The Role of Normal Stress and Stress Heterogeneity in the Inferred Depth-Independent Stress Drop

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10-Sec Summary:

Why does stress drop not observably increase with depth? Continuum model shows that stress heterogeneity increases when the fault size becomes much larger than the nucleation scale. Since the nucleation scale decreases with depth, the heterogeneity increases as well. For more heterogenous stress fields, the average stress drop decreases. As a result the stress drops at depth are less than expected for a uniformly stressed, single-degree-of-freedom system.

Abstract

Earthquake stress drops are inferred to be independent of their source depth, contradicting standard linear scaling predictions for frictional stick-slip models of earthquakes, assuming increasing fault normal stress due to rock overburden. Here, we examine the scaling between averaged stress drops and increasing normal stress for simulated earthquakes sequences in continuum rate-and-state fault models. Our models exhibit a power-law-like scaling that is weaker than the linearity predicted by traditional friction models. This result occurs as the fault dimension becomes increasingly larger than the earthquake nucleation scale with increasing normal stress. Consequently, the averaged behavior of ruptures becomes increasingly dominated by conditions for rupture propagation, reflecting more heterogeneous shear stress conditions. As natural faults can be considerably larger than the smallest earthquakes they host, such weaker scaling between averaged rupture conditions and normal stress may partially explain the lack of an inferred depth dependence of earthquake stress drops.

Motivation

Q: How can we reconcile this contradiction between theory and observation?

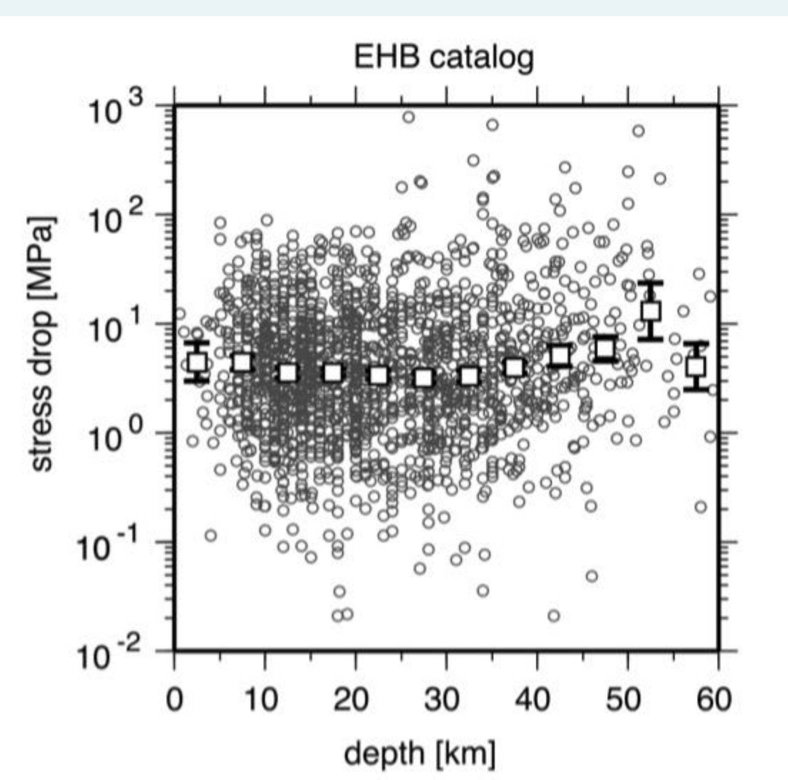
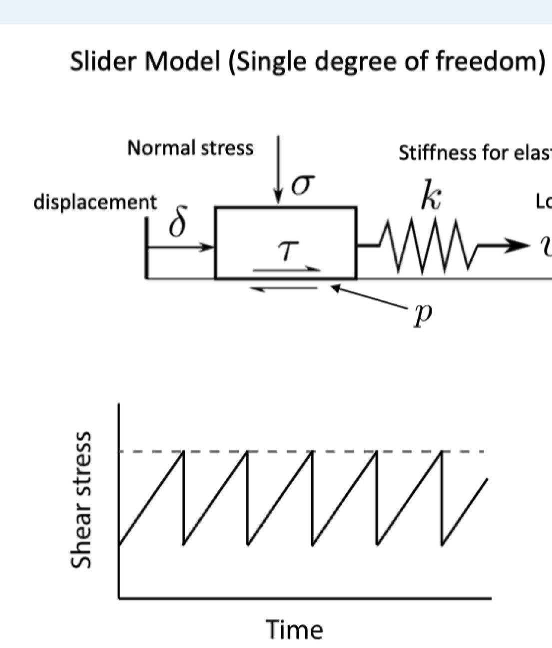


Fig 1. Seismological observation (Allmann & Shearer, 2009) suggests that stress drop is independent of depth.

Earthquake stress drop measured from the duration and amplitude of seismic waves is inferred to be depth-independent. Assuming normal stress increases with depth due to rock overburden, this suggests that stress drop is also independent of normal stress.



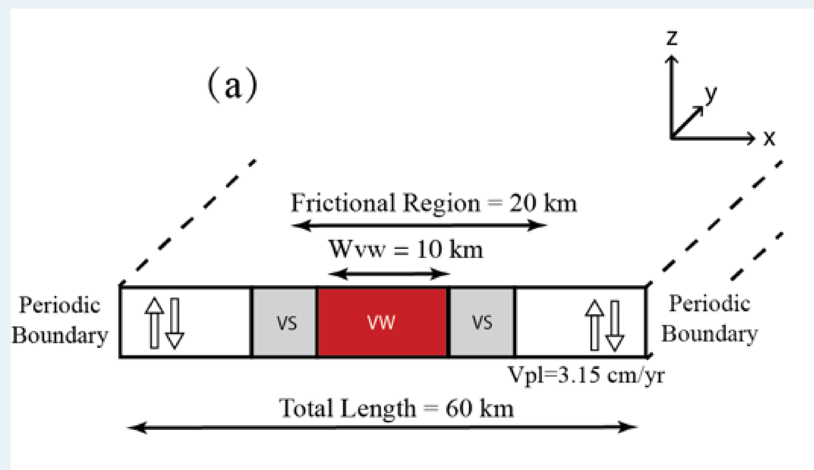
$$\tau = \mu\,\sigma_{eff}$$

$$\Delta\tau \propto \sigma_{eff}$$

However, this observation conflicts with classic conceptual models of earthquake ruptures as frictional sliding events. A fundamental property of Coulomb friction is that the shear stress is proportional to normal stress. As a result, changes in shear stress reflected in the earthquake stress drop are expected to be directly influenced by normal stress.

Fig 2. Conceptual model of earthquakes suggests that stress drop is proportional to normal stress.

Method



$$\tau = \mu\sigma$$

$$\mu = \mu_0 + a\,log\left(\frac{V}{V_0}\right) + b\,log\left(\frac{\theta V_0}{D_c}\right)$$

$$\frac{d\theta}{dt} = 1 - \frac{\theta V}{D_c}$$

Fig 3. Model setups.

We employed the numerical methodology of Lapusta et al. (2000) to simulate all stages of earthquake sequences, including spontaneous earthquake nucleation, rupture propagation, postseismic deformation, and interseismic loading. We consider a one-dimensional (1D) fault embedded in a two-dimensional (2D) uniform and isotropic elastic medium (Fig. 3) loaded with a long-term tectonic loading rate. The fault is governed by the standard Dieterich-Ruina rate-and-state friction law, with the frictional state evolution governed by the aging law. We keep all parameters fixed except for increasing normal stress. We then examine the scaling relationship between averaged stress drop and normal stress.

Results

Increasing Complexity in Earthquake Sequence

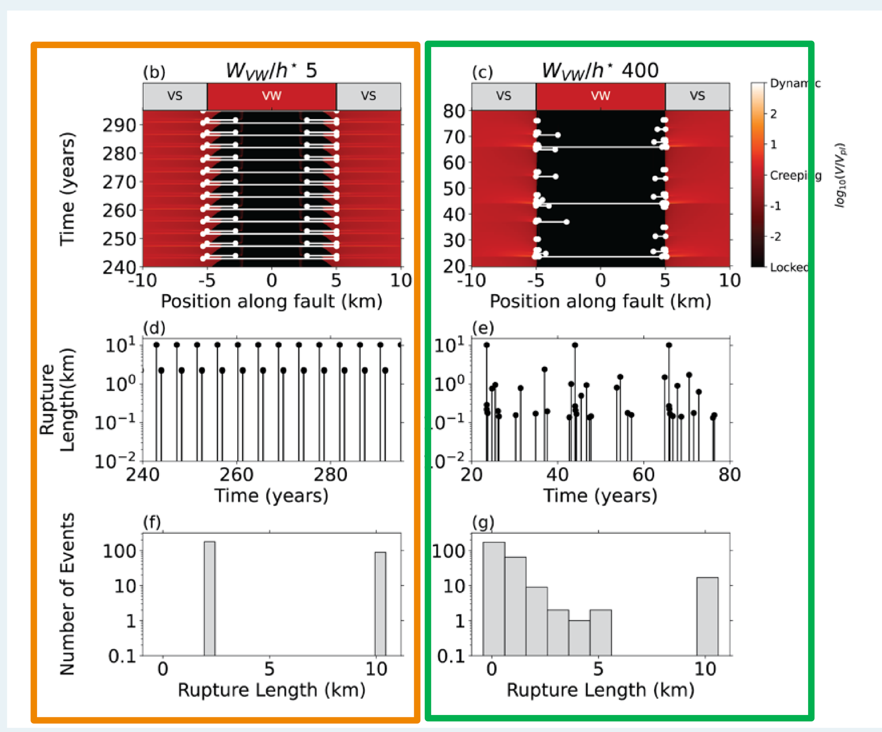


Fig 4. Simulated earthquake sequences.

	Left	Right
Normal Stress	Low	High
Nucleation Scale	Large	Small
Sequence	Simple	Complex
Magnitude Distribution	Simple	Power Law (GR)

High normal stress
- ➢ Complex event sequence

Increasing Heterogeneity in Prestress Conditions

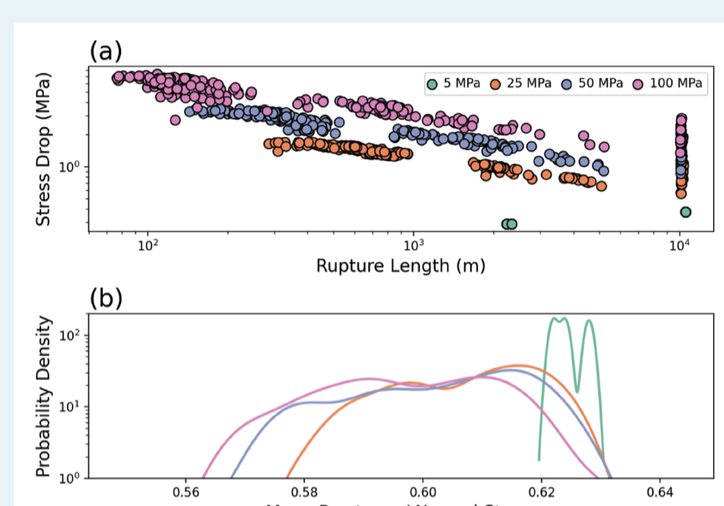
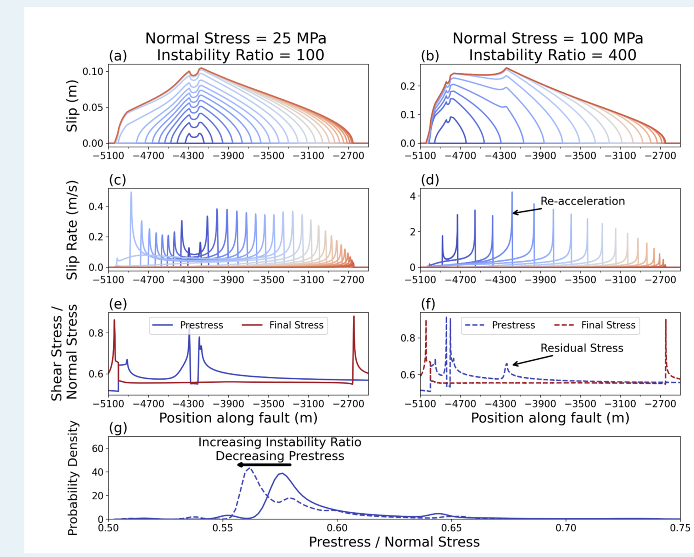


Fig 5. (a) Stress drop from models with increasing normal stress. (b) PDF of prestress conditions.

Fig 5 (a) Average stress drops for ruptures with varying rupture lengths for models with increasing normal stress and instability ratio. (b) Distribution of averaged rupture prestress normalized by fault normal stress across ruptures in each fault model, illustrating a wider range of average prestress conditions taking part in simulated ruptures for models with increasing normal stress and instability ratio.

High normal stress
- ➢ Complex event sequence
- ➢ Redistributed shear stress
- ➢ Heterogeneous shear stress field

Prestress Heterogeneity Facilitates Rupture Propagation into Low Prestress Regions



High normal stress
- ➢ Complex event sequence
- ➢ Redistributed shear stress field
- ➢ Heterogeneous prestress conditions
- ➢ Heterogeneity helps rupture propagate into low-stress regions
- ➢ Lower stress drop than the expectation from the linear scaling relation

Fig 6. Example events show that residual stress help rupture propagate into low stress regions.

Stress Drop Scales with Normal Stress Following Sublinear Power Law

In our models, stress drop follows a sublinear power-law with increasing normal stress, which is weaker than the linear scaling relation:

$$\Delta\tau \propto \sigma^{\zeta}$$
$$\zeta < 1$$

A sublinear power-law further predicts that the dependence of stress drop on normal stress, defined as the derivative of stress drop with respect to normal stress, asymptotically approaches zero as the fault scale becomes much larger than the nucleation scale:

$$\frac{\Delta\tau}{\sigma} \propto \sigma^{\zeta-1} \to 0$$

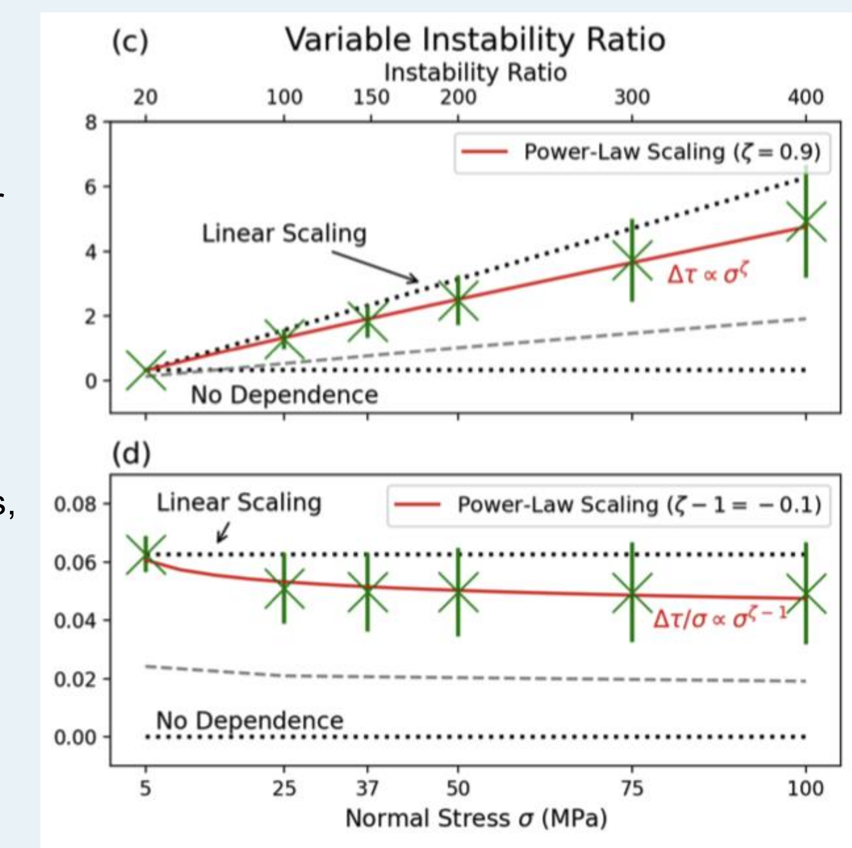


Fig. 7 The scaling relationship between stress drop and normal stress.

Take-aways

- As the increase of normal stress, the nucleation scale decreases, leading to complex earthquake sequences and hence heterogeneous prestress conditions.
- The spontaneous evolved heterogeneity of prestress condition is in favor of rupture propagation into low stress regions.
- As earthquakes grow larger than their nucleation size and their averaged behavior is increasingly dominated by heterogeneous prestress conditions for rupture propagation.
- As a result, in continuum model, averaged stress drop follows a sublinear power-law scaling with normal stress, which predicts that the dependence of stress drop on normal stress asymptotically approaches zero as fault length becomes much larger than its nucleation scale.

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