Response of rate-and-state faults to periodic variations

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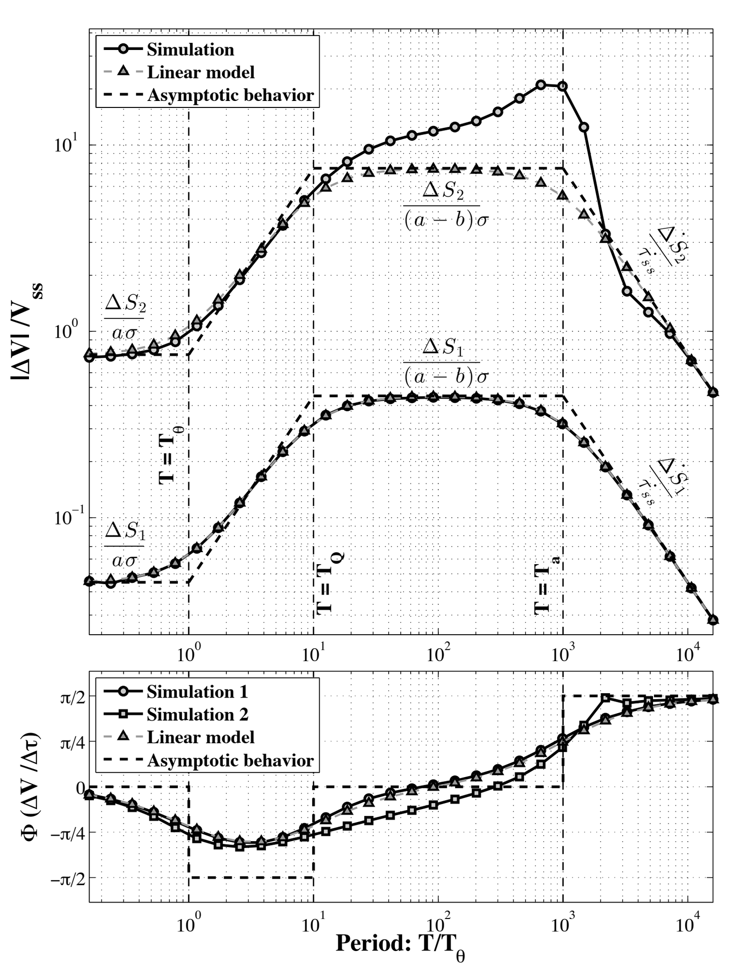
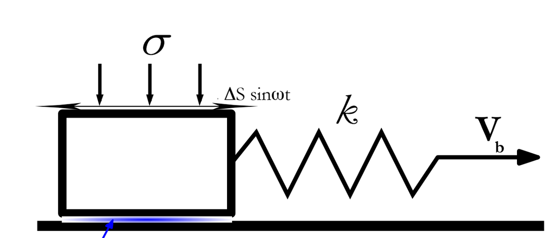
Abstract

Periodic loading has been reported to induce a detectable response on both seismic and aseismic faults. Slow slip events and associated non-volcanic tremor in Cascadia, Japan and Parkfield are sensitive to oscillatory stress perturbations induced by tides or seismic surface waves. On the seismic side, the microseismicity rate in the Nepal Himalaya appears to be modulated by the surface load variations of about 3kPa induced by the hydrological cycle, while no correlation is observed with solid Earth tides, although they induce stress variations of comparable amplitude. Such a decrease of sensitivity to periodic loads with decreasing period has also been observed in lab experiments. In the case of non-volcanic tremors, we show through analytical approximations and numerical simulations of the reponse of 1degree of freedom spring-slider system that rate strengthening fault areas that are near velocity neutral at steady-state, i.e. $\partial\mu/\partial \ln V \approx 0$, are highly sensitive to periodic loading within a certain range of periods, which depends on the frictional properties. These aseismic periodic transients can in turn induce a periodic modulation of the tremor activity. To assess the conditions needed to explain the Himalayan seismicity observations, we consider velocity weakening faults. We find that the behavior of a simple 1D spring-slider system cannot explain the lower sensitivity to semi-diurnal than to annual load variations. We suggest that, in that case, the finite dimension of faults plays a key role. To support this idea, we simulate the response of a finite size fault obeying rate-and-state friction, using the Boundary Integral CYCLe of Earthquakes (BICYCLE) code. These simulations yield a period dependent response to periodic stress variations alike that observed in Nepal and in lab experiments.

1 Rate-strengthening faults: sensitivity of non-volcanic tremors

Response of a spring-slider with rate-strengthening friction to a harmonic Coulomb stress perturbation:



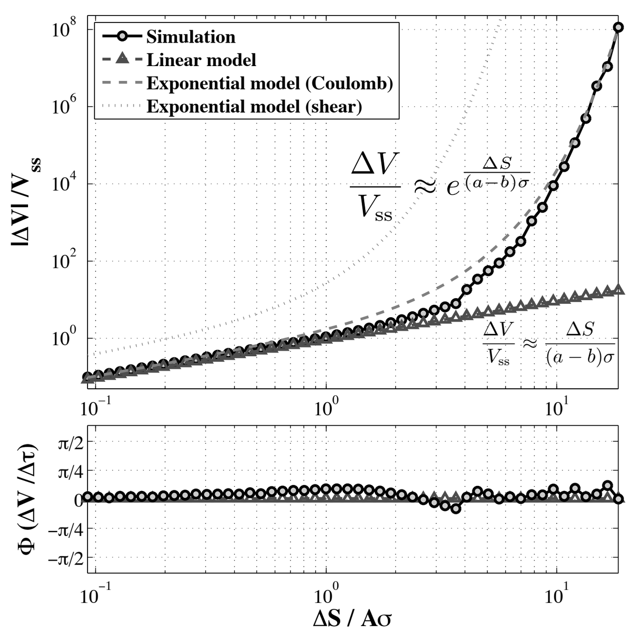


$$\tau(t) = \sigma\left(\mu + A\ln\frac{V}{V_0} + B\ln\frac{\theta V_0}{D_c}\right) \quad A > B$$

Response of a spring-slider system to small harmonic Coulomb stress perturbations of different periods and amplitudes $\Delta S_1 = 0.9$ kPa and $\Delta S_2 = 15$ kPa. The system is undergoing constant loading at velocity $V_{ss} = 0.02$ m/yr under mean normal stress $\sigma = 5$MPa. The normalized spring stiffness is $k/\sigma = 0.002$ m^{-1}. The other parameters are: $\mu_{ss} = 0.7$, $a = 0.004$, $b = 0.0036$ and $D_c = 0.2$ mm. Upper panel: Amplitude of the creep rate variations. The black lines with circles represents the results of the simulations (one circle for each period tested). The dashed grey lines with triangles represent the small perturbation approximation for each simulation while the dashed black lines indicate the corresponding asymptotic behavior of the system with equations indicated on the plot. The critical periods T_θ, T_Q and T_a are also indicated on the plot. Lower panel: Phase difference between the creep rate and the Coulomb stress variations.

$$T_\theta = 2\pi\theta_{ss} = 2\pi\frac{D_c}{V_{ss}} \qquad T_Q = \frac{a}{a-b}T_\theta$$

$$T_a = \frac{(a-b)\sigma}{kD_c}T_\theta$$



Non linear response of a spring-slider system to small harmonic stress perturbations for different amplitudes. The period T of the perturbation is such that $T/T_Q = T_a/T = 2.5$. The parameters are the same as in the previous figure, except for the fault parameter $b = 0.00385$ and $D_c = 0.5$ mm, so that $A = |A(\omega)| = 1.08(a\text{-}b) \approx (a\text{-}b)$. The meaning of the different lines is given in the legend. Upper panel: Amplitude of the creep rate variations. The expression for the exponential models is indicated in the figure, taking either the Coulomb stress or only the shear stress, and replacing $(a\text{-}b)$ by the actual value of A. The linear approximation is also indicated on the plot. The lower panel shows the phase difference between the creep rate and the Coulomb stress variations.

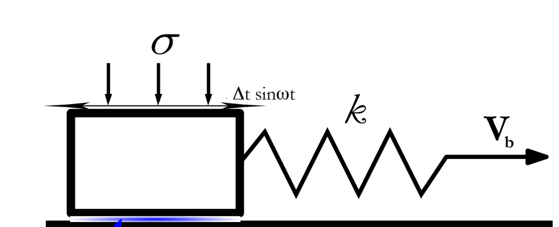
For velocity neutral faults ($a\text{-}b \approx 0$), amplification possible of the perturbation for the right range of periods. Possible explanation for the sensitivity of non-volcanic tremors to tides and passing seismic waves without resorting to extremely low normal stresses.

2 Rate-weakening faults: sensitivity of earthquakes

Dieterich (1994) model

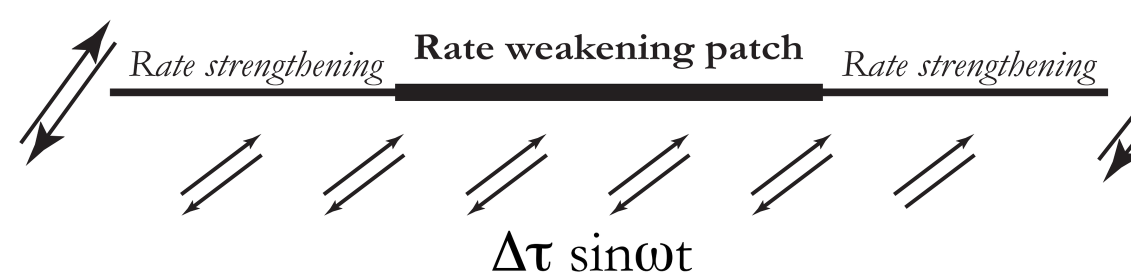
Spring-slider system under rate-weakening rheology. Only the timings of seismic events are modified.

$$\frac{\Delta R}{r} = \frac{\dot{\Delta\tau}}{\dot{\tau_a}}\frac{1}{t_a - i/\omega} \qquad \dot{\tau_a} = kV_b \qquad t_a = \frac{A\sigma}{\dot{\tau_a}}$$

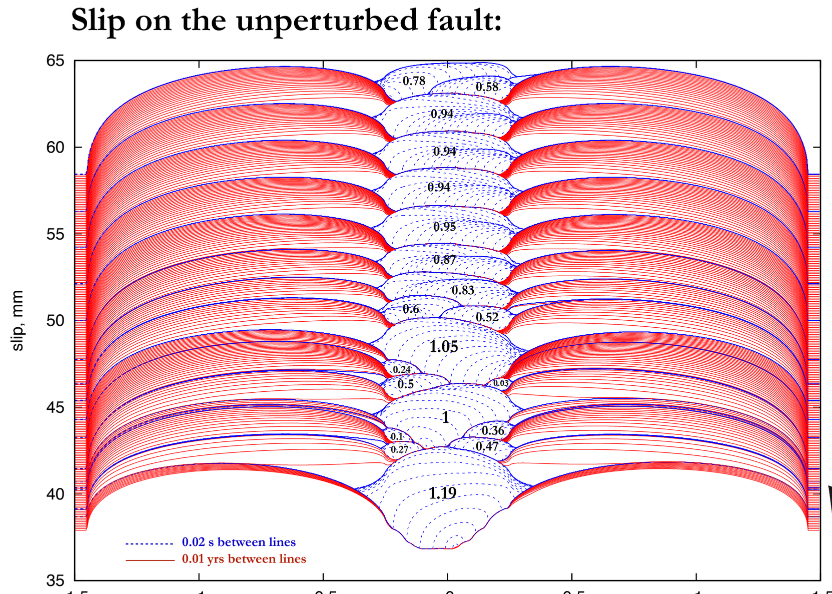


$$\tau(t) = \sigma\left(\mu + A\ln\frac{V}{V_0} + B\ln\frac{\theta V_0}{D_c}\right) \quad A < B$$

Finite fault model (BICYCLE)

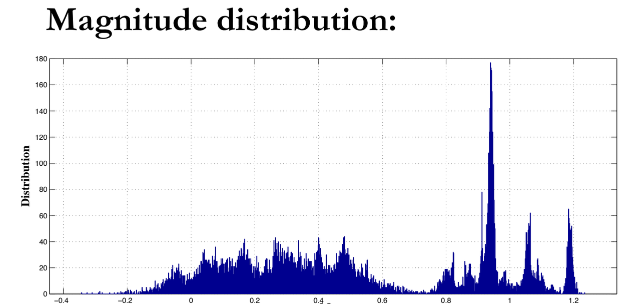


Slip on the unperturbed fault:

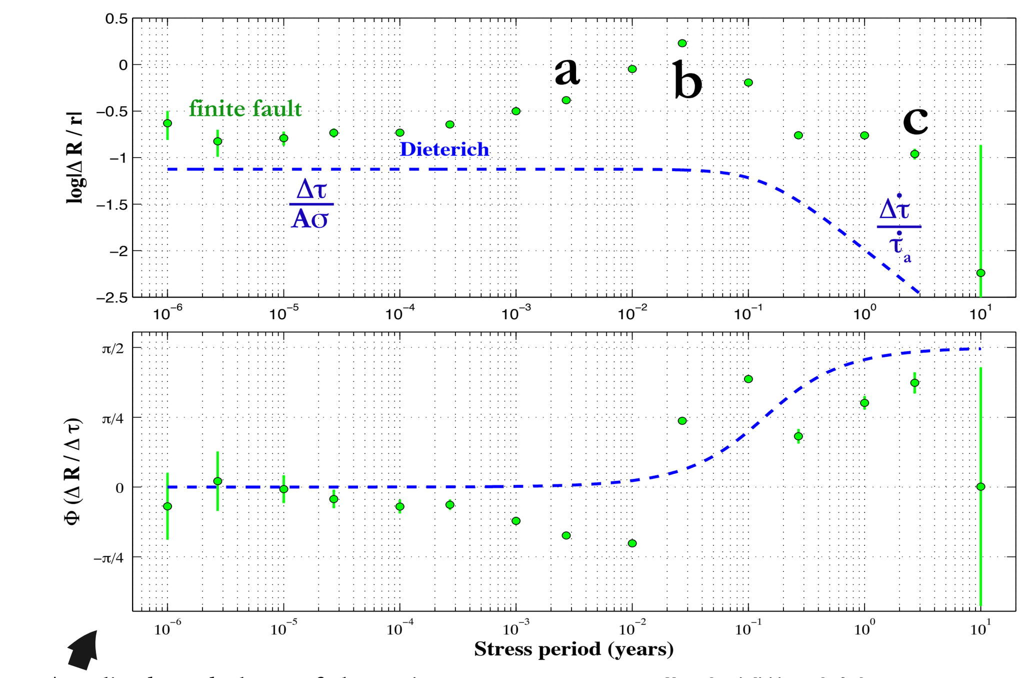


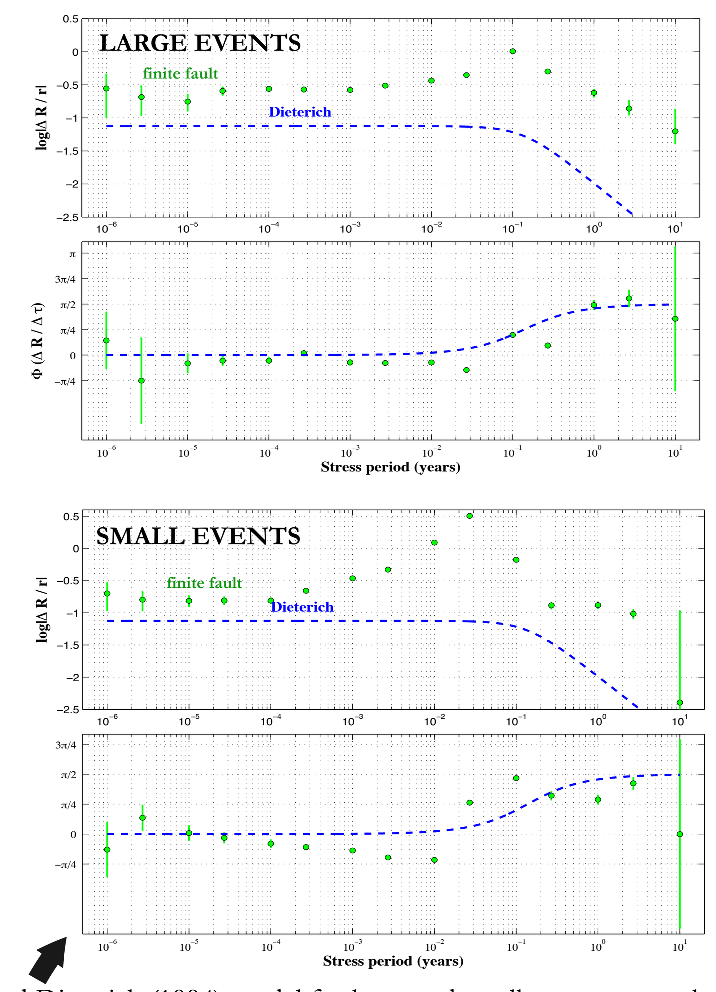
Slip on the fault, with magnitude of events indicated on each event.

Magnitude distribution:

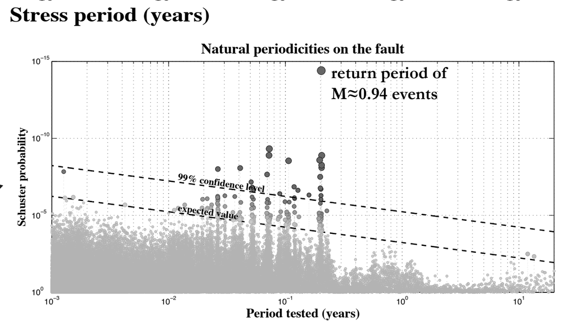


Magnitude distribution of events happening on an unperturbed fault. The fault naturally has some complexity, but most of the events are $M \approx 0.94$.





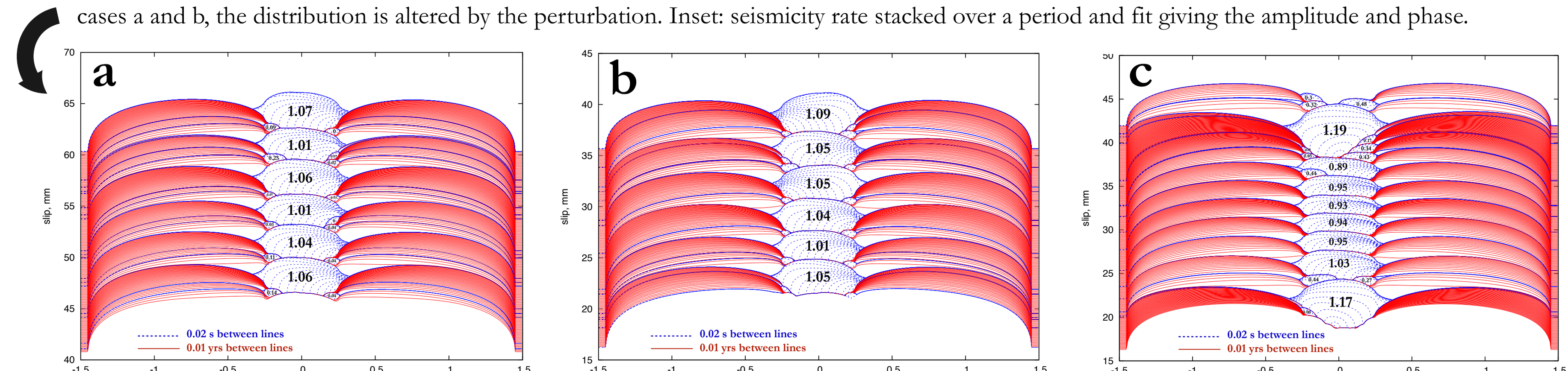
Amplitude and phase of the variations of seismicity rate from finite faults simulations and Dieterich (1994) model.

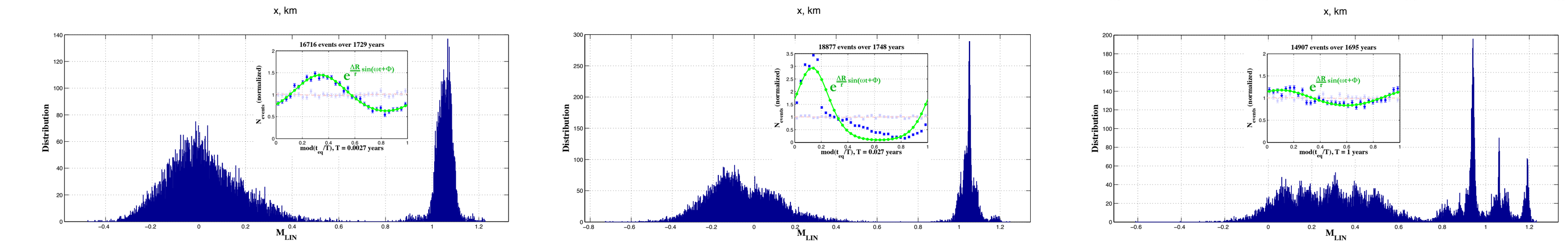


Spectrum indicating the natural periodicities in the timing of events on the unperturbed fault.

Amplitude and phase of the variations of seismicity rate from finite faults simulations and Dieterich (1994) model for large and small events separatly.

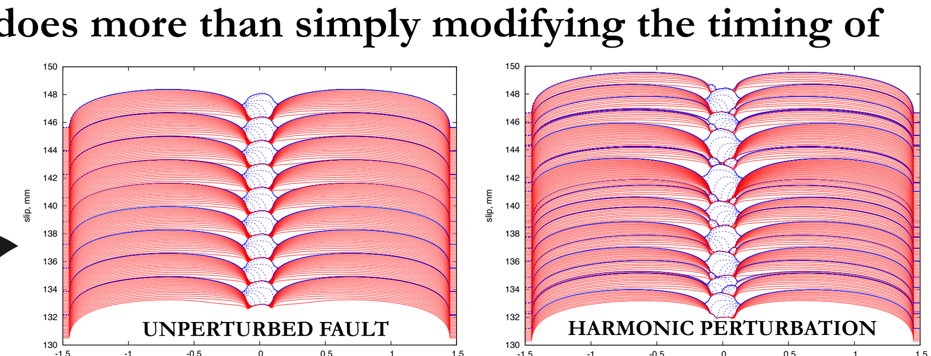
Details for 3 perturbed cases, indicated on the plot above. Upper plot: history of slip on the fault. In the cases a and b, the perturbation causes the fault to have a steady behavior made of large $M \approx 1.05$ events, followed by 2 to 4 small events. Lower plot: Distribution of magnitudes for each case. In the cases a and b, the distribution is altered by the perturbation. Inset: seismicity rate stacked over a period and fit giving the amplitude and phase.





In the finite fault model, the perturbation does more than simply modifying the timing of events, it actually impacts on the population of events that the fault produces. It can both stabilize the fault (above case) or create complexity (case to the right).

Behavior of a fault with a smaller rate-weakening patch, unperturbed, and under a harmonic perturbation of period T = 0.02 yrs.



Conclusion

For a rate-strengthening rheology, a simple spring slider system shows that under velocity neutral conditions, a harmonic perturbation falling within the right range of periods can be amplified and result in large creep rate variations on the fault. This could explain the observed correlation of non-volcanic tremors with tides or passing seismic waves. For a rate-weakening patch, a finite fault model predicts a much higher sensitivity of the seismicity to stress perturbations than a simple spring-slider system would. This comes from the effect that a stress perturbation can have on the nucleation zone.