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 questions fundamental to earthquake science.

- Do small and large earthquakes initiate similarly?
- How do local heterogeneities in frictional properties translate into patterns of stable and unstable fault slip?
- What model features result in foreshock-like events, i.e. smaller events that occur during the nucleation of larger events?

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.

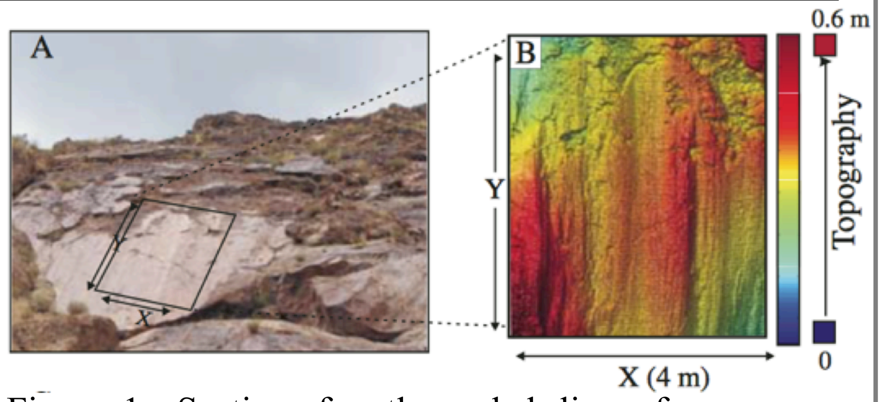


Figure 1a: Section of partly eroded slip surface on Dixie Valley fault. 1b: LIDAR of fault surface topography as a color-scale map [Figures from Sagy et al., 2007].

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 in the slow slip zone accompanying the slow nucleation phase, and preceding the experimental mainshock.

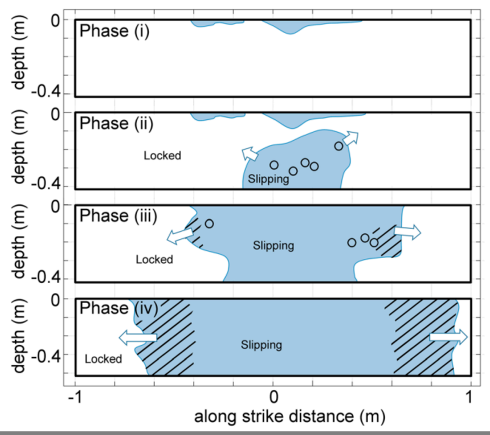
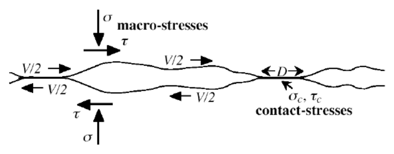


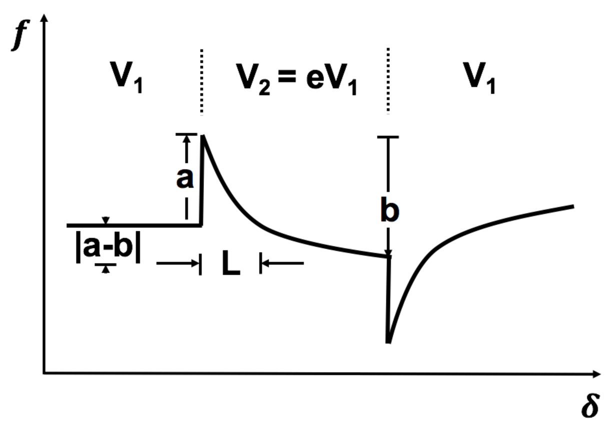
Figure 2a: Observation of nucleation from the experiments done by McLaskey and Kilgore [Figure from McLaskey and Kilgore (2013)]. The schematic shows the fault cross sections and the approximate locations of slipping regions and the expansion of the slipping front during nucleation. The small circles are observed foreshocks, swarms of small earthquakes that are seen to occur before the mainshock.
2b. Schematic of asperities on an interface.



Model and Simulation Process

Rate-and-state dependent friction model

$$\tau = \bar{\sigma} f = \bar{\sigma}\left[f_* + a\ln\frac{V}{V_*} + b\ln\frac{V\theta}{L}\right];\ \dot{\theta} = 1 - \frac{V\theta}{L}$$

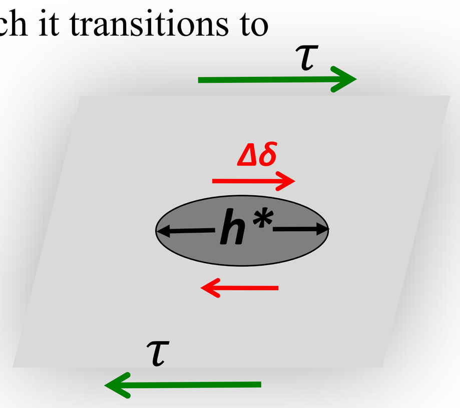


Nucleation size

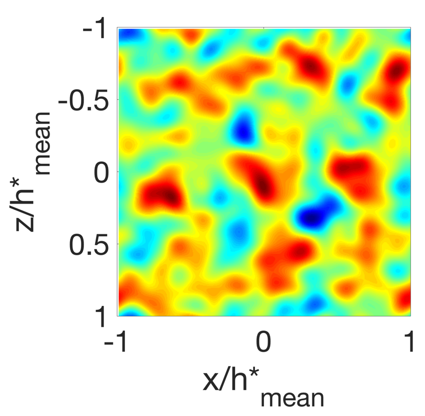
The minimum size of the stably slipping zone beyond which it transitions to inertially-controlled slip.

Nucleation size estimate for interface with uniform properties:

$$h^* = \frac{\pi}{2}\frac{\mu}{(\sigma - p)}\frac{bL}{(b-a)^2}$$



Fractal distributions used to realize heterogeneity in frictional properties



In roughness related studies, like *Brodsky et al.* (*2011*), fractal distributions are utilized to describe the self-similar nature of fault roughness. For modeling purposes, the distribution is generated by spatial random field modeling technique (*Mai and Beroza, 2011*).

Figure 3: A typical fractal distribution of normal stress used in the study, the domain is normalized with respect to the mean nucleation size estimate (h^*_{mean}) corresponding to σ_{mean}.

Representative Model Domain

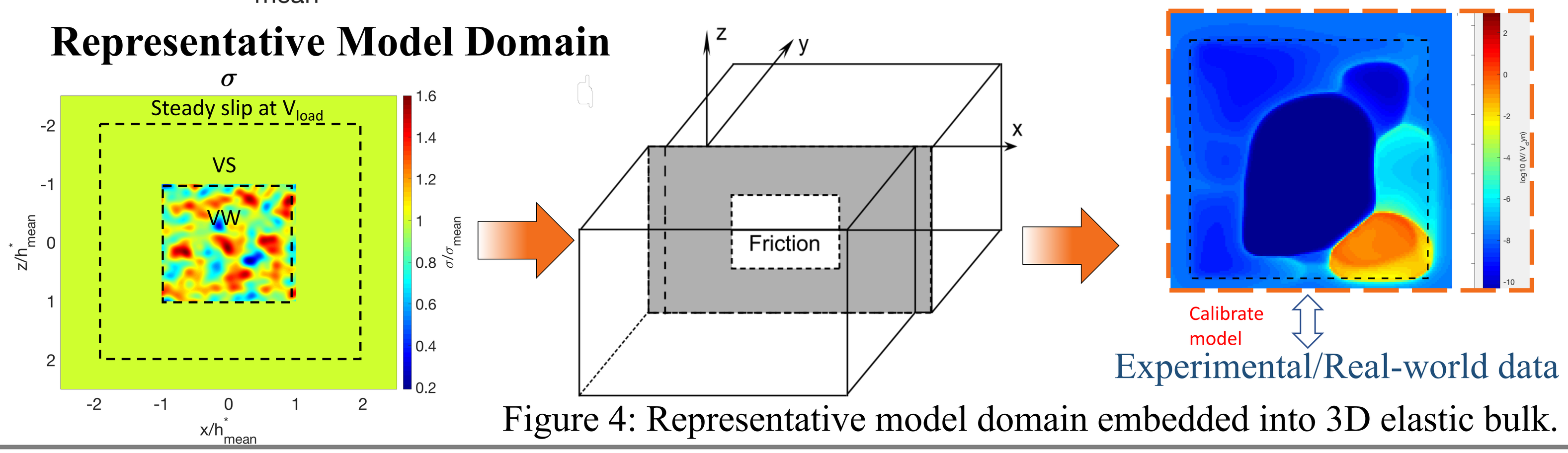
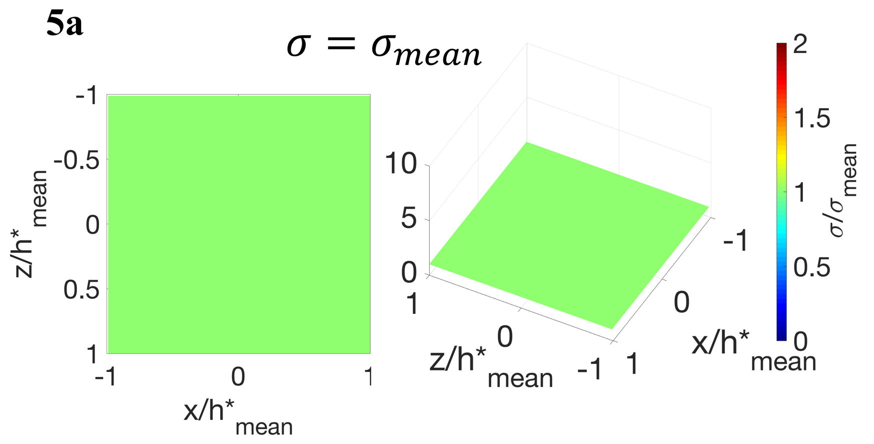


Figure 4: Representative model domain embedded into 3D elastic bulk.

Nucleation process on interfaces with heterogeneous normal stress distributions



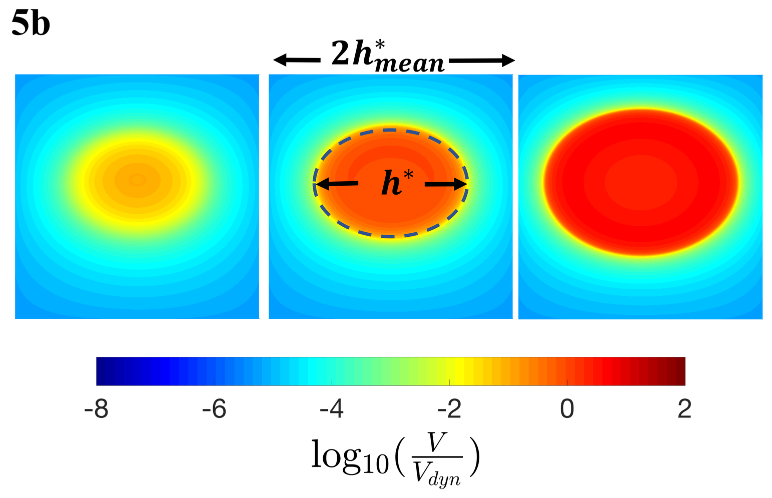
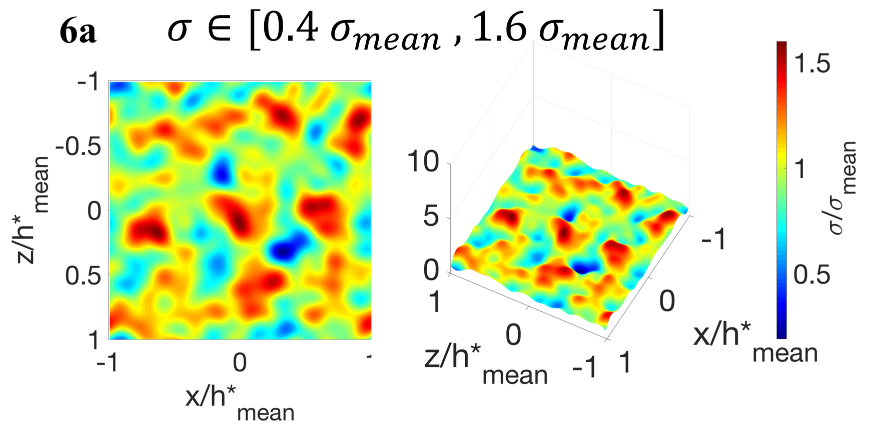


Figure 5a: 2D and 3D views of uniform normal stress distribution. 5b. Slip velocity contours on a fault interface (size ~ $2h^*_{mean}$) with uniform normal stress distribution of 5 MPa. The slip begins close to the center of the model, quasi-statically meanders within a localized zone, reaches a scale approximately equal to the nucleation size estimate, and thereafter, transitions to a dynamic slip event.



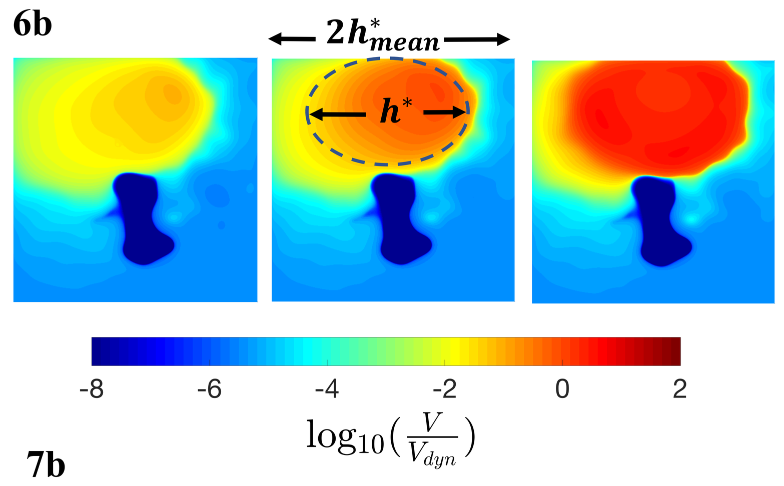
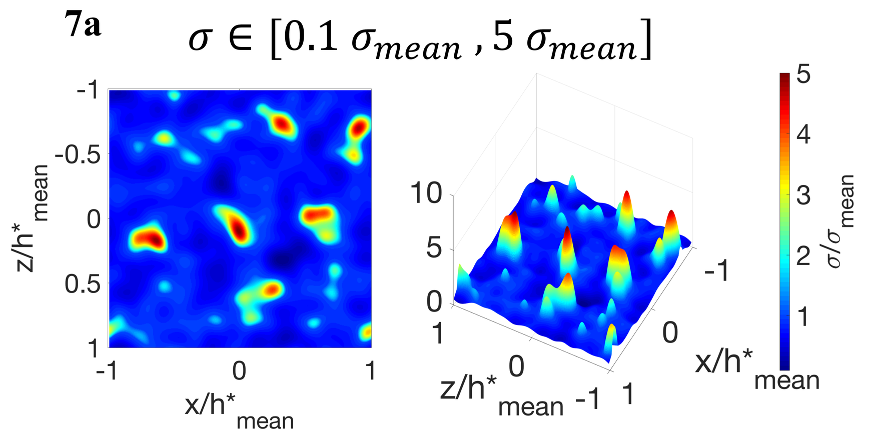
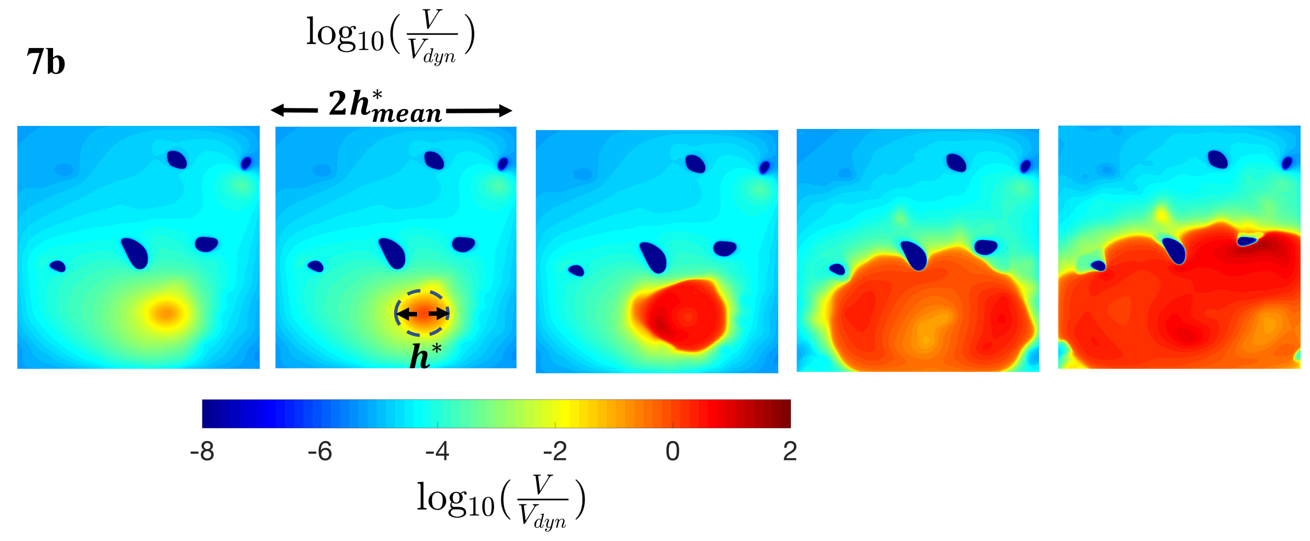
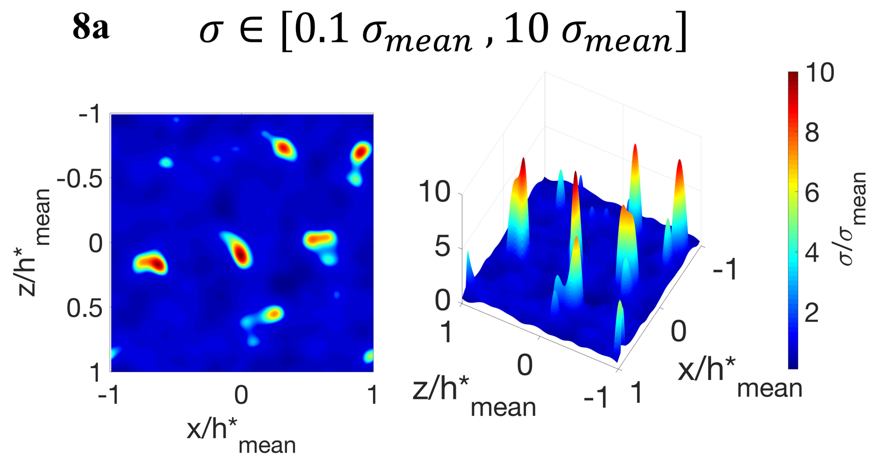


Figure 6a: 2D and 3D views of the fractal distribution of normal stress of amplitude $\pm 60\%\ \sigma_{mean}$, superimposed in the model. 6b. The nucleation behavior is more or less similar to the uniform case. Events nucleate from scales approximately equal to h^*_{mean} estimate, at different asperities.





7a. 2D and 3D views of the modified fractal distribution with $\sigma_{peak} = 5\ \sigma_{mean}$
7b. Slip velocity contours from the model. The mainshock is nucleating from a scale much lower than that of the nucleation size estimate, which is half the size of the panel.



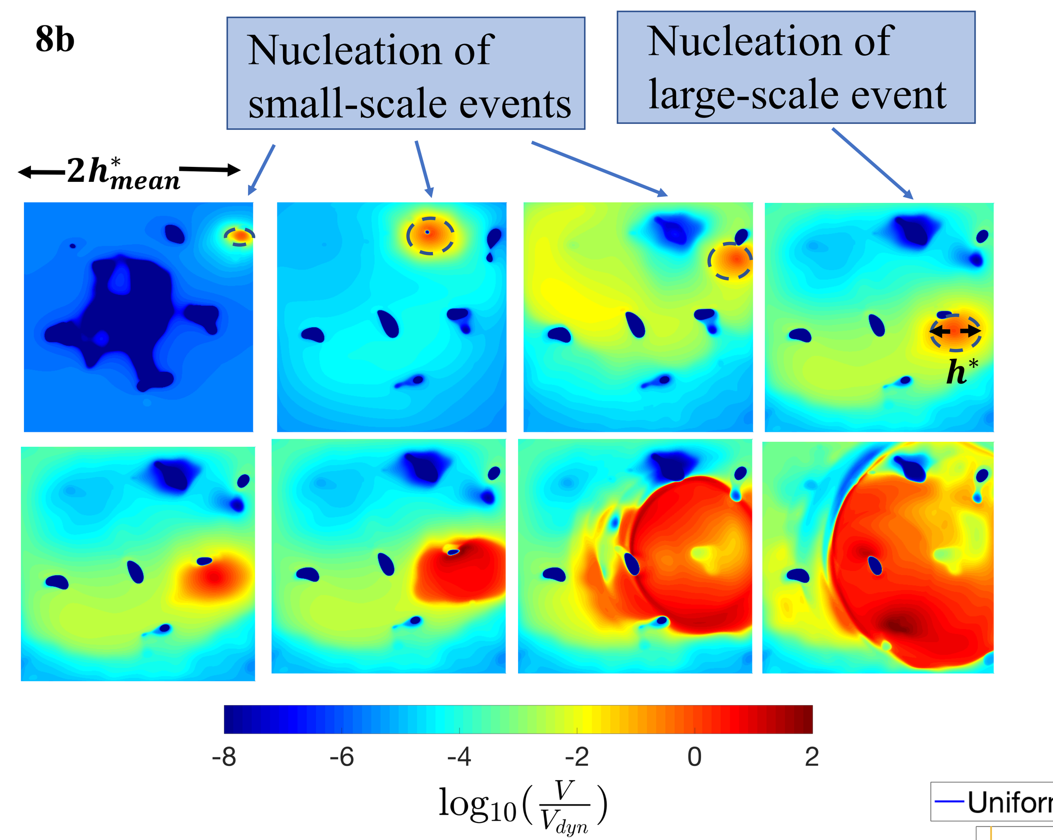


Figure 8a: Modifying the fractal distribution to obtain stronger heterogeneity and promote small-scale events. 2D and 3D views of the modified fractal distribution $\sigma_{peak} = 10\sigma_{mean}$.
8b. Slip velocity contours of a typical mainshock cycle.
The first three panels show the nucleation of small scale events at different asperities, and the fourth panel indicates the nucleation of the mainshock, which is initiating from a much smaller scale relative to the mean nucleation size estimate.

Large events are small events that run away

A continuum of behavior scenarios are observed on 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, 6b).
- Clusters of large events nucleating from small scales, even in the absence of small-scale events (Figure 7b) in intermediate models with sufficiently strong asperities.
- Both small-scale events and large events nucleating from smaller scales (Figure 8b). In this scenario, large events are small events that run away.

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 lengthen the interseismic period in the modified fractal model (Figure 9).

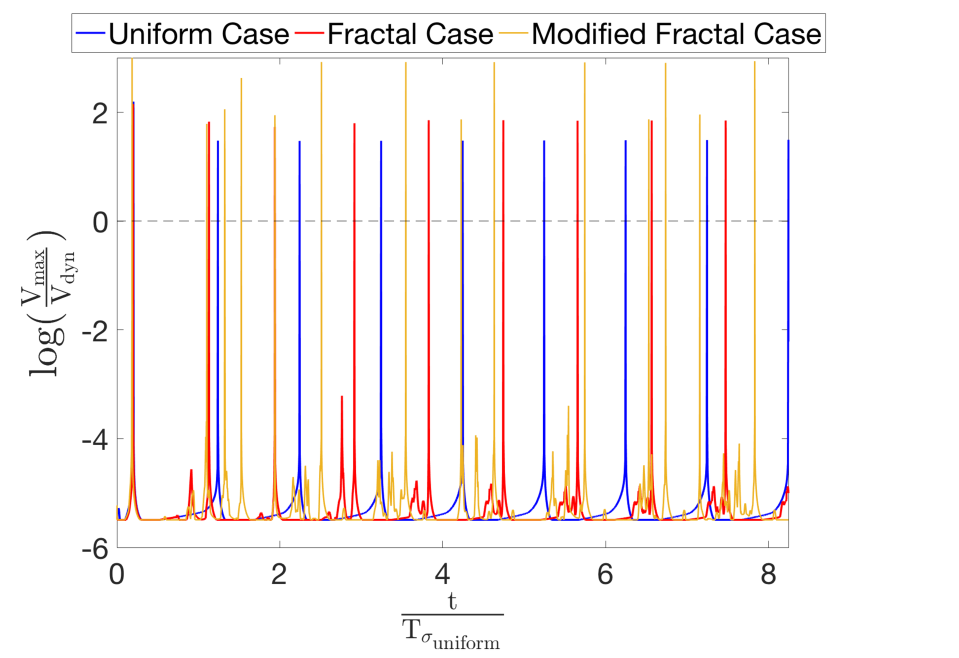


Figure 9: Comparing interseismic period between mainshocks across the uniform, fractal and modified fractal normal stress models.

Conclusions

- Nucleation on interfaces with fractal distribution of normal stress, with a strength variation of $\pm 60\%\ \sigma_{mean}$, 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.