Rupture complexity promoted by damaged fault zones in earthquake cycle models

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Pulse-like ruptures tend to be more sensitive to stress heterogeneity than crack-like ones. For instance, a stress-barrier can more easily stop the propagation of a pulse than that of a crack. While crack-like ruptures tend to homogenize the stress field within their rupture area, pulse-like ruptures develop heterogeneous stress fields. This feature of pulse-like ruptures can potentially lead to complex seismicity with a wide range of magnitudes akin to the Gutenberg-Richter law. Previous models required a friction law with severe velocity-weakening to develop pulses and complex seismicity. Recent dynamic rupture simulations show that the presence of a damaged zone around a fault can induce pulse-like rupture, even under a simple slip-weakening friction law, although the mechanism depends strongly on initial stress conditions. Here we aim at testing if fault zone damage is a sufficient ingredient to generate complex seismicity. In particular, we investigate the effects of damaged fault zones on the emergence and sustainability of pulse-like ruptures throughout multiple earthquake cycles, regardless of initial conditions.

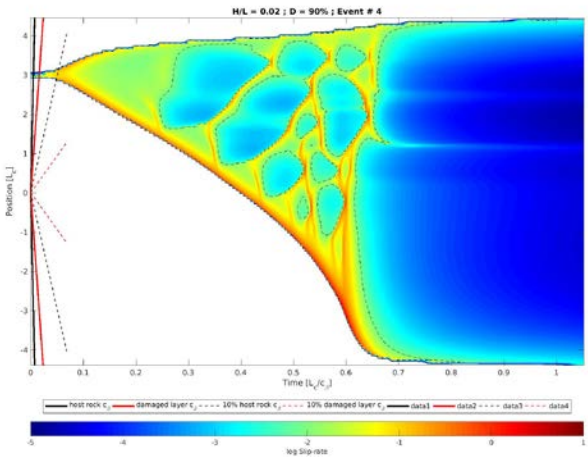

Figure 1. Example of complex rupture in a fault surrounded by a low rigidity layer. Colors show the space-time distribution of slip velocity.

We consider a fault bisecting a homogeneous low-rigidity layer (the damaged zone) embedded in an intact medium. We conduct a series of earthquake multi-cycle simulations to investigate the effects of two fault zone properties: damage level D and thickness H. The simulations are based on classical rate-and-state friction, the quasi-dynamic approximation and the software QDYN (https://github.com/ydluo/qdyn). Our numerical results show the development of complex rupture patterns in some damaged fault configurations, including events of different sizes, as well as pulse-like, multi-pulse (Fig. 1) and hybrid pulse-crack ruptures. We further apply elasto-static theory to assess how D and H affect ruptures with constant stress drop, in particular the flatness of their slip profile, which is an indicator of pulse-like rupture. A form of complex seismicity, involving smaller events nucleated near the fault edges, is well explained by the ratio of fault length to a theoretical estimate of nucleation size in damaged zones. We find qualitative agreement between our theoretical and computational results regarding the range of damaged zone properties that enable pulse-like rupture and complex seismicity. Secondary rupture fronts in individual ruptures tend to nucleate and arrest near residual stress heterogeneities left by previous events.