Detachment fronts and the onset of friction

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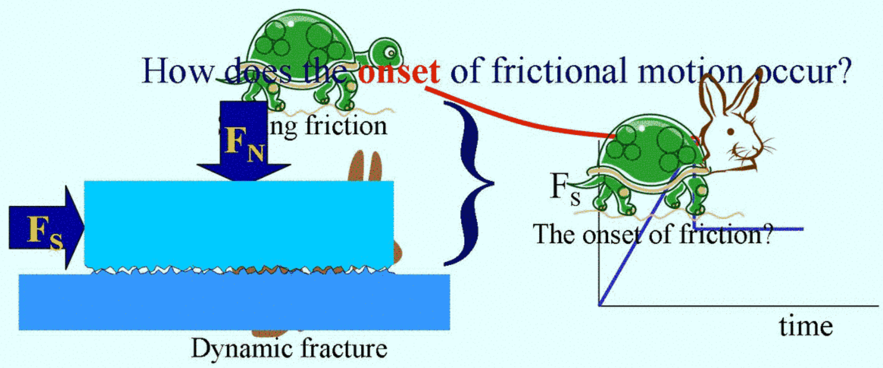
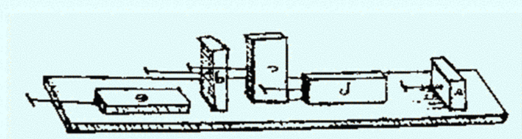
How does the **onset** of frictional motion occur?



Reference: S. M. Rubinstein, G. Cohen, and J.F., Nature **430**, 1005-1009 (2004).

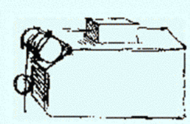
The Study of Friction

Leonardo Da Vinci (1452-1519)



1. The areas in contact have no effect on friction.
2. If the load of an object is doubled, its friction will also be doubled.
   ➔ $F_S \propto F_N$
3. Friction is related to the roughness of the material in question

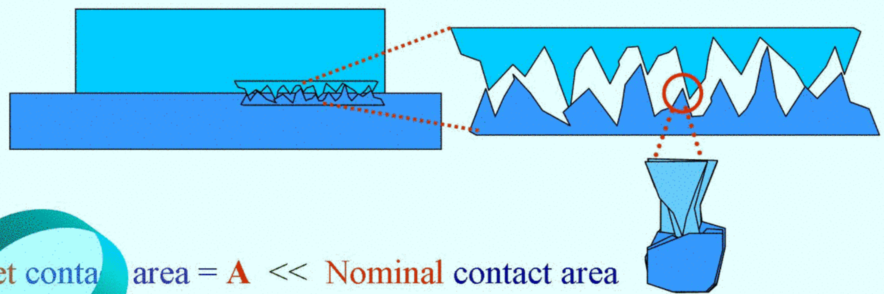
Guillaume Amontons (1663-1705)
Charles August Coulomb (1736-1806)



➔"Static" and "Dynamic" friction:

$F_S = \mu_S F_N$ (v = 0)
$F_S = \mu_D F_N$ (v > 0)

Explaining the Amontons-Coulomb law:



- Net contact area = **A** << Nominal contact area
- Huge pressures at the contact points deform the materials
- A grows until pressure = yield strength, σ_Y

  ➔ $A = F_N / \sigma_Y$
- Motion: Fracture of contacts

  ➔ $F_S = \tau_C A$, where τ_C = shear strength

F. Philip Bowden and David Tabor (1950)

➔ $F_S = \tau_C A = F_N (\tau_C / \sigma_Y) = \mu F_N$

Sliding friction:

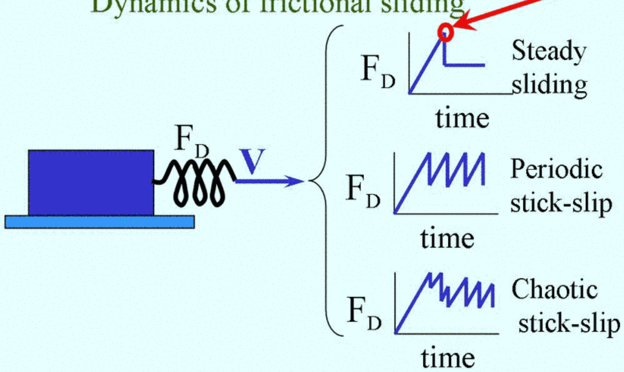
Rate and State Friction Laws

$$F_S = [\mu_0 + a \cdot \log(V/V_0) + b \cdot \log(V_0 \theta / L)] \cdot F_N$$

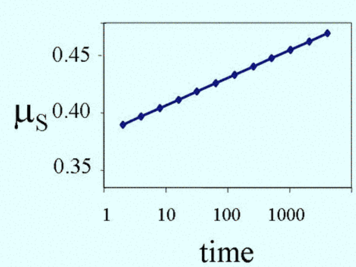
$$d\theta/dt = 1 - \theta V / L$$

(θ is a "state variable" and **V** the sliding velocity)

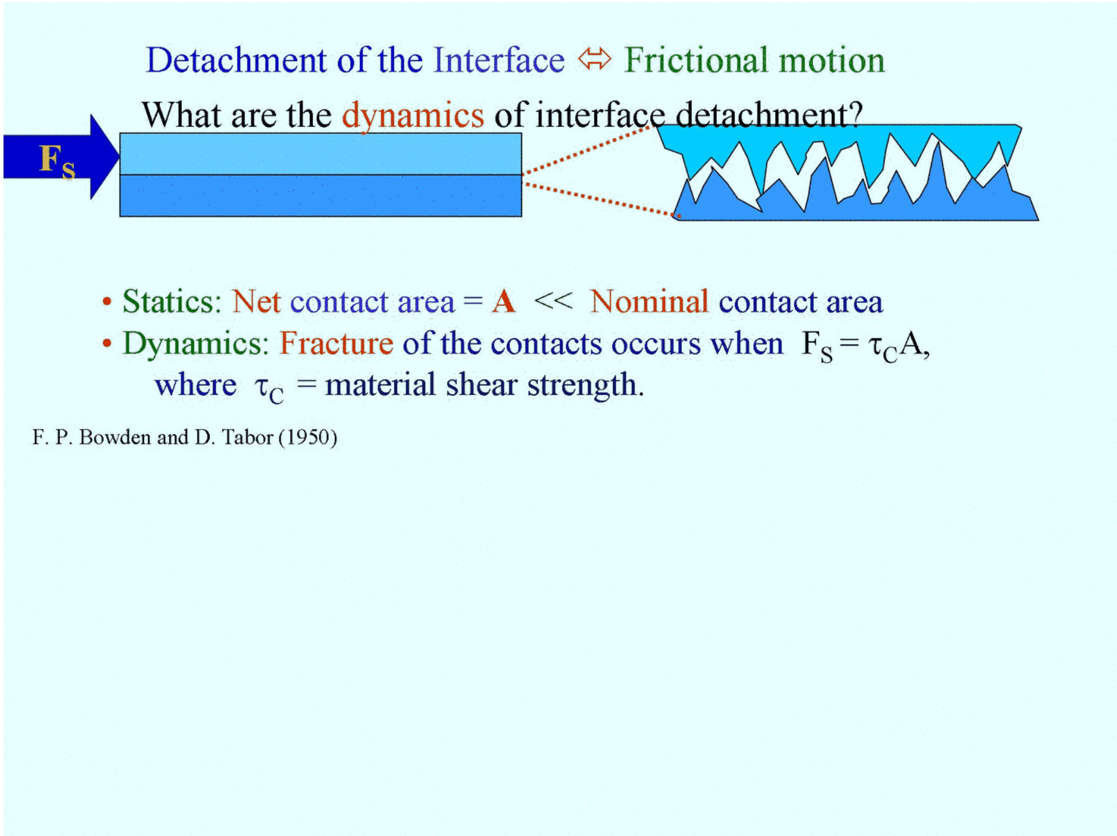
Dynamics of frictional sliding

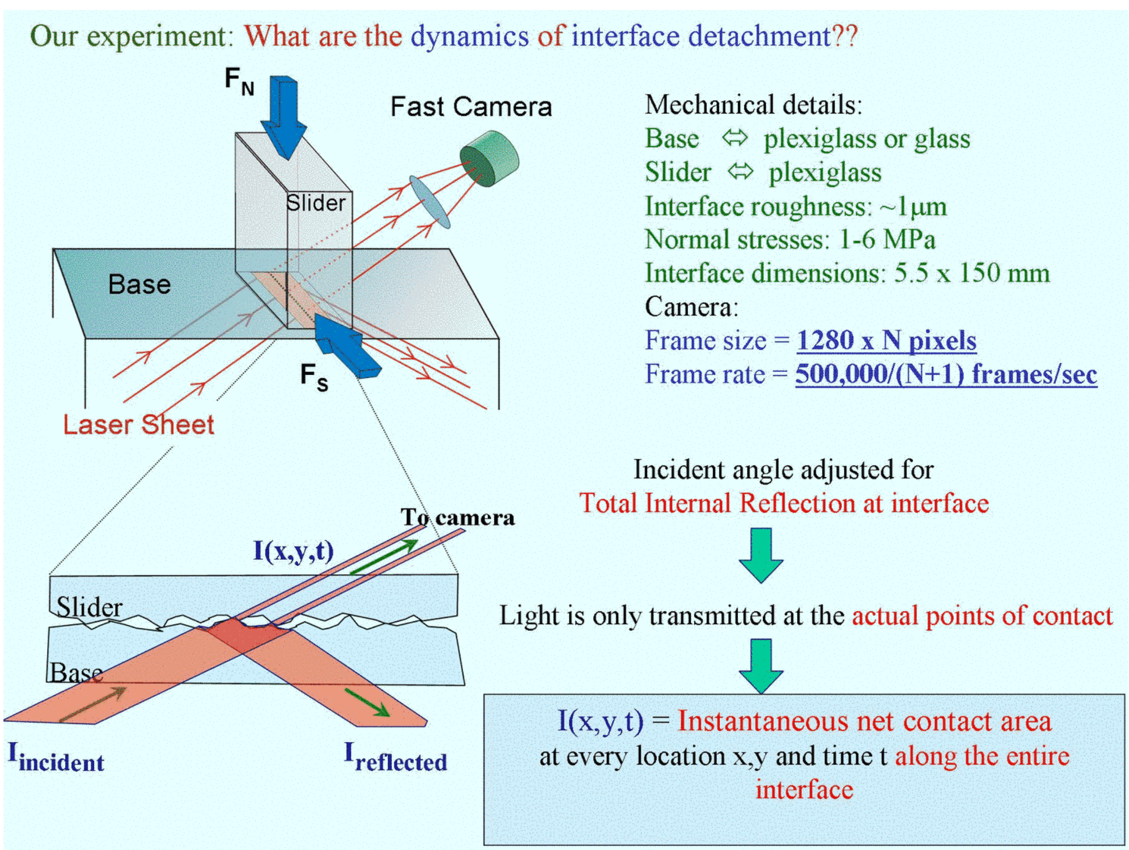


"Aging" of μ_S

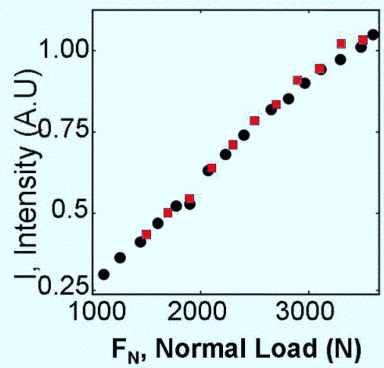


Dieterich, J., *Pure Appl. Geophys.* **116**, 790 (1978)
Ruina, A.L. *J. Geophys. Res.* **88,** 10359 (1983)
Baumberger, T., Berthoud, P. & Caroli, *Phys. Rev.* **B60**, 3928 (1999)


Detachment of the Interface ⇔ Frictional motion
What are the dynamics of interface detachment?
F_S
• Statics: Net contact area = A << Nominal contact area
• Dynamics: Fracture of the contacts occurs when $F_S = \tau_C A$, where τ_C = material shear strength.
F. P. Bowden and D. Tabor (1950)


Our experiment: What are the dynamics of interface detachment??
F_N
Fast Camera
Slider
Base
F_S
Laser Sheet
Mechanical details:
Base ⇔ plexiglass or glass
Slider ⇔ plexiglass
Interface roughness: ~1μm
Normal stresses: 1-6 MPa
Interface dimensions: 5.5 x 150 mm
Camera:
Frame size = 1280 x N pixels
Frame rate = 500,000/(N+1) frames/sec
To camera
I(x,y,t)
Slider
Base
$I_{incident}$
$I_{reflected}$
Incident angle adjusted for
Total Internal Reflection at interface
Light is only transmitted at the actual points of contact
I(x,y,t) = Instantaneous net contact area
at every location x,y and time t along the entire interface

Does the method work? “Static” measurements:



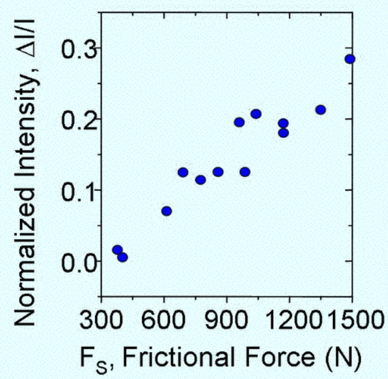
The net contact area increases linearly with F_N

$I \propto F_N \rightarrow A \propto F_N$

Dieterich, J. H. & Kilgore, B. D. *Pure and Applied Geophysics* **143**, 283-302 (1994).

I is a direct measure of both the net contact area, A, and the frictional force, F_S

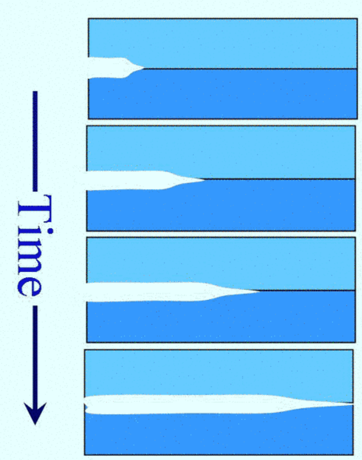
$F_S = \mu F_N \propto A \propto I$



Static measurements ⇔ Verification of Bowden and Tabor!

Detachment of the Interface ⇔ Frictional motion

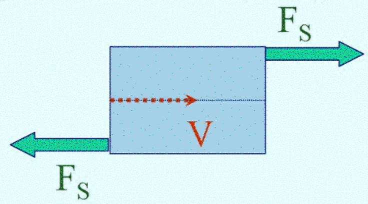
What are the dynamics of interface detachment?



Is interface detachment governed by the propagation of coherent **(crack-like)** fronts?

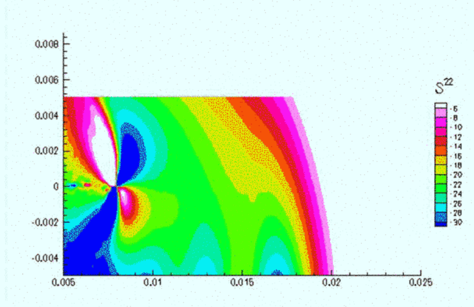
Is interface detachment a Dynamic Fracture Problem?

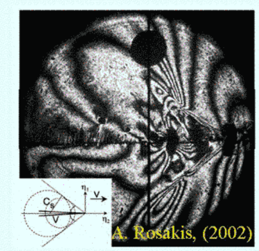
Friction as a fracture process: Mode II (Shear) Fracture



Shear fracture:

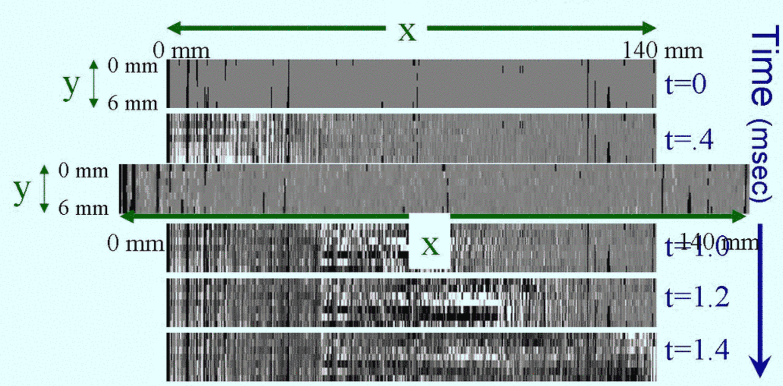
- Can only occur along a weak interface – otherwise tensile fracture occurs
- Shear cracks with **point-like stress field singularities** at their tip can propagate for all $V < V_R$ and for the special velocity of $V=\sqrt{2}V_S$ (V_S is the shear wave speed).
- Any other shear fracture velocities can only occur for a **spatially distributed dissipation zone**[2,3] ahead of the fracture.





1. Freund, L. B., *J. Geophys. Res.* **84**, 2199-2209 (1979)
2. Rosakis, A. J., Samudrala, O. & Coker, D. *Science* **284**, 1337-1340 (1999);Needleman,A.,1999,*J.Mech.Phys.Solids*,**66,** 847.K.
3. Xia, A.J. Rosakis, and H. Kanamori, Science **303,** 5665 (2004).

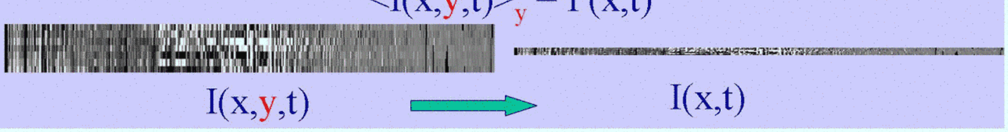
The Dynamic behavior of the interface: I(x,y,t) = ?

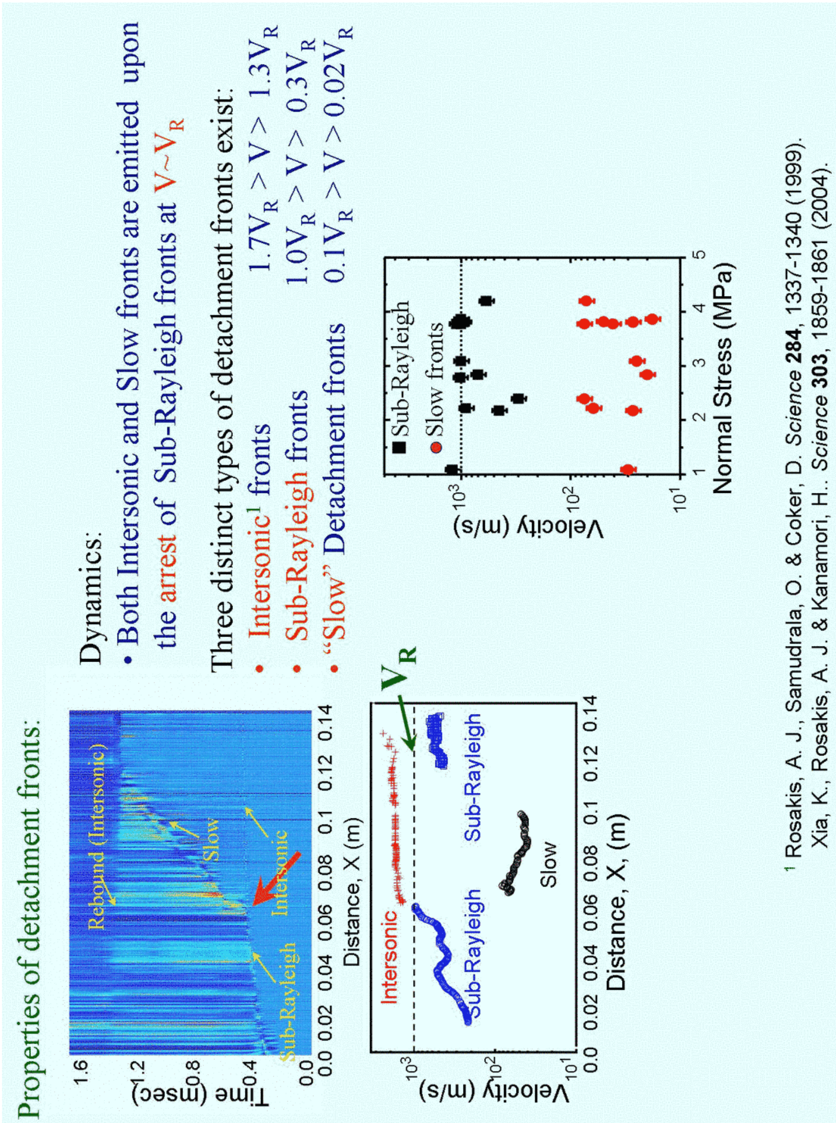


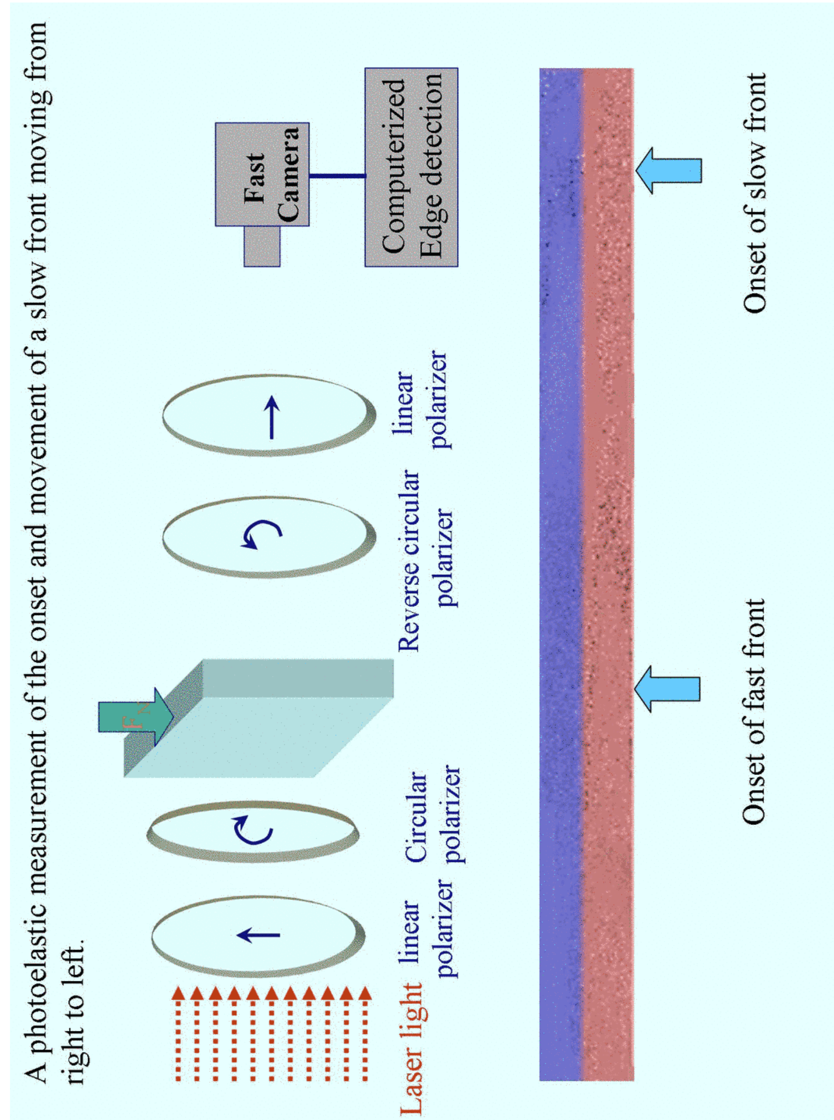
Interface detachment occurs by means of crack-like fronts propagating in the x direction along the interface

As the fronts are quasi-1D, we will now (for simplicity) consider:

$\langle I(x,y,t)\rangle_y = I(x,t)$




Properties of detachment fronts:
Dynamics:
• Both Intersonic and Slow fronts are emitted upon the arrest of Sub-Rayleigh fronts at V~V_R
Three distinct types of detachment fronts exist:
• Intersonic[1] fronts 1.7V_R > V > 1.3V_R
• Sub-Rayleigh fronts 1.0V_R > V > 0.3V_R
• "Slow" Detachment fronts 0.1V_R > V > 0.02V_R
Time (msec)
Distance, X (m)
Rebound (Intersonic)
Slow
Intersonic
Sub-Rayleigh
Velocity (m/s)
Distance, X, (m)
V_R
Intersonic
Sub-Rayleigh
Slow
Sub-Rayleigh
Slow fronts
Normal Stress (MPa)
1 Rosakis, A. J., Samudrala, O. & Coker, D. Science 284, 1337-1340 (1999).
Xia, K., Rosakis, A. J. & Kanamori, H.. Science 303, 1859-1861 (2004).


A photoelastic measurement of the onset and movement of a slow front moving from right to left.
Laser light
linear polarizer
Circular polarizer
Reverse circular polarizer
linear polarizer
Fast Camera
Computerized Edge detection
Onset of fast front
Onset of slow front

Experiments in Granite

M.Ohnaka and L. Shen, JGR **104**, 817 (1999)

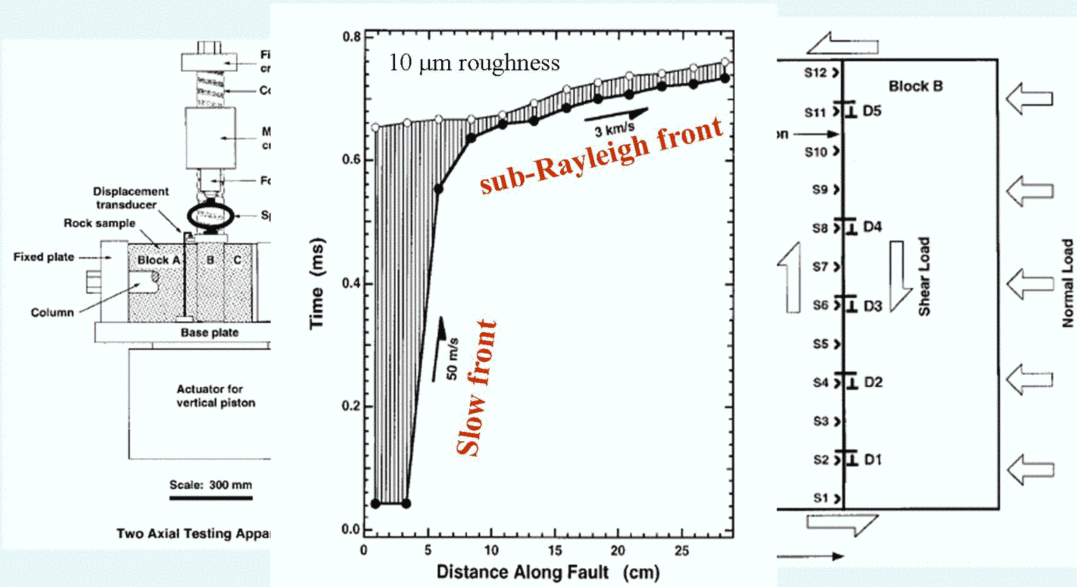
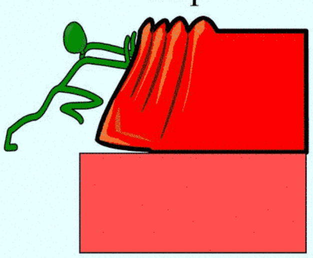


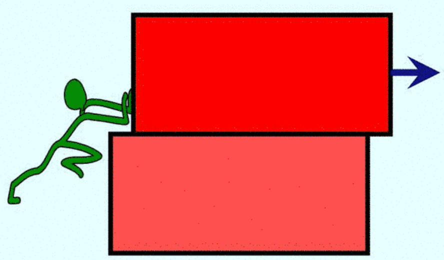
Figure 26. Space-time view of the nucleation zone for a slip failure event (E40117comb) on the extremely smooth fault. The hatched portion indicates the zone in which the slip weakening is proceeding with time.

Frictional slip vs. Frictional Sliding

Slip



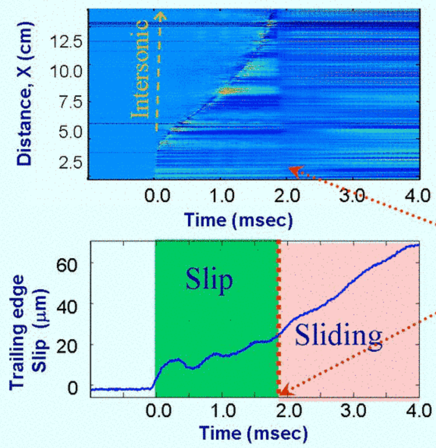
Sliding

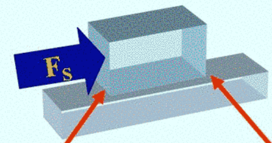


Local displacement along the interface **Global translation of the interface**

Interface Fracture { The transition from slip to sliding?
The transition from static to dynamic friction?

Slip along the interface:



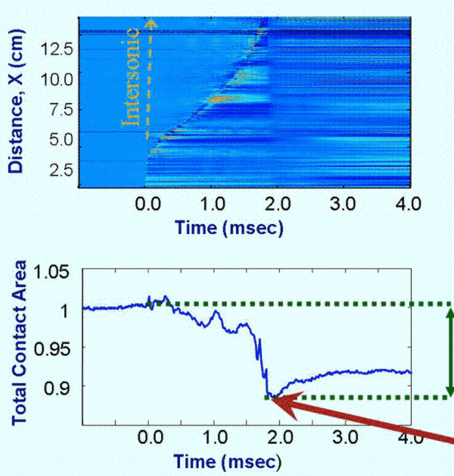


Onset of motion at leading edge

- No slip occurs upon passage of Intersonic fronts
- Slip at the trailing edge occurs during propagation of both Sub-Rayleigh and Slow Detachment fronts
- No slip at the leading edge occurs until the arrival of either the Slow or Sub-Rayleigh fronts – at that time **sliding** of the blocks occurs

Contact area reduction by detachment fronts:

The transition from static to dynamic friction

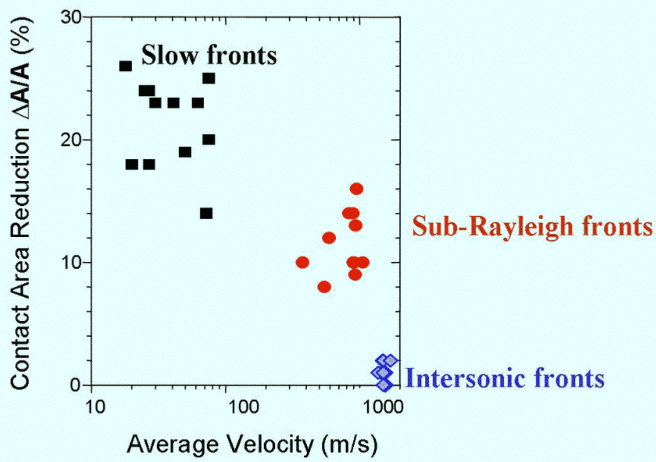


$\Delta I/I = \Delta A/A \sim (\mu_S - \mu_D)/\mu_S = 12\%$

Initiation of "aging"

- The total reduction of surface area by the slow and sub-Rayleigh fronts drives the transition from "static" to "dynamic" friction.
- Aging of the contact surface is initiated immediately upon the onset of sliding

Efficiency of the different fronts in contact area reduction:



- Intersonic fronts produce a negligible reduction of contact area
- Slow detachment fronts are twice as efficient as Sub-Rayleigh fronts in reducing the net contact area

Summary: The transition from static to dynamic friction
or
the dynamics of fault nucleation

1. Slip occurs via three different types of detachment fronts which propagate at highly different velocities.
2. Both slow detachment and intersonic fronts are emanated upon arrest of sub-Rayleigh fronts – upon their arrival at V_R
3. All three detachment fronts nearly always are observed – either alone or together with the other fronts
4. Negligible slip and contact area reduction result from the passage of intersonic fronts.
5. Slow detachment fronts are twice as efficient as sub-Rayleigh fronts in contact area reduction

Relevance to earthquakes: The dynamics of fault nucleation

Sub-Rayleigh fronts	⇔	"Standard" earthquakes ($0.2V_R < V < 0.9V_R$)
Intersonic fronts	⇔	"Intersonic" earthquakes (e.g. Izmit 1999[1])
Slow detachment fronts	⇔	???

Slow earthquakes[2] = slow detachment fronts?

Characteristics of "slow" or "silent" earthquakes

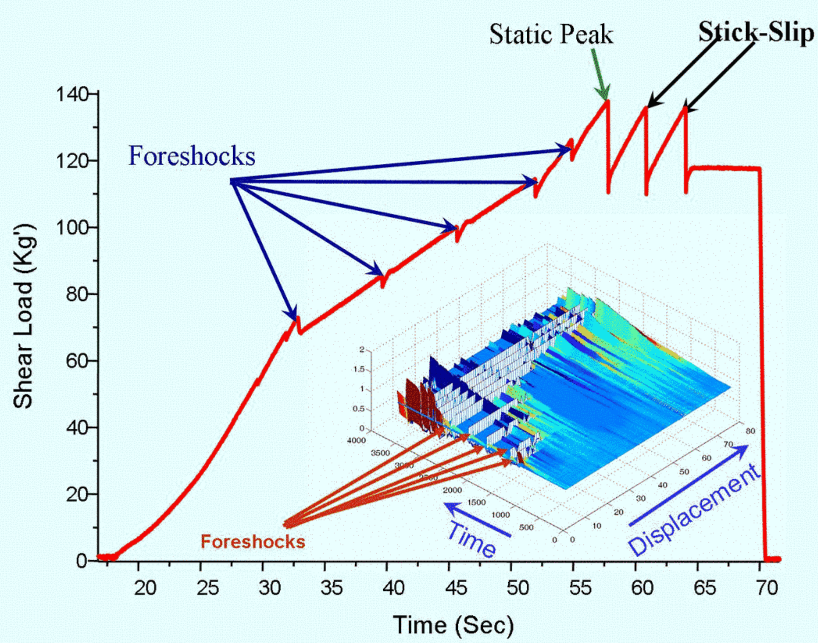
- Significant slip/strain release (measured with GPS /strainmeters)
- "silent" – having a weak atypical seismic signature.

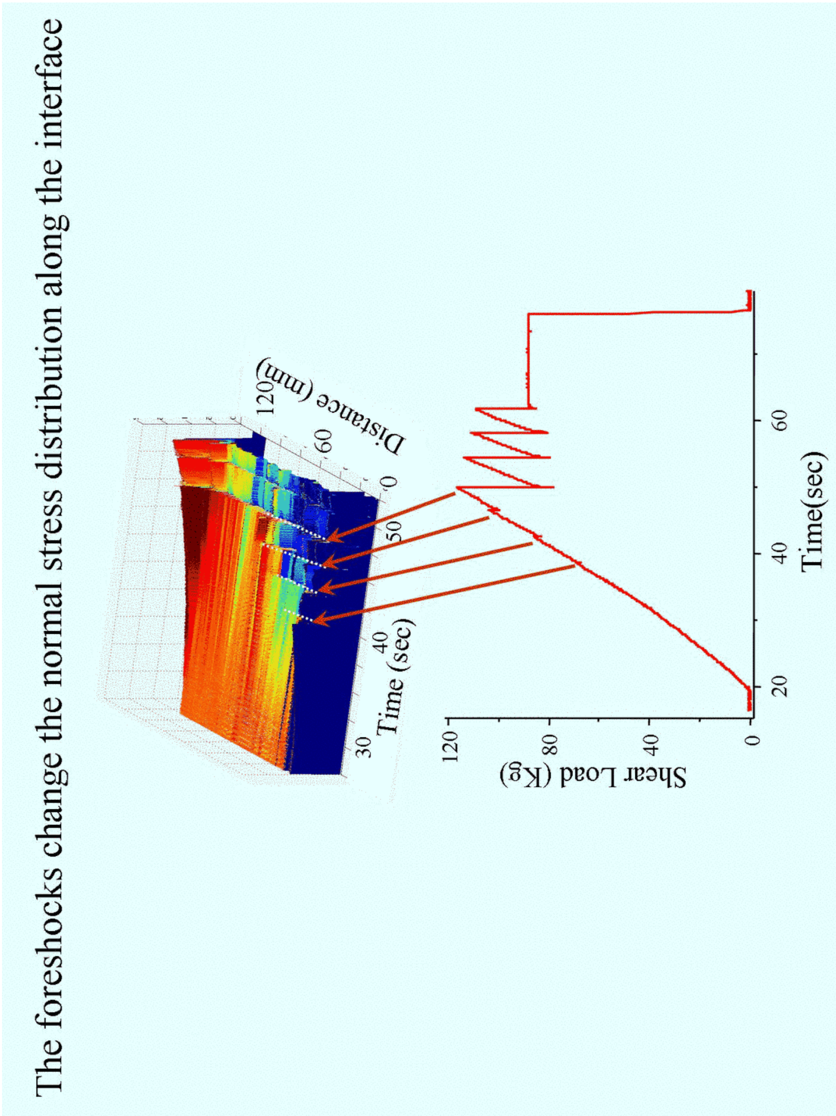
Question:

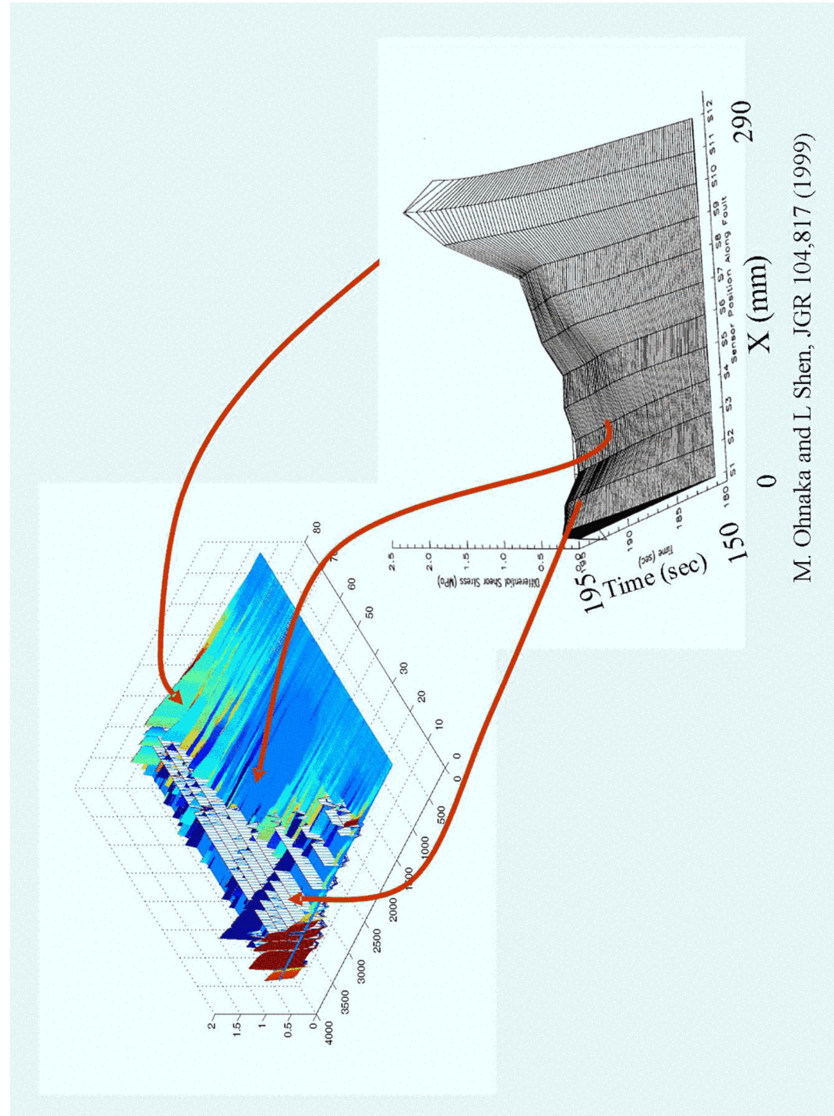
Slow detachment fronts are nearly always observed in experiments.
Are silent earthquakes more common than currently believed?

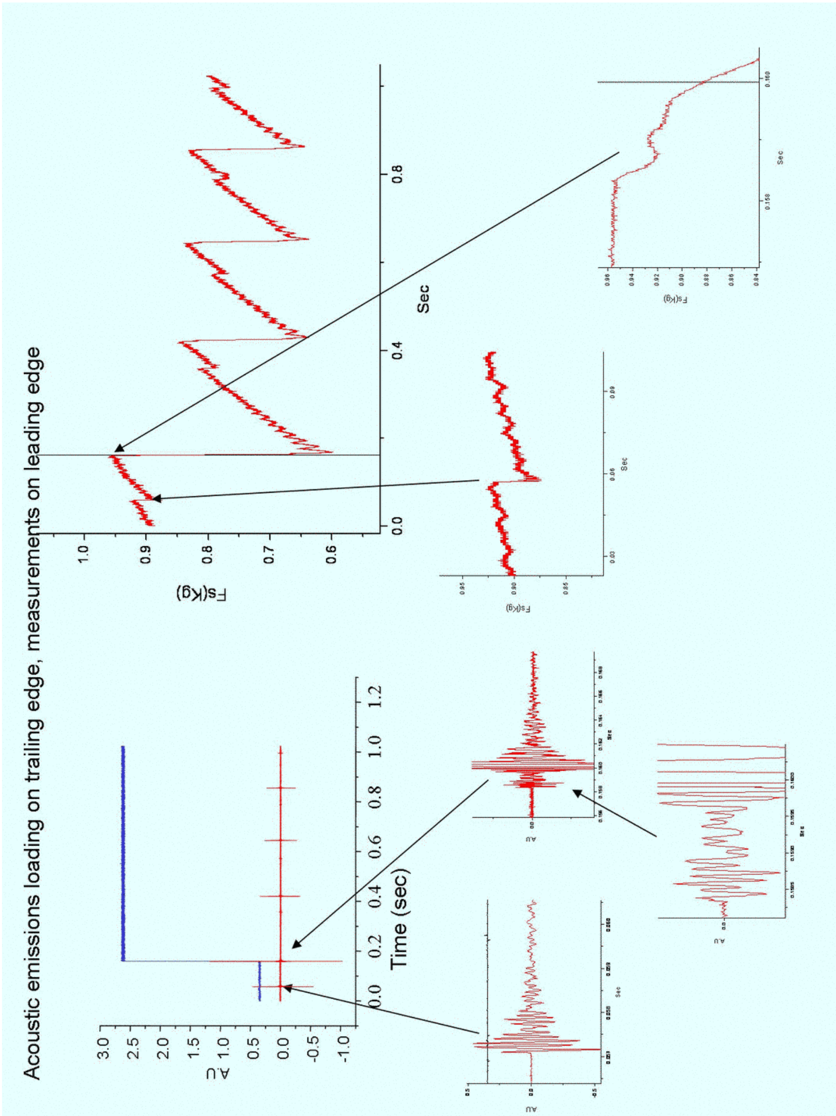
[1] Bouchon, M. et al. *Geophys. Res. Lett.* **28**, 2723-2726 (2001).
[2] Crescentini, L., Amoruso, A. & Scarpa, R. *Science* **286**, 2132-2134 (1999);
Linde, A. T. & Sacks, I. S. *Earth and Planetary Science Letters* **203**, 265-275 (2002).
Rogers, G. & Dragert, H. *Science* **300**, 1942-1943 (2003).

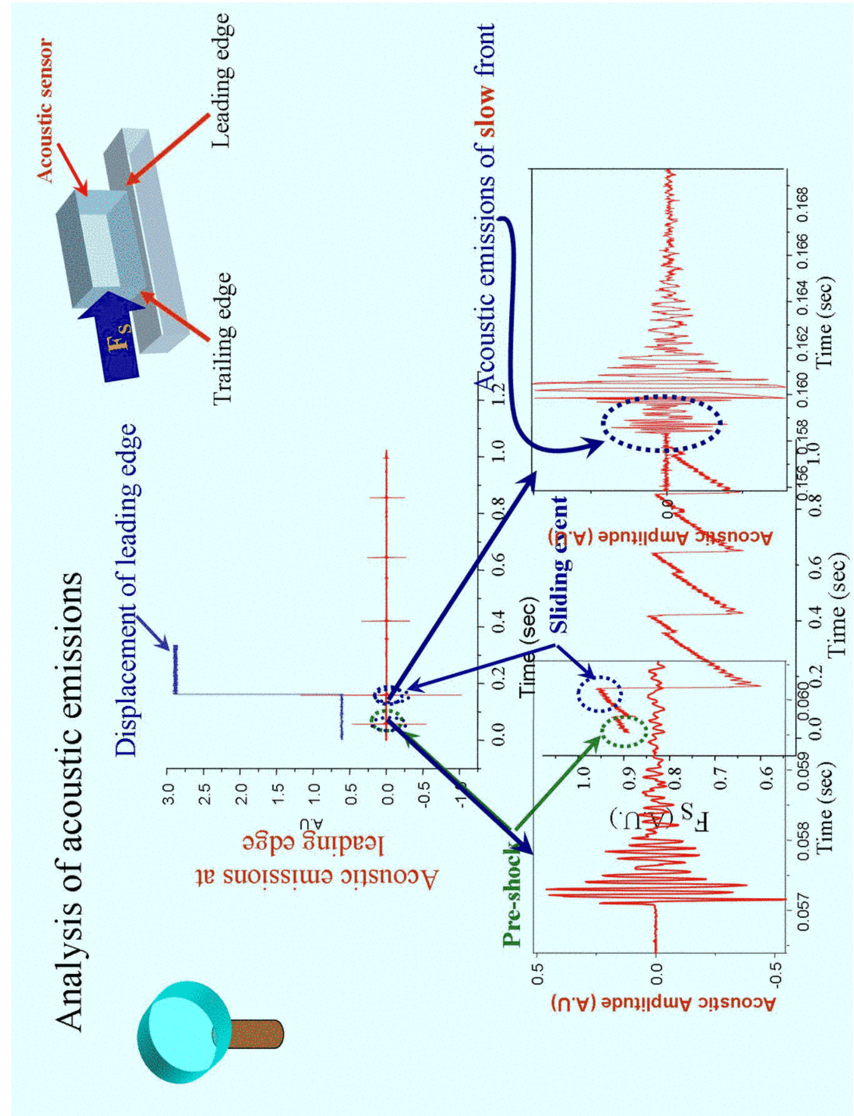
Foreshocks and the loading history

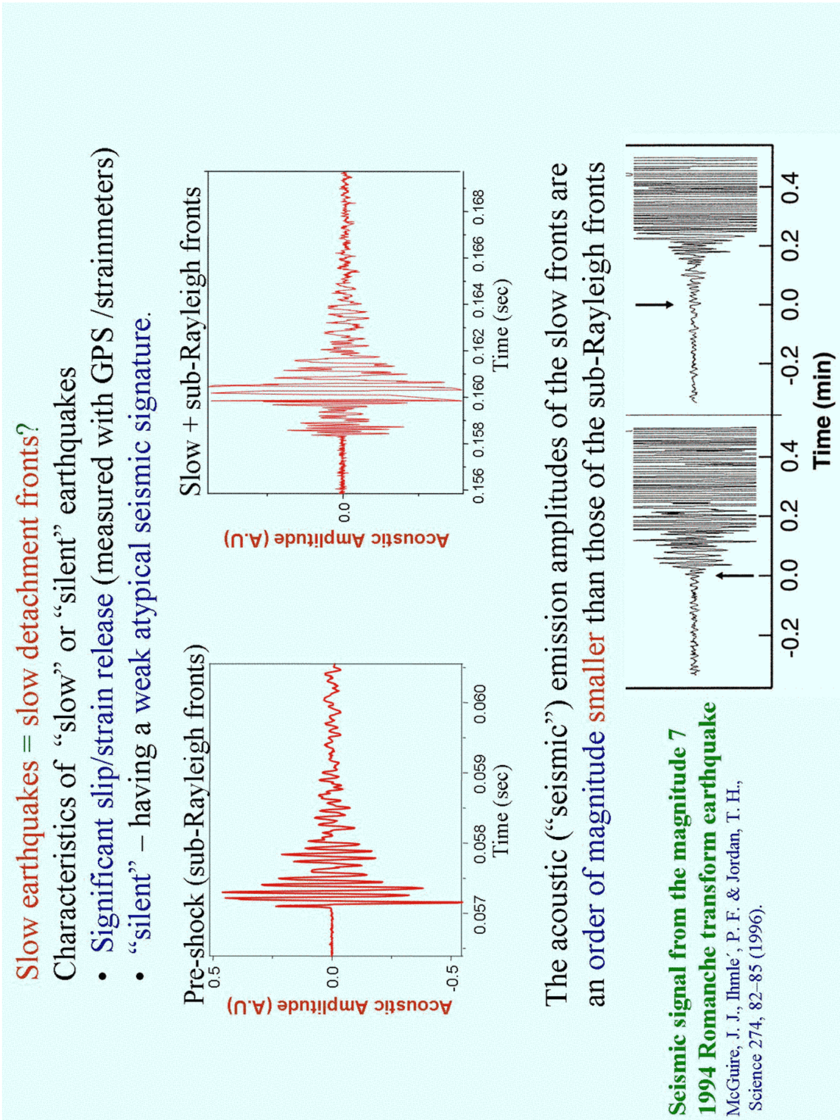



The foreshocks change the normal stress distribution along the interface
Distance (mm)
Time (sec)
Shear Load (Kg)
Time(sec)


X (mm)
Time (sec)
M. Ohnaka and L Shen, JGR 104,817 (1999)


Acoustic emissions loading on trailing edge, measurements on leading edge
A.U
Time (sec)
Fs(Kg)
Sec


Analysis of acoustic emissions
Acoustic sensor
Leading edge
Trailing edge
Displacement of leading edge
Acoustic emissions at leading edge
Acoustic emissions of slow front
Sliding event
Pre-shock
Acoustic Amplitude (A.U)
Time (sec)


Slow earthquakes = slow detachment fronts?
Characteristics of "slow" or "silent" earthquakes
• Significant slip/strain release (measured with GPS /strainmeters)
• "silent" – having a weak atypical seismic signature.
Pre-shock (sub-Rayleigh fronts)
Acoustic Amplitude (A.U)
Time (sec)
Slow + sub-Rayleigh fronts
Acoustic Amplitude (A.U)
Time (sec)
The acoustic ("seismic") emission amplitudes of the slow fronts are an order of magnitude smaller than those of the sub-Rayleigh fronts
Seismic signal from the magnitude 7 1994 Romanche transform earthquake
McGuire, J. J., Ihmle', P. F. & Jordan, T. H., Science 274, 82–85 (1996).
Time (min)