Coupled Thermo-Poro-Mechanical Effects in Earthquakes and Slow Slip Events

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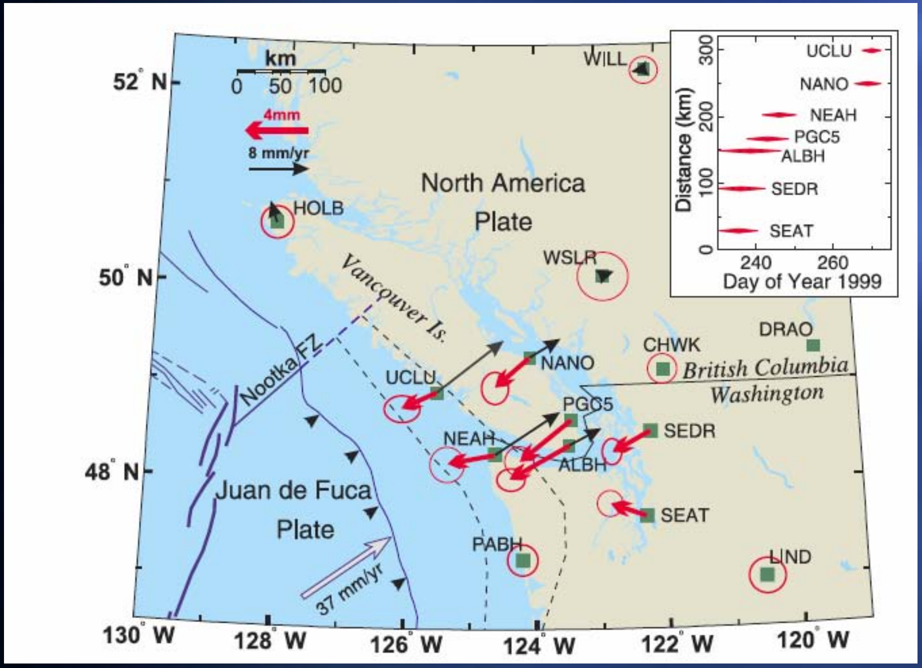
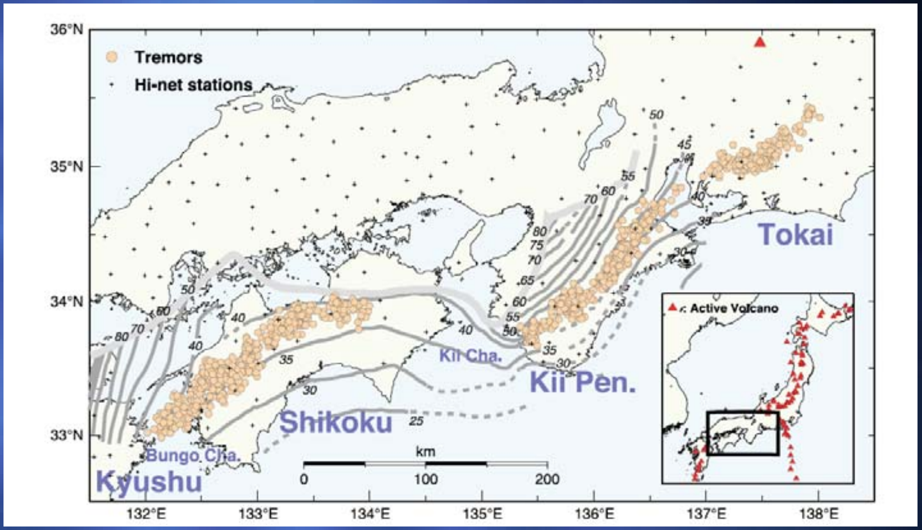
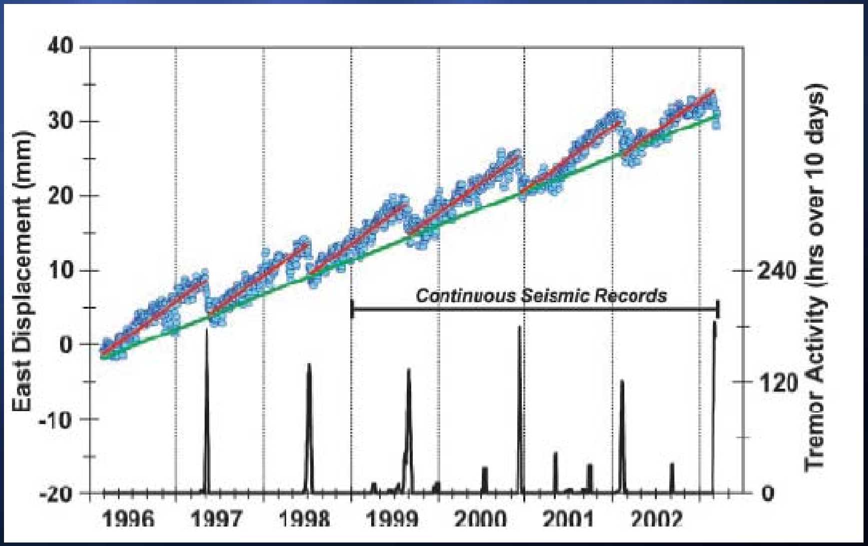
Episodic Tremor and Slip

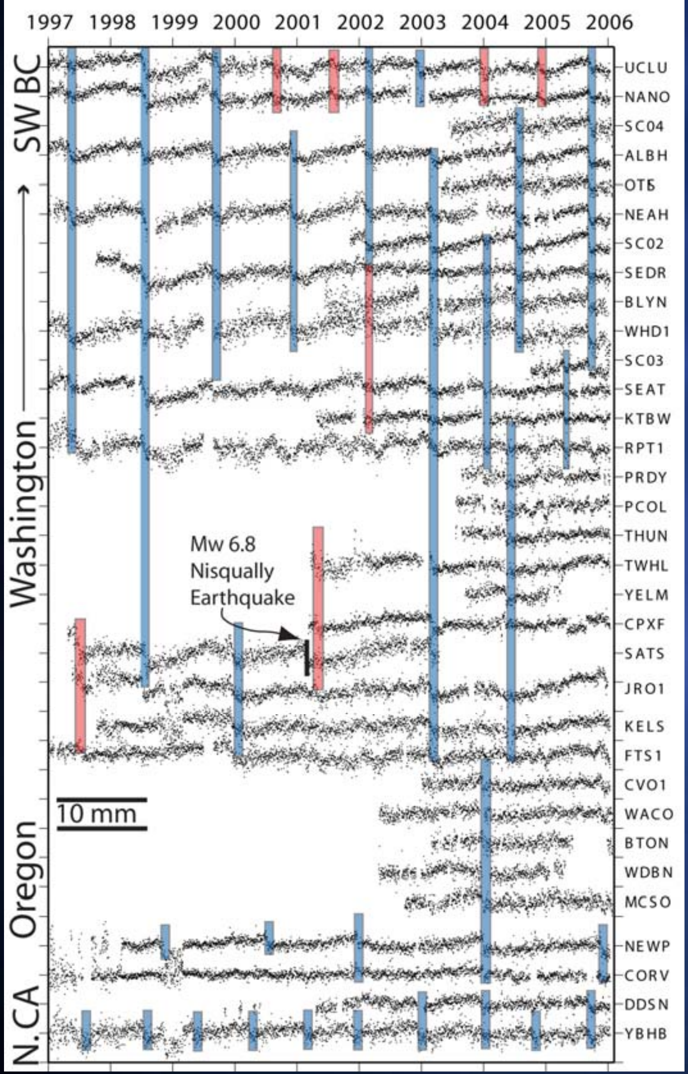


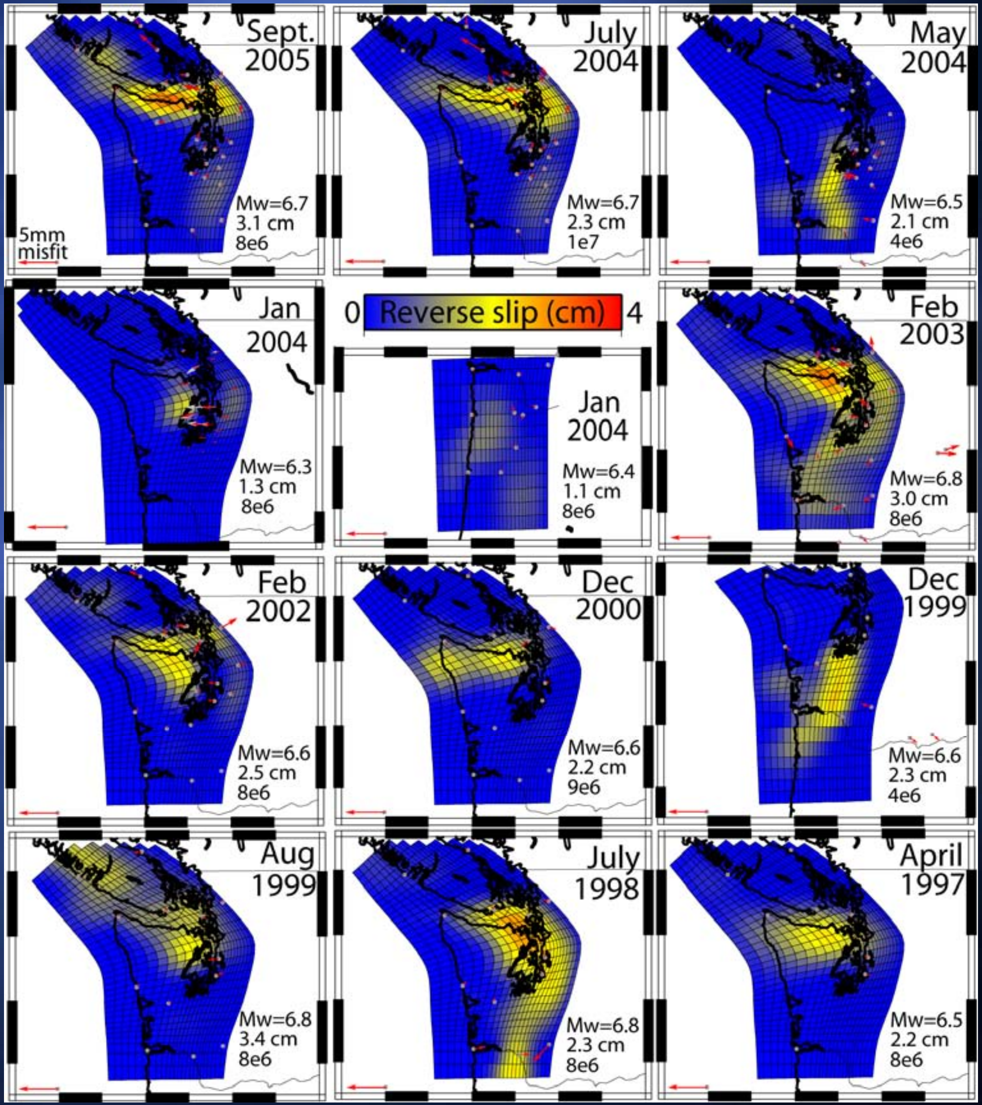




Dragert et al, Science, 2001
Obara, Science, 2002
Rogers and Dragert, Science, 2003

Cascadia Slow Slip Events

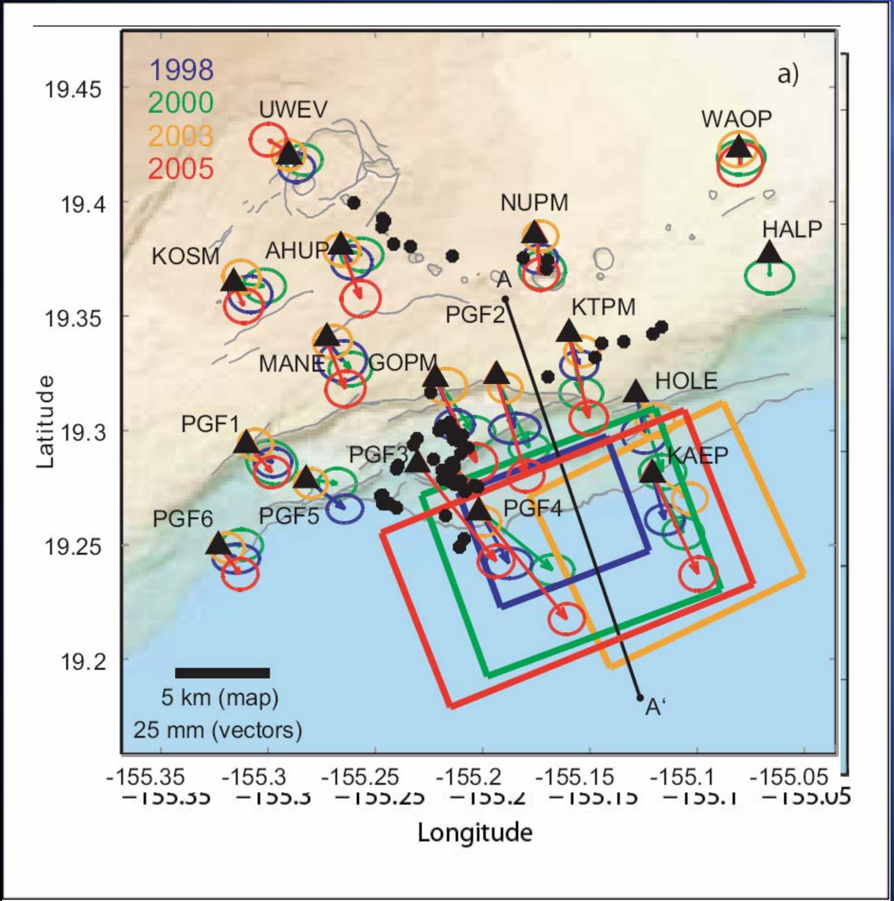


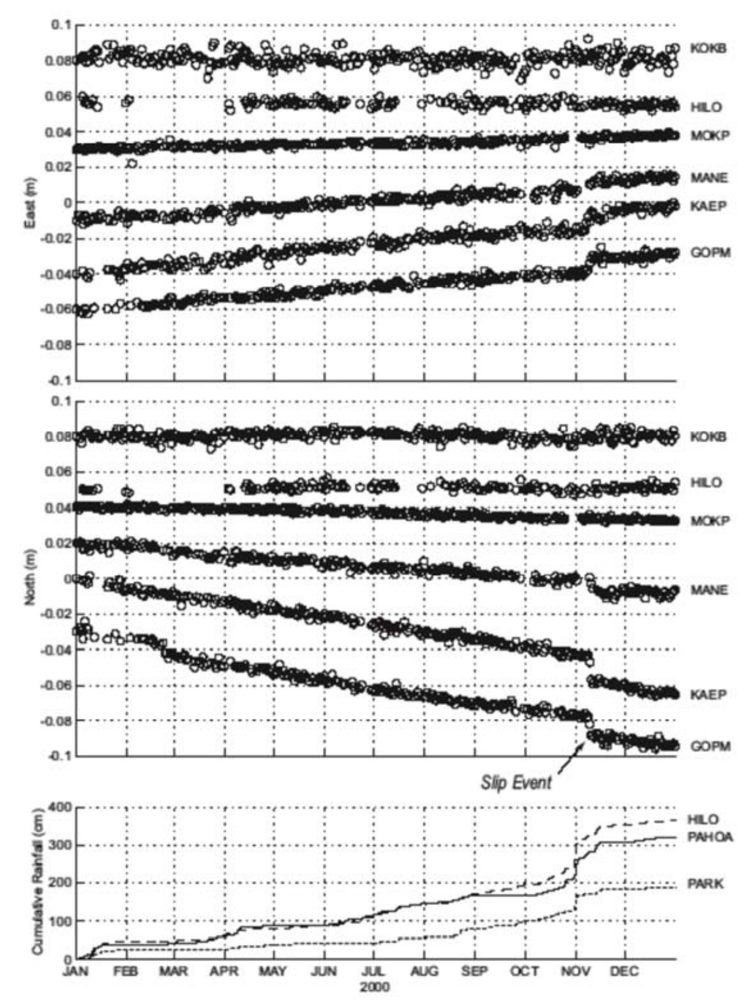


Szeliga et al, in review
Figure Courtesy of Tim Melbourne

Slip rate ~ 10 x plate-rate

Kilauea Silent Earthquakes





Cervelli et al, Nature, 2002; Segall et al, Nature 2006

Mechanics of Slow Slip?

•Change in frictional behavior at high slip speed [e.g., Shibazaki and Iio, 2003].

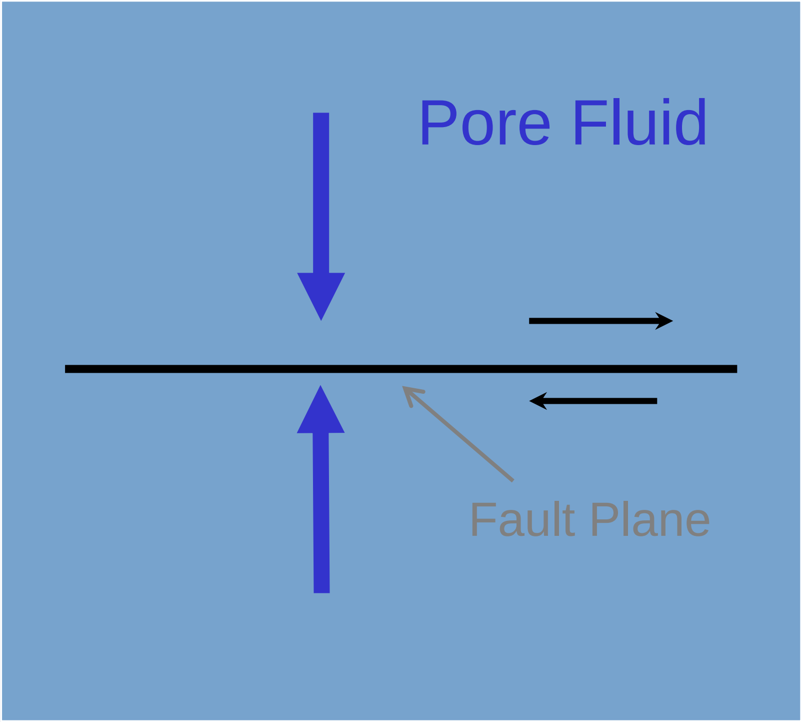
•Rate-state friction near neutral stability [Liu and Rice, 2007.

•Dilatant stabilization of slip [this study].

Under what circumstances might a deep slow slip event trigger a damaging megathrust earthquake?

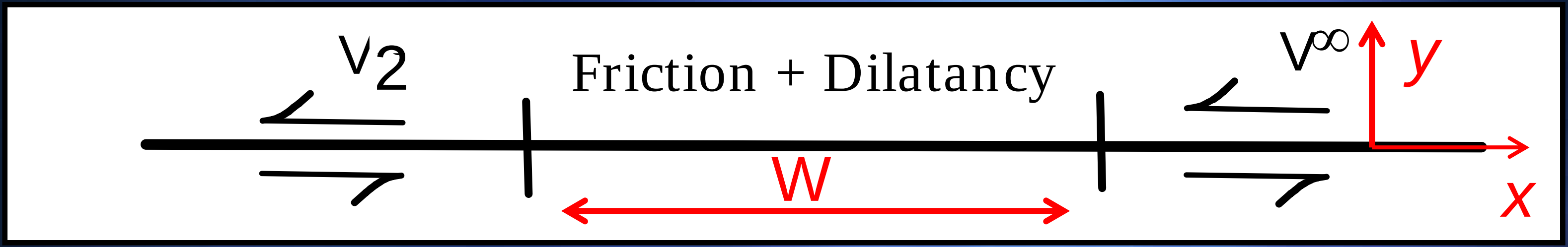
Dilatant Strengthening

- Frictional sliding causes dilatancy
- Fault zone pore pressure decreases if dilatancy rate exceeds rate of fluid influx
- Increases effective normal stress inhibiting slip



[Rice 1975; Rice and Simons, 1976l Rudnicki, 1979; Martin, 1980]

Dilatancy and Slow Slip



Equation of motion :
$$\frac{G}{2\pi}\int_{-\infty}^{\infty}\frac{\partial u/\partial\xi}{\xi - x}d\xi - \mu(v,\theta)(\sigma - p) = \frac{\rho v_s}{2}v$$

Friction law :
$$\mu = \mu_0 + a\ln\left(\frac{v}{v_0}\right) + b\ln\left(\frac{\theta v_0}{d_c}\right)$$

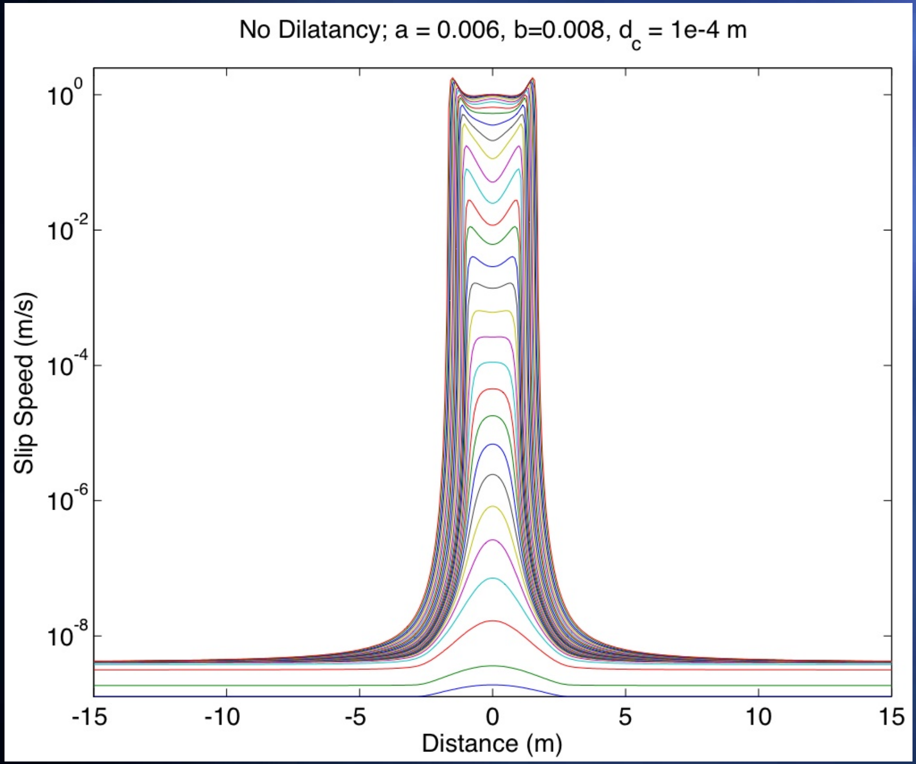
Evolution law :
$$\frac{d\theta}{dt} = 1 - \frac{\theta v}{d_c} \qquad \frac{d\theta}{dt} = -\frac{\theta v}{d_c}\ln\left(\frac{\theta v}{d_c}\right)$$

Pore pressure diffusion :
$$\frac{\partial p}{\partial t} = \frac{1}{\eta\beta}\frac{\partial}{\partial y}\left(\kappa\frac{\partial p}{\partial y}\right) - \frac{1}{\beta}\frac{d\phi}{dt}$$
$$\frac{dp}{dt} = \frac{p^{\infty} - p}{t_f} - \frac{1}{\beta}\frac{d\phi}{dt}$$

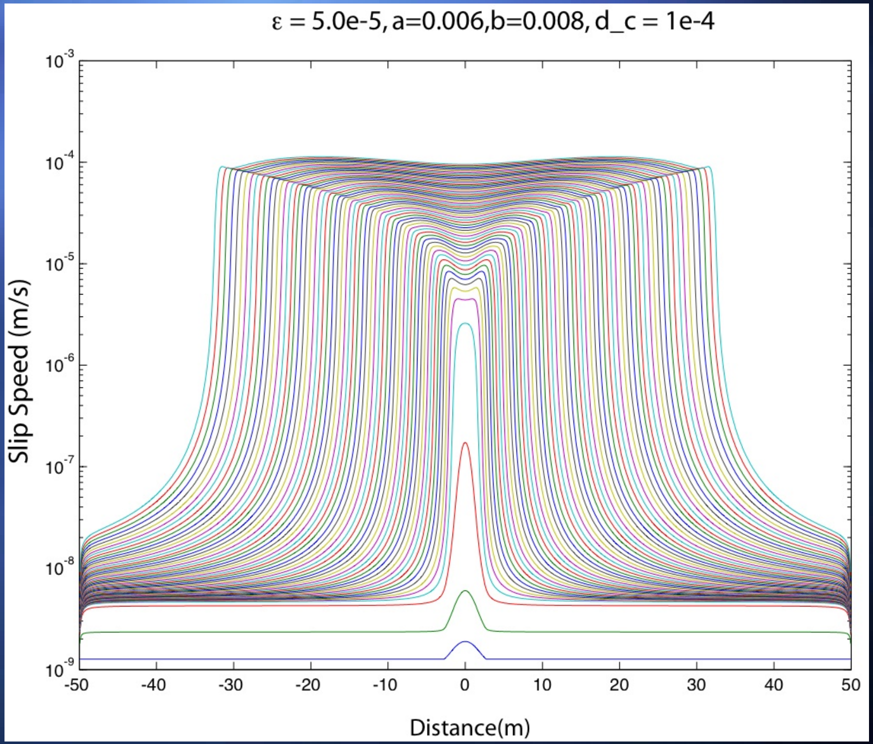
Dilatancy law :
$$\frac{d\phi}{dt} = -\epsilon\frac{\dot{\theta}}{\theta}$$

Effect of Dilatancy on Slip-rate

No Dilatancy

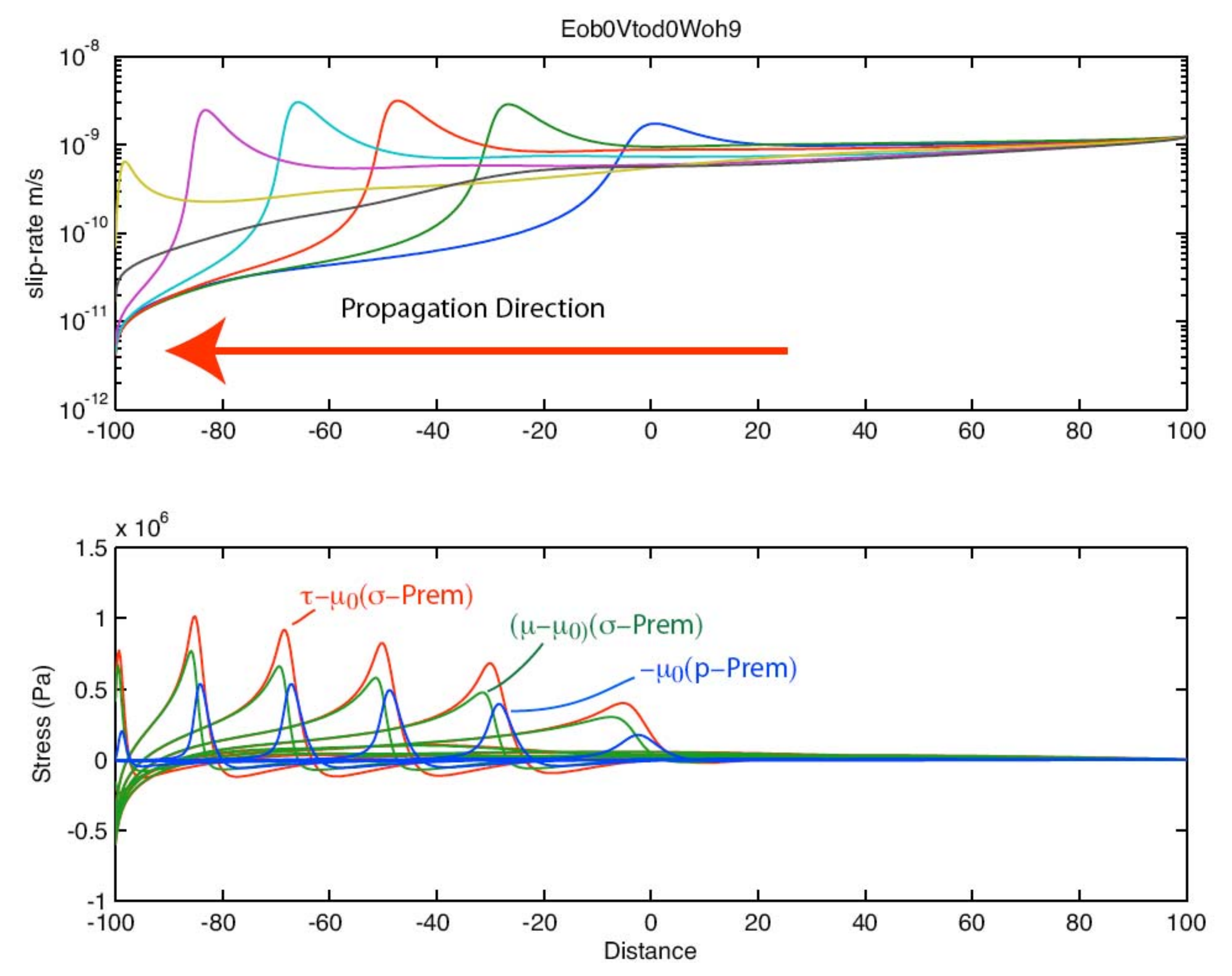


Dilatancy

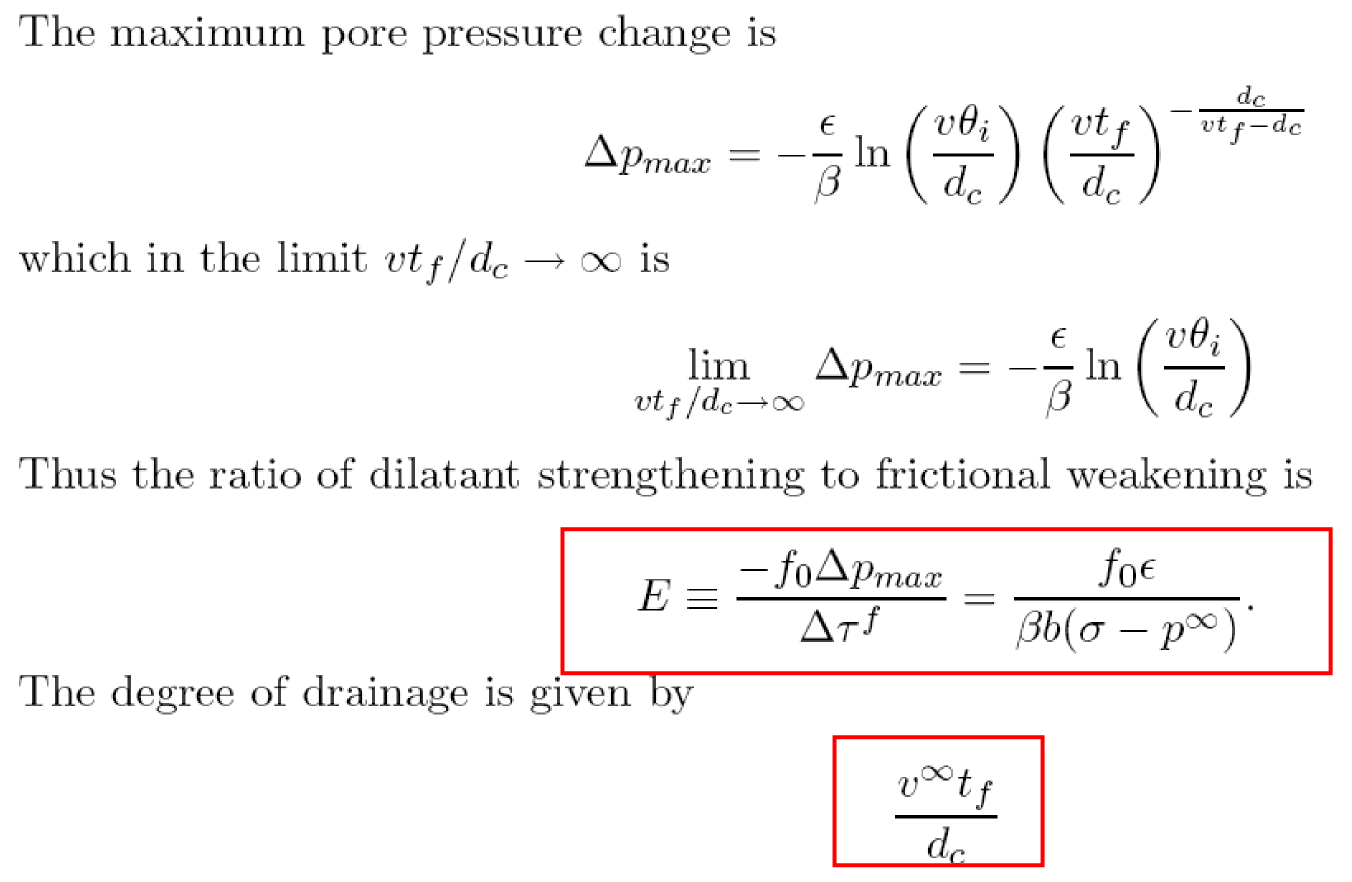


Two dimensional elasticity, rate-state friction with dilatancy (Segall and Rice, 1995), and one dimensional membrane diffusion.

Slow Slip in Subduction Geometry



Scaling Parameters



The maximum pore pressure change is

$$\Delta p_{max} = -\frac{\epsilon}{\beta} \ln\left(\frac{v\theta_i}{d_c}\right) \left(\frac{vt_f}{d_c}\right)^{-\frac{d_c}{vt_f - d_c}}$$

which in the limit $vt_f/d_c \to \infty$ is

$$\lim_{vt_f/d_c \to \infty} \Delta p_{max} = -\frac{\epsilon}{\beta} \ln\left(\frac{v\theta_i}{d_c}\right)$$

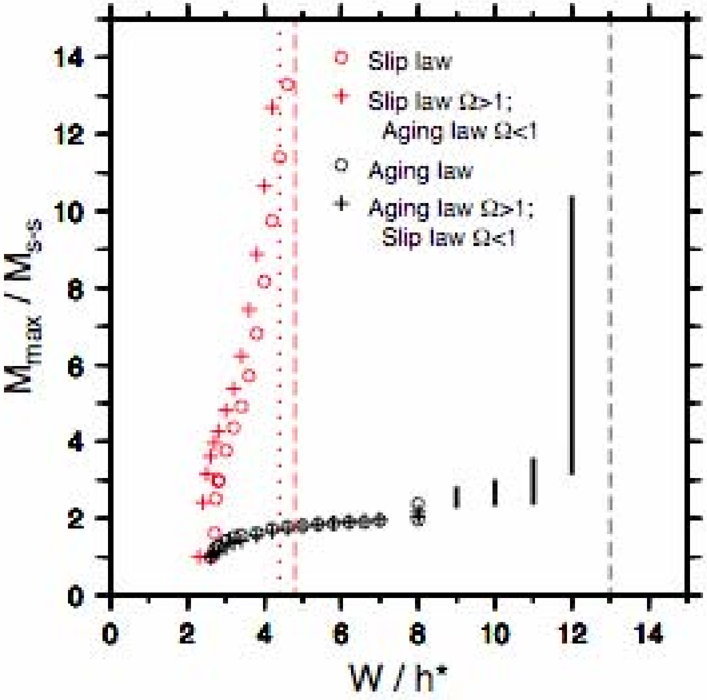
Thus the ratio of dilatant strengthening to frictional weakening is

$$\boxed{E \equiv \frac{-f_0 \Delta p_{max}}{\Delta \tau^f} = \frac{f_0 \epsilon}{\beta b(\sigma - p^\infty)}.}$$

The degree of drainage is given by

$$\boxed{\frac{v^\infty t_f}{d_c}}$$

Without Dilatant Strengthening, W/h is limited*

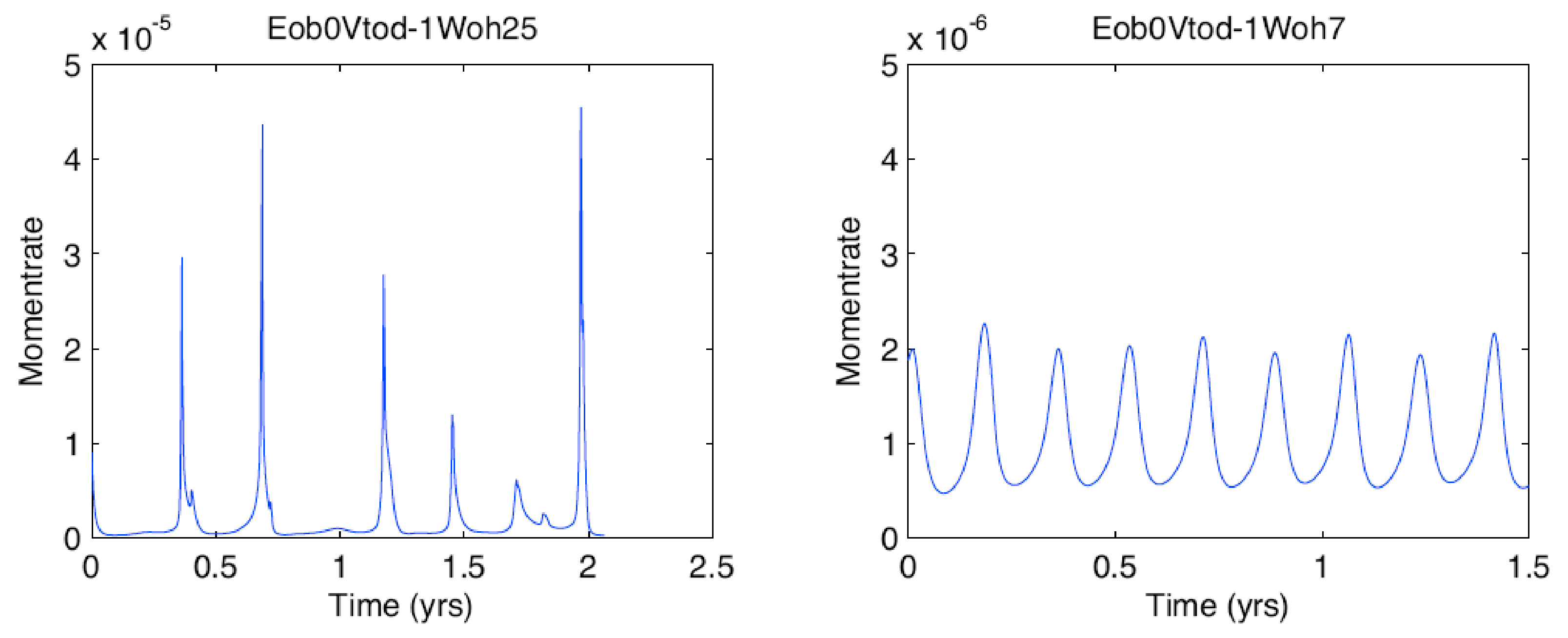


Courtesy Allan Rubin

Moment Rate

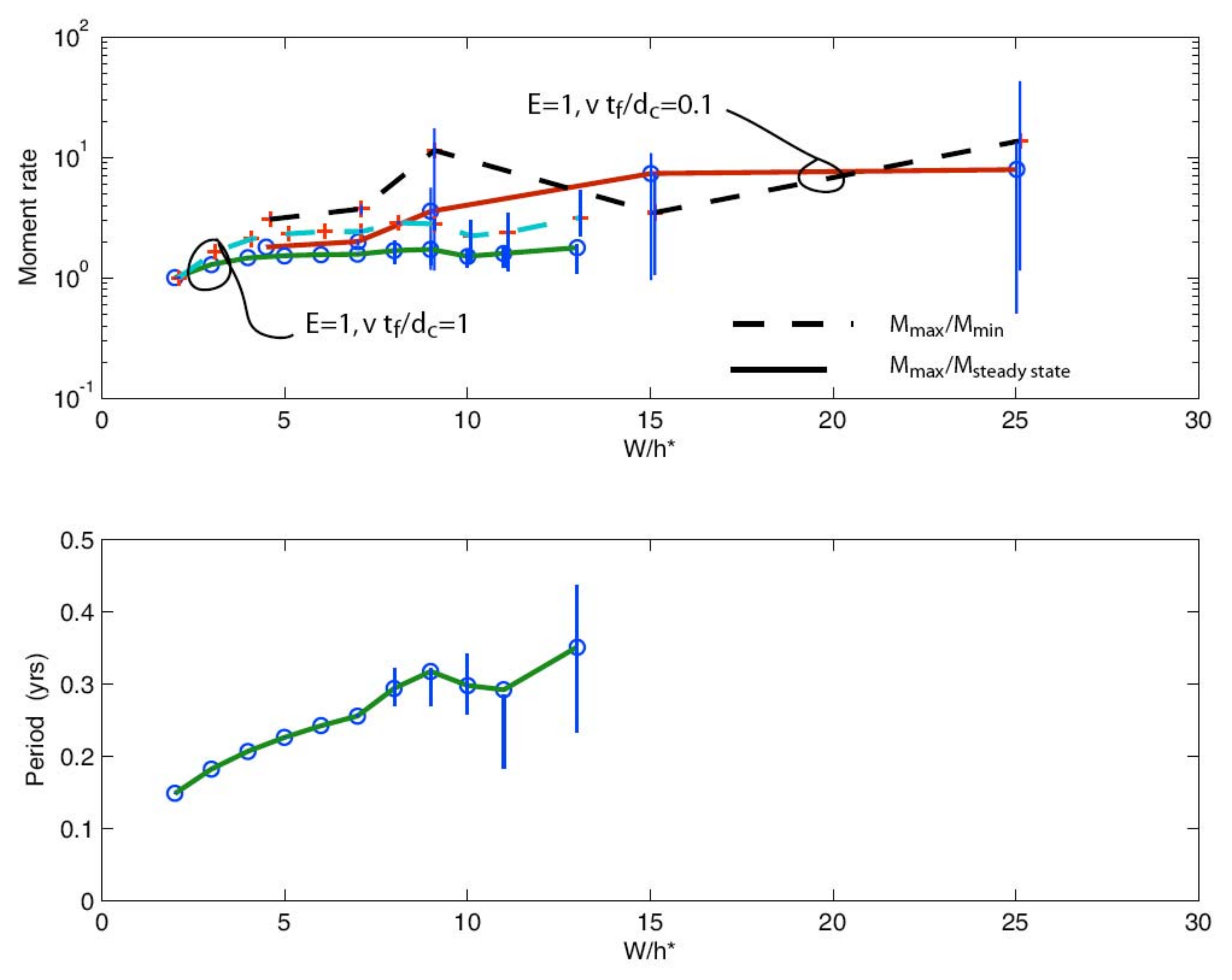
W / h* = 25

W / h* = 7



Critical crack dimension h* for nucleation (Ruina, 1983)

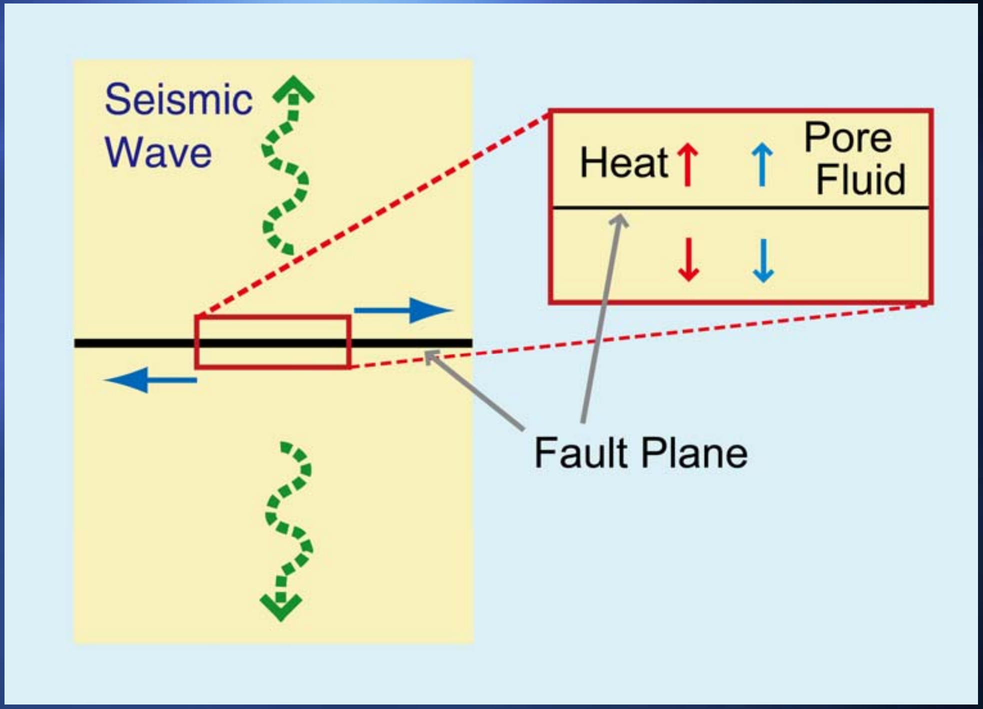
With Dilatancy W/h* appears to be essentially unbounded



QuickTime™ and a
decompressor
are needed to see this picture.

Thermal Pressurization

- Frictional sliding generates heat
- Pore fluid expands more than rock
- Pore pressure increases if rate of heat production exceeds rate of fluid and heat transport
- Reduces effective normal stress

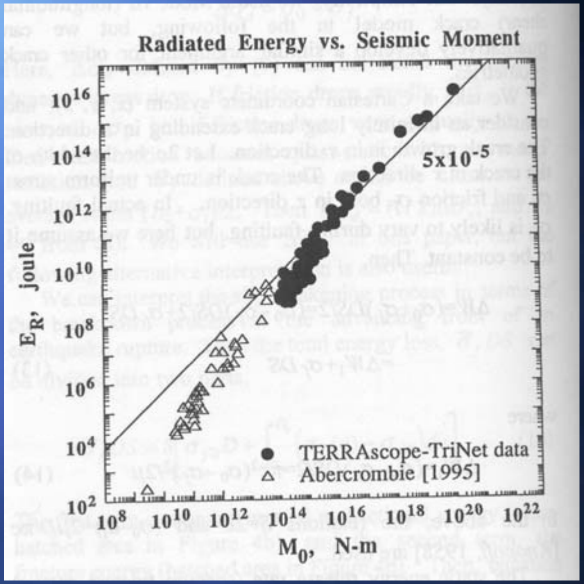


Sibson (1973), Lachenbruch (1980); Mase and Smith (1985, 1987); Lee and Delaney (1987); J. Andrews (2002): Noda and Shimamoto (2005); Wibberly and Shimamoto (2005): Rempel and Rice (2006); Rice (2006); Bizzari and Cocco (2006); Segall and Rice (2006)

Questions

1. At what point do shear heating effects dominate frictional weakening?

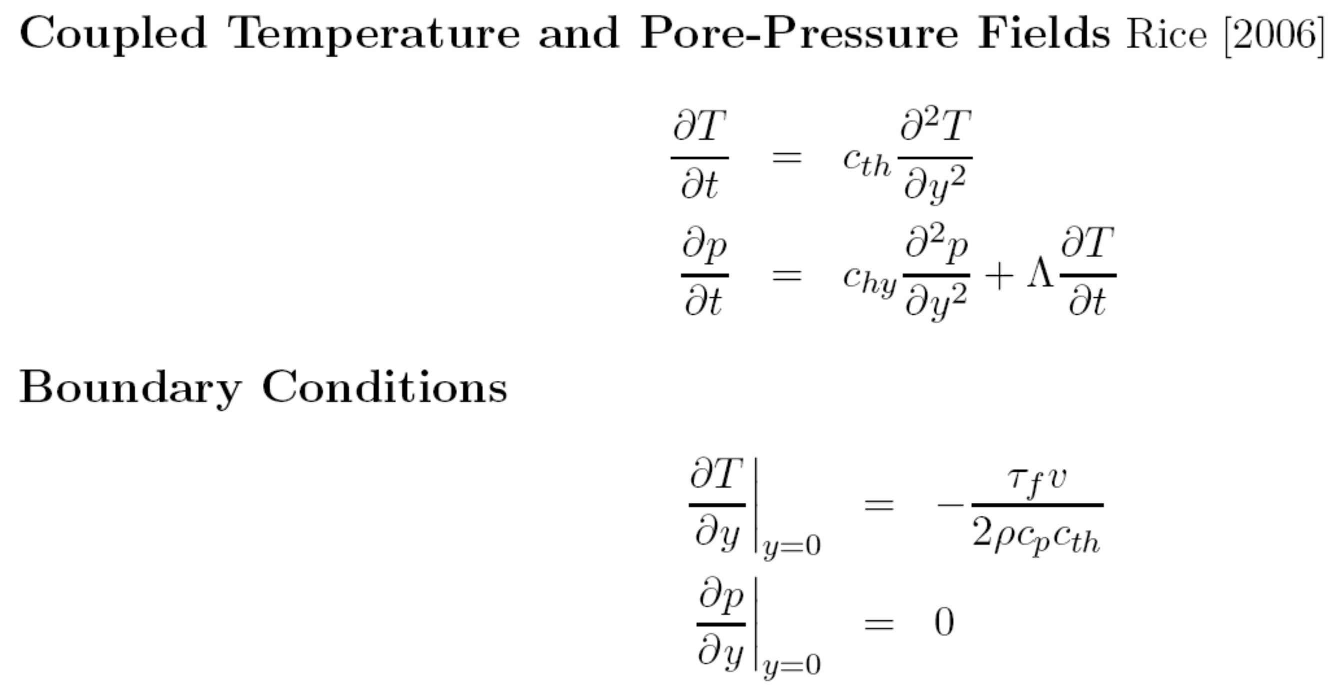
- “Since the thermal process is important only for large earthquakes …” Kanamori and Heaton, 2000
- .Andrews [2002] also suggests thermal pressurization effects important at ~ M 3-4.



Kanamori and Heaton, 2000

- How does thermal pressurization influence earthquake slip and slip rate?
- Will an increase in pore-pressure limit the temperature rise and inhibit melting?

Shear Heating Induced Thermal Pressurization



Coupled Temperature and Pore-Pressure Fields Rice [2006]

$$
\begin{aligned}
\frac{\partial T}{\partial t} &= c_{th}\frac{\partial^2 T}{\partial y^2}\\
\frac{\partial p}{\partial t} &= c_{hy}\frac{\partial^2 p}{\partial y^2} + \Lambda\frac{\partial T}{\partial t}
\end{aligned}
$$

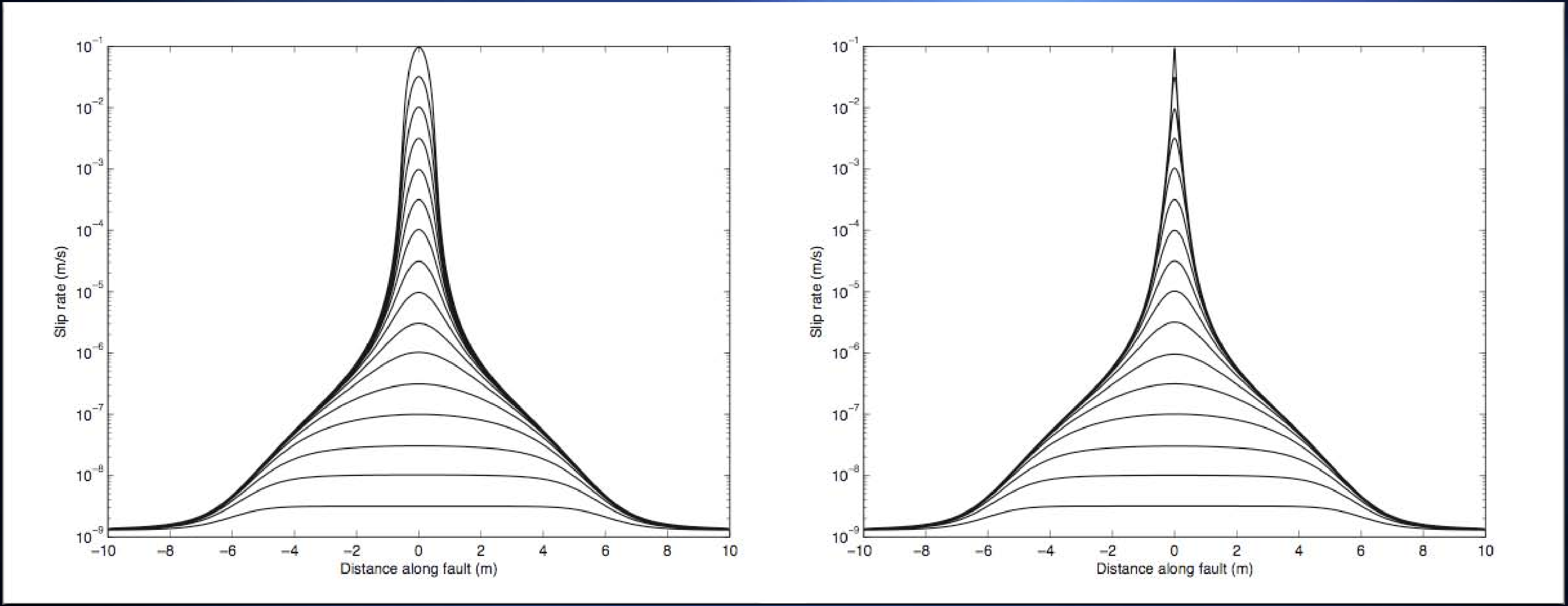
Boundary Conditions

$$
\begin{aligned}
\left.\frac{\partial T}{\partial y}\right|_{y=0} &= -\frac{\tau_f v}{2\rho c_p c_{th}}\\
\left.\frac{\partial p}{\partial y}\right|_{y=0} &= 0
\end{aligned}
$$

Influence of Thermal Pressurization on Nucleation Dimension

Without Thermal Pressurization

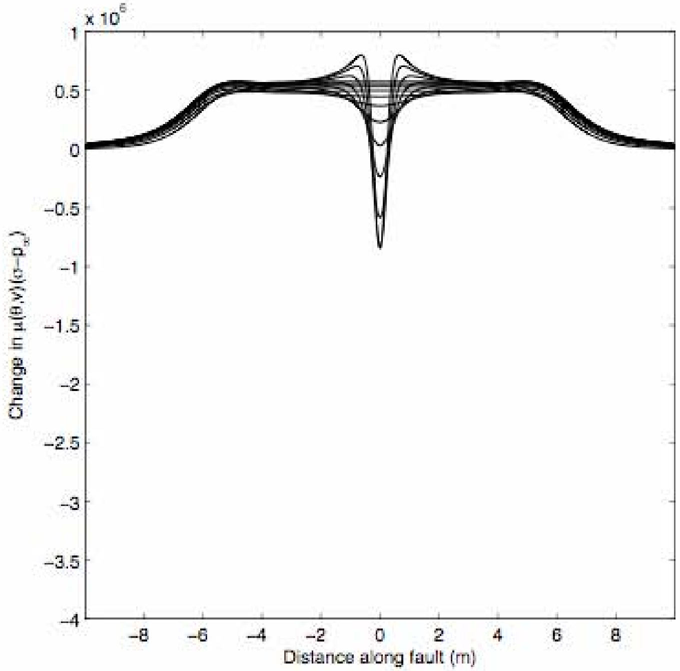
With Thermal Pressurization



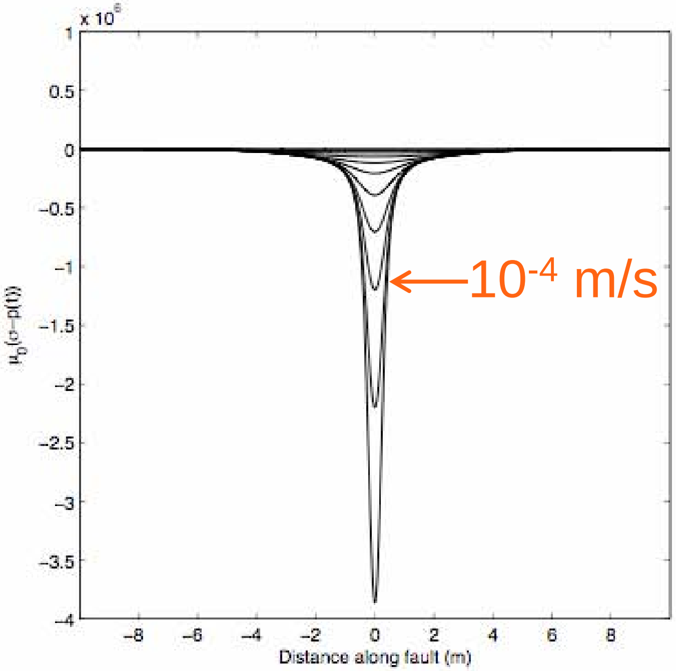
Aging Law, a/b = 1/3; Dieterich (1992), Rubin and Ampuero (2005)

Weakening Mechanisms

Change in $\mu(\theta,v)(\sigma - p_0)$



Change in $\mu_0(\sigma - p)$

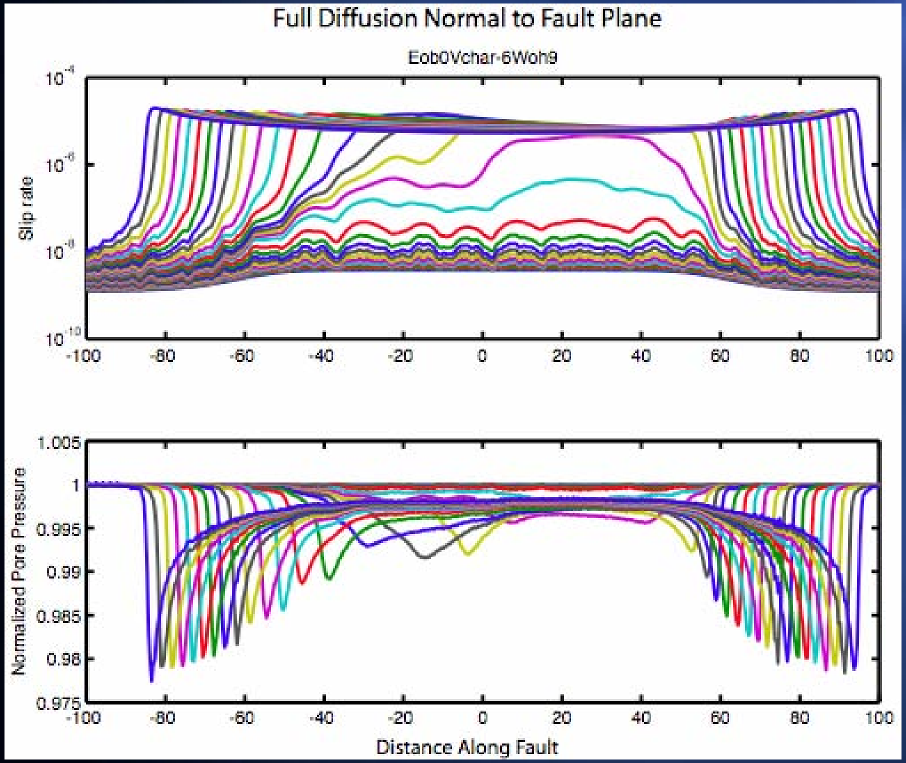


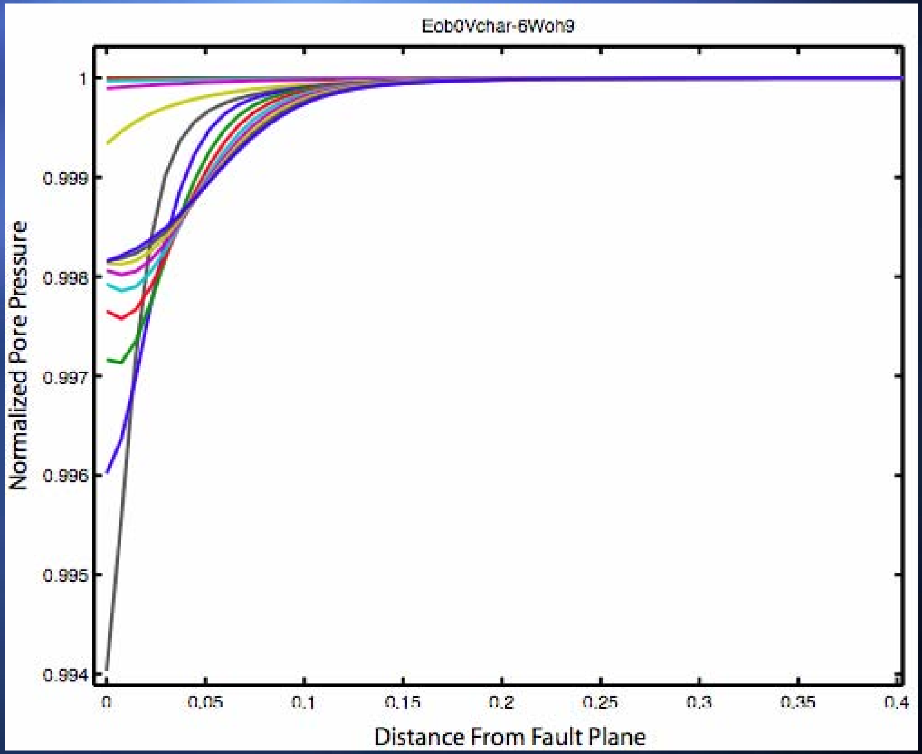
10^{-4} m/s

Conclusions and Speculations

1. Dilatancy capable of stabilizing against rapid slip.
2. Slip rates and repeat times plausibly in the range of observed slow-slip events.
3. In the absence of dilatancy thermal pressurization becomes important well before seismic slip-rates.
4. Slow vs. fast slip may be controlled by competition between dilatant strengthening and

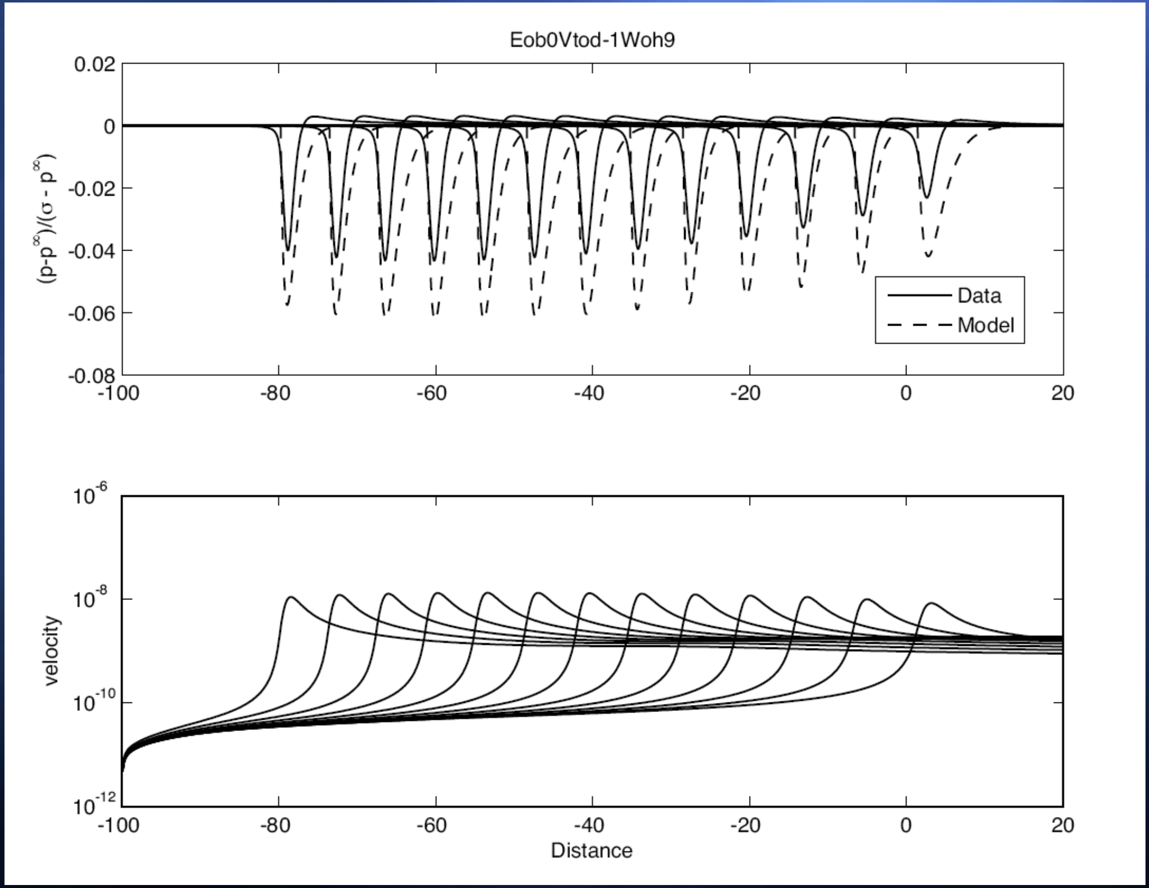
Full Diffusion Normal to Fault



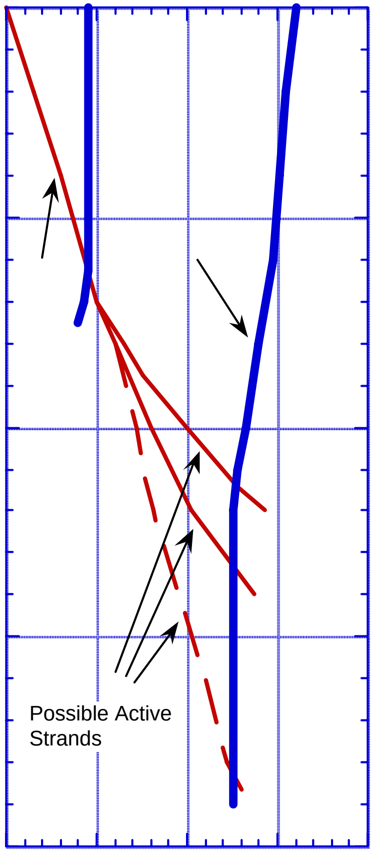


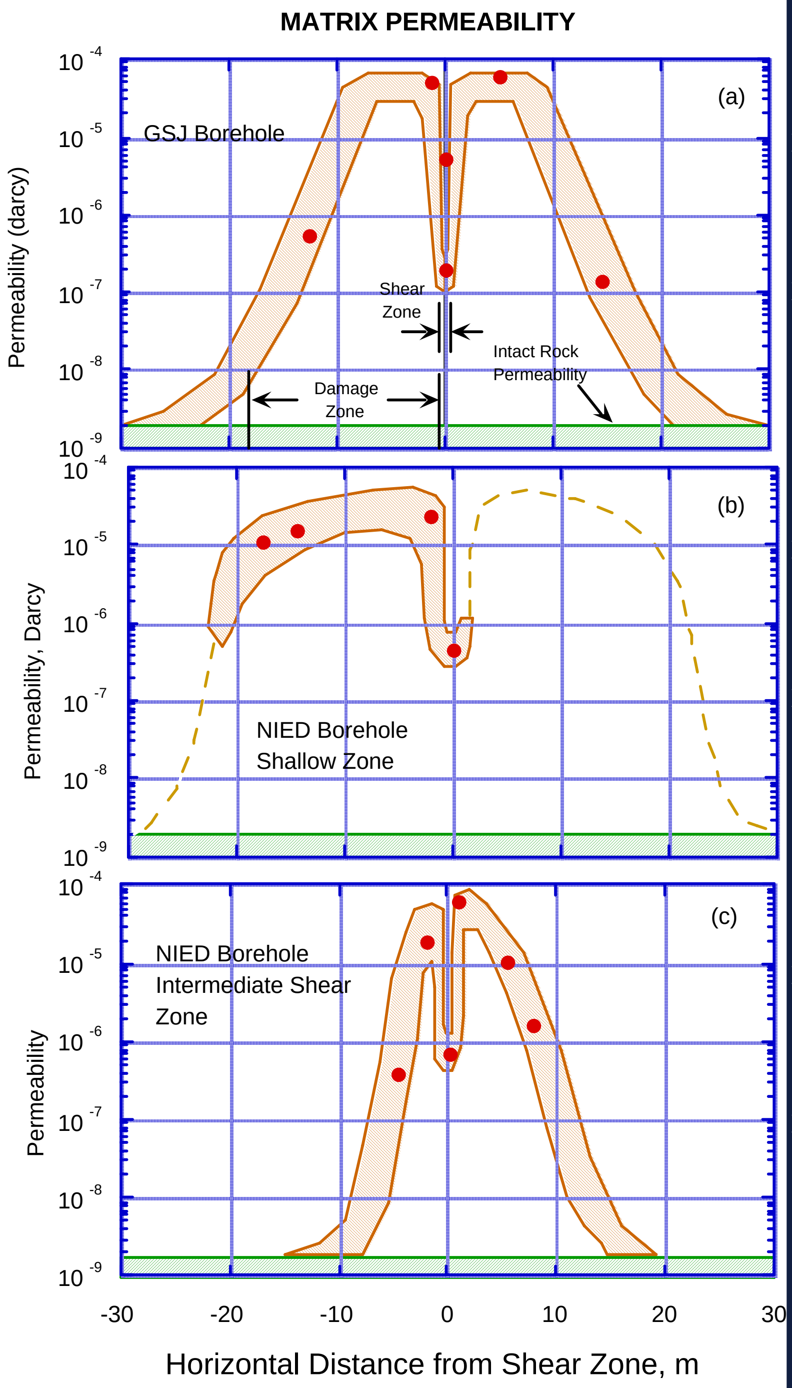
For step change in slip speed

$$\Delta p(t) = -\frac{\epsilon}{\beta} \ln\left(\frac{v\theta_i}{d_c}\right) \frac{vt_f}{d_c - vt_f} \left(e^{-vt/d_c} - e^{-t/t_f}\right)$$



Lockner, Naka, Tanaka, Ito and Ikeda, “Permeability and strength of core samples from the Nojima fault of the 1995 Kobe earthquake”, *USGS Open File Rpt.* 00-129, 2000





10^{-17} m^2

10^{-19} m^2

10^{-17} m^2

10^{-19} m^2

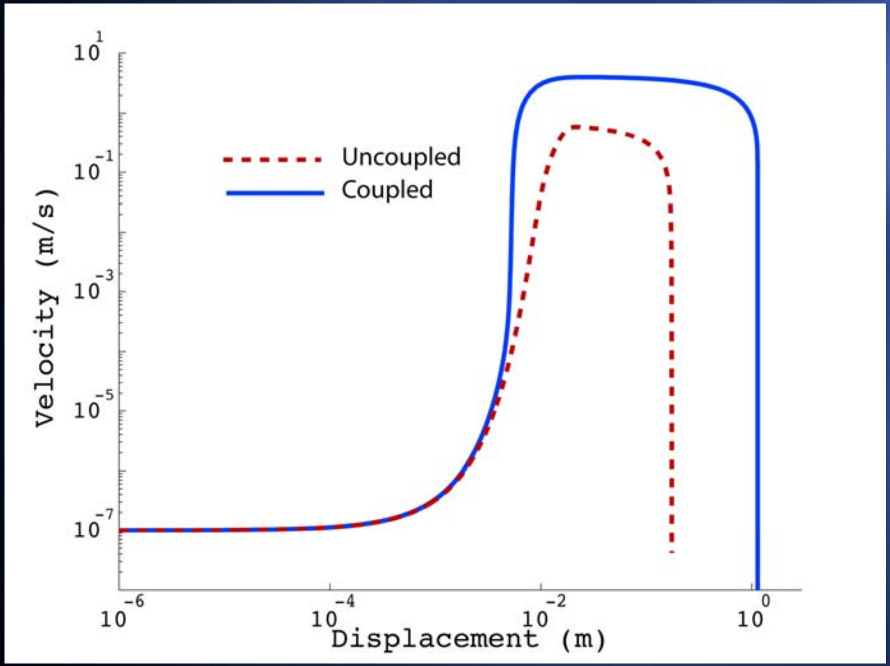
10^{-17} m^2

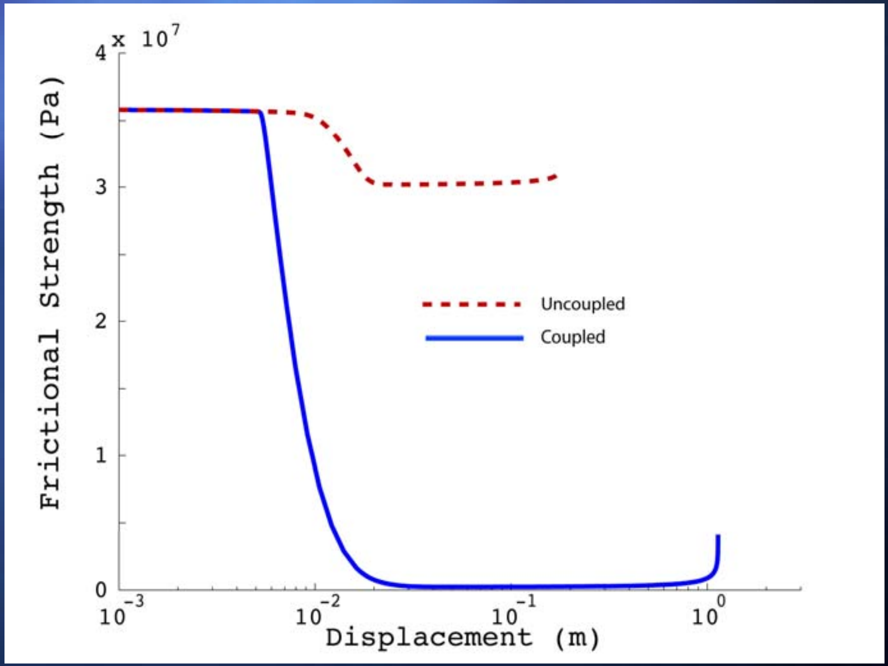
10^{-19} m^2

These are spring slider models

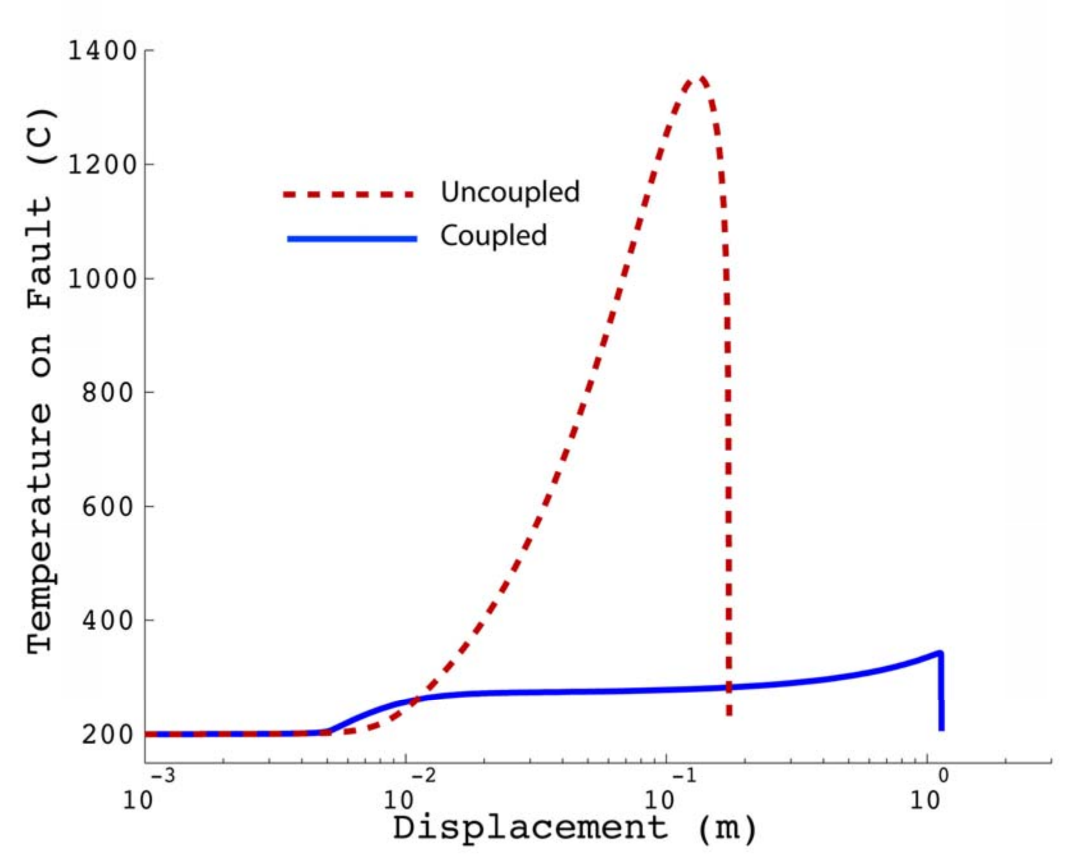
General Case with Rate-State Friction

- Thermal pressurization causes large displacement, slip velocity, and low frictional stress



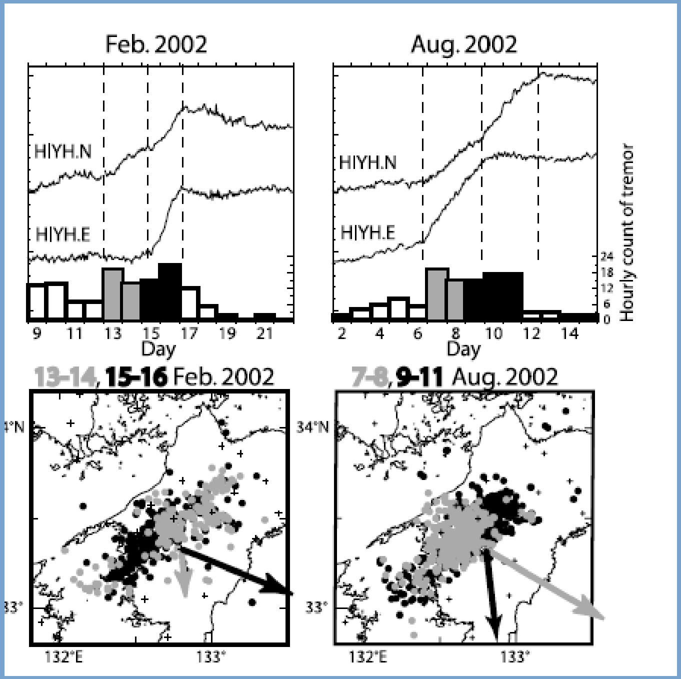


Thermal Pressurization limits temperature and inhibits melting

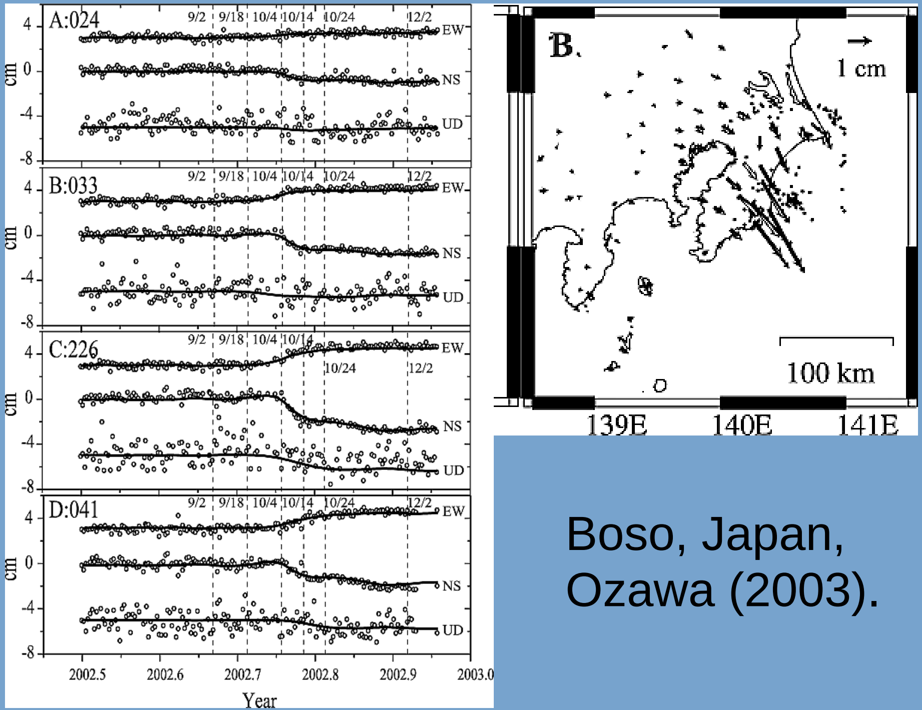


Slow Slip Events World Wide

- Cascadia [Dragert et al, 2001; Miller et al, 2002, Szeliga et al, 2004].
- Southwest Japan [Hirose et al, 1999; Miyazaki et al, 2006; Ozawa et al, 20002]
- Mexico [Kostoglodov et al, 2003, Lowry et al, 2005.]
- New Zealand [Douglas, 2005,]
- Kilauea volcano [Cervelli et al 2002, Segall et al, 2006,Brooks et al, 2006].

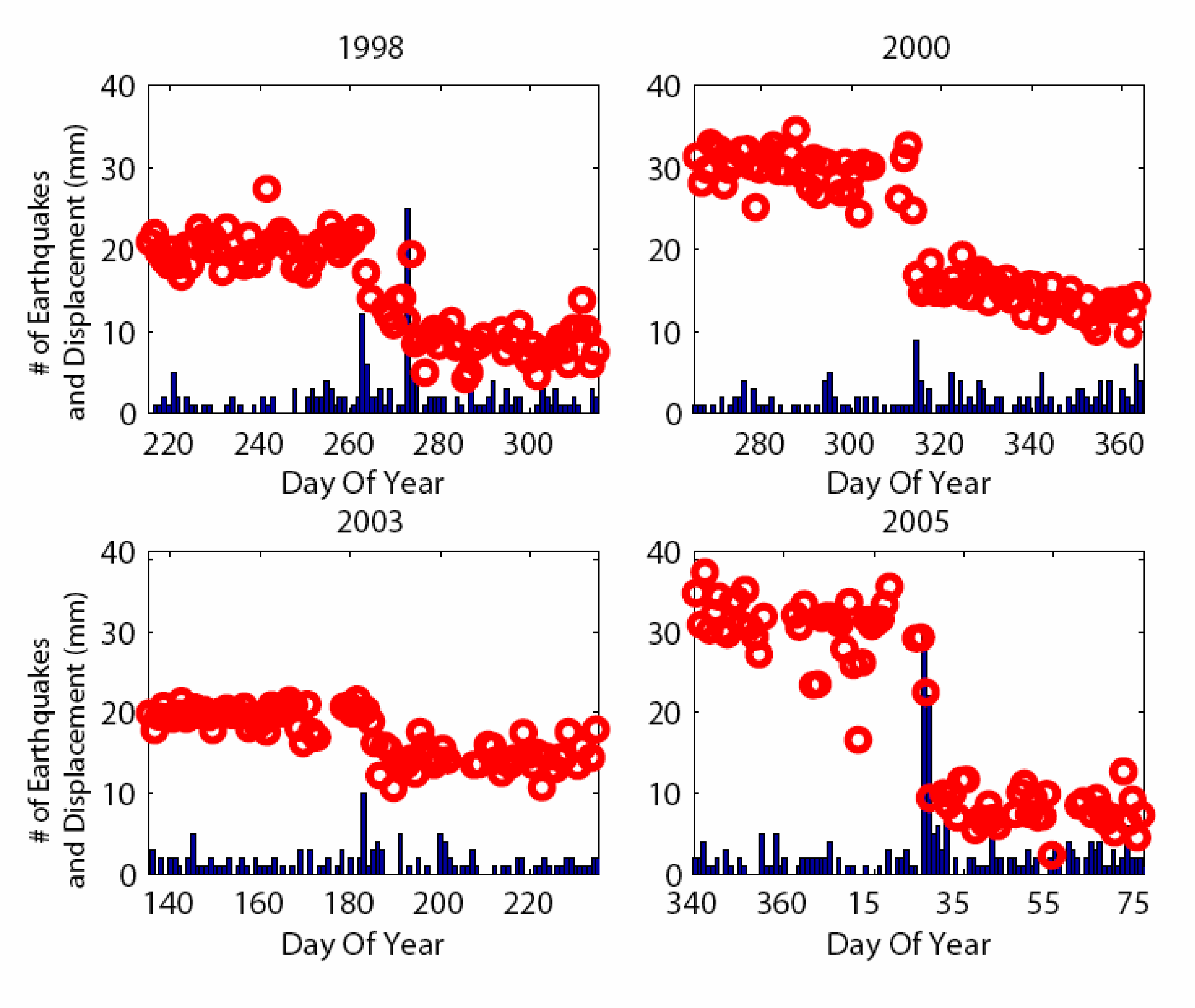


S.W. Japan, Obara, 2004



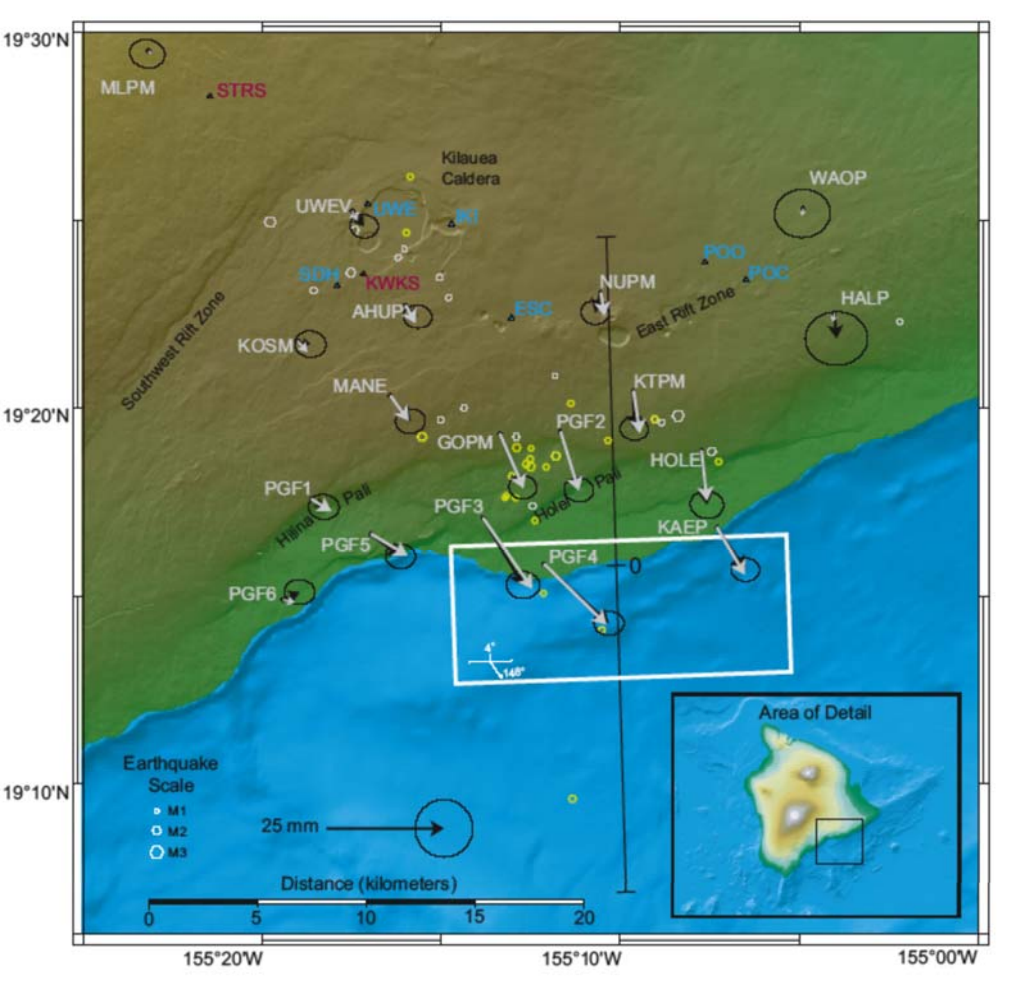
Boso, Japan, Ozawa (2003).

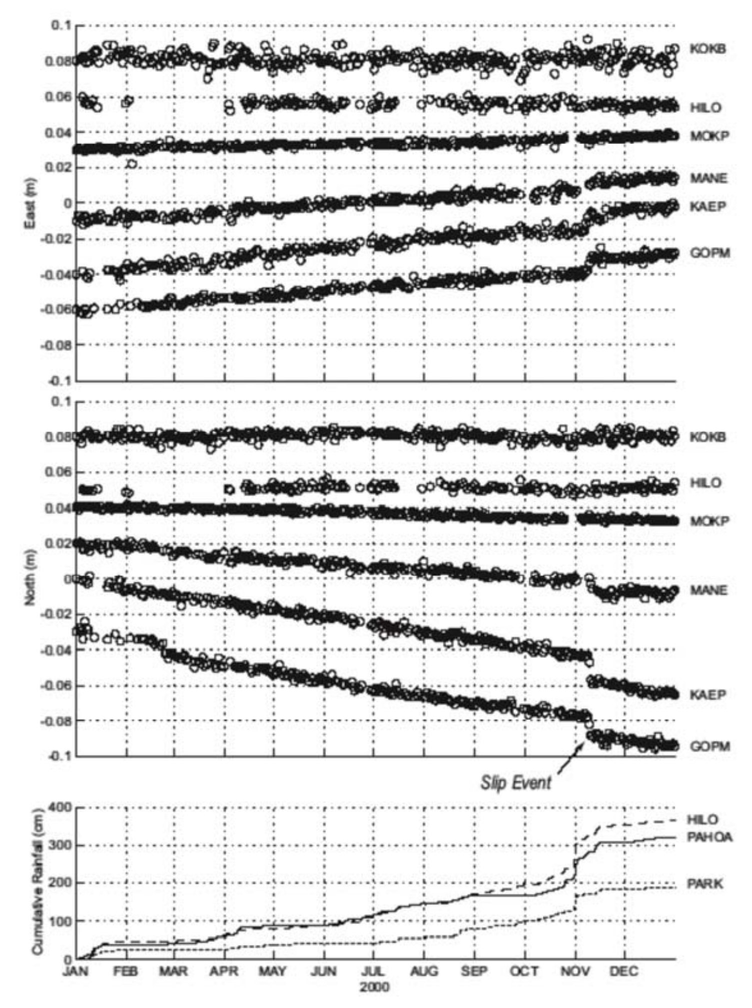
Seismicity Triggered by Slow Slip



Segall et al, Nature, 2006

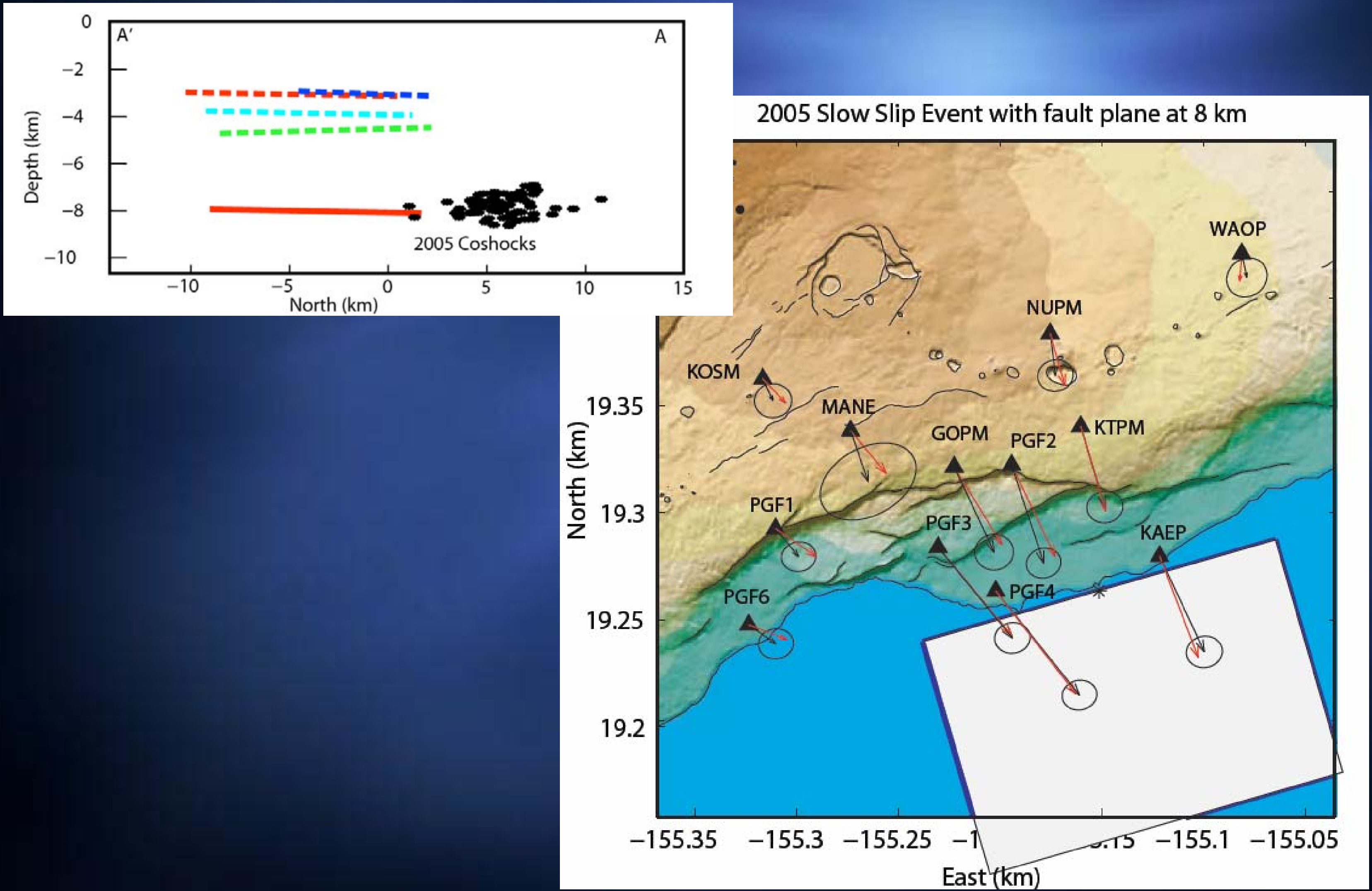
Kilauea Silent Earthquake





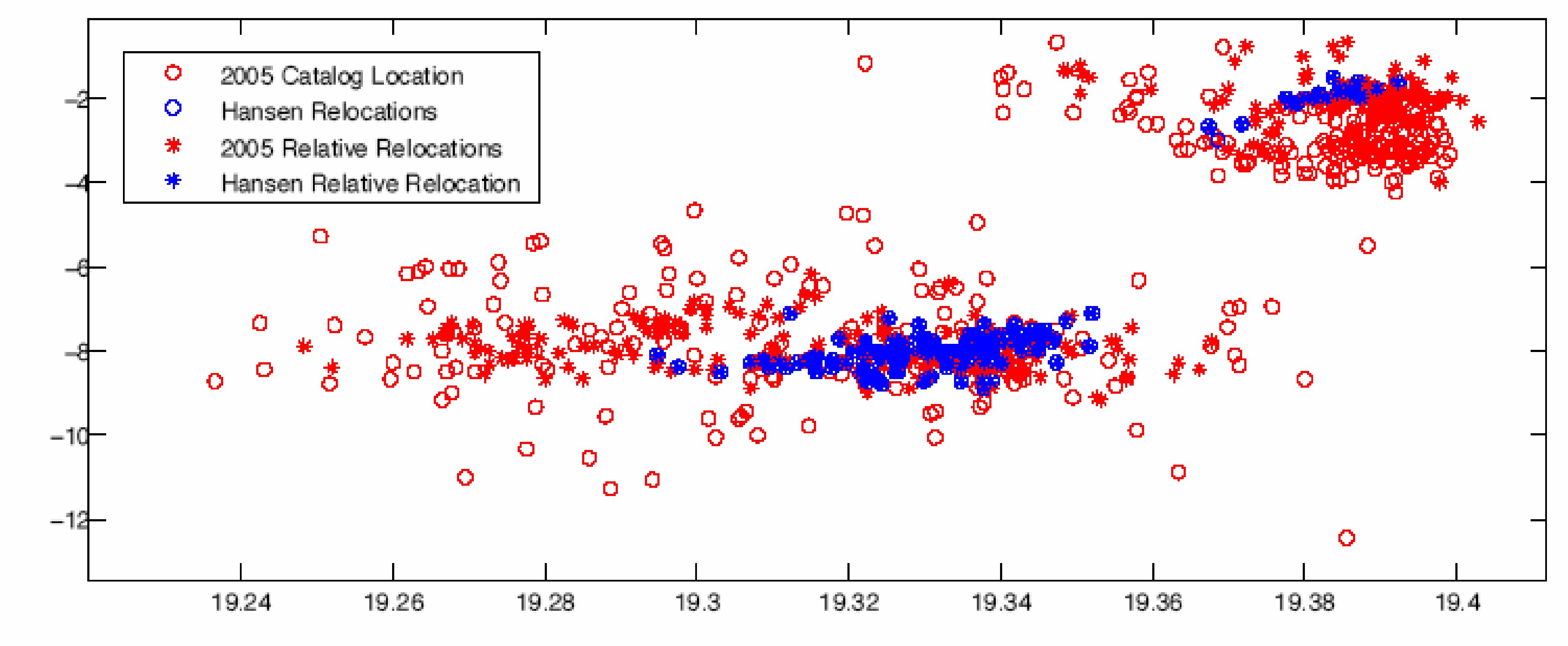
Cervelli et al, Nature, 2002

8km Deep Fault Fits GPS Data



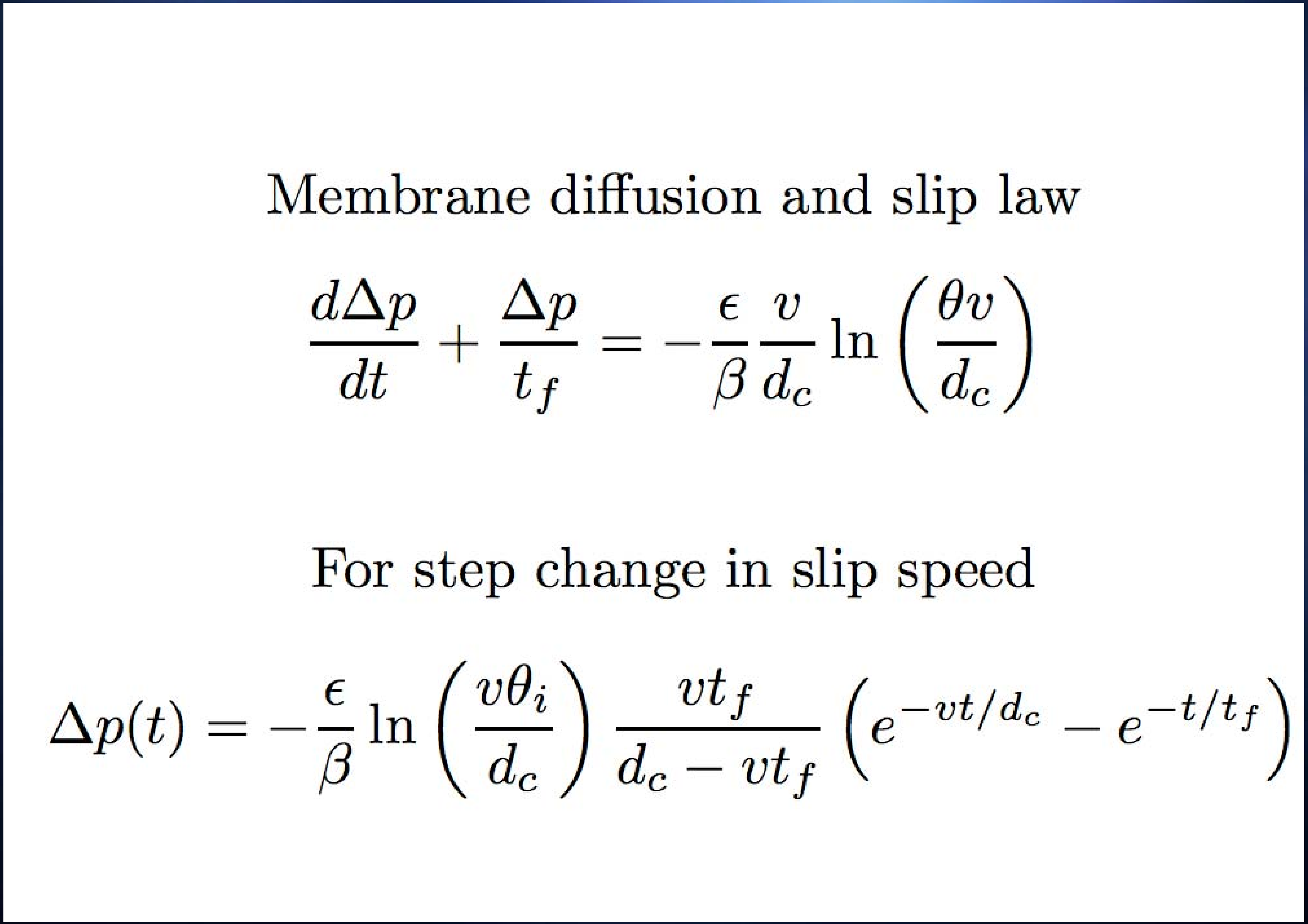
2005 Slow Slip Event with fault plane at 8 km

Relocated Earthquakes



Segall et al, Nature, 2006

Analytical Approximation



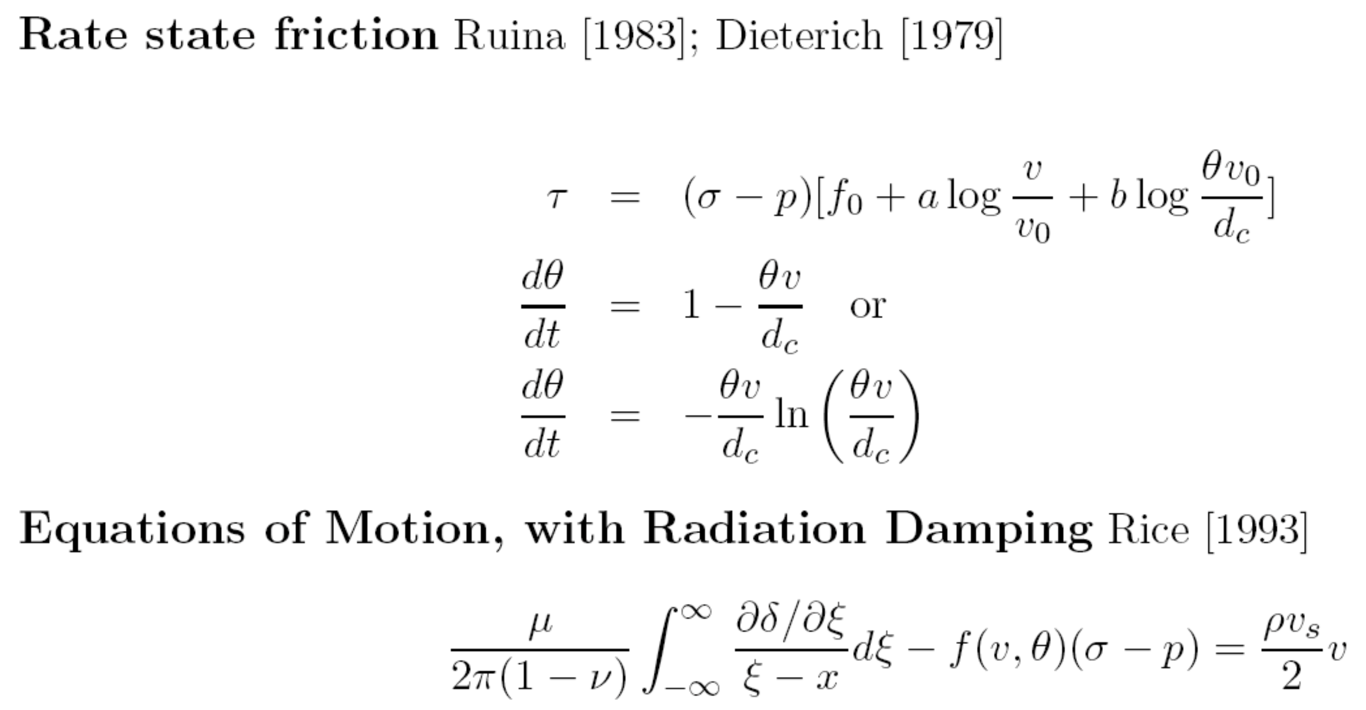
Membrane diffusion and slip law

$$\frac{d\Delta p}{dt} + \frac{\Delta p}{t_f} = -\frac{\epsilon}{\beta}\frac{v}{d_c}\ln\left(\frac{\theta v}{d_c}\right)$$

For step change in slip speed

$$\Delta p(t) = -\frac{\epsilon}{\beta}\ln\left(\frac{v\theta_i}{d_c}\right)\frac{vt_f}{d_c - vt_f}\left(e^{-vt/d_c} - e^{-t/t_f}\right)$$

Shear Heating Induced Thermal Pressurization



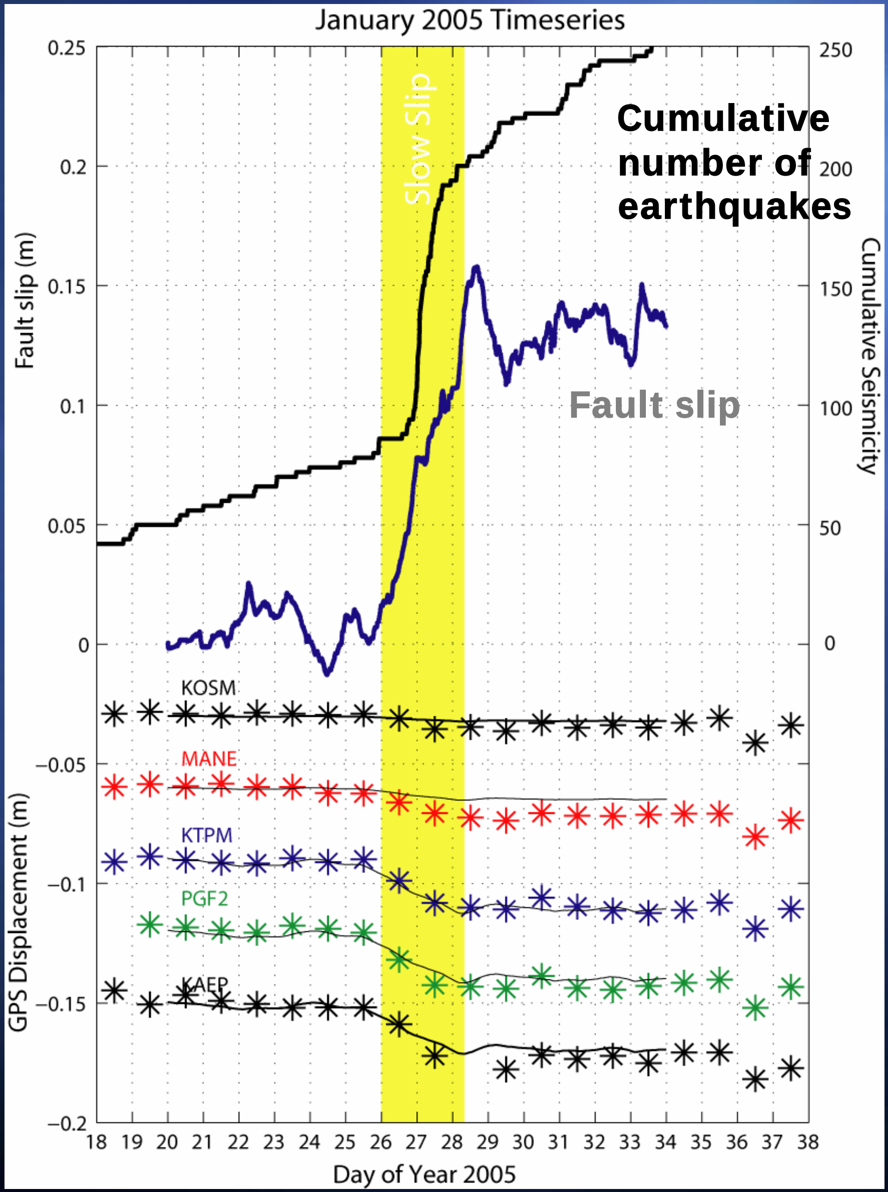
Rate state friction Ruina [1983]; Dieterich [1979]

$$\begin{aligned}
\tau &= (\sigma - p)[f_0 + a \log \frac{v}{v_0} + b \log \frac{\theta v_0}{d_c}] \\
\frac{d\theta}{dt} &= 1 - \frac{\theta v}{d_c} \quad \text{or} \\
\frac{d\theta}{dt} &= -\frac{\theta v}{d_c} \ln \left(\frac{\theta v}{d_c} \right)
\end{aligned}$$

Equations of Motion, with Radiation Damping Rice [1993]

$$\frac{\mu}{2\pi(1-\nu)} \int_{-\infty}^{\infty} \frac{\partial\delta/\partial\xi}{\xi - x} d\xi - f(v,\theta)(\sigma - p) = \frac{\rho v_s}{2} v$$

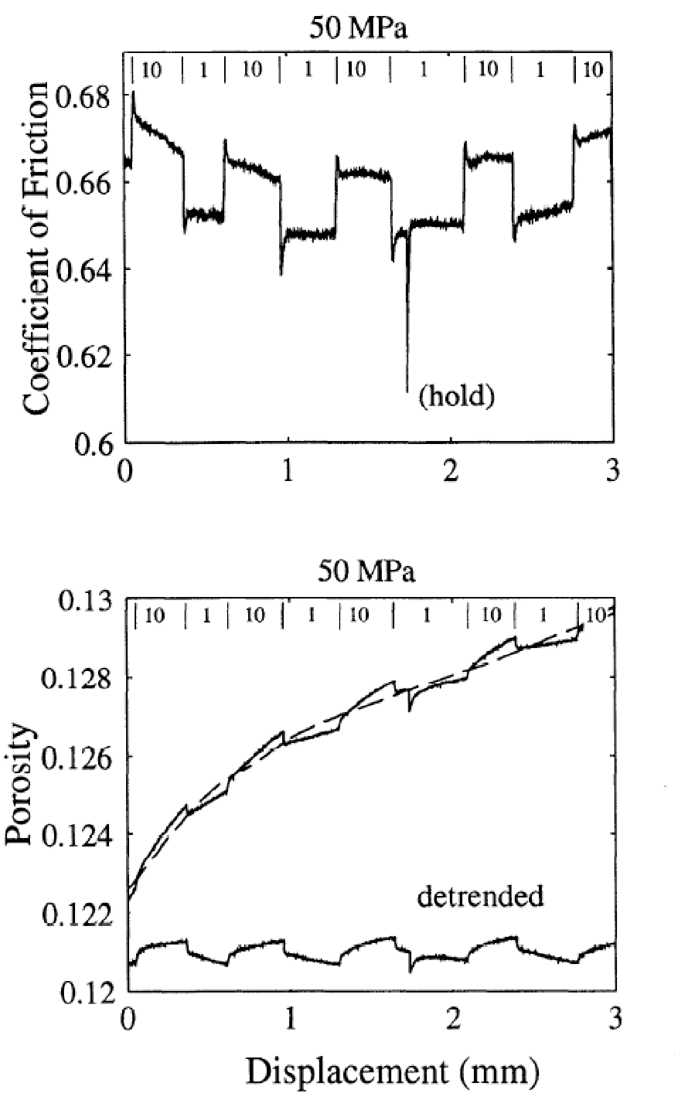
Earthquakes Lag Slip

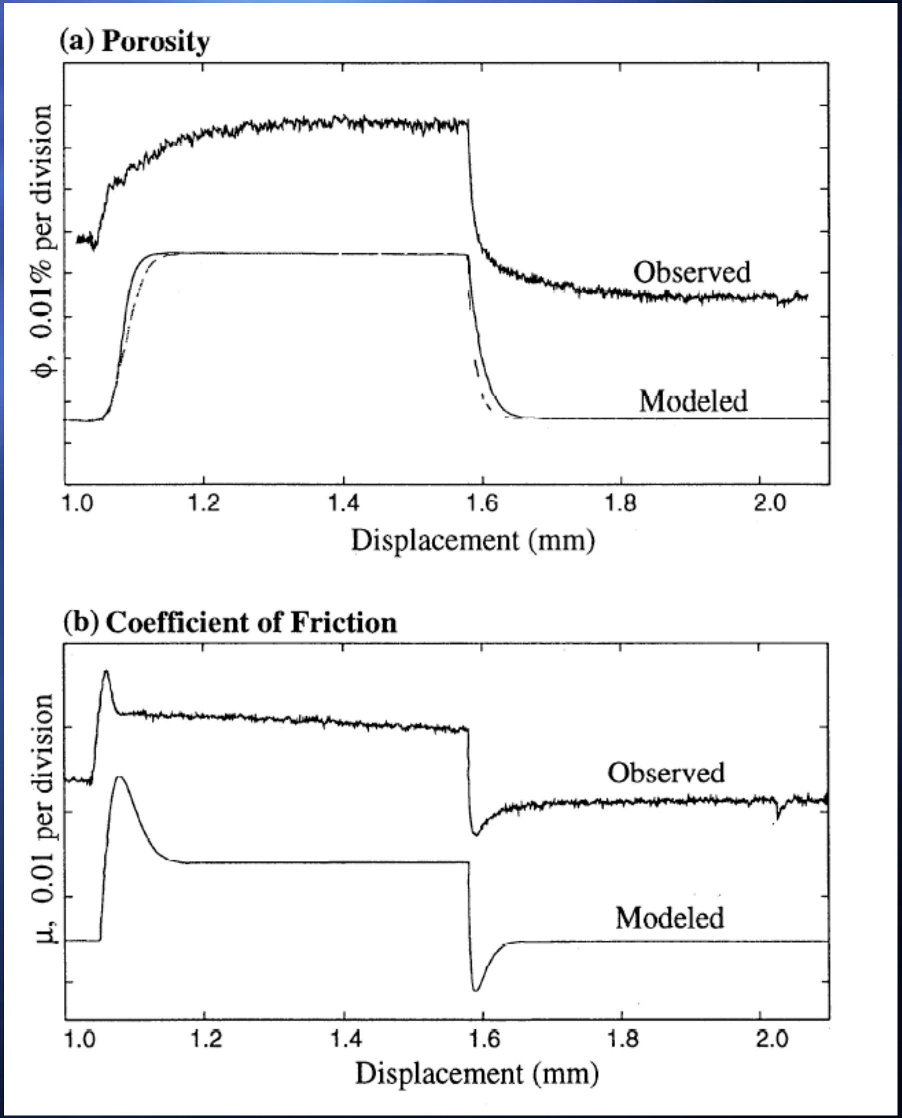


2005 Slow Slip Event

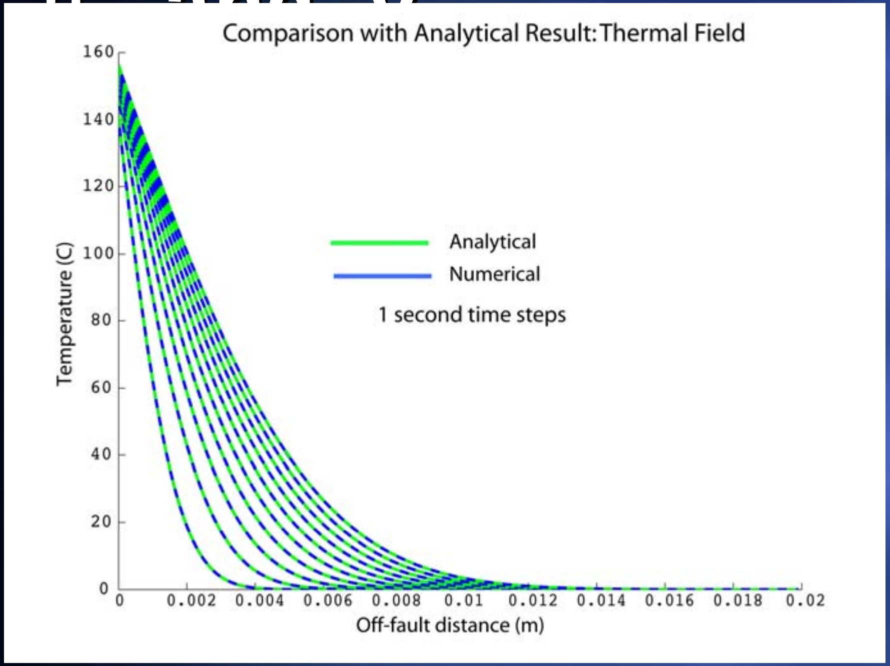
Segall et al, Nature, 2006

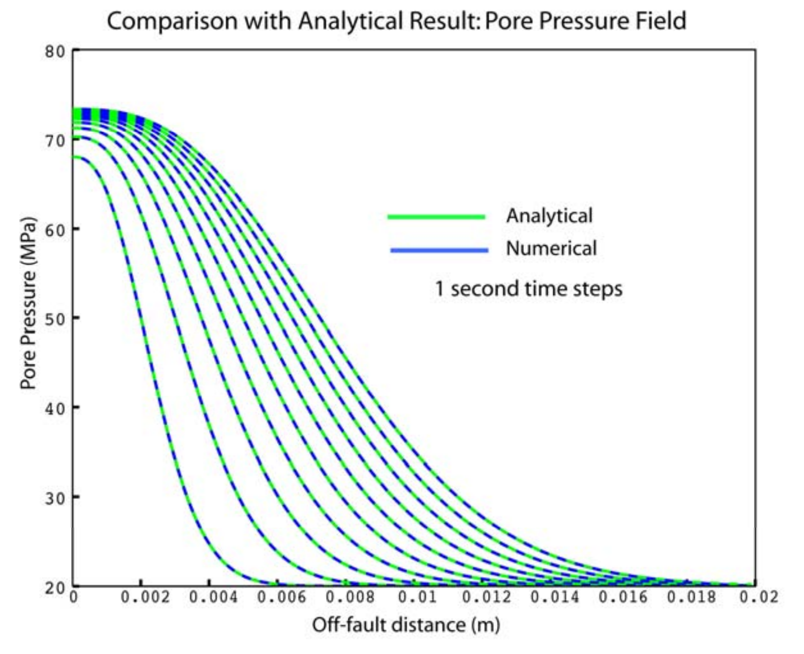
Dilatancy Constitutive Law (Segall and Rice, 1995), based on Marone lab data





Test of Finite Difference: Const μ and v


Comparison with Analytical Result: Thermal Field


Comparison with Analytical Result: Pore Pressure Field

$$T(y,t) - T_0 = \left(1 + \sqrt{\frac{c_{hy}}{c_{th}}}\right)\left(\frac{\sigma_n - p_0}{\Lambda}\right)\left[\operatorname{erfc}\left(\frac{Y}{2\sqrt{D}}\right) - \exp(Y+D)\operatorname{erfc}\left(\frac{Y}{2\sqrt{D}} + \sqrt{D}\right)\right]$$

$$Y = \frac{|y|}{\sqrt{c_{th}L^*/v_c}}$$

Analytical Result,
Rice (2006)

$$\begin{aligned} p(y,t) - p_0 \quad &= \quad \frac{\sqrt{c_{th}} + \sqrt{c_{hy}}}{c_{hy} - c_{th}}(\sigma_n - p_0)\left\{\sqrt{c_{hy}}\left[\operatorname{erfc}\left(\frac{Y'}{2\sqrt{D}}\right) - \exp(Y'+D)\operatorname{erfc}\left(\frac{Y'}{2\sqrt{D}} + \sqrt{D}\right)\right]\right. \\ &\left. -\sqrt{c_{th}}\left[\operatorname{erfc}\left(\frac{Y}{2\sqrt{D}}\right) - \exp(Y+D)\operatorname{erfc}\left(\frac{Y}{2\sqrt{D}} + \sqrt{D}\right)\right]\right\} \end{aligned}$$

$$Y' = \frac{|y|}{\sqrt{c_{hy}L^*/v_c}}$$