stress distribution on the ATF is constrained by the kinematic coupling model, while the initial stress distribution on the other faults is identical to the homogeneous reference model (with R_0=0.70, section 3.3.1)****. Therefore, the secondary faults are not affected by the partly-creeping Alto Tiberina fault.***

18) L249 is this o.k., that a 1D model is being used, rather than a 3D model?

We have added a justification for the use of a 1D model instead of a 3D model.

L270-271 ***We choose not to use the 3D velocity model of Latorre et al. (2016) due to its limited spatial extent which does not fully cover the ATF and the challenge of merging properly the 3D model with a larger one.***

19) L260 but remember that a 1D velocity model is being used, not a 3D velocity model, so ground motions are unlikely to be accurate.

We agree and now acknowledge in the main text (L286-288) that the use of a 1D velocity model may limit the realism (see answer to your comment n°7).

20) Section 4.1.3: most authors hypothesize that nucleation location is very important, for almost all dynamic rupture simulations. Cite a reference here?

We agree and have modified the beginning of Section 4.1.3 (L338-340), see our answer to your comment n°8.

21) L.339:342 I wonder if this text should instead be in the discussion section because what is being described is potential work for the future, rather than work done here.

This paragraph, discussing an alternative parametrization for the friction properties of the data-constrained simulations, is no longer in the manuscript as it was redundant with a paragraph in the discussion (L450-462) that covered similar topics. See also our response to your comment n°1.

21) 5.1 Coulomb stress changes on the hanging wall faults:
I think that this section should move back into the main text, rather than being here.

The Coulomb stress change analysis is now moved into the results section 4.3 (L370).

22) L94 "migrated eastward" perhaps mention the time over which this migration occurred?

We modified the sentence as follow:
*L.104-107: It is the easternmost, youngest, and only active fault of six subparallel east-dipping low-angle normal faults that have successively accommodated **in the last ~10 My** (along with associated high-angle antithetic normal faults) extension in the Northern Apennines as it migrated eastward (Barchi et al., 1998; Collettini et al., 2002; Collettini and Barchi, 2002)*

23) L97 “long term slip rate” over which time period.

We modified the sentence:
L.110 *The Gubbio fault has accommodated ~3~km of slip with a long-term slip rate estimated at 1.65–1.9 mm/y**, assuming all the displacement occurred during the Quaternary.***

24) Hopefully ‘kinematic” coupling is defined later in the text

We use the term “kinematic coupling” (ratio of slip deficit to long-term slip rate) to avoid confusion with “seismic coupling” (fraction of slip released seismically). We modified the sentence L236:

*The kinematic coupling model **(giving the ratio of slip deficit to long-term slip rate)** of Anderlini et al. (2016) obtained from interseismic GPS data suggests …*