Transient Fault Slip in the framework of rate-and-state and Frenkel-Kontorova models

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Rate-and-state model

Formulation:

Frictional strength $\tau = \sigma\left[f^* + a\ln(\frac{V}{V^*}) + b\ln(\frac{V^*\theta}{D_c})\right]$ with slip law: $\frac{\partial\theta}{\partial t} = -\frac{V\theta}{D_c}\ln(\frac{V\theta}{D_c})$

Slow slip occurs in a velocity-weakening region (a<b) characterized by high pore pressure and along-dip size W, located at intermediate depth between the locked seismogenic zone and the deeper stable zone. The fault is loaded by steady creep at depth.

Adjustable parameters:

1) the ratio of frictional viscosity to frictional weakening (a/b),

2) the ratio of along-dip size of the slow-slip zone to a characteristic nucleation length, W/h* where h*=μ/(σ(b-a)) D_c and

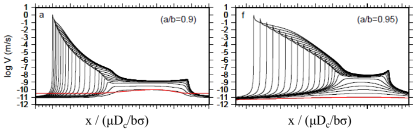
3) the ratio of effective normal stress to shear modulus, aσ/μ

Limitations:

"The friction law is described at a **point on the surface** … the **state at one point is unaffected by the state at other points** on the surface (i.e. no diffusion of state along the surface is included)" [Ruina, 1983]"

General predictions:

- Development of a slip instability in velocity weakening faults
- The slip instability takes the form of a propagative, accelerating slip pulse
- The slip instability reaches seismic slip velocities if W/h* >>1



Rubin and Ampuero (2009)

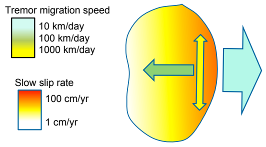
Predictions for transient fault slip :

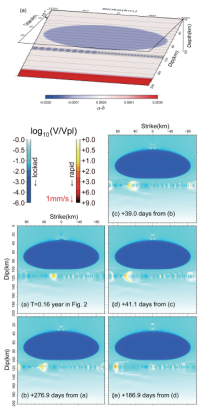
- Spontaneous, periodic slow slip transients are possible only if W/h* ~1
- Several observable quantities can be related to model parameters:
  - Recurrence time ~ $\sqrt{(a/(b-a))}\, D_c/V_{load}$
  - Peak slip velocity and propagation speed: $V_{prop} \sim \mu/b\sigma\, V_{max}/\ln(V_{max}/V_{load})$
  - Stress drop ~ $(b-a)\,\sigma\,\ln(V_{max}/V_{load})$
- The model is highly constrained by these observations: only finely tuned models can fit the ensemble of observations of slow slip

Recent developments :

Models that do not suffer from the "fine tuning" issue include:
- dilatancy-hardening models (Rubin/Segall),
- friction laws with N-shaped velocity-dependence at steady-state (Shibazaki)
- collective behavior of brittle asperities surrounded by creep (Ampuero/Ariyoshi)

The latter model additionally predicts a variety of tremor migration patterns (forward slow migration, rapid tremor reversals and along-dip fast migrations)

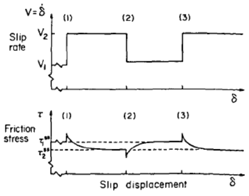


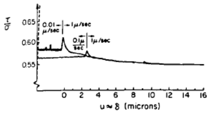


Ariyoshi et al (2010)

Motivation

Friction laboratory experiments [Dietrich, 1979; Ruina, 1980]





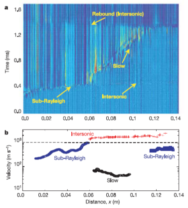
Friction force variation due to step change in slip rate (from [Ruina, 1983])

Idealized evolution of friction stress, when the slip rate is changed (from [Ruina, 1983])

- A steady state friction logarithmically dependent on slip rate V: $\tau(V)$=constant+C*ln(V), where C may be positive or negative in different materials or environments
- Positive instantaneous slip rate dependence: positive (negative) jump in stress when slip rate is suddenly increased (decreased), proportional to $\ln(V_2/V_1)$.
- A long-term decrease (increase) in friction stress following the positive (negative) jump in slip rate, occurs over a characteristic slip length that is independent of slip rate.

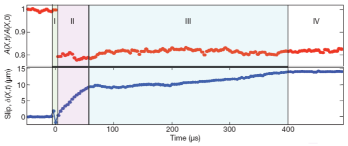
New generation of friction laboratory experiments

[Rubinstein & Fineberd, 2004; Rubinstein et al, 2007; Ben-David et al, 2010]



The dynamic of slip before overall sliding:

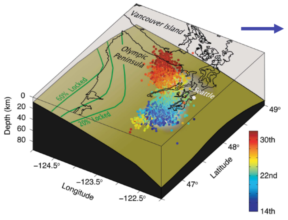
a) An (x,t) plot of relative intensity measurement proportional to the net contact area;
b) Velocity records in space corresponding to the slow, sub-Rayleigh, and intersonic fronts seen in **a)** (from [Rubinstein & Fineberd, 2004])



The detachment process and the evolution of frictional slip. Simultaneous measurements of the local dynamics of contact area A(t);A(X,t) and slip before, during and after the passage of a precursor event. The measurements reveal three distinct initial phases of the dynamics: detachment (phase I), rapid slip (phase II) and slow slip (phase III). (from [Ben-David, Rubinstein & Fineberd, 2010])

- detachment front precedes slip
- non-uniform contact area arises dynamically via a series of rapid crack-like precursors

Field experiments [*Kao et al*, 2006; *Ghosh et al.*, 2010]



Location of a migrating tremor during an ETS episode in January 2007 in the Cascadia subduction zone. *Image courtesy of A. Wech and K. Creager*

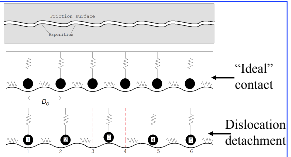
- periodicity of ETS (~1 year)
- tremor migration: 1) strike direction with a velocity of 10 km/day; 2) up- and down-dip at velocity of ~50 km/hr
- scaling law for slow earthquakes: seismic moment M_0 is proportional to the rupture duration T [Ide et al, 2007]

Frenkel-Kontorova model

Formulation [Gershenzon, 1994; Gershenzon, et al, 2009]

$$\frac{\partial^2(\delta/D_c)}{\partial(x/D_c)^2} - \frac{\partial^2(\delta/D_c)}{\partial(tc/D_c)^2} = \frac{A^2}{2\pi}\sin(2\pi\delta/D_c)$$

δ is the relative displacement of the friction surfaces in the slip direction, c is the velocity, D_c is the typical distance between microasperities, A is the dimensionless scaling factor



The sinusoidal term at the right side of the equation reflects the presence of bumps on friction surfaces of effective height A. Essentially A is the amplitude of the potential field on the sine-shaped surface and it is a function of geometry and the adhesive properties of asperities.

Adjustable parameters:

1) the typical distance between microasperities D_c
2) scaling factor A (could be derived from the rupture and slip velocities)

	Plasticity in crystals	Lab friction experiments	Faults
D_c	Atomic distance	~1 μm	~30 mm
A	~1	~10^{-2}	~10^{-3}

Limitations:

In order to apply the FK model to plate dynamics, one need to suppose that plate surfaces are covered quasi-periodically by micro-asperities with a **characteristic spacing** between them.

General predictions [Gershenzon, Bykov & Bambakidis, 2009]:

- appearance of defects (dislocations ≡ slip pulse), which may propagate with any velocity less than seismic velocity
- existence of two types of detachment fronts with different propagation velocities (Fig. 1)
- spatial and temporal nonuniformity of contact area and slip velocity
- slip is quantized by D_c

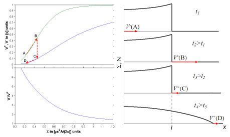


Fig. 1 The velocities of detachment front propagating through stressed area (V^-) and from stressed to unstressed nd their ratio as a function of stress Σ. The path ABCD shows the hypothetical changes of detachment front velocity. The sudden drop of the front velocity (in a few times), observed in the experiments, may be explained by the switching of front from the stressed area to unstressed area (path BC). The right panel schematically depicts spatial distribution of stress and density of dislocations in arbitrary units for 4 consecutive moments of time associated with points A, B, C, and D; the red arrows show the position and magnitude of the detachment front.

Predictions for transient fault slip [Gershenzon, Bambakidis, Hauser, Ghosh, & Creager, submited]:

- periodicity of ETS (Fig. 2)
- tremor migration pattern:
strike direction with velocity of 10 km/day (Fig. 3), dip direction at velocity of ~50 km/hour (Fig. 4)
- scaling law for slow events (M_0~T)

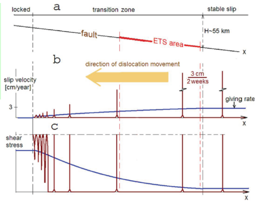


Fig. 2 Schematic representation of the subduction zone (a), spatial distribution of slip velocity (b) and shear stress (c) in Cascadia. Note the difference between actual (brown) and spatially averaged (blue) slip velocity and shear stress. The distance between the left edge of the ETS zone and the locked zone is exaggerated.

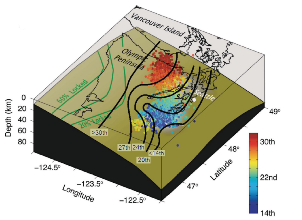


Fig. 3 Location of a migrating tremor during an ETS episode in January 2007 in the Cascadia subduction zone. The successive positions of the dislocation (black curves) from before 14th January until after 30th January are shown.

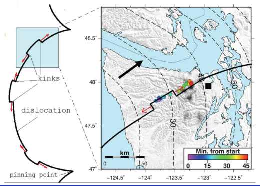


Fig 4. The solid black curve depicts a dislocation front with kinks moving parallel (red arrows) to the dislocation front. The expanded region to the right shows a slip-parallel tremor streak in the Cascadia subduction zone with rapid down-dip short-term migration of the tremor with a velocity of 65 km/hr. Colored circles on the maps represent tremor locations. Time is color-coded to show tremor migration. The black solid square marks the seismic array used to observe the tremor streak. The arrow indicates the overall slip direction of the Cascadia subduction zone. Dashed contour lines show plate interface depth in km.