Testing earthquakes nucleation models from the response of Himalayan seismicity to secular and periodic stress variations

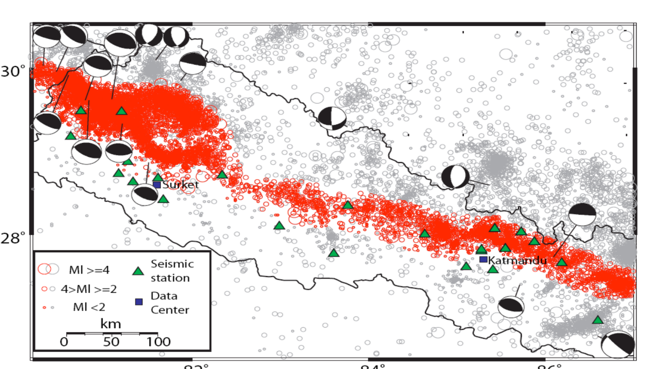
Thomas Ader , Nadia Lapusta, Jean-Philippe Avouac

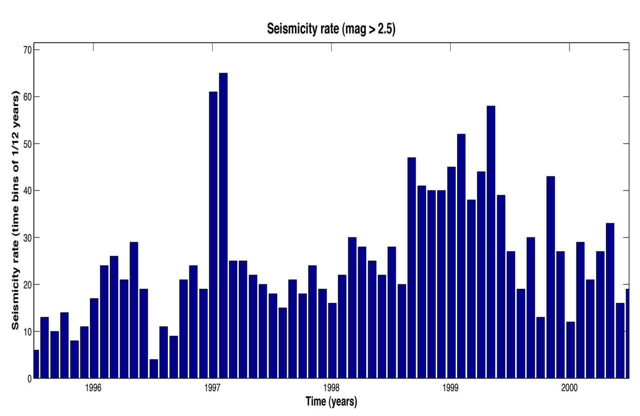
Department of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125

Abstract

We analyze the relationship between seismicity and temporal stress variations in the Himalaya to constrain earthquake nucleation process. In addition to the secular stress load induced by crustal shortening across the range, the Himalayan arc is also submited to 2 periodic stress variations of comparable ~3 kPa amplitudes but different periods: 12.4 hours period variations are induced by earthtides while 1-year period variations are induced by surface load variations associated with the seasonal hydrological cycle. The seismicity shows no apparent correlation with earthtides, but seasonal prominent seasonal variations. These observations are used to test models of earthquake nucleation. Both Coulomb and Dieterich model fail at explaining the relative correlations to tides and seasonal variations, but a more realistic finite fault model seems able to reproduce the observations.

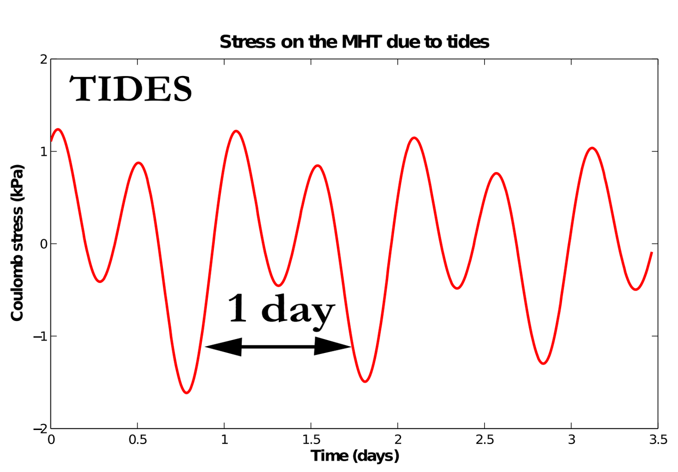
1. Seasonal variations of seismicity

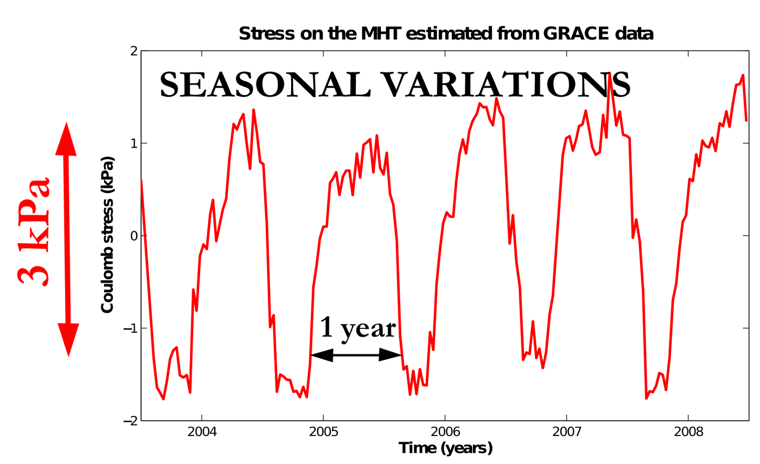




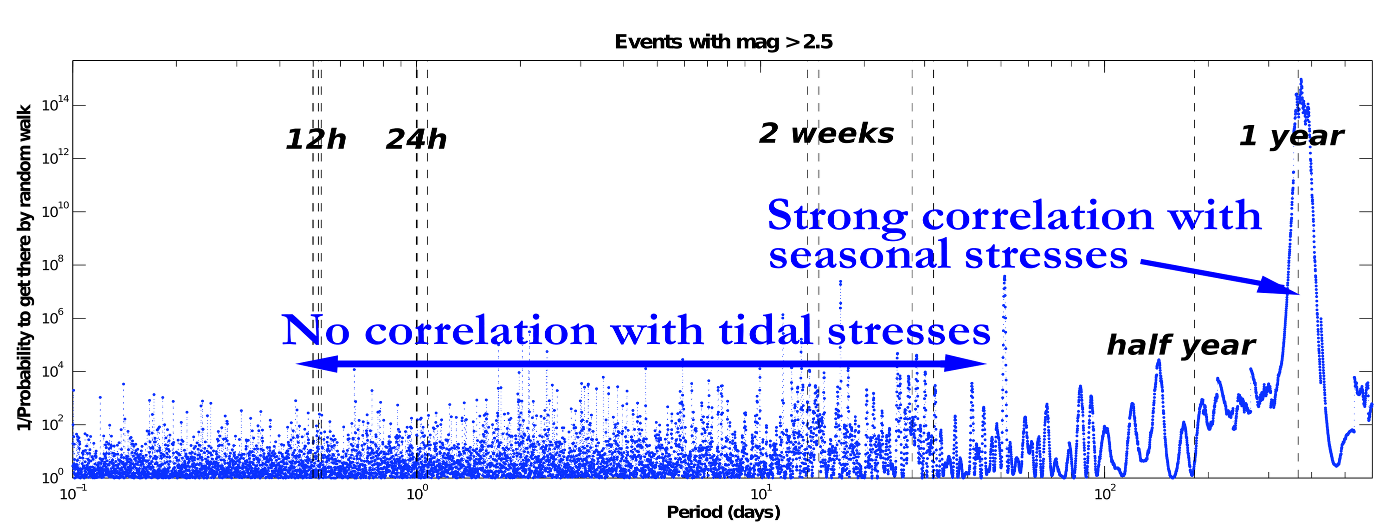
Left: Seismicity of Nepal (from Bollinger et al.). Earthquakes in red are the ones used in this study. **Right:** Seismicity rate. The rate is about 30% higher in the Winter than in the Summer.

Periodic stresses on the MHT





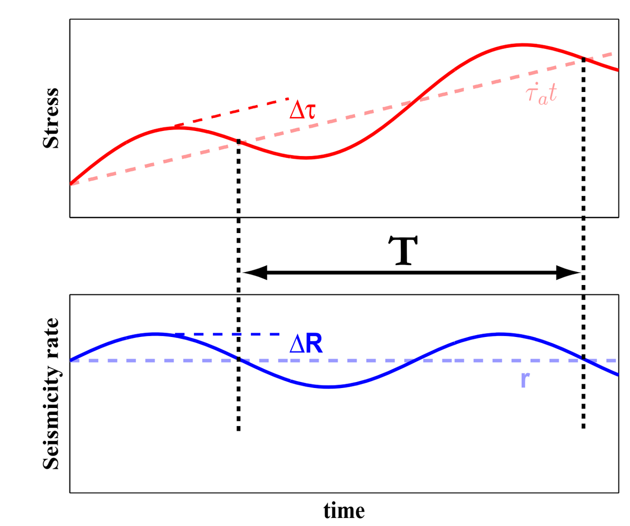
Correlation stress-seismicity



Schuster spectrum for the seismicity catalog, measuring the probability of different periodicities in the earthquake catalog's times of events. The vertical dashed black lines show the different periodicities of tides, the half-year and year period.

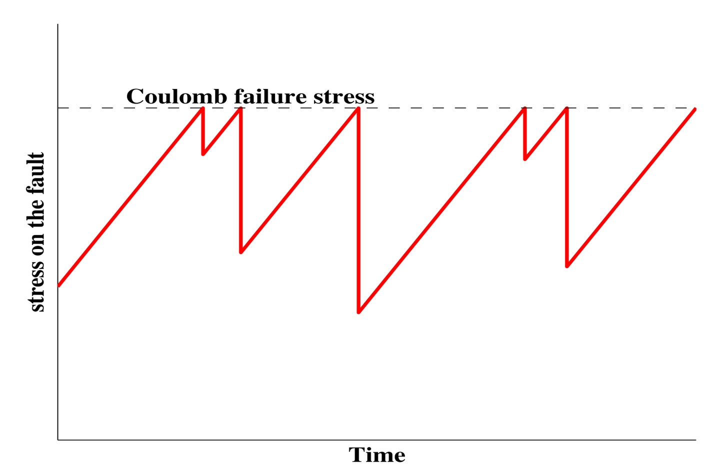
2. Models

We want to model the relationship between harmonic perturbations of stress and the response of seismicity. We analyze 3 models of increasing complexity: the Coulomb failure model, Dieterich (1994) model and a finite fault model. Hereafter, a fault undergoing a constant stress rate $\dot{\tau}_a$ has a constant seismicity rate r, and harmonic stress perturbations of amplitude Δτ and period T generate variations of the seismicity rate of amplitude ΔR, as shown on the opposite cartoon.



2.1 Coulomb failure model

The faults rupture when they reach the Coulomb failure stress:

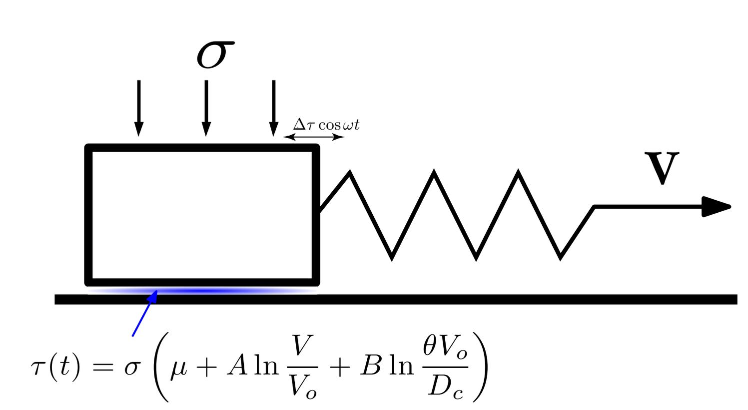


$$\frac{\Delta R}{r} = \frac{\dot{\Delta\tau}}{\dot{\tau_a}} \quad (1)$$

Cartoon showing the possible stress on a fault following a Coulomb failure model under constant stressing rate. The seismicity rate is directly proportional to the stress rate. Quantities in equation (1) are indicated in the figure at the top of the column.

2.2 Dieterich (1994) model

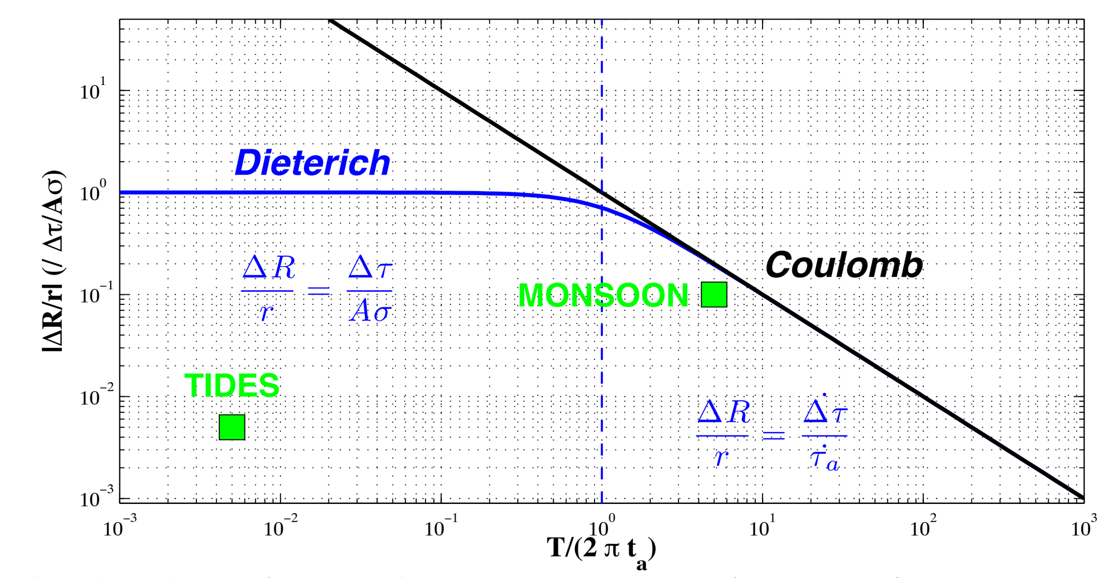
Spring-slider system with a rate and state law: fixed nucleation size.

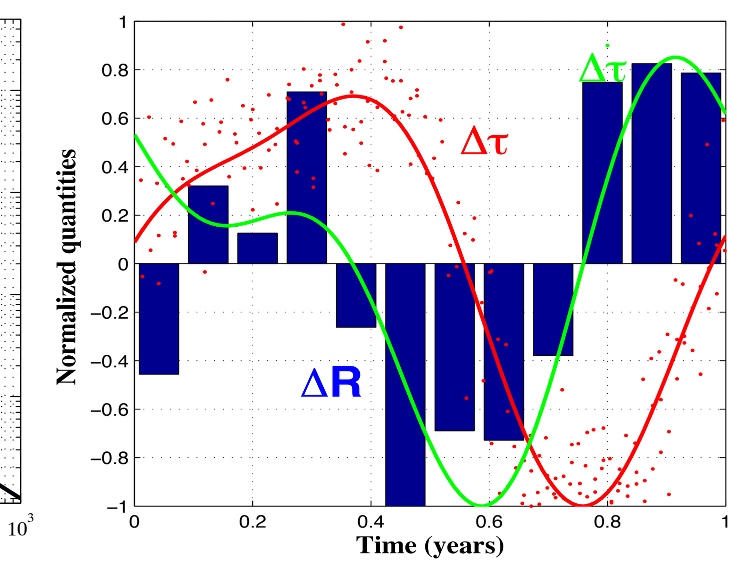


$$\tau(t) = \sigma\left(\mu + A\ln\frac{V}{V_o} + B\ln\frac{\theta V_o}{D_c}\right)$$

$$t_a = \frac{A\sigma}{\dot{\tau_a}} \qquad \frac{\Delta R}{r} = \frac{\Delta\tau}{\dot{\tau_a}}\frac{1}{t_a - iT/(2\pi)} \quad (2)$$

Cartoon showing the main assumptions behing Dieterich model and equation giving seismicity rate variations under the combination of a constant stressing rate and a harmonic perturbation. Quantities in equation (2) are indicated in the figure at the top of the column.

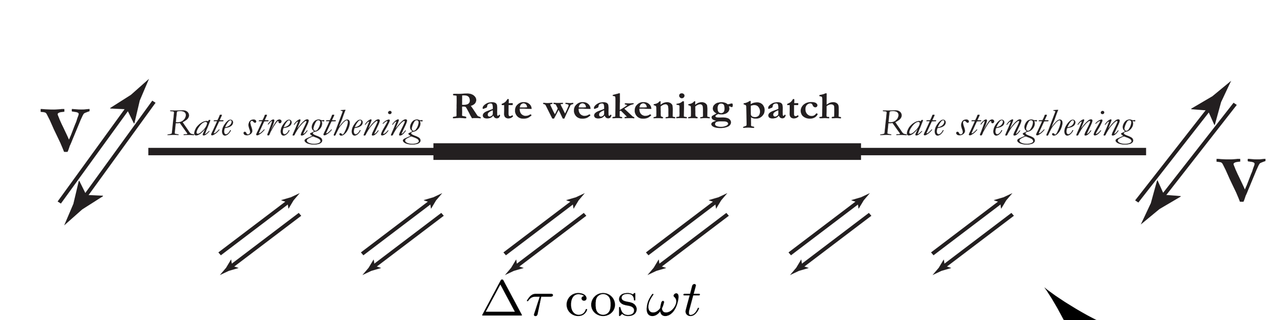




Left: Correlation between harmonic stress perturbations and seismicity rate perturbation according to Coulomb and Dieterich models (equations (1) and (2)). Both models converge at large periods whereas at short periods, Dieterich model displays a correlation of the seismicity rate with the stress perturbation itself rather than the stress rate perturbation. The observations are qualitatively reported in green. The correlation of the seismicity with the seasonal variations seems to follow a Coulomb model, while the correlation with tides is too small to be observed. **Right:** Comparative plot of the seismicity rate variations, stress variations and stress rate variations on the MHT underneath Nepal stacked over 1 year. The seismicity rate apparently correlates with the stress rate variations.

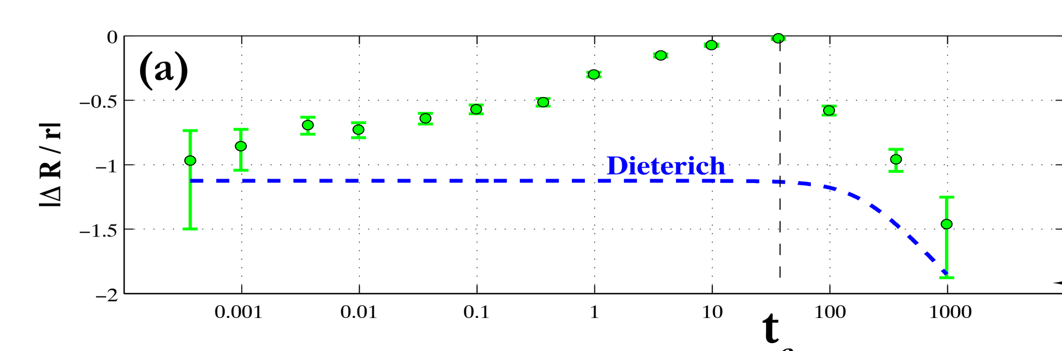
None of those models explain the relative correlation to the tides and the monsoon.

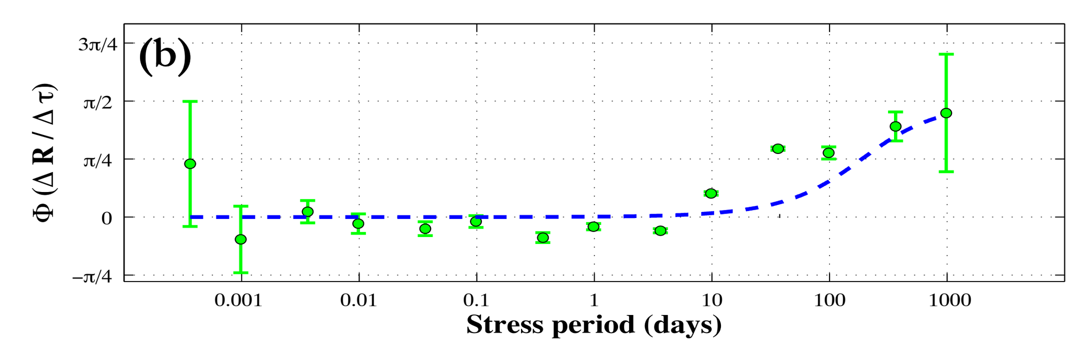
2.3 Finite fault model



V = 1cm/yr
A = 0.008
B = 0.012
σ = 5 MPa
Δτ = 3kPa
D_c = 5μm
$\dot{\tau}_a$ = 300 kPa/yr

Top: Fault used for the simulations. The fault consists of a rate weakening patch embedded within a rate stengthening medium. On the edges, the fault slips at a constant rate **V**, and the whole fault undergoes harmonic stress perturbations Δτ cosωt. The values of fault parameters are indicated to the right of the cartoon.





Left: (a) Amplitude of the seismicity rate variations and **(b)** phase between the stress perturbations and the seismicity variations from the simulation. For comparison, the predictions of the Dieterich model are indicated as a dashed blue line. The phase agrees fairly well with the predictions of the Dieterich model, suggesting that seismicity correlates with stress perturbations at short periods and with stress rate perturbations at large periods. However, Dieterich model underpredicts the amplitude of the correlation. The finite fault model seems to reproduce the decreasing correlation of seismicity with decreasing stress perturbation periods, as we seem to observe in Nepal.

Conclusion

The finite fault modeling is the only one able to successfully reproduce a decreasing correlation of the seismicity rate with the harmonic stress perturbation at short periods. This suggests that the sensitivity to small stress variations is enhanced by the fact the creep on the fault varies spatially. More work still has to be undertaken in order to asssess more quantitatively how the seismicity rate responds to stress variations.