Friction in Rocks

Assigned Reading:

{Marone, 1998 #3905; Chapter 8 in \Paterson, 2005 #5865}

Resource reading:

{Scholz, 1990 #4288; Ruina, 1985 #1586}

Physical processes

Asperities

Ploughing
Over-riding
Asperity deformation: Fracture or squashing

Wear tracks:

Carrot shaped grooves with length similar to stick-slip distance
Continuous wear tracks
Trails of asperity detritus

Gouge formation:

Angular to sub-angular or rounded particles
Widely varying sizes from sub –micron to 100's of microns
Density and coherence increase when the surfaces are wet

Thickness of the gouge layer increases as distance of sliding increases

Melting

Psuedotachylyte

Gouge and gouge deformation:

Riedel shears
Y-shears

Stress to cause sliding:

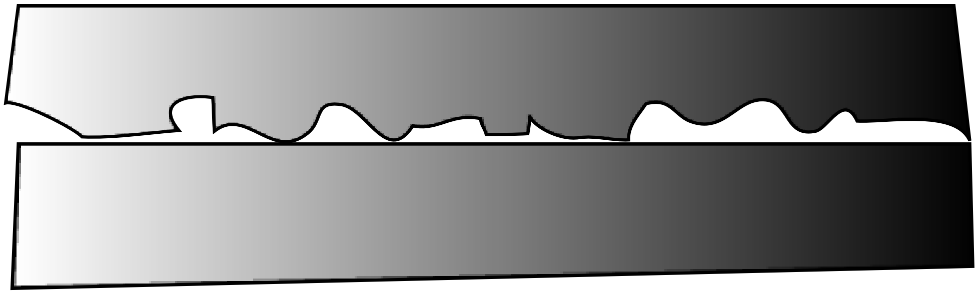
Amonton's Law (Amonton, da Vinci)

Force required to start sliding depends on the area of the surfaces being pressed together, the normal load, the material, and, in some cases, the surface roughness.

$F = \mathrm{M}_{sliding} W$

In general, the force is linearly proportion to the area, so normalizing per unit area:

$\tau = \mu \sigma_n$ Amonton's law



Physical Basis for Amonton's Law

Suppose surface is rough on the microscale,
Then if a small fraction of the area supports the whole load, material may yield on the asperities.
$W = Y A_{contact}$ where W is the normal load, Y is the yield stress, $A_{contact}$ is the actual contact area of all the asperities.

Then if the contacts are welded the frictional stress becomes,

$$F_{shear} = S_{shear} A_c = S_{shear} \frac{W}{Y}$$

Þ $m = {}^{S_{shear}}\!/_{Y}$

Byerlee's Law:

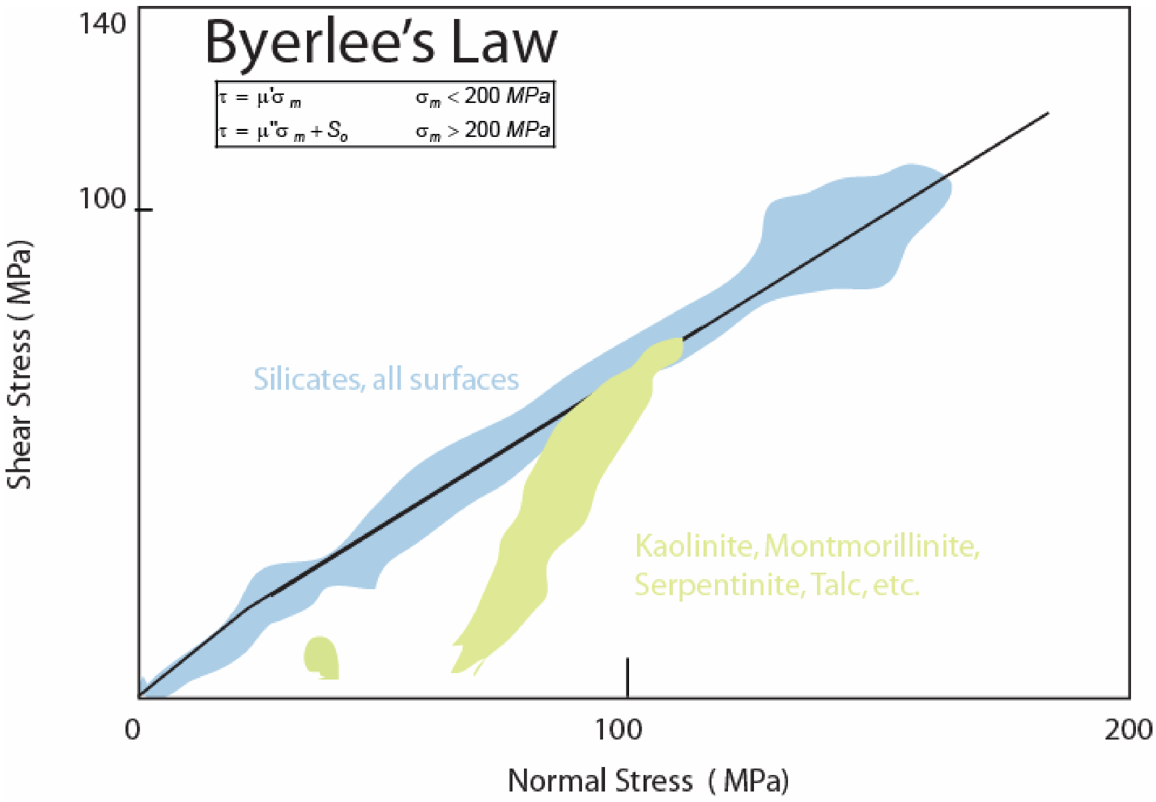
Rock	μ		Mineral	μ
Granite	0.5-0.7		Quartz	0.1-0.2 dry 0.2-0.3 wet
Gabbro	0.2-0.7		Microcline	“
Sandstone	0.5-0.7		Calcite	“
Marble	0.4-0.8		Hydrous min.	0.3-0.7 dry; 0.15-0.4 wet
Serpentinite	0.3-0.5			

Coefficient of friction seems quite similar, regardless of surface preparation and rock type.

For many rocks, it is empirically found that the relation between the normal and shear stresses obeys a bilinear form:

$$\boxed{\begin{array}{ll} \tau = \mu'\sigma_m & \sigma_m < 200\ MPa \\ \tau = \mu''\sigma_m + S_o & \sigma_m > 200\ MPa \end{array}}$$

Where μ' is 0.85; μ" is 0.6 and S_o is 50 MPa.



Phenomenology:

Surface Roughness Important for Low Loads (Engineering):

Low normal loading <2.0 MPa

(Many engineering applications)

Depends on

Surface conditions, joint wall compressive stress,
basic friction angle

$$\tau = \sigma \tan\left[JRC \cdot \log\left(JCS / \sigma \right) + \phi_o \right]$$

JRC is joint roughness coefficient
JCS is joint wall compressive stress
ϕ_o is basic friction angle

Higher normal loading:

Relatively independent of surface roughness

Moisture and Pore pressure:

Somewhat inconclusive: dry surfaces have larger mu than wet.
Surfactants larger mu than pure

Temperature and Sliding Rate

Dry conditions:

In silicates with non interlayer water: no marked temperature or rate dependence. However, small variations in rate dependence of the order of 10% occur, and do seem to be important for stability.
In minerals with interlayer water present, temperature may increase mu

Stick-Slip Behavior:

{Brace, 1966 #1434}{Brace, 1966 #1434}
Oscillatory variation in τ
Stable sliding: constant sliding resistance
Amplitude of stick slip events varies rather widely

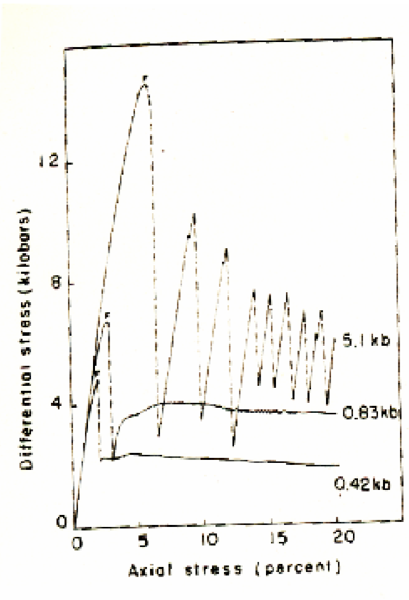
Remarks:

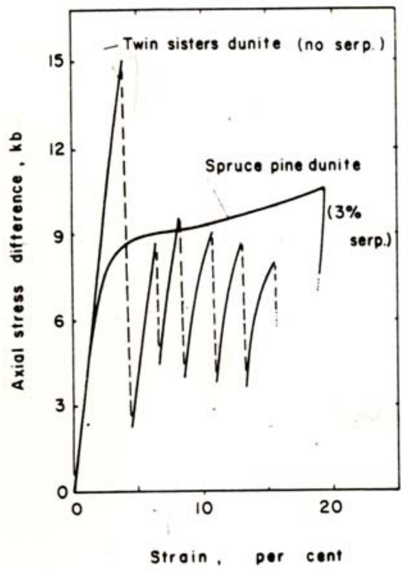
Coefficient of static friction:
Measured in slide-hold-slide tests:

Phenomenology:

Strong minerals promote stick slip
Serpentine greases friction
Carbonates tend to be stable sliders

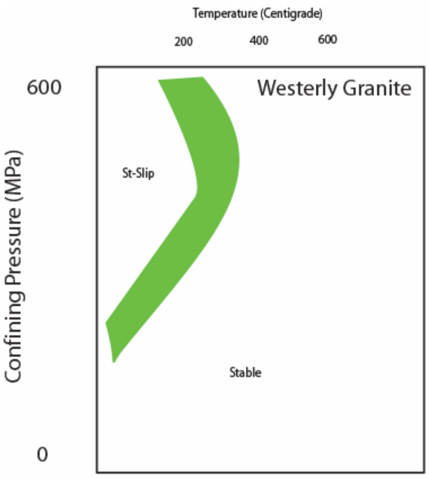
Smooth surfaces promote stick slip

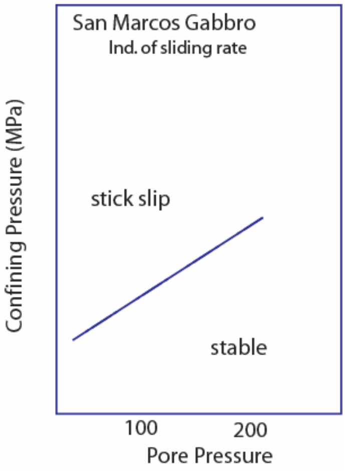


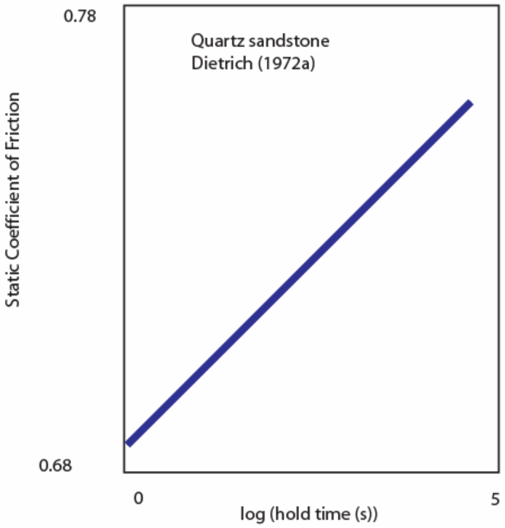


Rough surfaces retard it at normal loads <100 MPa
But, stick slip when > 100 MPa

Gouge often inhibits stick slip, although the type of gouge may be important,And slip distance may also be important
Increase in temperature promotes stable sliding
Increase in pressure promotes stick slip.
For a summary see Paterson and Wong, 2005.







Melting promotes stable behavior, but permeability may be an important parameter

Velocity dependence of Friction

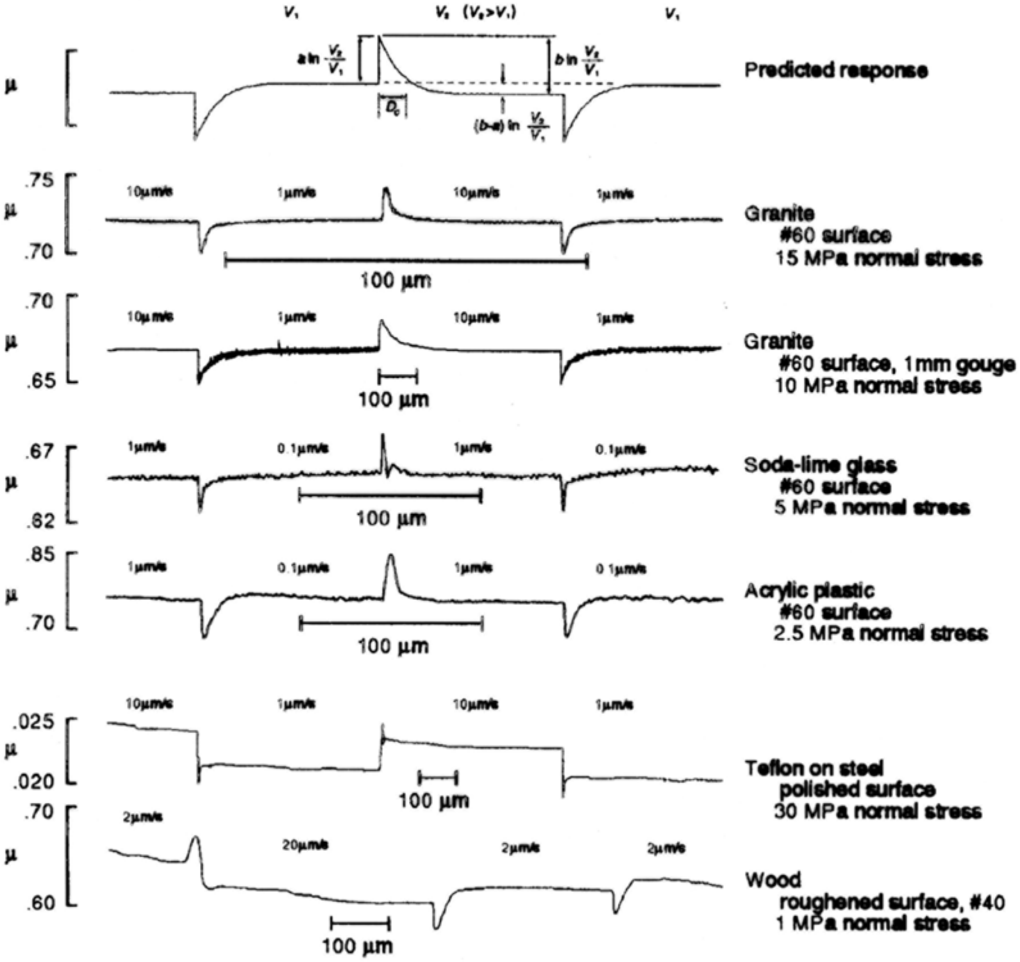


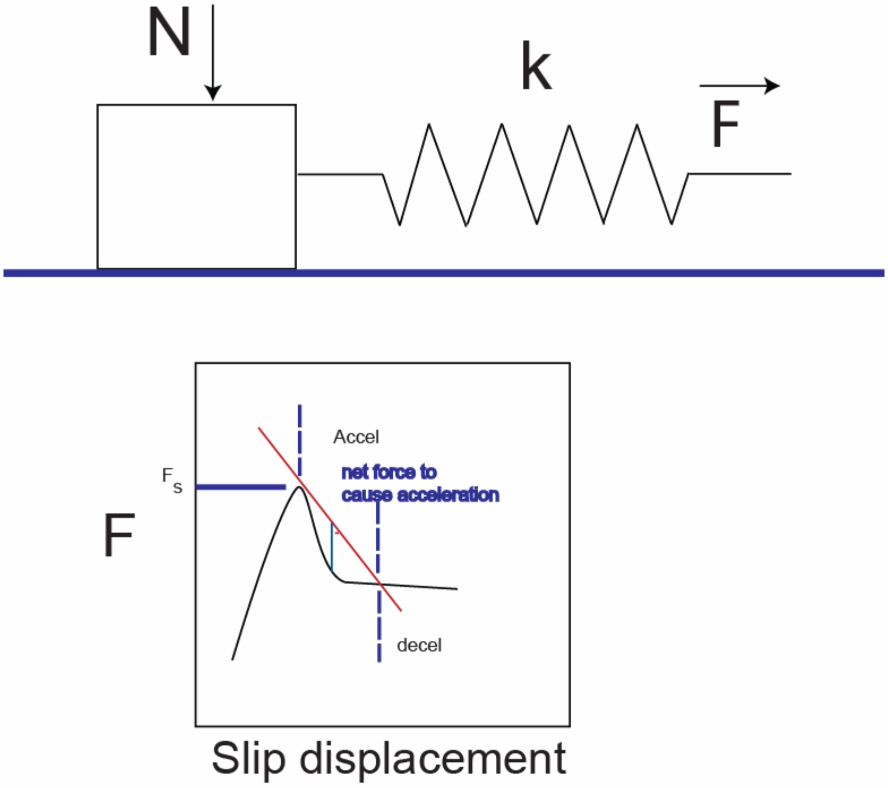
Figure 6 Friction behavior for a wide range of materials is shown for step changes in load point velocity (Dieterich & Kilgore 1994). The predicted response is that given by the rate and state friction laws. The data show remarkable similarity, indicating wide applicability of the rate and state friction formalism.

Stability of Sliding:

Instability of sliding requires weakening of fault with increasing displacement {Tse, 1986 #1620}[*Price*, 1982]

Single block slider with change in velocity

Criterion for instability involves interaction with surrounding material.



Conditions for stability:

If $\frac{d\mu_{ss}}{dv} > 0$ then velocity strengthening, always stable.

If $\frac{d\mu_{ss}}{dv} < 0$ then velocity weakening, and if $K_{loading}/K_c > 1$

then stability depends on size of perturbation

If $\frac{d\mu_{ss}}{dv} < 0$ (velocity weakening)

and $K_{loading}/K_c < 1$ then always unstable

Velocity dependence of Friction

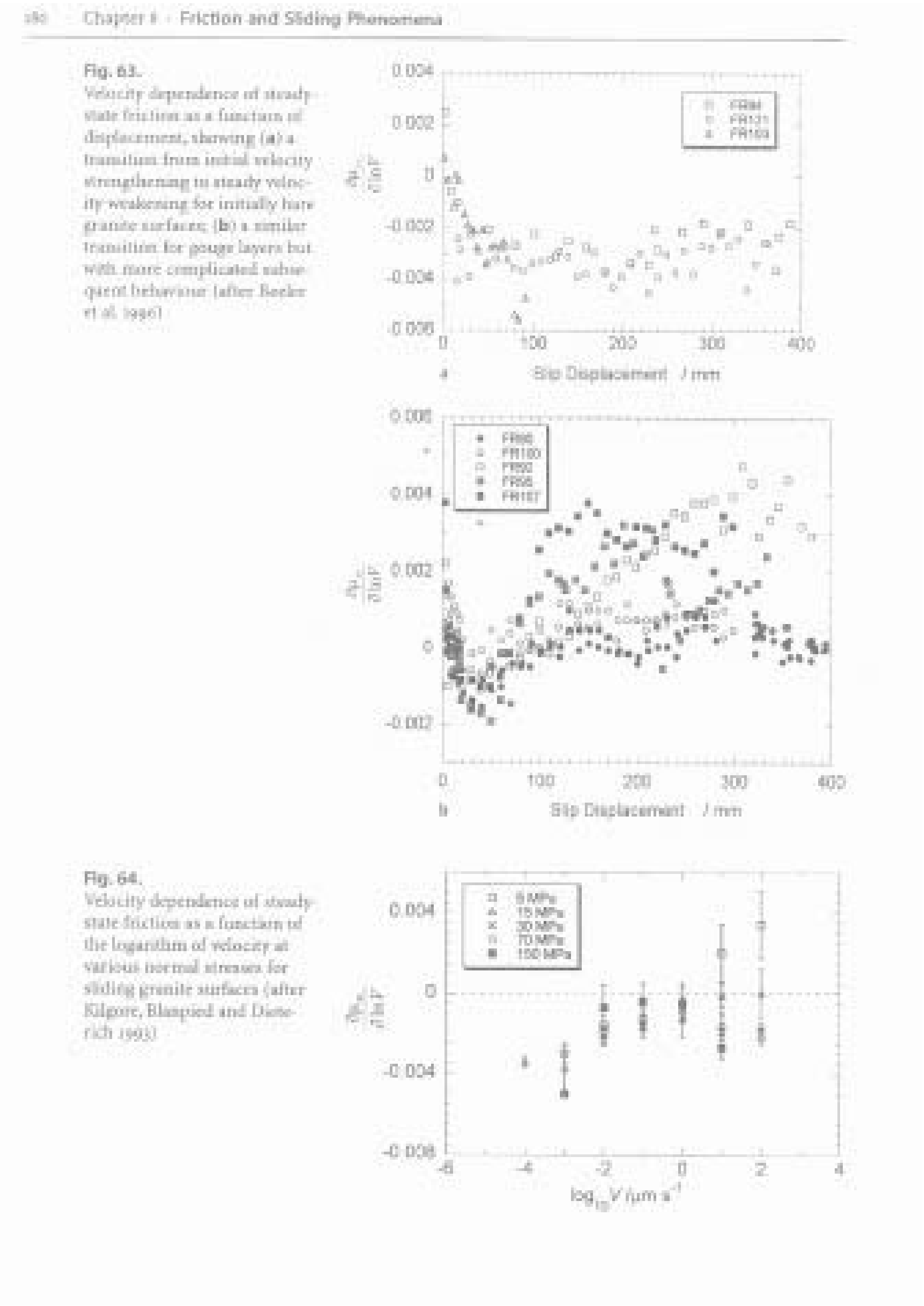


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Fig. 63.
Velocity dependence of steady-state friction as a function of displacement, showing (**a**) a transition from initial velocity strengthening to steady velocity weakening for initially bare granite surfaces; (**b**) a similar transition for gouge layers but with more complicated subsequent behaviour (after Beeler et al. 1996)

Fig. 64.
Velocity dependence of steady-state friction as a function of the logarithm of velocity at various normal stresses for sliding granite surfaces (after Kilgore, Blanpied and Dieterich 1993)

Brief Theoretical Interlude:

Constitutive Behavior:

Yield laws:

Criterion for Inelastic behavior

No explicit prediction of rates, e.g. Byerlee's law

Flow laws:

Predicton of the evolution of strength,

Often involves a relation with strain rate

References:

[*Ruina*, 1985; *Stouffer and Dame*, 1996]

State variable approach

- To accommodate evolving structure include internal state variables (ς_i), measures of the elements of structure *Stouffer and Dame* [1996, pp. 267-272],
- The state variable approach has also been widely used to describe brittle sliding along faults [*Dietrich*, 1978; *Price*, 1982; *Ruina*, 1985]

Three general equations are needed:

- **state or evolution equation** (1)

$$\dot{\varsigma}_m = \Sigma\left(\dot{\varepsilon}^I_{ij}, \sigma_{kl}, T, P, f_p, \varsigma_r, \ldots\right)$$

- a **kinetic equation** (2)

$$\dot{\varepsilon}^I_{ij} = \mathrm{E}\left(\sigma_{kl}, T, P, f_p, \varsigma_r, \ldots\right)$$

- **kinematic equation** (3) that prescribes the total strain resulting from a given deformation path. Are

$$\varepsilon_{ij} = \varepsilon^{EL}{}_{ij} + \int \square \dot{\varepsilon}^I_{ij} dt$$

Choosing State Variables:

ς_r

Parsimony

Equipresent

Avoidance of History

Objectivity

No dependence on Spatial and Temporal Reference Frames

Consequences: Strain and time excluded

Some Possible State Variables

External Thermodynamic Variables

Lithostatic Pressure
Lithostatic Deviatoric Stress
Pore Pressure
Temperature
Chemical fugacity

Implicit Internal State Variables

Internal Friction Variables
Hardness

Explicit Internal State Variables:

Porosity
Packing geometry
Grain size,
Grain size distribution
Dislocation Structure
Reaction Progress
Lattice Orientation Distribution
Vacancy content

Friction constitutive laws:

Rate-State Laws

Assumption is that static and dynamic coefficient of friction are related and that two parameters (at least) are important.
Velocity
History dependent state variable.

$$t = Function\left\{s_n(all\ \ past\, t),\, V(all\ \ past\, t)\right\}$$

$$t = s_n g Function\left\{V(all\ \ past\, t)\right\}$$

$$t = s_n g Function\left\{V(t), q_i(t)\right\} \quad \text{where } q_i \text{ evolves with t.}$$

In simplest form, Rate State Kinetic Equation involves two variables, velocity, and state, θ.
And four material properties, μ', a, b, D_c

$$\tau = \tau' + A\ln\left(\frac{V}{V'}\right) + \Psi$$

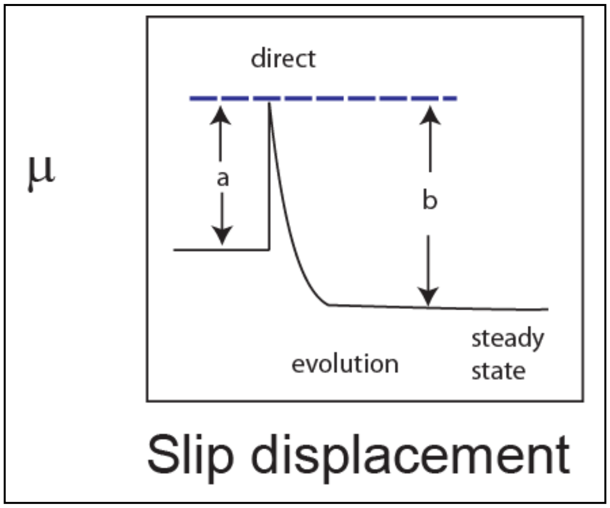
In terms of μ

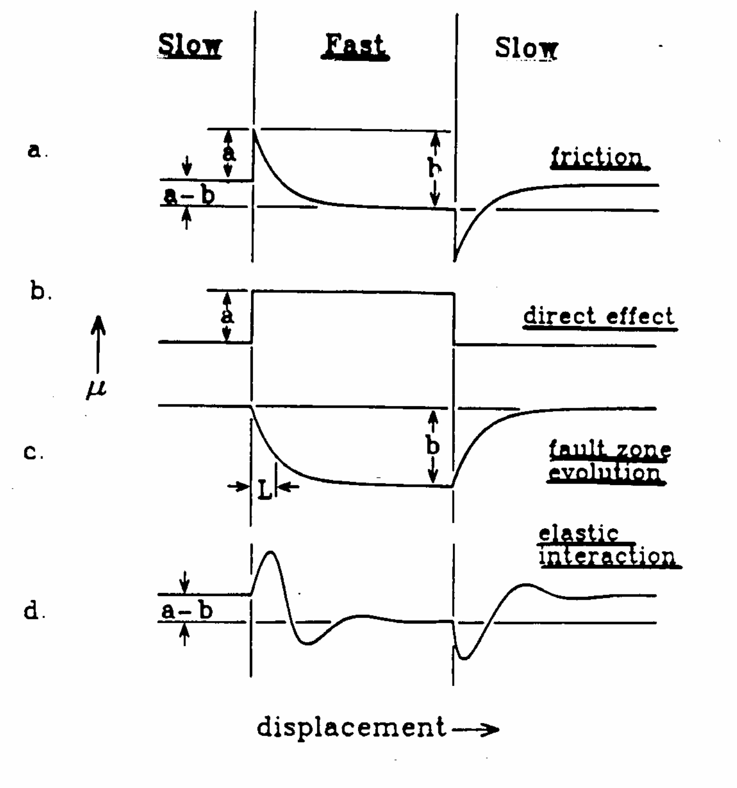
$$\boxed{\mu = \mu' + a\ln\left(\frac{V}{V'}\right) + b\ln\left(\frac{V'\theta}{D_c}\right)}$$

First term is the direct effect, while the second is an evolutionary term.
The variable, θ, must evolve.
The criterion for instability is still

$$\mu_{ss}(V_2) - \mu_{ss}(V_1) = (a-b) < 0$$

Some non trivial questions emerge:
What is θ and how does it evolve?
Indeed, what is the physical meaning of a, b, and D_c ?





Evolution laws:

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

Slowness law (Dietrich)

$$\frac{d\theta}{dt} = \frac{v\theta}{D_c} \ln\left(\frac{v\theta}{D_c}\right)$$

Slip law (Ruina)

Other evolution equations exist, but all have the common characteristic:
Direct increase with increase in velocity
Fading memory.

References:

Dietrich, J. H. (1978), Modeling of rock friction, 1, experimental results and constitutive equations, *Journal of Geophysical Research, 84,* 2161-2168.
Price, R. H. (1982), Effects of anhydrite and pressure on the mechanical behavior of synthetic rocksalt, *Geophys. Res. Lett., 9,* 1029-1032.
Ruina, A. L. (1985), Constitutive relations for frictional slip, in *Mechanics of Geomaterials: Rocks, Concrete, Soils,* edited by Z. P. Bazant, pp. 169-188, John Wiley and Sons, London.
Stouffer, D. D., and L. T. Dame (1996), *Inelastic deformation of metals: Models, mechanical properties and metallurgy*, 502 pp., John Wiley & Sons, New York.