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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 2

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

1) Previous models have studied fully dynamic earthquake cycles on a fault with asperities [e.g., Lui and Lapusta, “Repeating microearthquake sequences interact predominantly through postseismic slip", Nature Communications, 2016]. A review of these previous studies is lacking in the introduction section. In particular, how can the modeling approach in this paper contribute to our understanding of earthquake cycles?

Following the referee's recommendation, we shall add in the Introduction a short review of previous papers studying fault slip in the presence of friction heterogeneities, in particular Mikumo and Miyatake (1995), Beroza and Mikumo (1996), Somerville et al. (1999), Pisarenko (2002), Mai and Beroza (2002), Johnson (2010), Lui and Lapusta (2016) and Zielke et al. (2017).

As to the contribution of the present paper to our understanding of seismic cycles, one of the merits of discrete fault models is to allow a systematic study of the evolution of the system as a function of initial conditions. This is possible because the evolution can be represented as an orbit in a low-dimensional state space, which can be continued for an arbitrary number of cycles. Examples of such studies have been given by Dragoni and Santini (2010, 2012) and Dragoni and Piombo (2015). However, in the present paper we focus on single events, showing how the initial conditions control the sequence of slipping modes during the event.

2) On Page 3, the asperity is characterized by a much higher friction than the surrounding region, which I don't think is necessarily true for a real fault. Could the authors provide some observations that support this view?

Friction on faults is of course a continuous function of position. However, it has been recognized that, when an earthquake occurs, most of the seismic moment is released by a small number of regions where friction is much higher than in the rest of the fault: this observation is at the basis of asperity models (e.g. Scholz, 1990). In these models, the fault surface is separated into two kinds of regions, characterized by high and low friction, respectively. It is assumed that a higher friction corresponds to a higher accumulated stress and to a larger slip (Somerville et al., 1999).

3) The model assumes a rate-dependent friction law instead of a rate and state dependent friction law that is observed in laboratory experiments and used in fully dynamic earthquake cycle models. The authors replied to the other reviewer that using rate and state dependent friction laws would “provide negligible improvements to our conclusions". However, if the friction changes over time as defined by the state variable, it will significantly affect the recurrence intervals of seismic events.

As noticed by the referee, our model does not include a dependence of friction on the

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state of the fault. This might imply a slow change of static friction with time, when the fault is at rest, and a change in the duration of interseismic intervals. This effect could be easily incorporated in the model by introducing a dependence of the parameters β and ϵ on time. However, we neglect this further complication at the present stage. This assumption of the model will be acknowledged in the revised version of the paper.

4) On Page 5, the authors mentioned that they consider the case of underdamping because seismic efficiency of faults is small. I don't think this is true. Radiation efficiency depends on the earthquake type and is not always small. I've attached Figure 8 from Venkataramen and Kanamori [2004]. For example, the radiation efficiency of tsunami earthquakes is usually lower than other types of earthquakes.

The radiation efficiency used by Venkataraman and Kanamori (2004) is not the seismic efficiency mentioned in our paper: the two quantities have different definitions. As shown by Kanamori (2001), the radiation efficiency is always greater than the seismic efficiency. Assuming the overdamped solution allows seismic efficiencies as large as 0.33 (Dragoni and Santini, 2017), corresponding to greater values of radiation efficiency, in agreement with observations.

5) It's hard to relate the proposed models to realistic cases. In section 4.1, the authors discussed the different earthquake models when Pk belongs to different segments on the face AECD. If we picked a region, e.g., Parkfield, how could we determine which segment it belongs to?

In section 4.1, the relationship between the stress state of the fault at the onset of a seismic event (corresponding to a point P_k in the state space) and the particular sequence of slipping modes in the event itself is discussed. For instance, if the state P_k belongs to the trapezoid $\mathbf{Q_1}$ on the face $AECD$ of the sticking region, the seismic event will be due to the sole slip of asperity 1 (i.e., one-mode event 10).

Different faults do not correspond to different subsets of the sticking region. If we focused on a given fault, the proper set of parameters for that specific fault (that is, the values of $\alpha, \beta, \gamma, \epsilon, \Theta$ and V) could be retrieved by exploiting inter-, co- and post-seismic field observations. In turn, the sticking region $\mathbf{H}$ corresponding to that particular fault could be determined and its geometric features could be studied as in section 4 and Appendix B. Once completed this preliminary analysis, one could associate an observed seismic event on the fault with a specific sequence of slipping modes (using the moment rate function of that event as a constraint, as explained in the reply to reviewer 1) and thus gain information on the stress state that originated the event. An exemplification of such procedure can be found in the work of Lorenzano and Dragoni (2018a), who modelled the Landers fault as a two-asperity fault and showed that the 1992 earthquake that took place on that fault could have been originated by any of the states belonging to the segment $\mathbf{s_2}$ of the face $BCDF$ of $\mathbf{H}$.

6) Fig.7 and Fig. 8 are not cited in the manuscript. Though the peak moment rate amplitudes are slightly different in the figures, the moment rate functions have very similar shapes for events 10 and 01. Why is that?

Figures 7 and 8 are cited at page 15, line 7. They show both the slip amplitude and the moment rate function of one-mode events 10 and 01, respectively. The features of the moment rate functions are a direct consequence of the solutions to the equations of motion from which they are calculated, according to Eq. (78). Specifically, the model predicts that events starting from a global stick phase and associated with the slip of a single asperity have the same duration and the same shape for the associated slip amplitude, as shown by Eqs. (42), (45), (61) and (63). As the reviewer pointed out, the only difference between the moment rate functions of the two events is their peak value: in fact, the final slip amplitude (63) of asperity 2 differ by a factor β from the final slip amplitude (45) of asperity 1, with $0 < \beta < 1$.

The aforementioned characteristics depend on the assumptions of asperities with equal areas and same radiation damping (section 2). These hypotheses have been relaxed by Lorenzano and Dragoni (2018b), who investigated how the difference between the asperity areas affects several aspects of the seismic events generated by a two-asperity fault.

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