Nucleation of earthquake slip on heterogeneous interfaces

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Introduction

Understanding how frictional instabilities initiate is an outstanding problem, with implications for earthquake forecasting and seismic hazard. The nucleation process on a uniform frictional interface has a relatively well-understood progression, but it is much more complex and not well understood on heterogeneous interfaces. To shed light on this process, we study the initiation of slip on rate-and-state fault interfaces with realistic, fractal-like distributions of normal stress. Using the diverse spectrum of nucleation behaviors observed in these models, our work is directed towards understanding several fundamental questions in earthquake science.

Motivating observations

Natural fault surfaces are not planar, but irregular at all scales. Non-planarity translates into significant variations of compressive stress across the fault, which in turn can modify friction properties, giving rise to complex dynamics. In addition, stability of slip depends on the effective normal stress on the interface. A widely accepted viewpoint is that the interaction of aseismic slip with such inherent heterogeneity results in microseismicity. This notion is supported by the experiments by Greg McLaskey and colleagues, which identify microseismicity at persistent locations.

Nucleation process on interfaces with heterogeneous normal stress distributions

![Figure 5a: 2D and 3D views of uniform normal stress distribution.](image)

![Figure 6a: 2D and 3D views of the fractal distribution of normal stress of amplitude ±600σ_{mean} superimposed in the model.](image)

Large events are small events that run away

A continuum of behavior scenarios are observed systematically strengthening the asperities in the modified fractal normal stress distribution:

- Exclusively large events nucleating from the scale of nucleation size corresponding to σ_{mean} (Figure 5b).
- Clusters of large events nucleating from smaller scales, even in the absence of small-scale events (Figure 7b) in intermediate models with sufficiently strong asperities.
- Both small-scale and large events nucleating from smaller scales (Figure 8b).

In this scenario, large events are small events that run away.

![Figure 8b: Slip velocity contours of a typical mainshock cycle.](image)

Interseismic period between mainshocks increases by the presence of small-scale events

The model with fractal distribution of normal stress has a lower recurrence time in comparison to the model with uniform normal stress distribution. The presence of small-scale events lengthens the interseismic period in the modified fractal model (Figure 9).

Conclusions

- Nucleation on interfaces with fractal distribution of normal stress, with a strength variation of ±600σ_{mean} is still similar to that of uniform normal stress case. Stronger heterogeneity is needed to reproduce microseismicity.
- As the heterogeneities become stronger, large earthquakes initiate from scales much smaller than the nucleation size estimates calculated for uniform interfaces with equivalent average properties.
- As the heterogeneities are made even stronger, small-scale events appear, complicating the nucleation process.

In this scenario, large events are small events that run away.

- With systematic variation in heterogeneity, we observe a continuum of behaviors ranging from purely fault-spanning events to persistent foreshock-like events interspersed between mainshock cycles.