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Solid Earth
Discussions

Interactive comment on "Factors controlling the sequence of asperity failures in a fault model" *by* Emanuele Lorenzano and Michele Dragoni

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Reply to reviewer 1

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We answer point-by-point to the reviewer's comments and requests. In the following, figure, page, line and section numbers refer to the Interactive Discussion version of the manuscript.

General comments:

1) Generally speaking, I find the treatment of the "earthquake" system overly simplified – to the degree that I want to question whether the provided results actually bear any insights into the recurrence of earthquake rupture (including the effect of viscoelastic relaxation). The authors mention that knowledge of the initial state of stress in the

system would allow to calculate/predict the following sequence of earthquakes i.e., asperity ruptures (in absence of stress perturbations). While this may be in theory correct, this approach is in my view not appropriate to describe earthquake rupture and recurrence, considering the spatial and temporal variation of physical parameters that in fact control earthquake rupture. In the present work, all that existing and important complexity is removed i.e., not considered.

The present fault model clearly provides a simplified description of real fault dynamics. However, if we aim to a neat understanding of the physics of the seismic source, unnecessary complications must be set apart and different phenomena must be considered separately. As a matter of fact, studying fault dynamics in the framework of a discrete dynamical system represents a tool for enlarging our understanding of the most significant and essential aspects of the seismic activity, such as the stick-slip mechanism governed by the system of forces on the fault. Also, the characterization of the fault as made of a finite number of asperities allows a description by means of a finite number of degrees of freedom, thus making the retrieval of the analytical solutions of the evolution equations possible (section 3). In this analytical framework,

the different phases of the evolution of the system and their distinctive features can be studied by means of a geometrical approach, calculating the orbit of the system in the state-space (section 4 and 6). Of course, taking several physical parameters and their spatial and temporal variation into account is important, but it would require a characterization by means of a model based on continuum mechanics or a numerical approach, which would make it difficult to highlight the basic mechanisms of fault dynamics.

As the reviewer pointed out, several geophysical phenomena are not taken into account in the present model. Some of them (e.g. the interaction between mechanically different regions on a fault, the role of asperity size, the interplay between external stress perturbations and viscoelastic relaxation on a fault) have been object of previous works in the framework of discrete fault models (e.g. Dragoni and Lorenzano, 2017; Lorenzano and Dragoni, 2018a,b) and could be introduced in the present model at the price of increased complication. However, this would go beyond the scope of the present work, which is further explained in the next reply.

2) The authors mention that the aim of the presented study is to expand on previous work (P2L19). But that is not really motivating anything. What are the authors actually trying to constrain/identify? How can the results applied? What insights regarding earthquake rupture does it provide? The study needs an improved motivation/introduction section.

In the present work, we consider a two-asperity fault in the presence of viscoelastic relaxation and provide a more detailed characterization of its dynamics with respect to previous studies (Amendola and Dragoni, 2013; Dragoni and Lorenzano, 2015). First of all, the radiation of elastic waves during seismic events is included, thus presenting a more complete and general solution to the equations of motion (section 3). Afterwards, we show how the particular sequence of slip episodes during a seismic event is controlled by the state of stress on the fault, both at the onset of the event itself (section 4.1) and at the beginning of the interseismic interval preceding the event (section 4.2). In particular, additional constraints with respect to previous works are determined using the condition for the consecutive, but separate, slips of the asperities as a discriminant factor. Then, we focus on these kinds of seismic events

and investigate their dependence on the seismic efficiency of the fault, the intensity of asperity coupling and asperity relative frictional strengths (section 6).

The possible insights on earthquake rupture the model can provide have been discussed by Dragoni and Lorenzano (2015), who also presented an application to the 1964 Alaska earthquake. The authors showed that a major role in this sense is played by the source time function associated with an earthquake. In fact, the number and the amplitudes of humps in a source time function are directly related with the number and sequence of slip episodes during the associated seismic event. An example is shown in Fig. 7 and Fig. 8 for one-mode events 10 and 01, respectively. In turn, the observation of the source function of a seismic event allows to set constraints on the (otherwise unknown) state of stress of the fault that caused it (section 4).

3) The proximity of the two asperities considered here relative to each other should play a role (on the probability of respective rupture modes) – maybe I missed it, but do the authors consider that point?

The proximity of the two asperities is one of the factors determining the value of the parameter α, which controls the intensity of coupling and, consequently, the stress transfer between the asperities (Eq. 1). In fact, by comparison with a model based on continuum mechanics, the specific value of α can be estimated as (Lorenzano and Dragoni, 2018)

$$\alpha = \frac{Avs}{2\dot{e}} \tag{1}$$

where A is the area of the asperities, v is the velocity of the tectonic plates, s is the tangential traction (per unit moment) imposed on one asperity by the slip of the other and $\dot{e}$ is the tangential strain rate on the fault due to tectonic loading. For nonoverlapping asperities, the traction produced by point-like dislocations is a good approximation for s (e.g. Dragoni and Lorenzano, 2016). Specifically, we have

$$s = \frac{5}{12\pi} a^{-3} \tag{2}$$

for strike-slip faulting and

$$s = \frac{1}{6\pi} a^{-3} \tag{3}$$

for dip-slip faulting, where a is the distance between the centroids of the asperities. We conclude that the strength of coupling between the two asperities is inversely

proportional to their distance.

The value of α influences several aspects of the dynamics of a seismic event, as predicted by the model. First of all, as shown in Appendix B, it contributes to define the subsets of the state space discussed in section 4, thus controlling the sequence of slip modes in a seismic event. Also, it determines the intensity of static stress drops on the asperities (section 5, Table 1). Finally, it governs the possible sequence of alternate slips of the asperities in a seismic event (section 6.3).

Specific comments:

1) P1L4 – colon after “degrees of freedom" indicates that a list of those is following – but that does not seem to be the case; please rephrase.

In the present model, the state of the fault is characterized by three state variables: the slip deficit of asperity 1, the slip deficit of asperity 2 and the temporal variation of the difference between the slip deficits due to viscoelastic relaxation. Accordingly, the system has three degrees of freedom, corresponding to the aforementioned state variables. We shall rephrase the Abstract in order to better explain the correspondence between the state variables and the degrees of freedom of the system.

2) P1L5 – the slipping modes should be mentioned here; current formulation too implicit/vague.

We shall rephrase in order to illustrate the difference between the three slipping modes.

3) Abstract – does not stand alone; the reader learns to some extend what the authors wanted to do but not what they learned/have found out; this needs to be included into the abstract.

We shall include the main results of our study in the Abstract.

4) P1L13 – replace “by asperity models": the “by" is wrong, the models don’t investigate anything.

The sentence shall be rephrased.

5) P1L22 – how are “non-asperities" defined/characterized? Needs to be mentioned here; they also have a role within the earthquake system and the authors need to state what that role is; include corresponding explanation in the model formulation section.

Asperities on a fault are defined as “unstable" or “strong" regions: they remain locked for most of the time and eventually undergo a sudden failure, catastrophically releasing the deformation energy stored in the medium with the emission of elastic waves. From a frictional point of view, they are characterized as velocity-weakening (VW) regions.

However, faults can accommodate tectonic motion in another way. This second mechanical behaviour is ascribed to “stable" or “weak" fault regions, which exhibit a slow, quasi-static creep during interseismic intervals and afterslip during post-seismic intervals. From a frictional point of view, they are characterized as velocity-strengthening

(VS) regions. In the present work, we neglect the possible presence of such “non-asperities" on the fault. In the framework of a discrete fault model, this problem has been discussed by Dragoni and Lorenzano (2017), who considered a fault containing an asperity and a weak region. The authors suggested a value of 0.1 for the ratio between the steady-state frictional stress of the weak region and the static frictional stress of the asperity: in fact, asperity models assume that weak regions may slip at a much lower stress level than asperities. By combining elements of the present model with the model of Dragoni and Lorenzano (2017), it would be possible to study the interaction between seismic slip, afterslip and viscoelastic relaxation; however, this kind of analysis is beyond the scope of the present work (see reply to general comment #2).

6) P2L17 – what the authors mean with “source functions"? Is that source time function? Please clarify.

We call “source function" the rate of release of seismic moment as a function of time, that is, the moment rate function. For the sake of clarity, the expression “source

function" shall be replaced with “moment rate function" throughout the manuscript.

7) P2L24 – the term “seismic efficiency" should be defined properly.

The seismic efficiency of the fault is defined as the ratio between the energy radiated as seismic waves and the total elastic energy released by a dislocation on the fault. We shall add this definition to the revised version of the manuscript.

8) P3L3 – language is vague “by a much higher friction than the surrounding region of the fault": be specific/quantitative please.

See reply to specific comment #5.

9) P3L4 – I cannot follow that logic: the authors argue that they can neglect the seismic moment contributed from the “weaker regions" of the fault that surround the asperities, but why? Regardless of strength, if the fault slips (coseismically) then it will contribute

to seismic moment, so I want to question the author's approach here; they need to better explain justify this simplification.

As a matter of fact, the fault region surrounding the asperities does give a contribution to the coseismic seismic moment release. However, one of the basic assumptions of asperity models is that the bulk of seismic moment release in a seismic event is ascribed to asperity slip, corresponding to the largest humps in the source time function of the event itself. A possible way to account for the contribution of the weaker fault region has been presented in the framework of a two-asperity discrete fault model by Dragoni and Santini (2015); the authors applied their model to the 1964 Alaska earthquake, showing that the slip of the weaker fault region contributed only to about 20% of the overall moment release associated with that event. Although taking this aspect into account would result in a better fit between the observed and modelled source time functions of an event, the conclusions of the theoretical study presented here would not be affected.

10) P3L20 – why using a rate-dependent law? Did the authors experiment with other

laws as well? Please better motivate the use of this friction law.

The purpose of the present work is to provide a macroscopic characterization of the mechanics of the seismic source, neglecting a detailed description of stress, slip and friction distribution on the fault. Accordingly, it is sufficient to replicate the typical stick-slip behaviour of the fault, a result that can be properly achieved by adopting the simplest formulation of a rate-dependent friction law, corresponding to a constant static friction threshold and a constant dynamic friction. The use of more accurate descriptions of frictional resistance such as the rate- and state-dependent friction laws (Ruina, 1983; Dieterich, 1994) would ony result in a more complex modelling and provide negligible improvements to our conclusions.

11) P12L8 – the authors will need to explain how their analytical toy model is able to inform our understanding of earthquake rupture and rupture sequences; after all, we don't know the “initial state of stress" and real faults do exhibit stress perturbations, along with a range of other processes and parameters that affect earthquake rupture and that are not considered here. So, how does the presented study help to learn

about earthquakes?

See reply to general comment #1.

References

Amendola, A. and Dragoni, M. (2013). Dynamics of a two-fault system with viscoelastic coupling, Nonlin. Processes Geophys., 20, 1 – 10, doi:10.5194/npg-20-1-2013.

Dieterich, J. (1994). A constitutive law for rate of earthquake production and its application to earthquake clustering. J. Geophys. Res., 99, 2601 – 2618, doi:10.1029/93JB02581.

Dragoni, M. and Lorenzano, E. (2015). Stress states and moment rates of a two-asperity fault in the presence of viscoelastic relaxation. Nonlinear Process. Geophys., 22(3), 349 – 359, doi:10.5194/npg-22-349-2015.

Dragoni, M. and Lorenzano, E. (2016). Conditions for the occurrence of seismic sequences in a fault system. Nonlin. Process. Geophys., 23(6), 419 – 433, doi:10.5194/npg-23-419-2016.

Dragoni, M. and Lorenzano, E. (2017). Dynamics of a fault model with two mechanically different regions. Earth Planets Space, 69(145), doi:10.1186/s40623-017-0731-2.

Dragoni, M. and Santini, S. (2015). A two-asperity fault model with wave radiation. Phys. Earth. Planet. In., 248, 83 93, doi:10.1016/j.pepi.2015.08.001.

Lorenzano, E. and Dragoni, M. (2018): A fault model with two asperities of different areas and strengths, Math.Geosci., https://doi.org/10.1007/s11004-018-9738-x.

Lorenzano, E. and Dragoni, M. (2018): Complex interplay between stress perturbations and viscoelastic relaxation in a two-asperity fault model, Nonlin. Process.

Geophys., 25, 251-265, https://doi.org/10.5194/npg-25-251-2018.

Ruina, A. (1983). Slip instability and state variable friction laws. J. Geophys. Res., 88, 10359 – 10370, doi:10.1029/JB088iB12p10359.