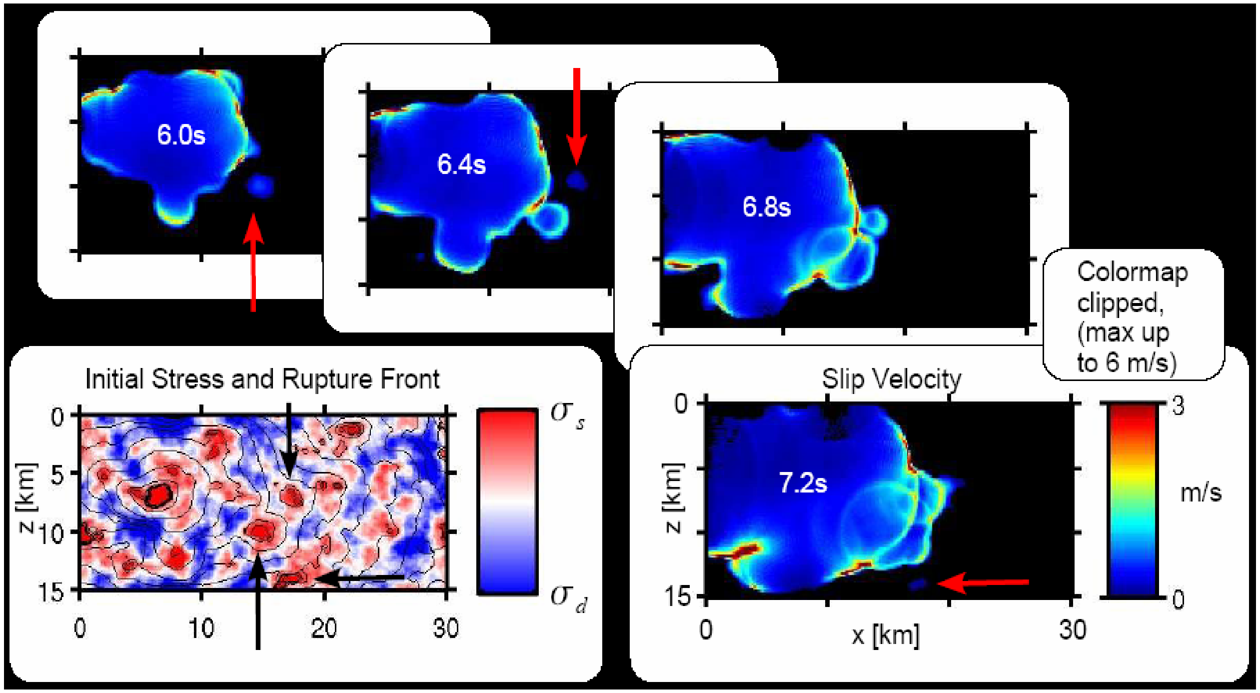
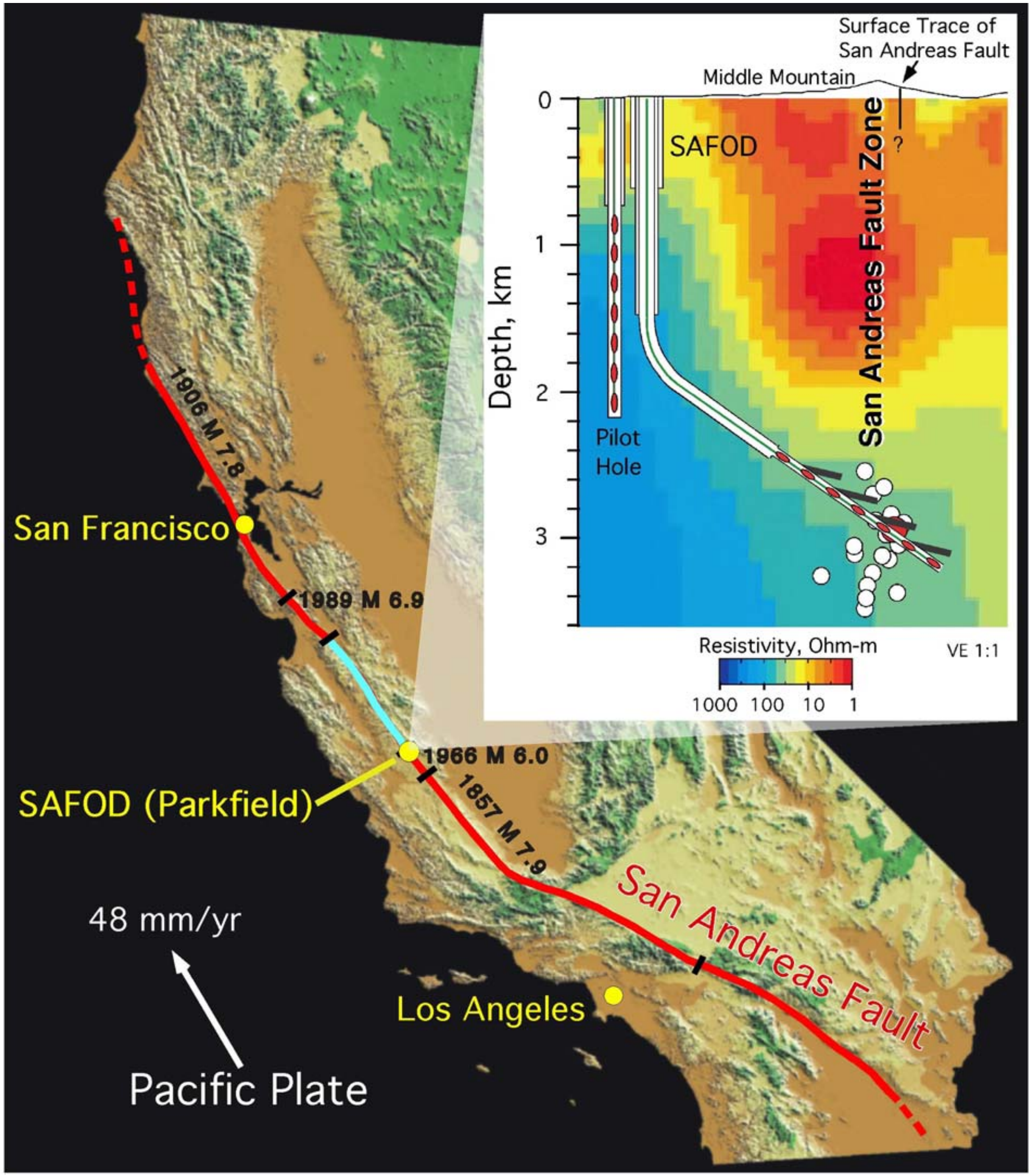
Challenges in earthquake physics and source imaging

Jean-Paul Ampuero and Nadia Lapusta (Caltech Seismolab)



- Main goals and current issues in earthquake dynamics
- The source imaging inverse problem
- Parallels with laboratory experiments
- Interaction of earthquakes and slow slip



Hickman, Zoback, Ellsworth, 2004

San Andreas Fault

Most regions are locked

Creeping section

Potential transient/deep creep on the locked segments

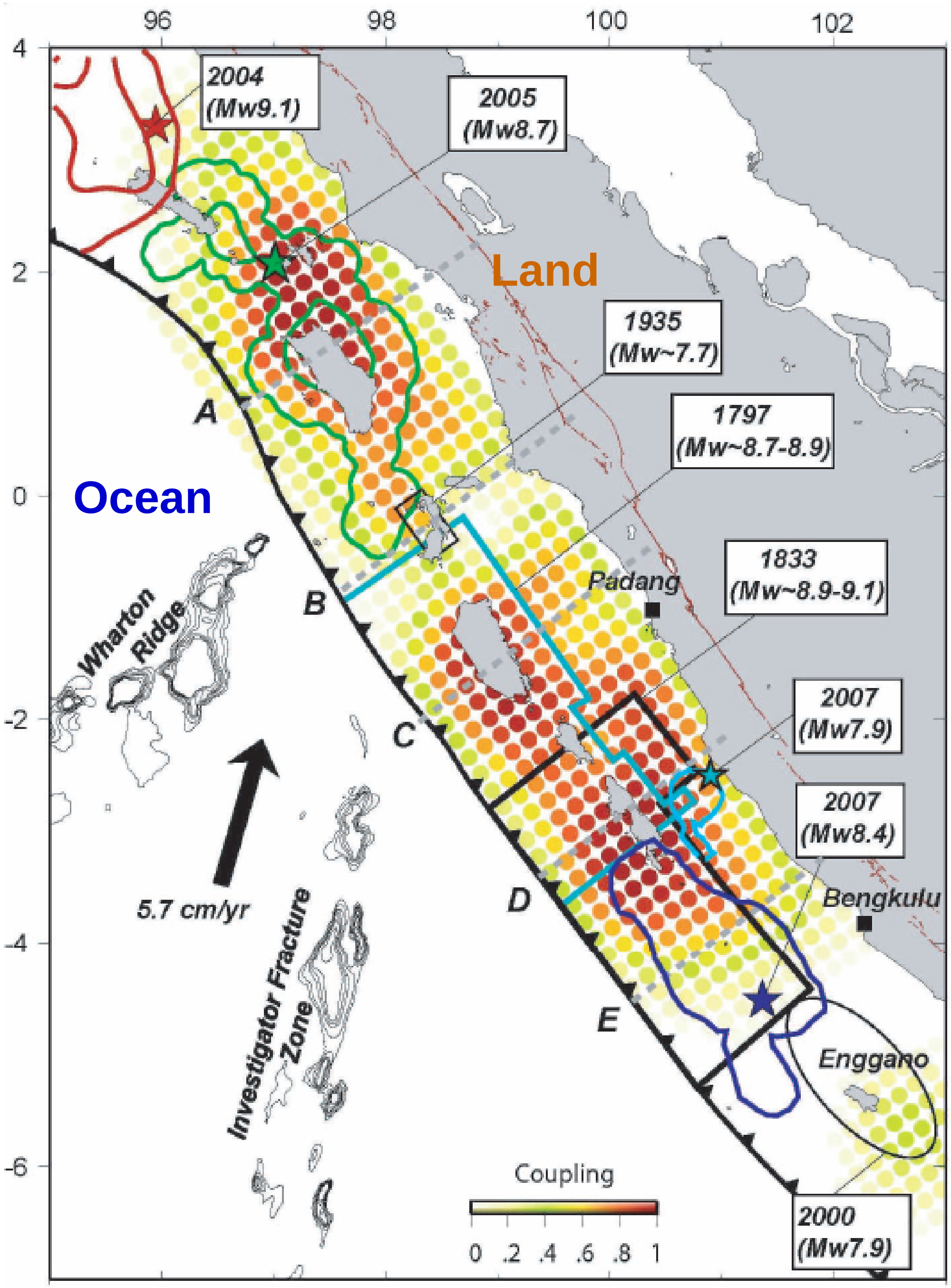
Parkfield M_W 6.0 earthquakes

(..., 1933, 1966, 2004)

Drilling at Parkfield (SAFOD)

Small repeating earthquakes

Complexity of slip behavior on natural faults



Sunda megathrust in Sumatra:

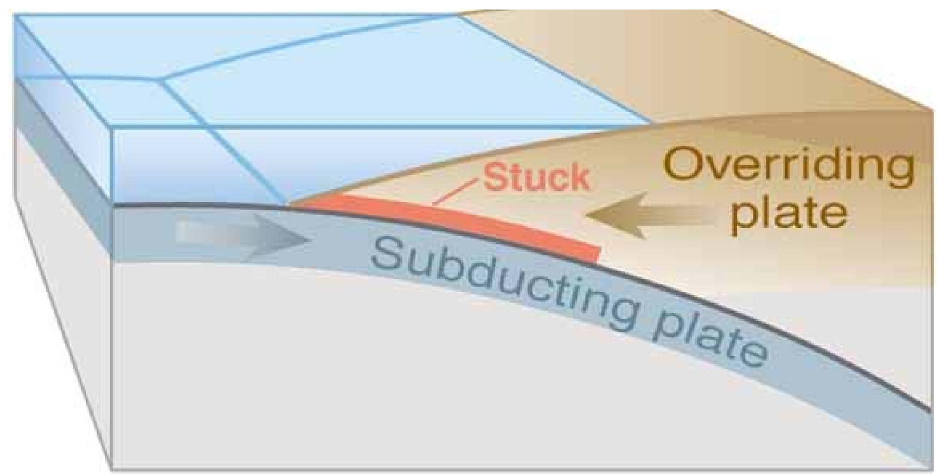
Parts are fully locked

(Coupling = 1)

Intermediate behavior

Parts slip with the long-term plate rate

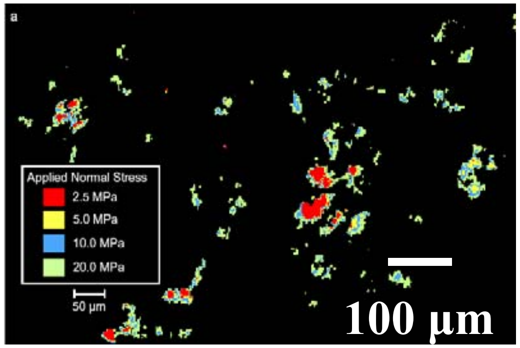
of 5 cm/yr (Coupling = 0, white)



Chlieh, Avouac, Sieh, Natawidjaja, and Galetzka, 2008

USGS website

Micromechanics of friction



Friction laws

$$\tau = \bar{\sigma}\left(f_o + a \ln \frac{V}{V_o} + b \ln \frac{V_o \theta}{L} \right)$$

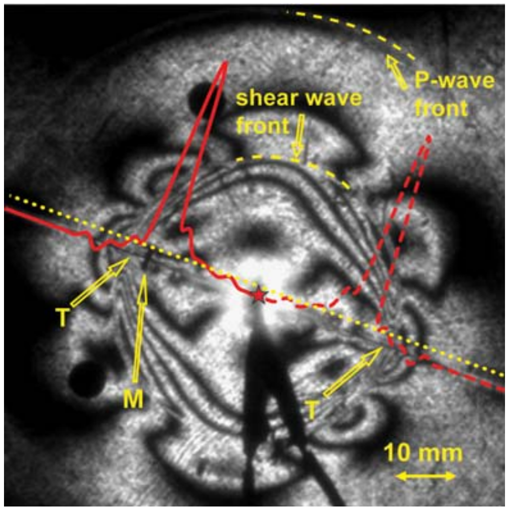
$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$

Comp. methodology

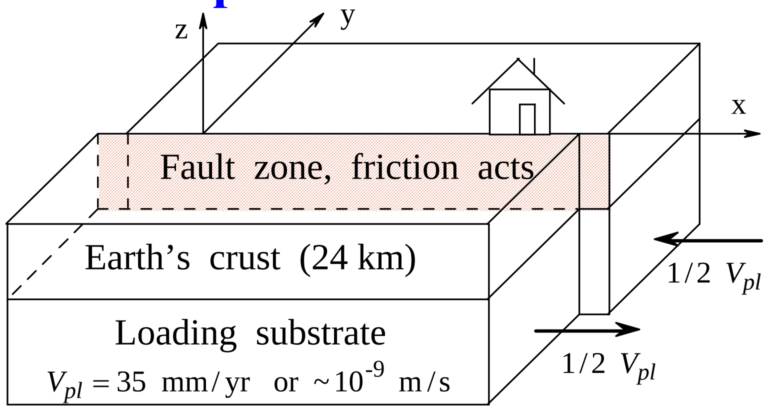
Boundary integral method

Spectral element method

Insight from lab experiments

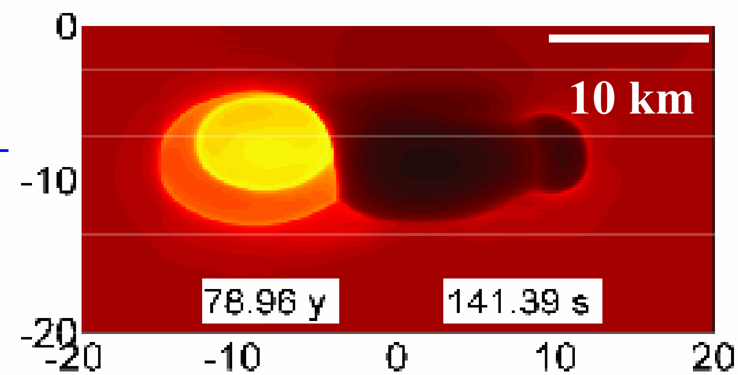


Simplified fault models

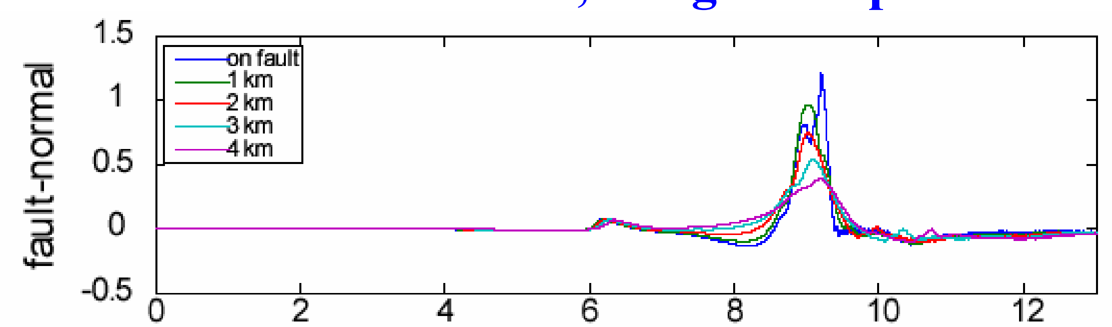


Supercomputer

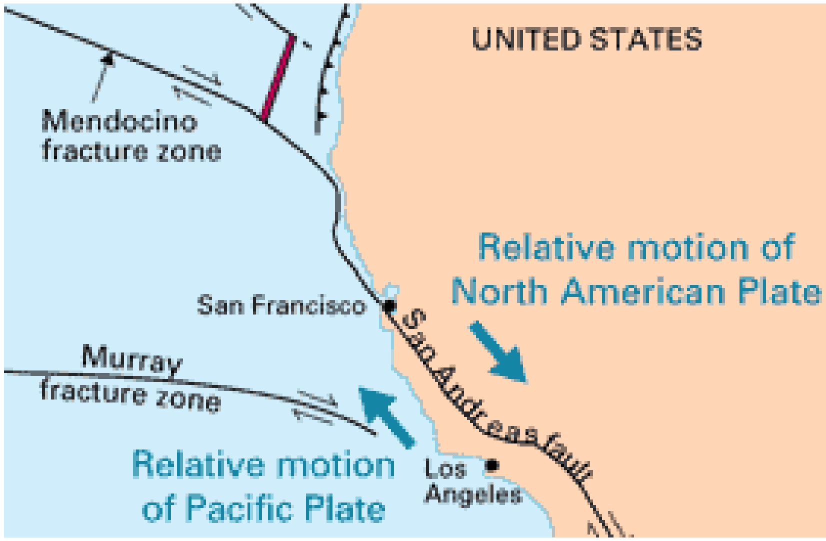
Simulations of fault slip



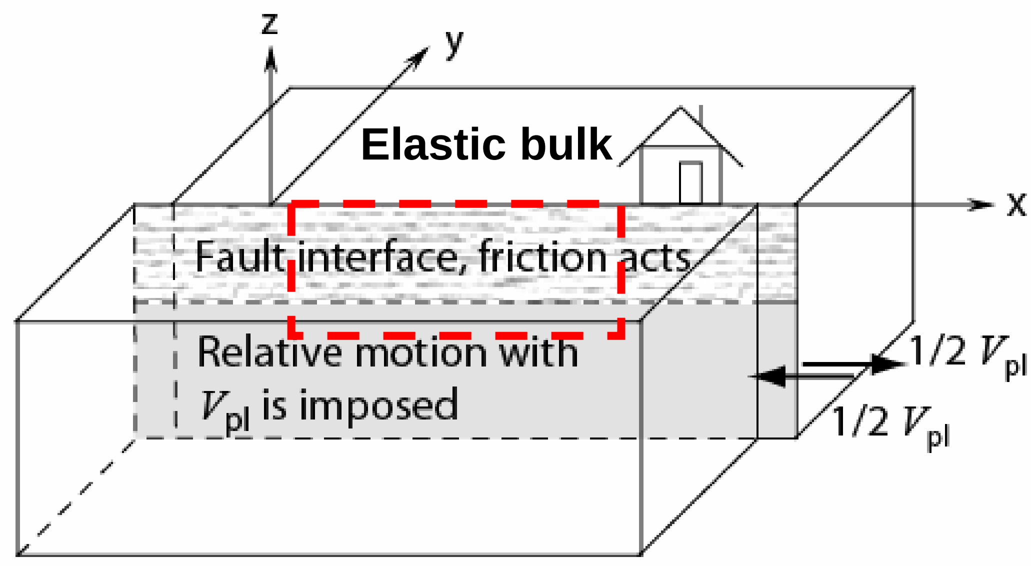
Synthetic data, comparison with field and lab observations, design of experiments

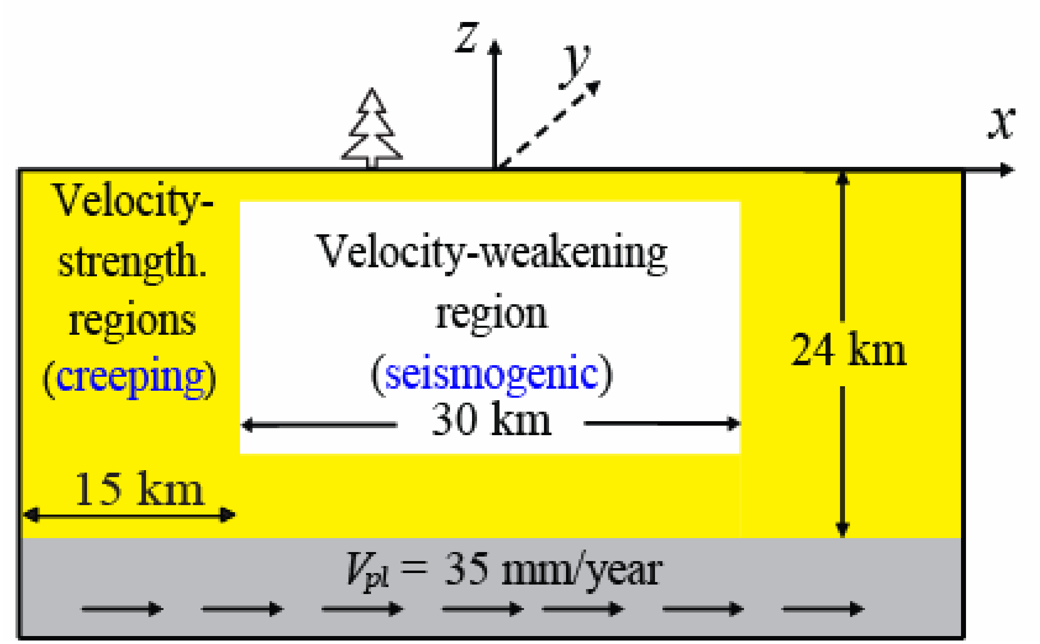


Model of a vertical strike-slip fault



http://pubs.usgs.gov/publications/text/dynamic.html





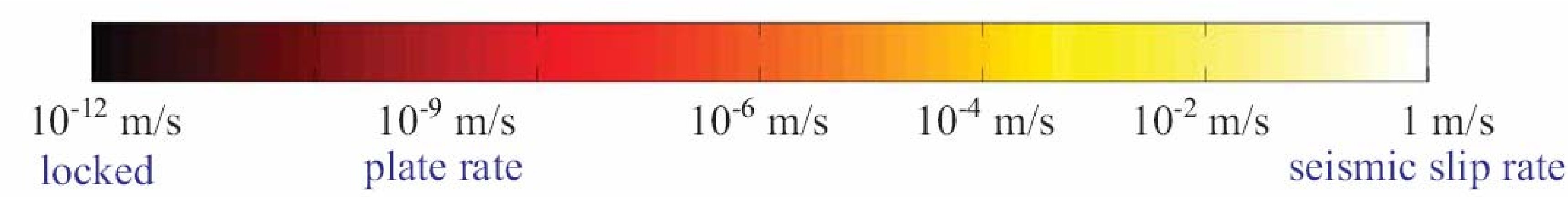
We use **boundary integral method**
to simulate ***spontaneous***
slip accumulation on the interface
by solving the system

Shear traction on the fault =

Friction strength of the fault

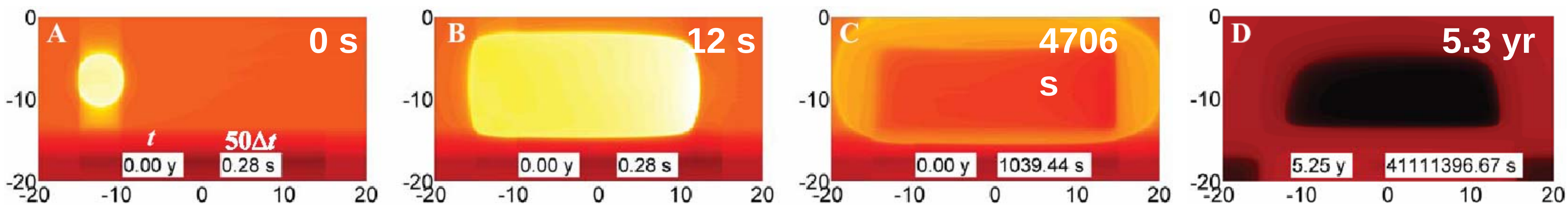
(Lapusta and Liu, JGR, 2009)

3D simulations of earthquake cycles:
Snapshots of relative slip velocity on the interface



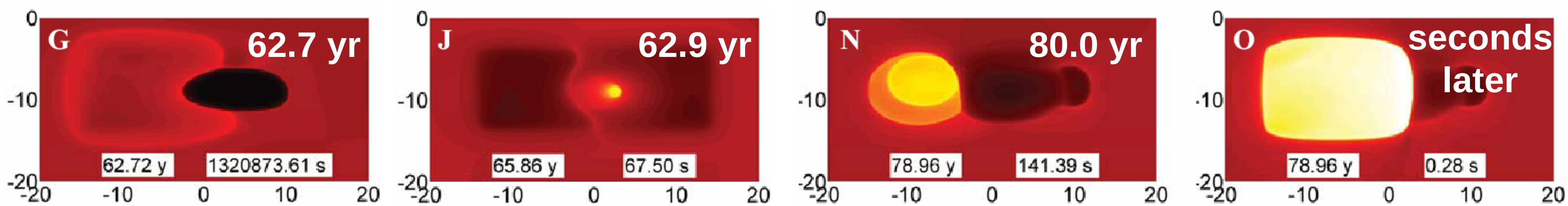
Large earthquake, lasts seconds.
Time steps < 0.01 s.

Postseismic slip, interface locks.
Large time steps.



60 years later: Aseismic transients,
small earthquake.

80 years later: Slow nucleation,
fast next large earthquake.



1 billion data points are manipulated at each time step; 100,000 variable time steps.

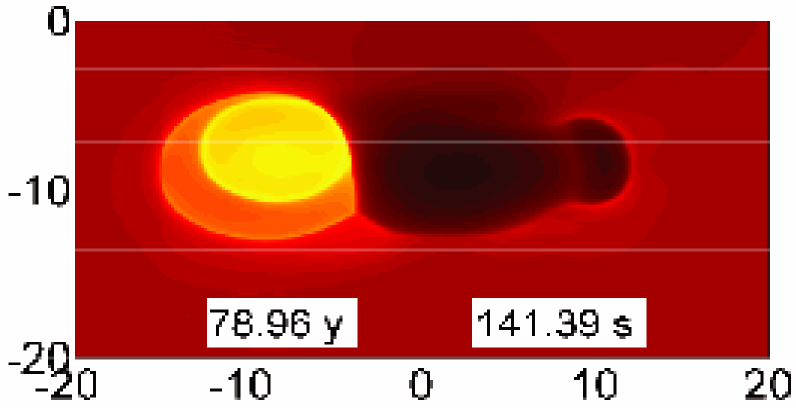
60 processors for this calculation, each with 2GB memory (GPS Beowulf cluster).

(Lapusta and Liu, JGR, 2009)

Interaction of slow slip and earthquakes

We simulate the entire slip history on a fault,

from stable slow sliding of creeping regions,
to aseismic processes in the stick-slip regions,
to dynamic rupture propagation,
and to postseismic slip.



This is the first methodology that combines:

spontaneous fault slip under slow tectonic loading;

full inertial (wave-propagation) effects during earthquakes;

3D fault model governed by lab-derived friction laws.

Combined with seismic and geodetic observations (SPACE?), these simulations can help determine constitutive properties of faults in terms of lab-derived laws.

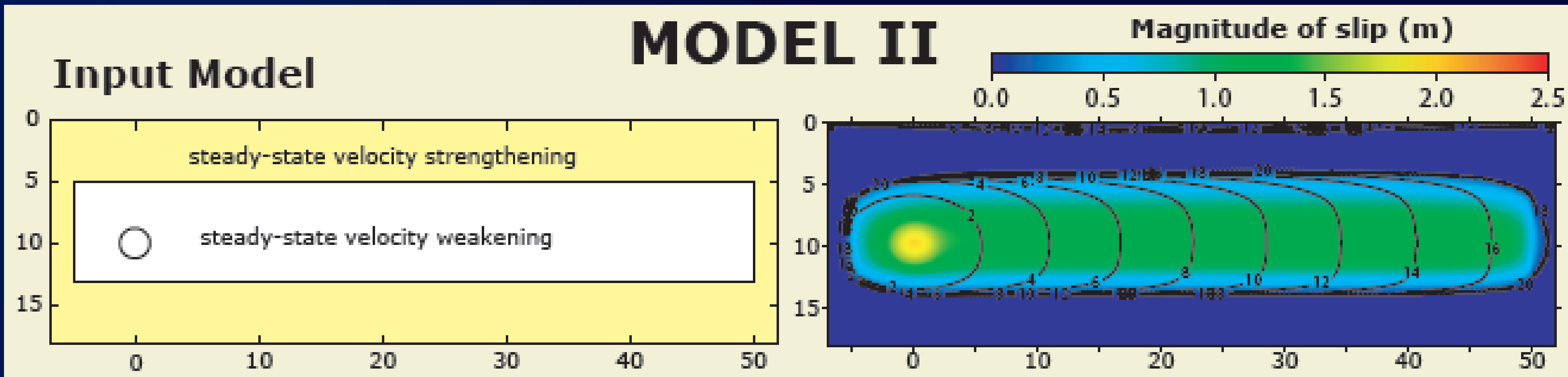
Collaboration with Ampuero, Avouac, Chen, Kaneko, Konca, Noda.

Examples of success:

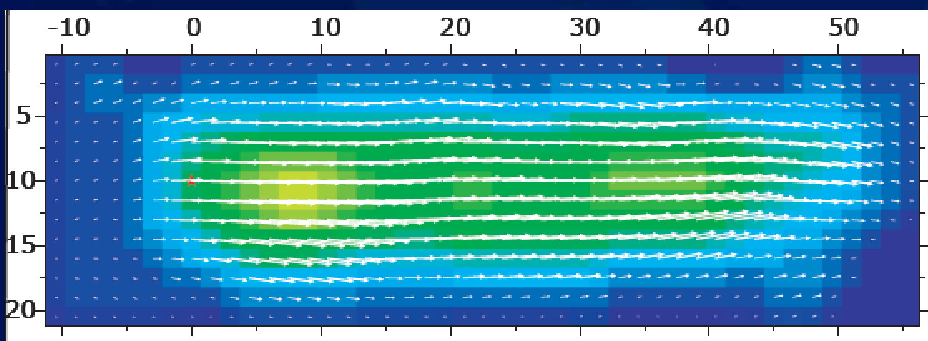
Explanation for scaling and source parameters of small repeating earthquakes.

Reproducing (qualitatively) complex behavior of the Sumatra megathrust.

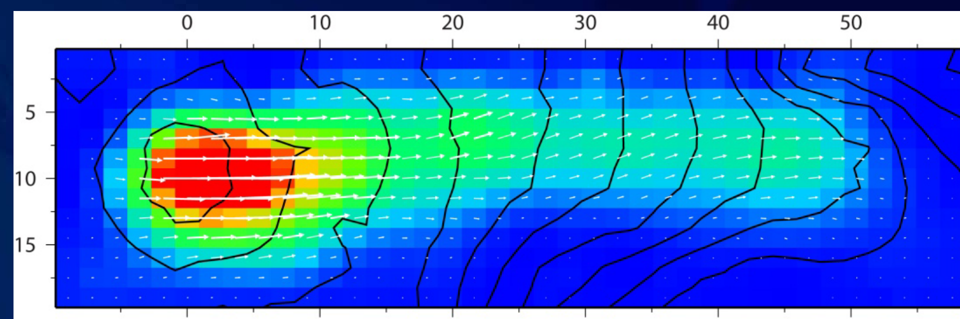
Inversion of a simulated earthquake (Konca, Kaneko, Lapusta, Avouac)



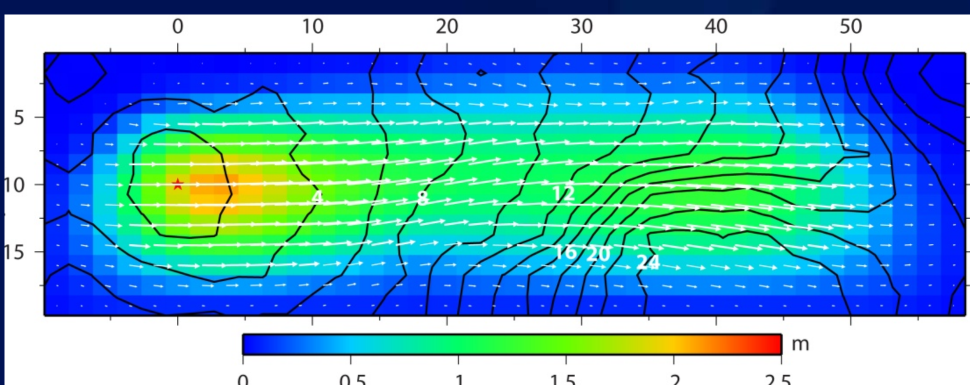
Inversion based on GPS data



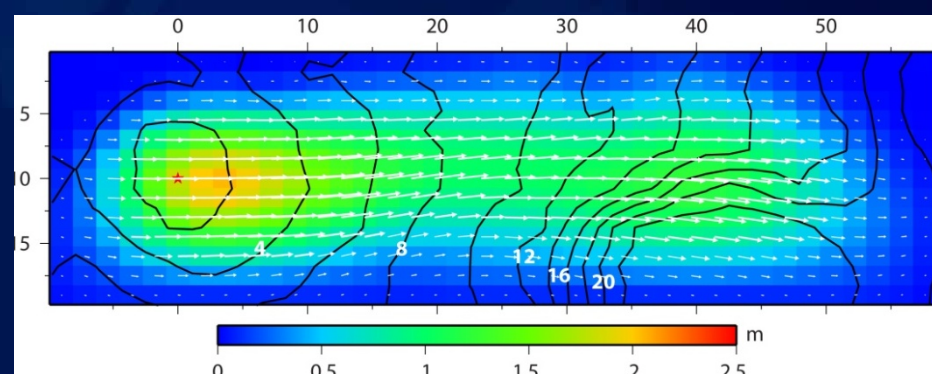
Inversion based on seismic data



Joint inversion 1

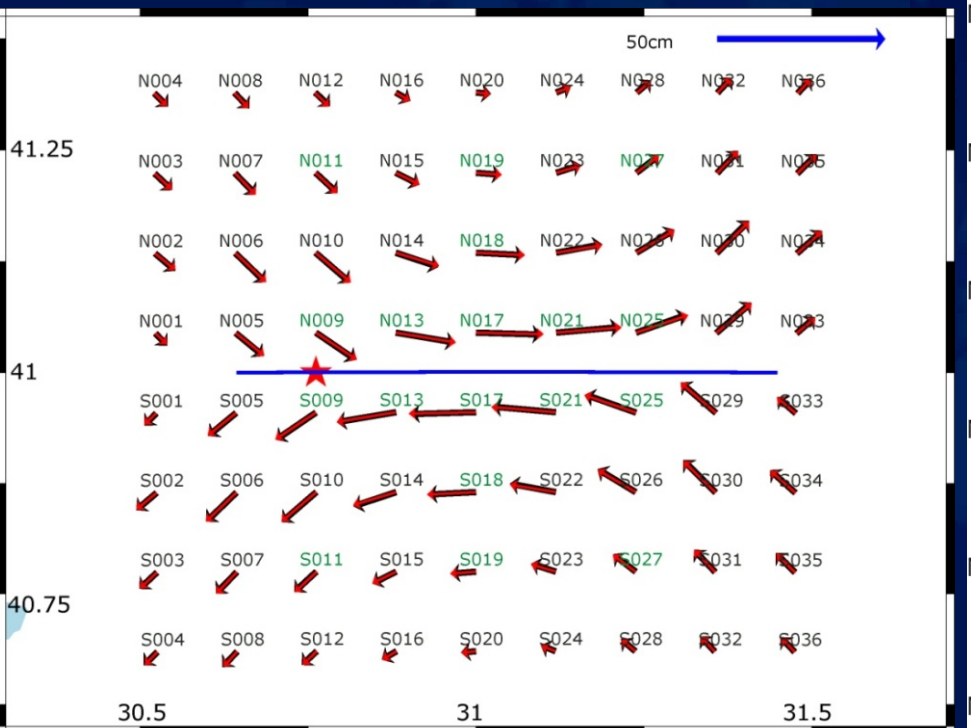


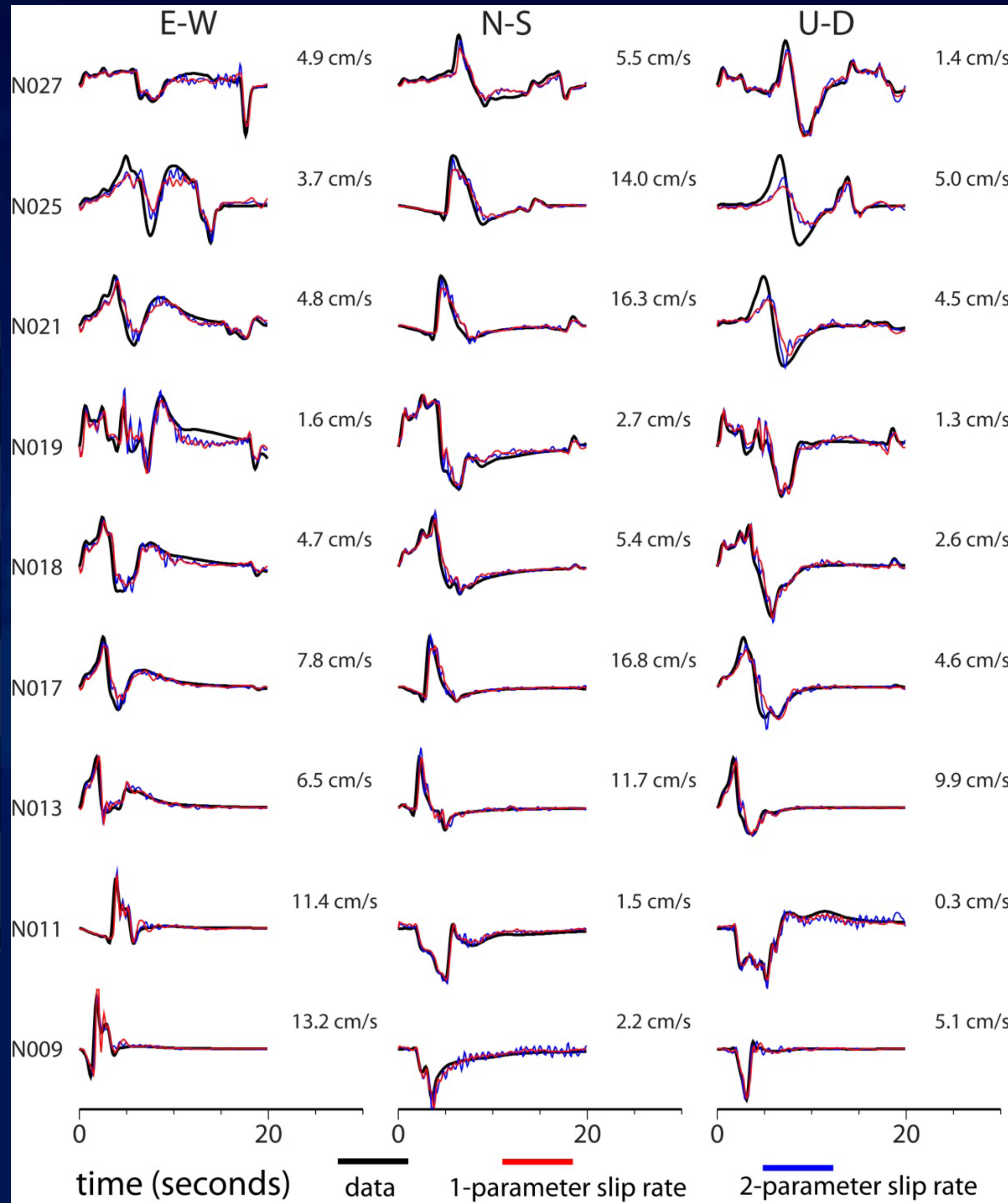
Joint inversion 2



Model 2: Fits to the data; notice the dense coverage assumed

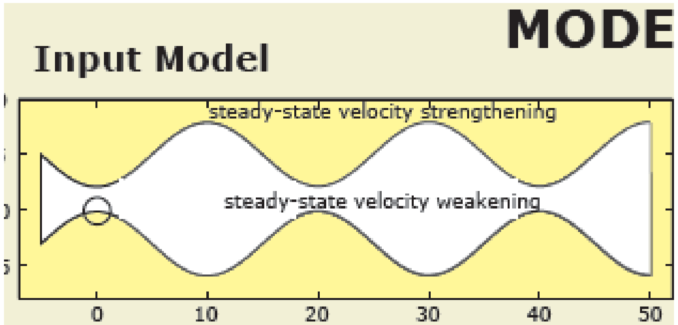
Fits to coseismic GPS motions





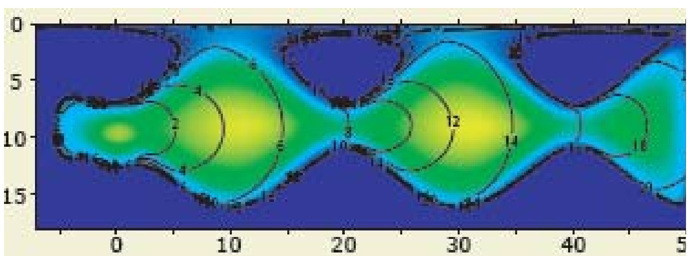
(Konca, Kaneko, Lapusta, Avouac)

Snapshots of slip rate

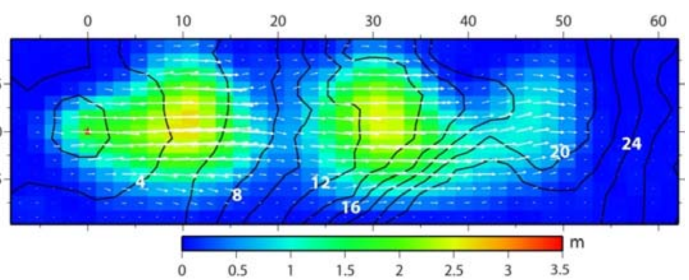


Final slip

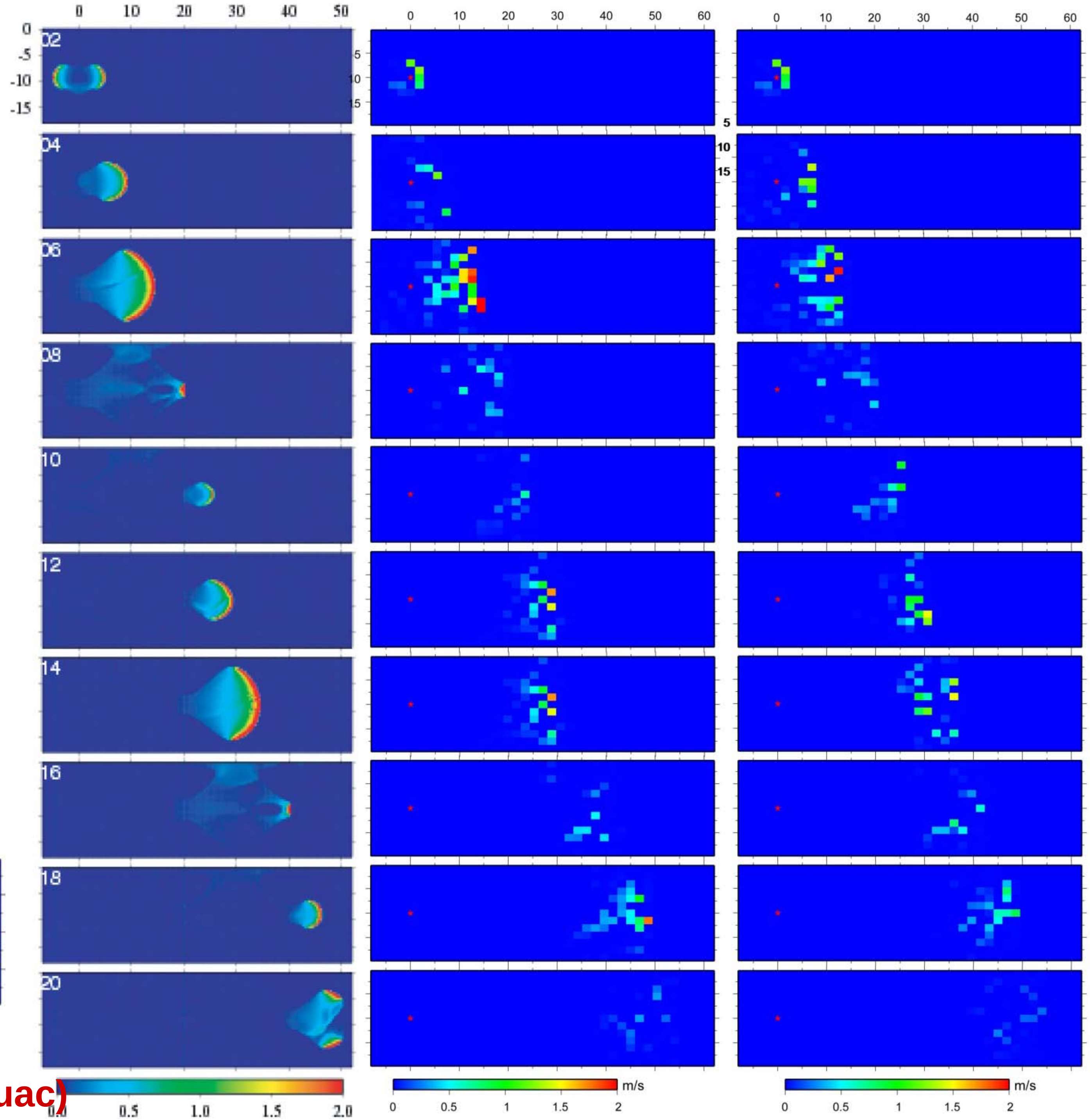
Dynamic simulation



Joint inversion of seismic and GPS data



Dynamic simulation | **Joint inversion of seismic and GPS data**

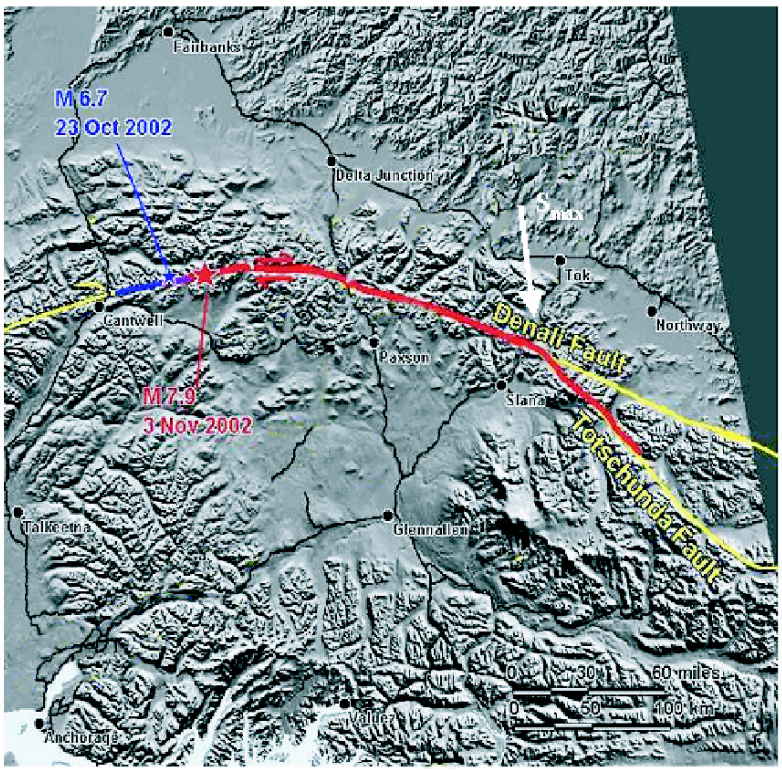


(Konca, Kaneko, Lapusta, Avouac)

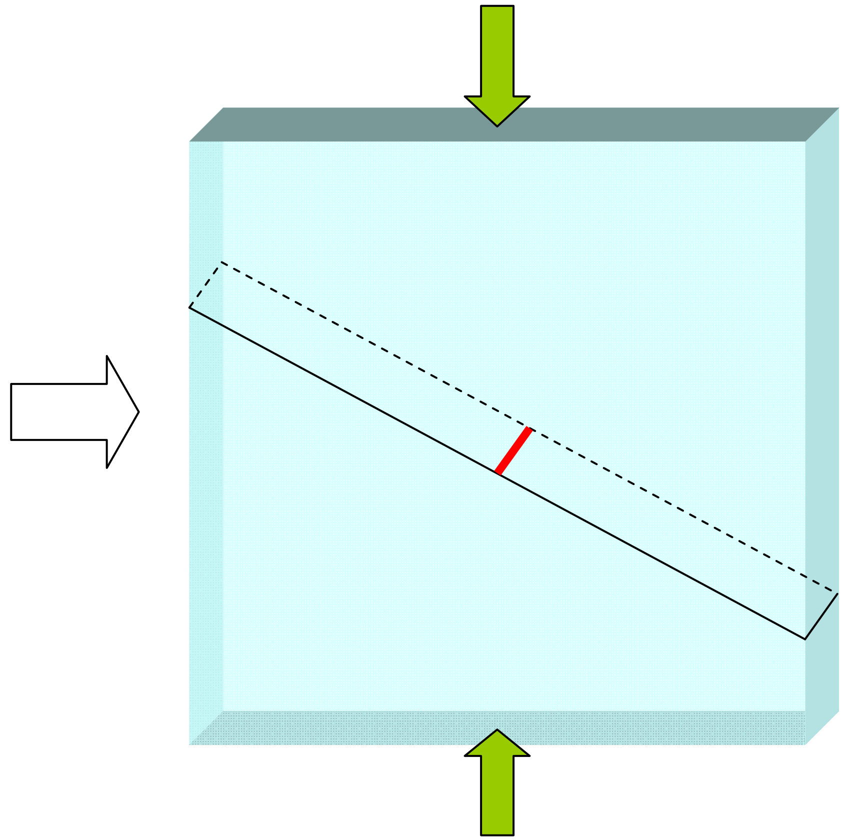
Rise times in laboratory earthquakes

Work with Xiao Lu and Ares Rosakis

M 7.9 , 2002 Denali, Alaska Earthquake

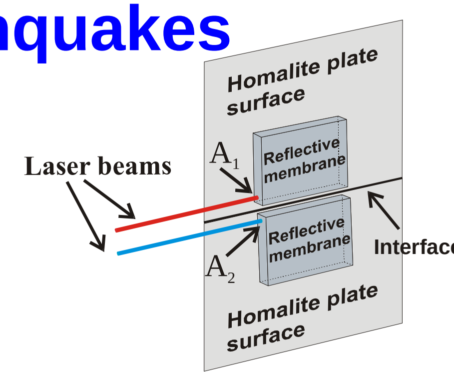


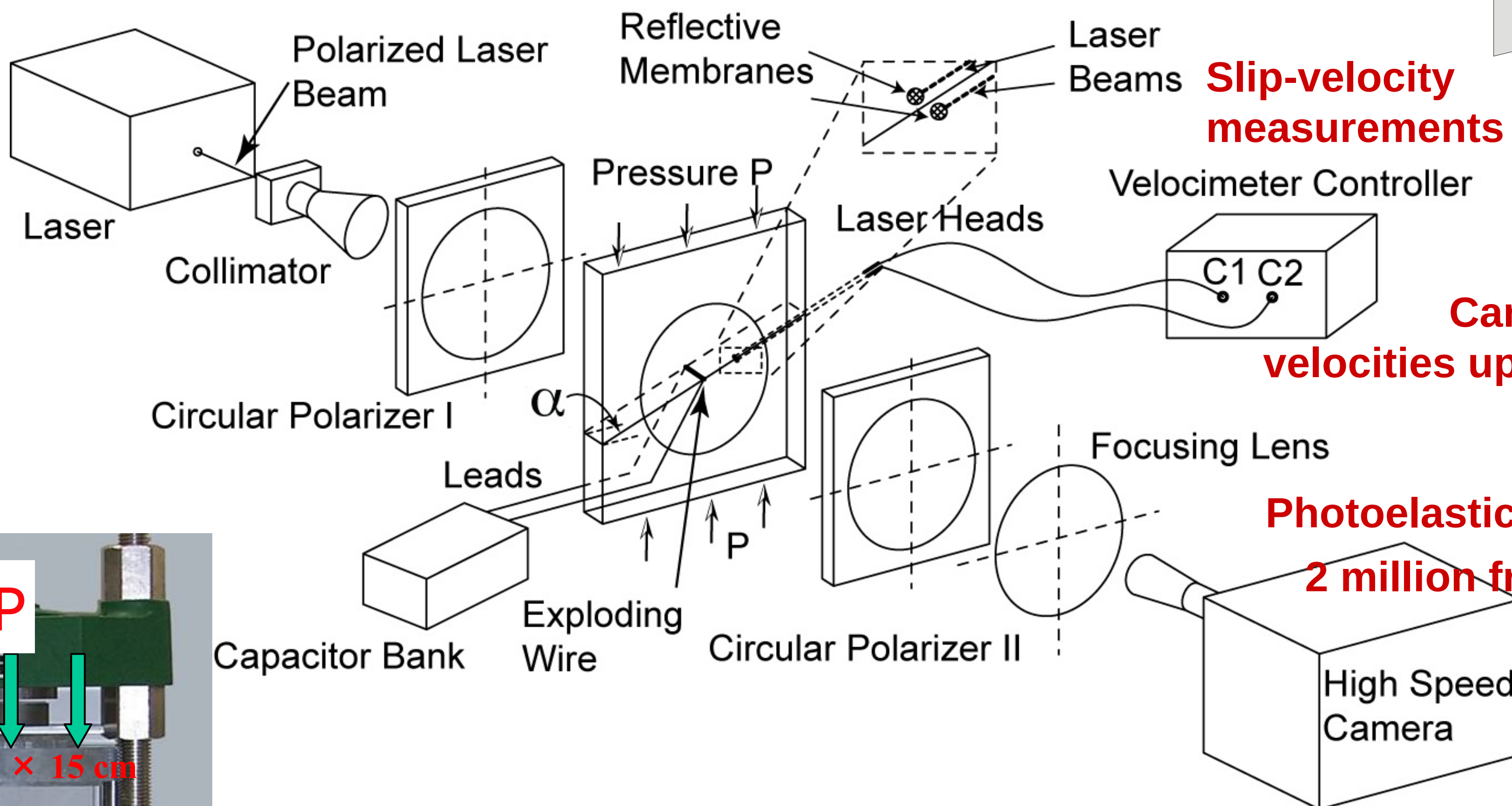
Laboratory Earthquake



Experimental setup that mimics crustal earthquakes

$$\text{Prestress} = \frac{\tau_0}{\sigma_0} = \tan\alpha\,;$$ **can be adjusted**



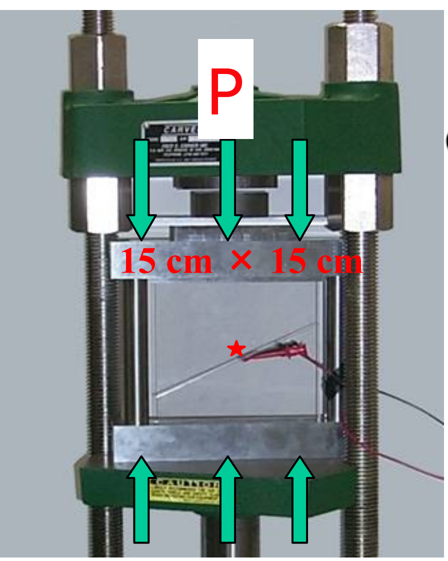


Slip-velocity measurements $\dot{\delta} \equiv \dot{u}_1^+ - \dot{u}_1^-$

Can measure velocities up to 10 m/s

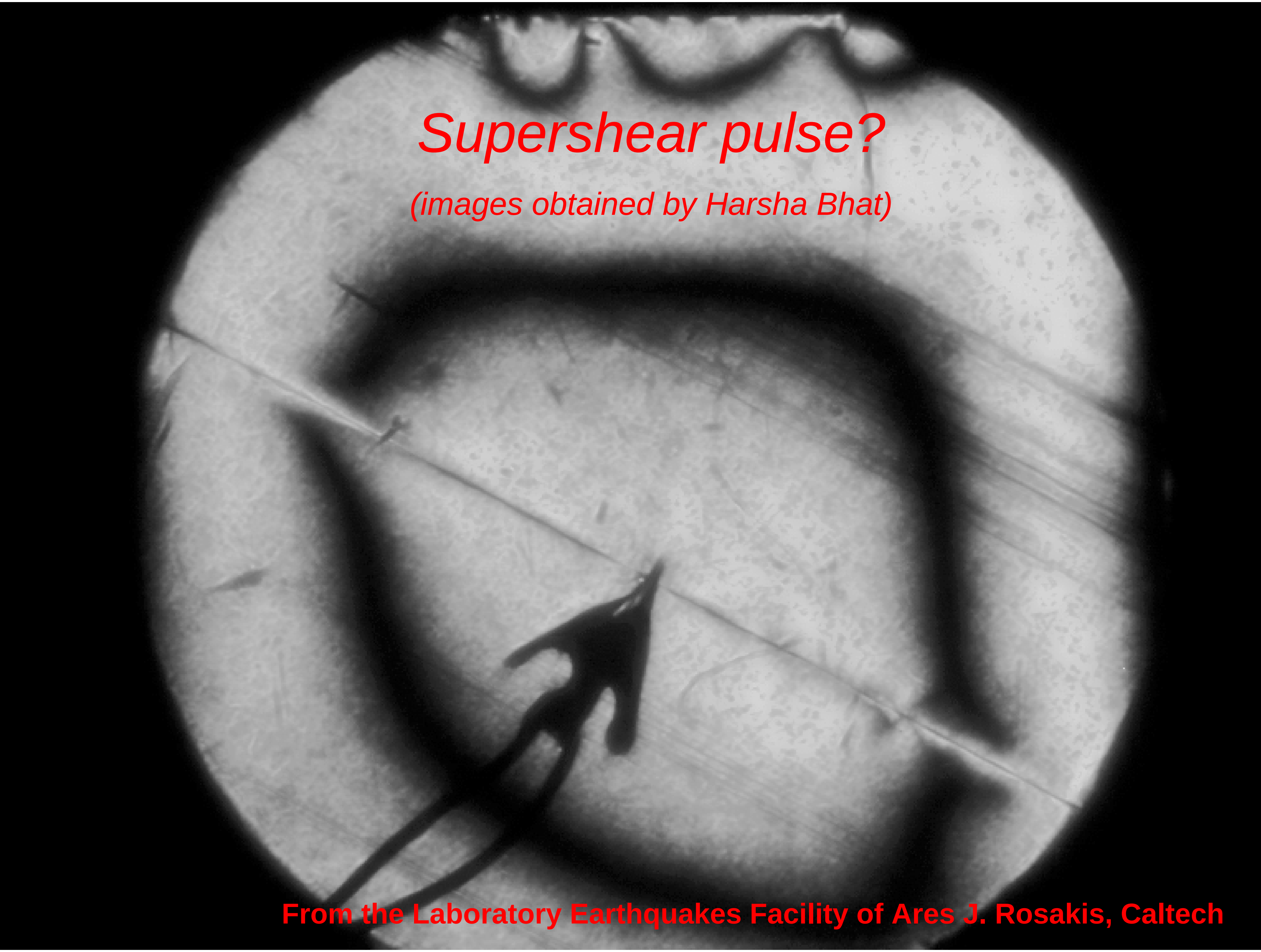
Photoelastic imaging

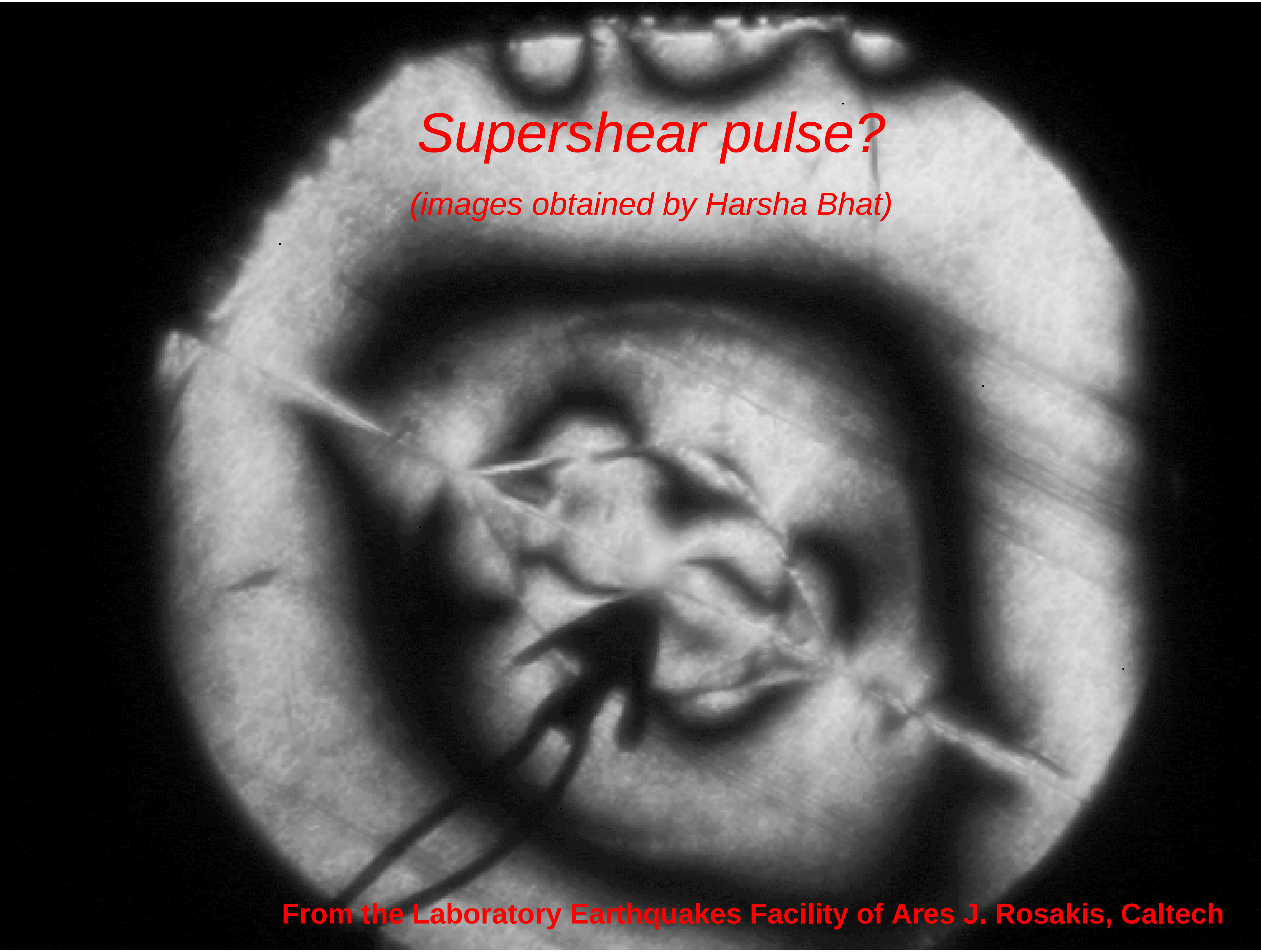
2 million frames/s



Xia, Rosakis and Kanamori, *Science,* 2004
Rosakis et al., *Treatise in Geophysics,* 2007
Lu, Lapusta, and Rosakis, *PNAS*, 104(48), 2007

From the Laboratory Earthquakes Facility of Ares J. Rosakis, Caltech


Supershear pulse?
(images obtained by Harsha Bhat)
From the Laboratory Earthquakes Facility of Ares J. Rosakis, Caltech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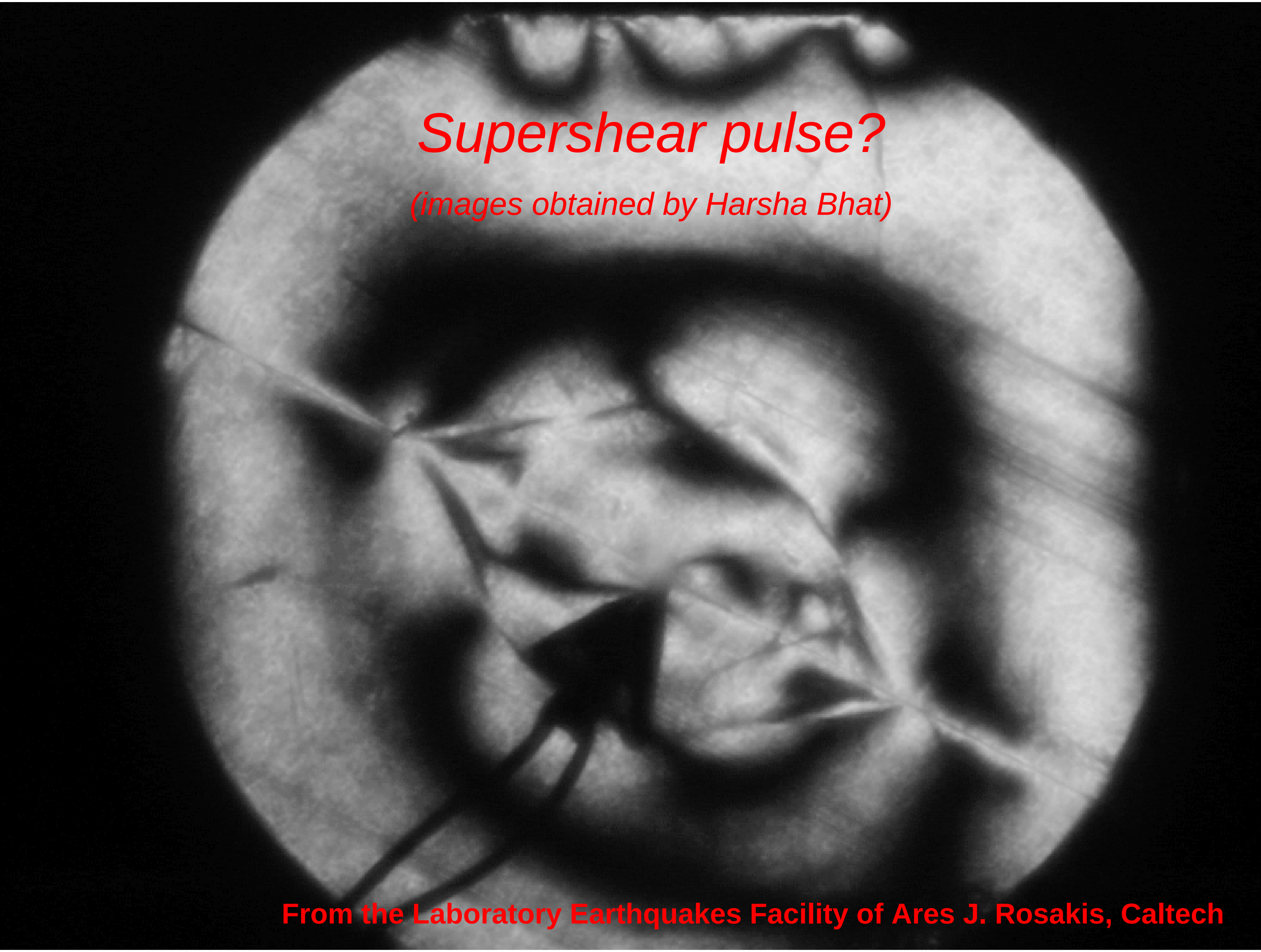
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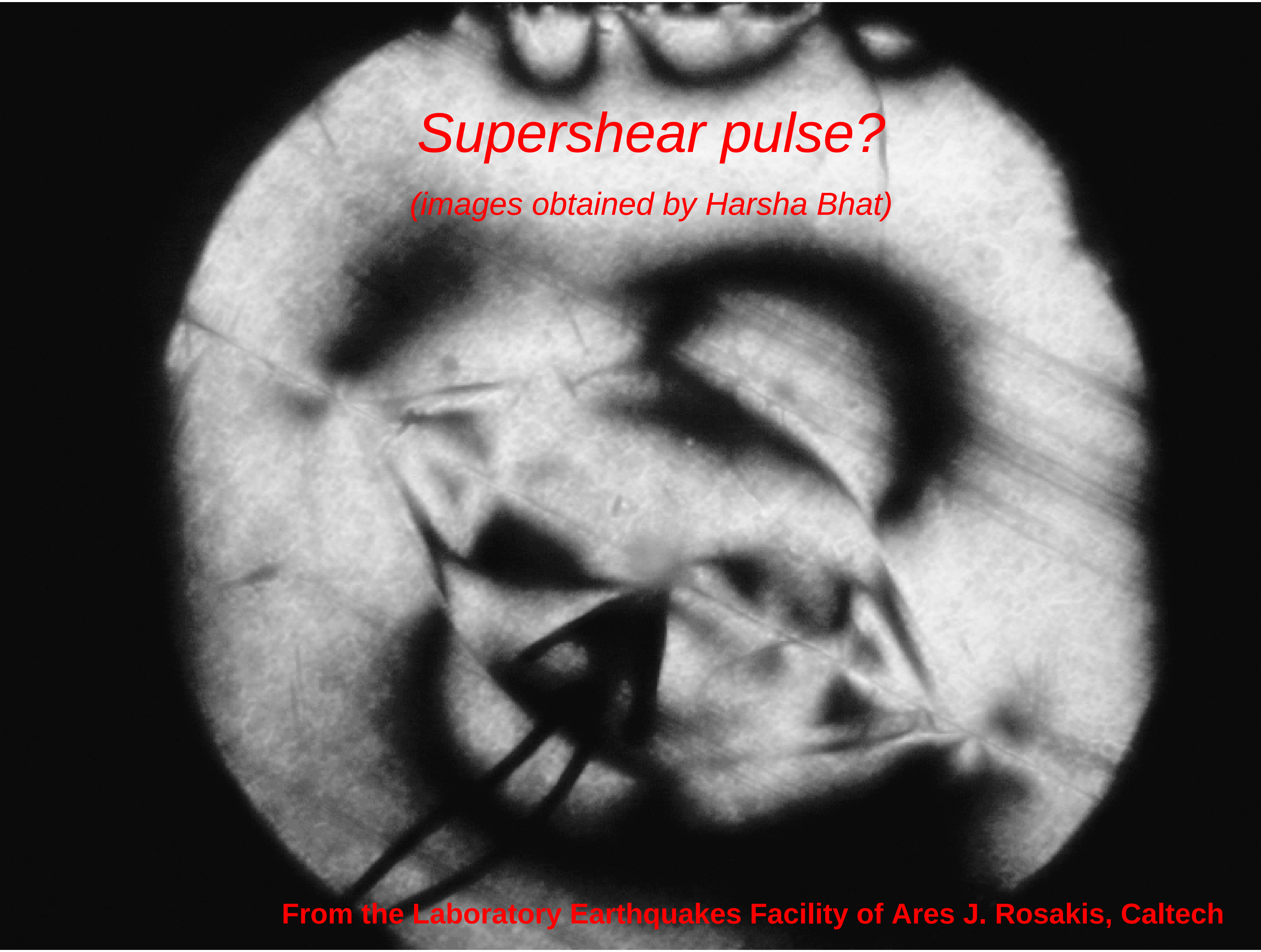
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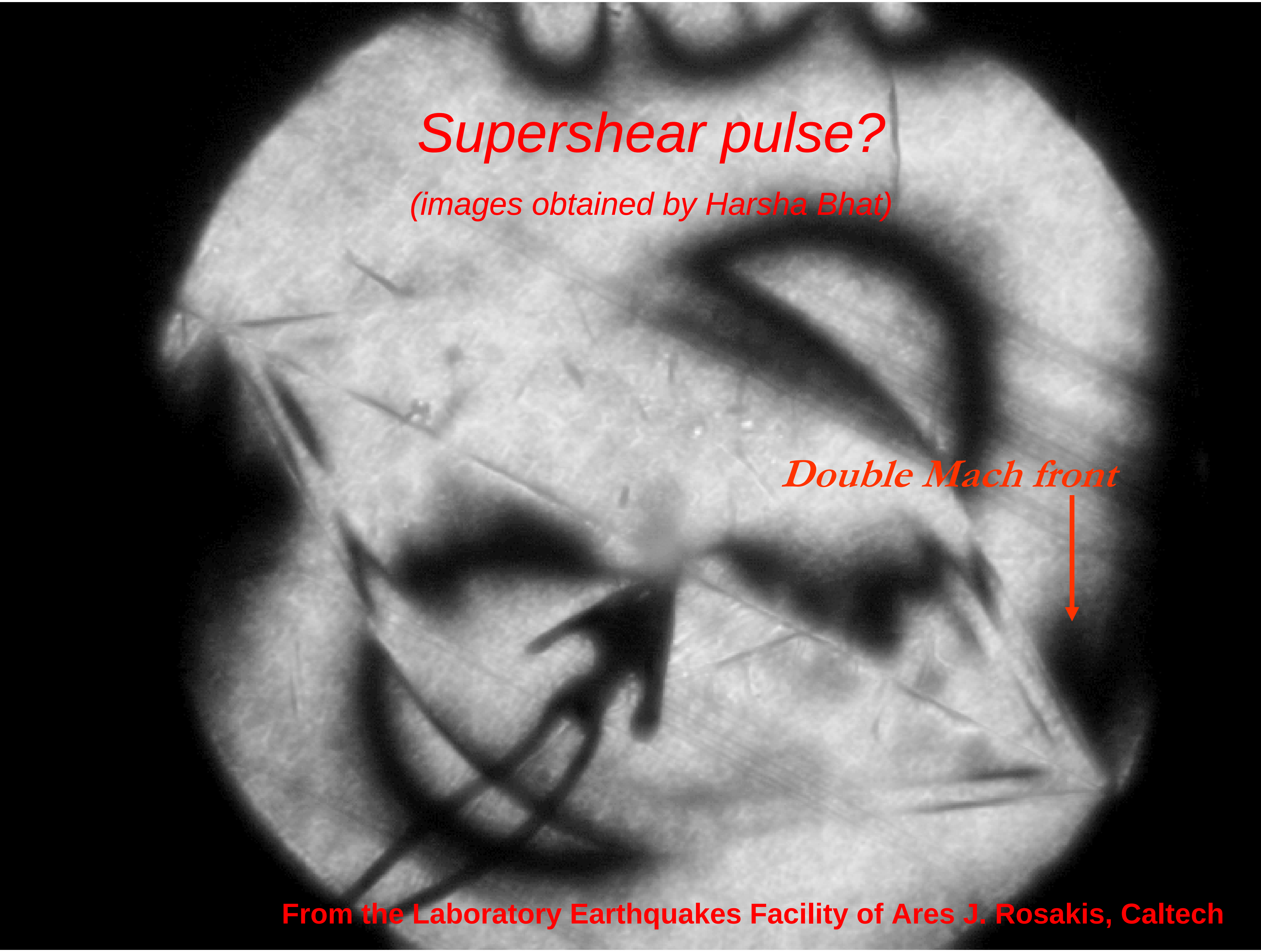

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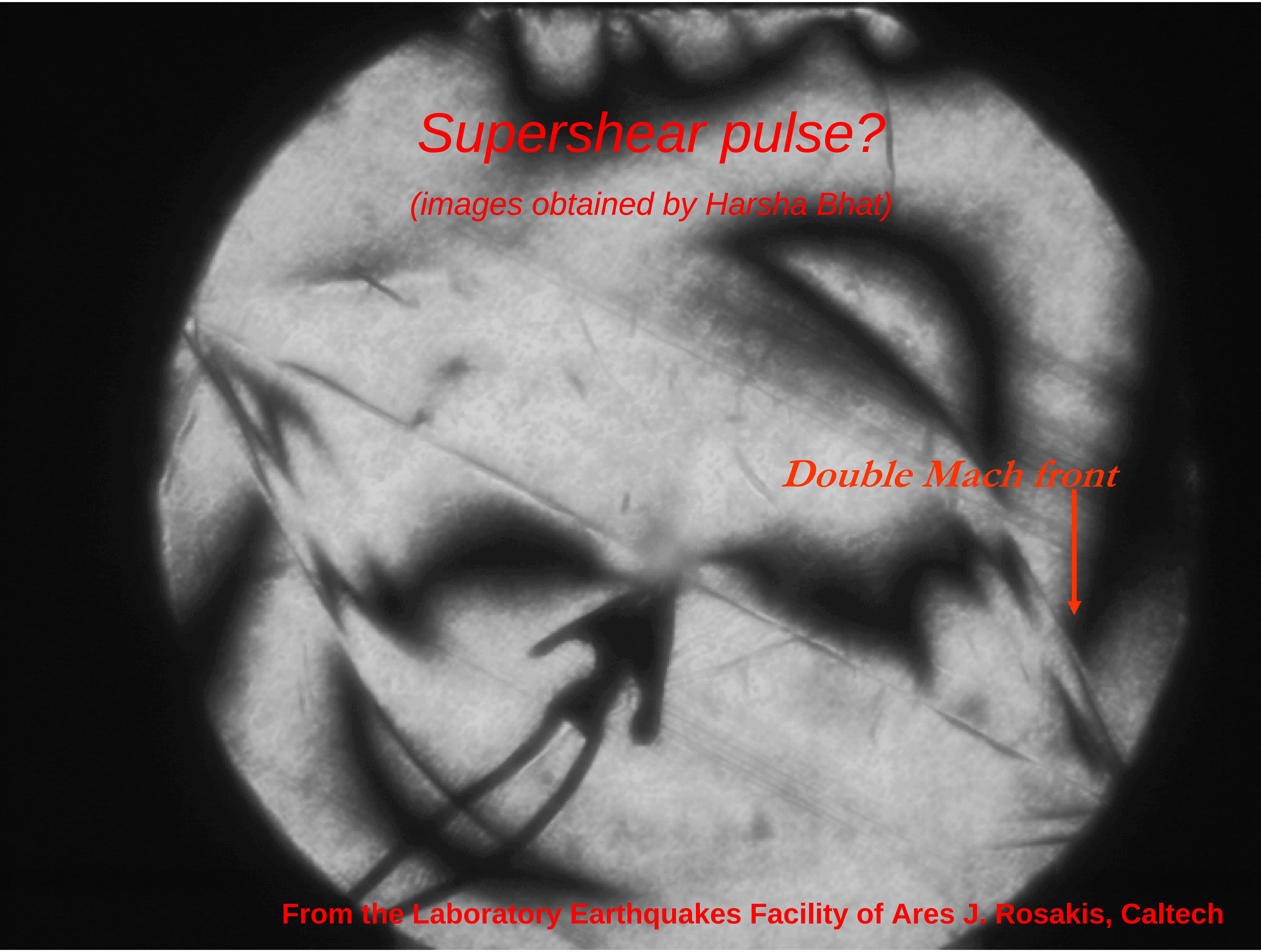
Supershear pulse?
(images obtained by Harsha Bhat)
Double Mach front
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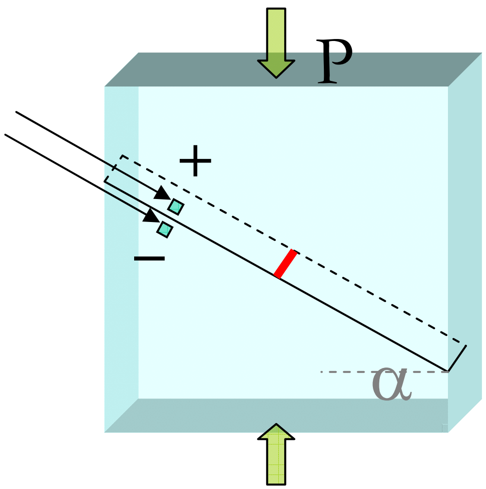
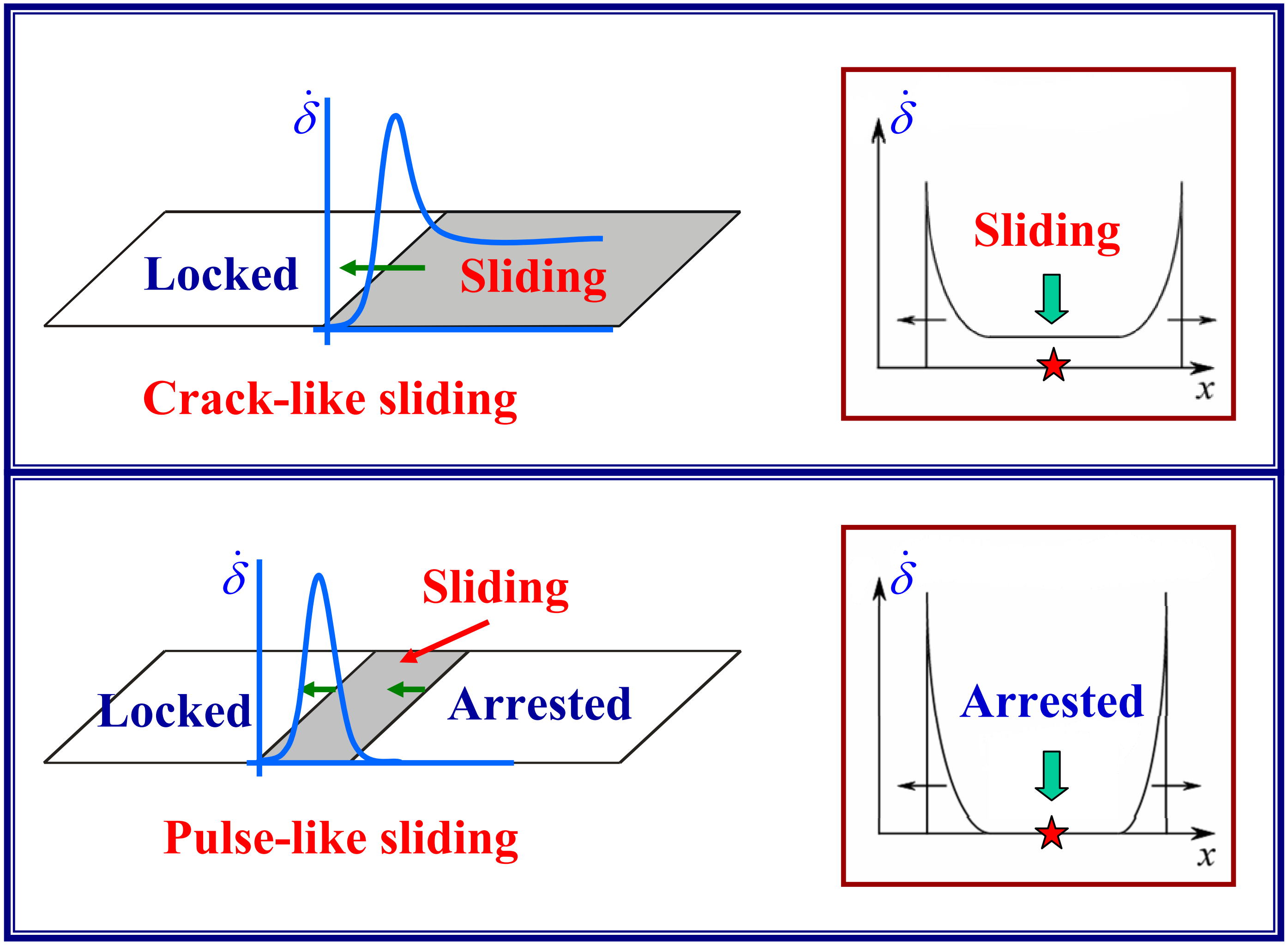
Using particle velocimeters to determine rise times



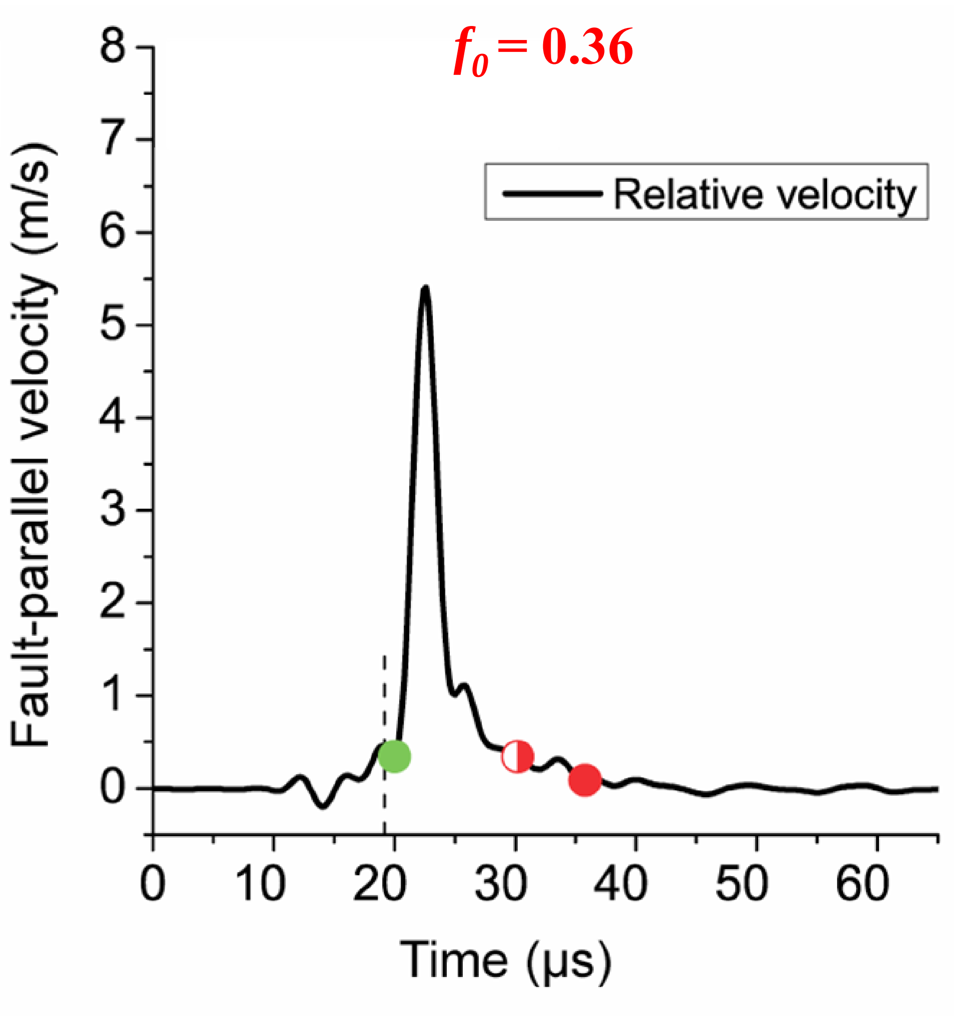
$$V = \dot{\delta} = \dot{u}_1^{+} - \dot{u}_1^{-}$$

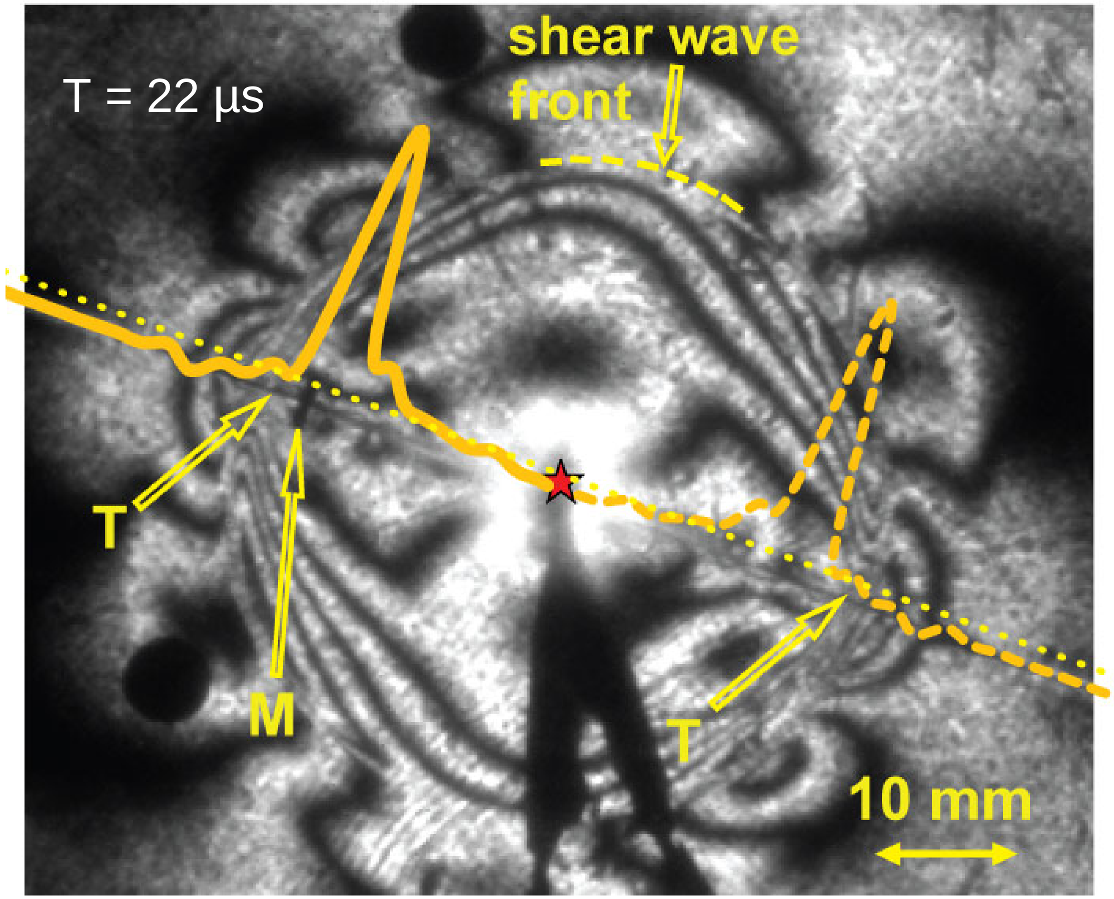


From the Laboratory Earthquakes Facility of Ares J. Rosakis, Caltech

First experimental observation of pulse-like rupture on an interface prestressed in shear

α = 20 degrees, P = 10 MPa, velocity measured at 20 mm





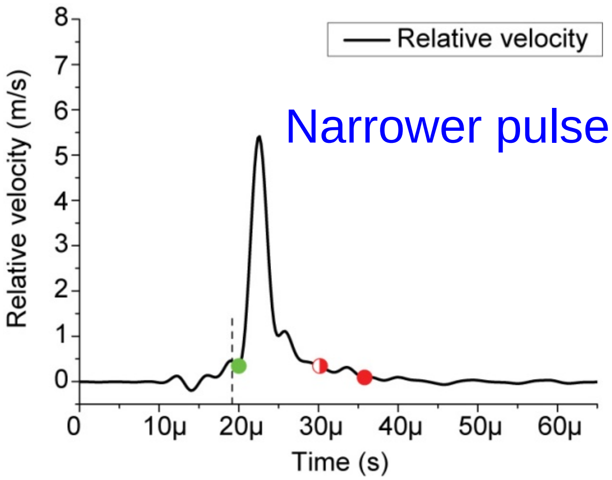
Lu, Lapusta, and Rosakis, *PNAS*, 2007

Non-dimensional shear prestress $= \tau_0 / \sigma_0 = f_0 = \tan\alpha$

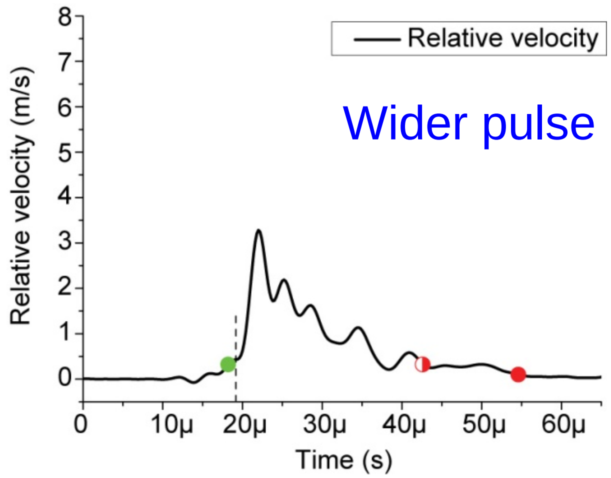
Systematic variation from pulses to cracks as shear prestress is increased

Non-dimensional shear prestress $= \tau_0 / \sigma_0 = f_0 = \tan\alpha$

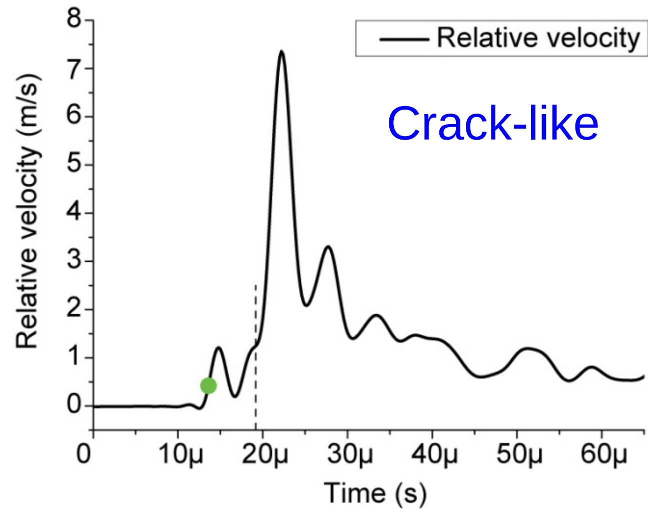
$\alpha = 20^0, \; f_0 = 0.36$

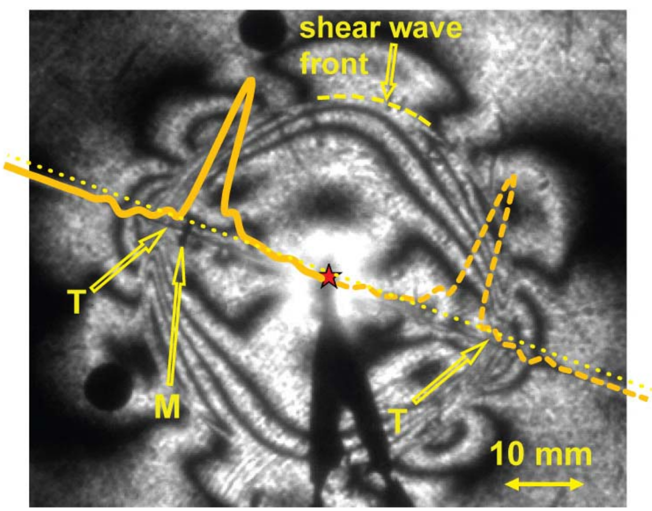


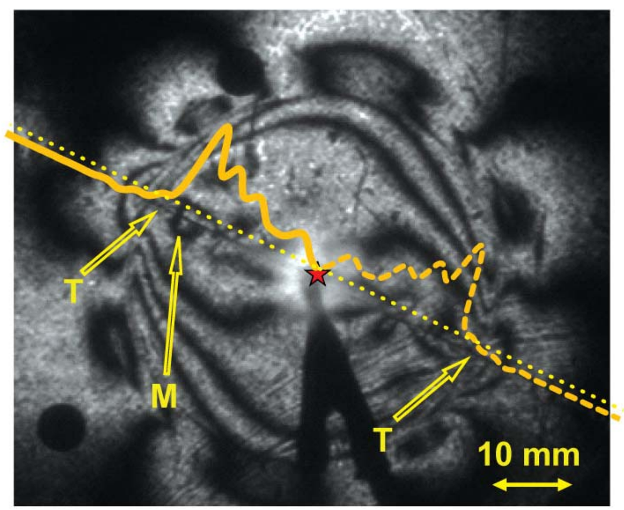
$\alpha = 25^0, \; f_0 = 0.47$

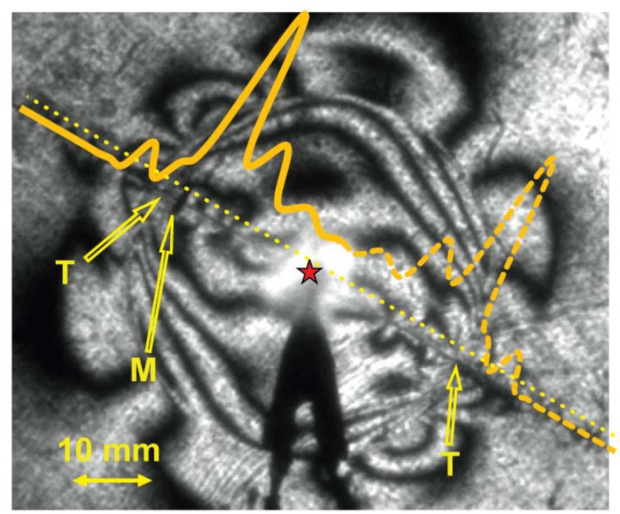


$\alpha = 30^0, \; f_0 = 0.58$









Lu, Lapusta, and Rosakis, *PNAS*, 2007

Challenges in earthquake physics and source imaging

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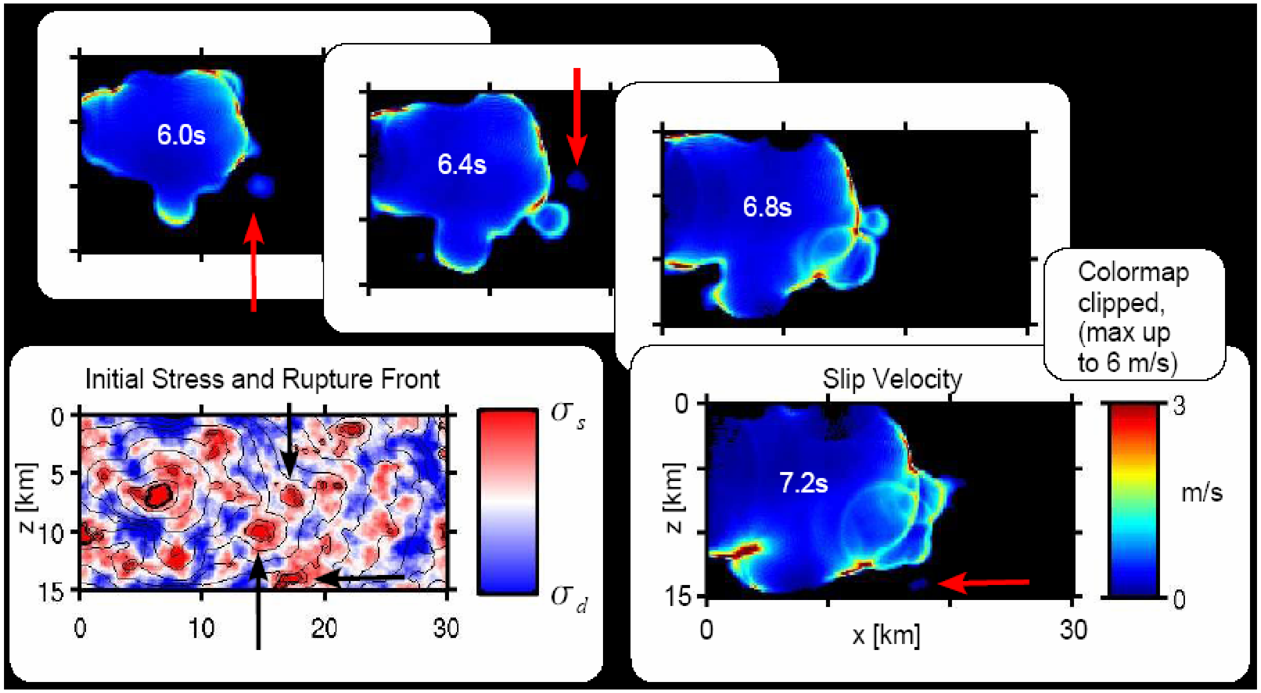

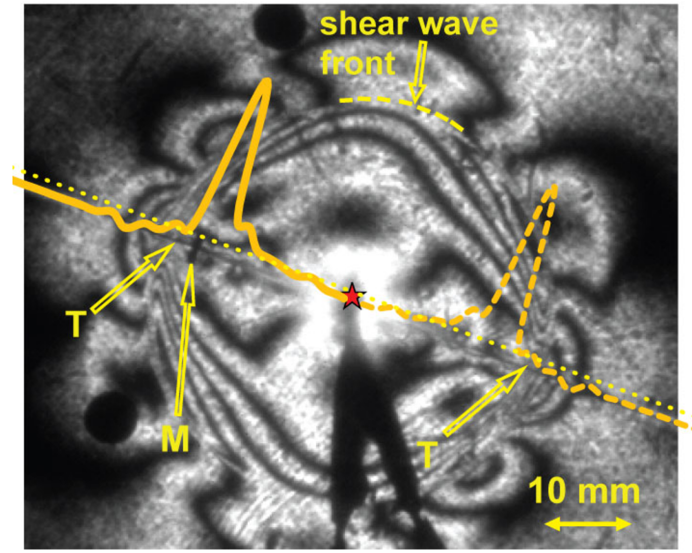

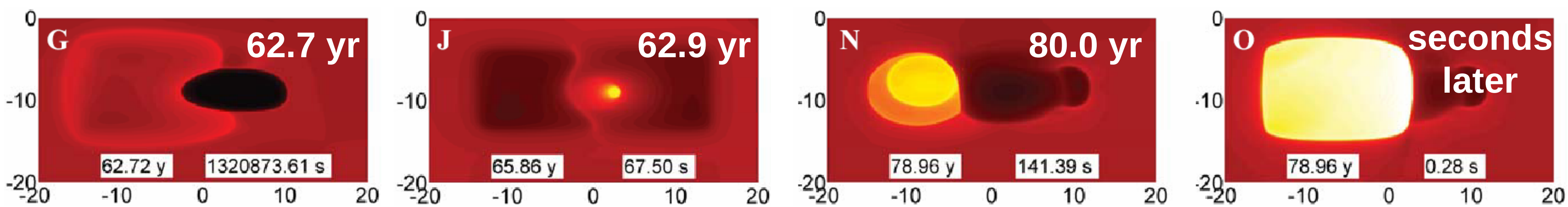

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