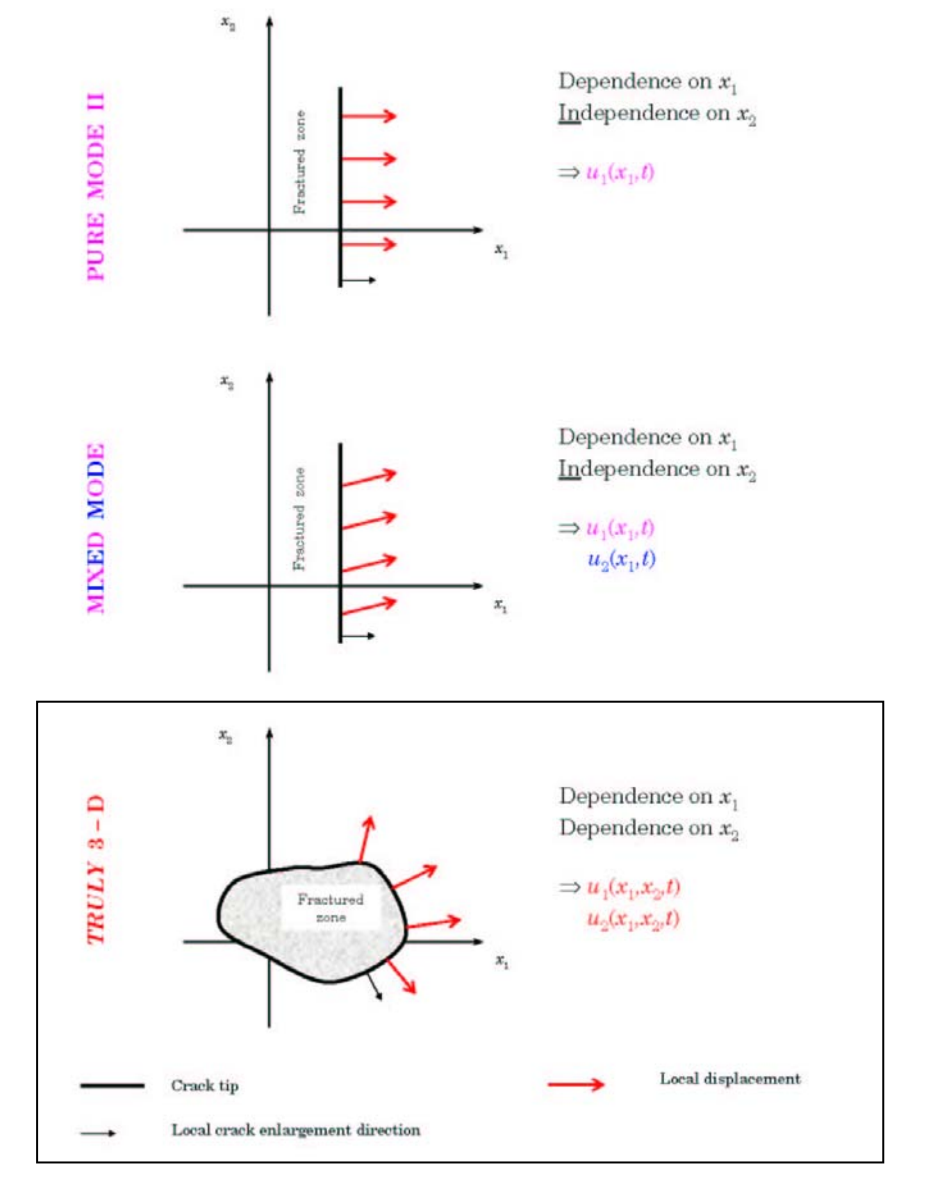
Rupture propagation in a *truly* 3 – D fault model

Remembering dimensionality ...

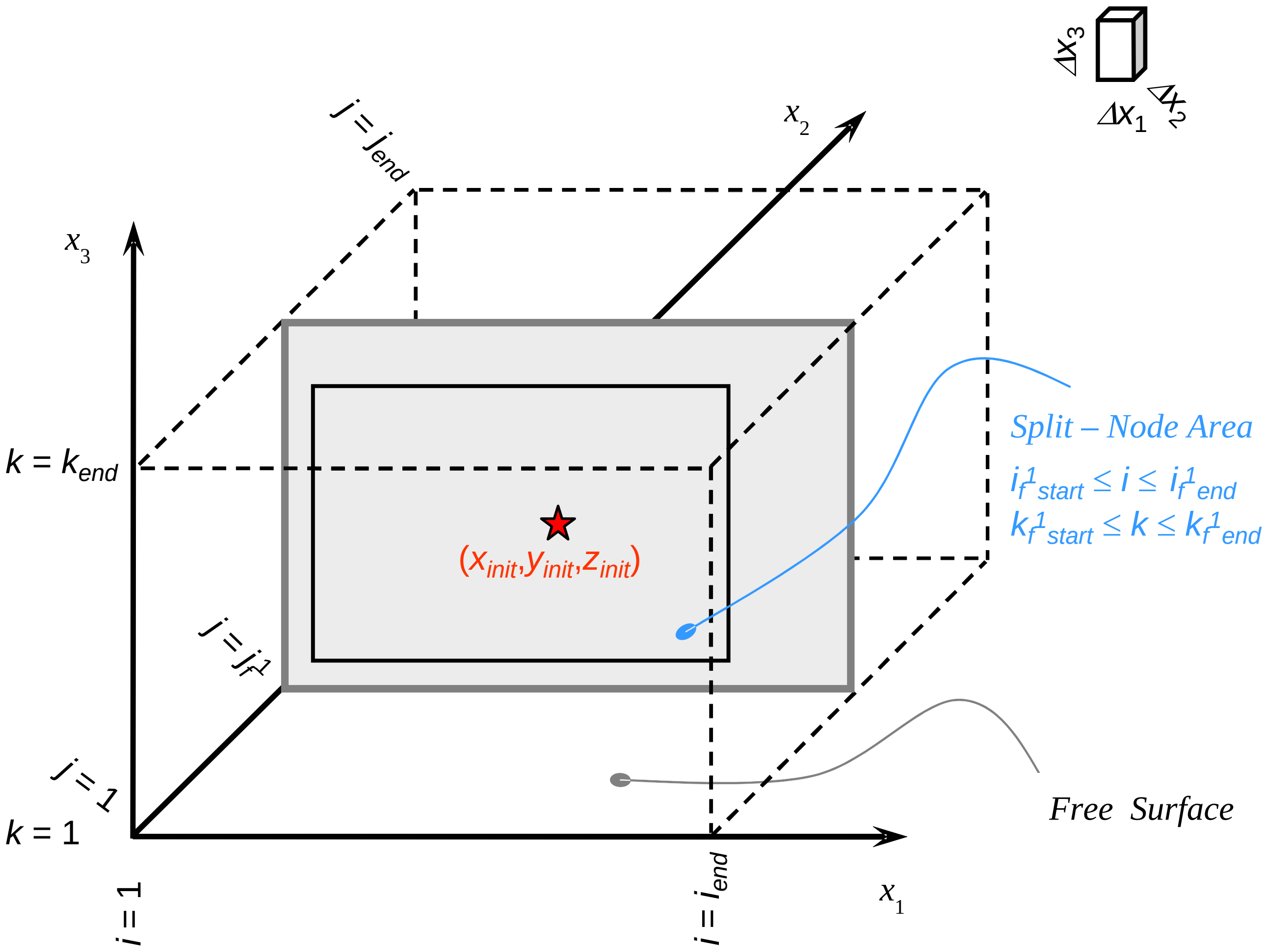


We solve a *truly* 3 – D rupture problem:

- Both two components of solutions depend on two spatial coordinates and on time;

- Shear traction is collinear with fault slip velocity (T // **v**), but the rake (i. e. the fault slip velocity azimuth) can vary during time.

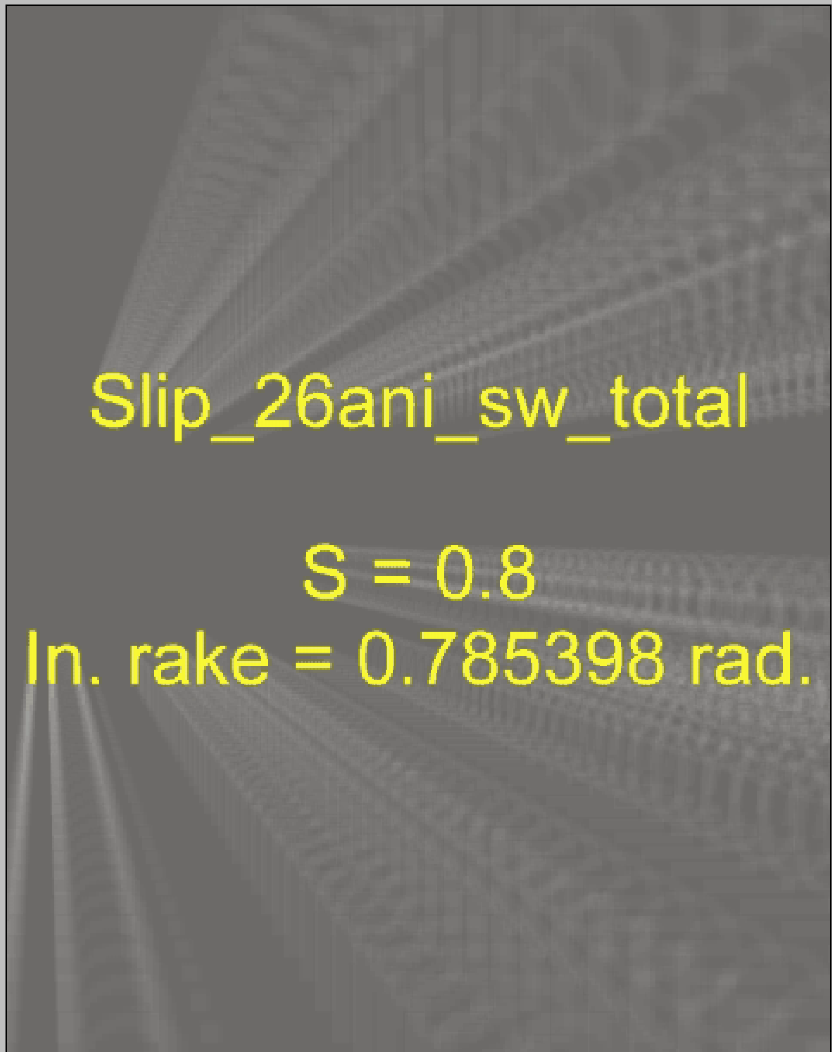
Numerical Method: FD 3 - D



$$\boldsymbol{u} = (\, u_1(x_1, x_3, t),\, 0,\, u_3(x_1, x_3, t)\,)$$

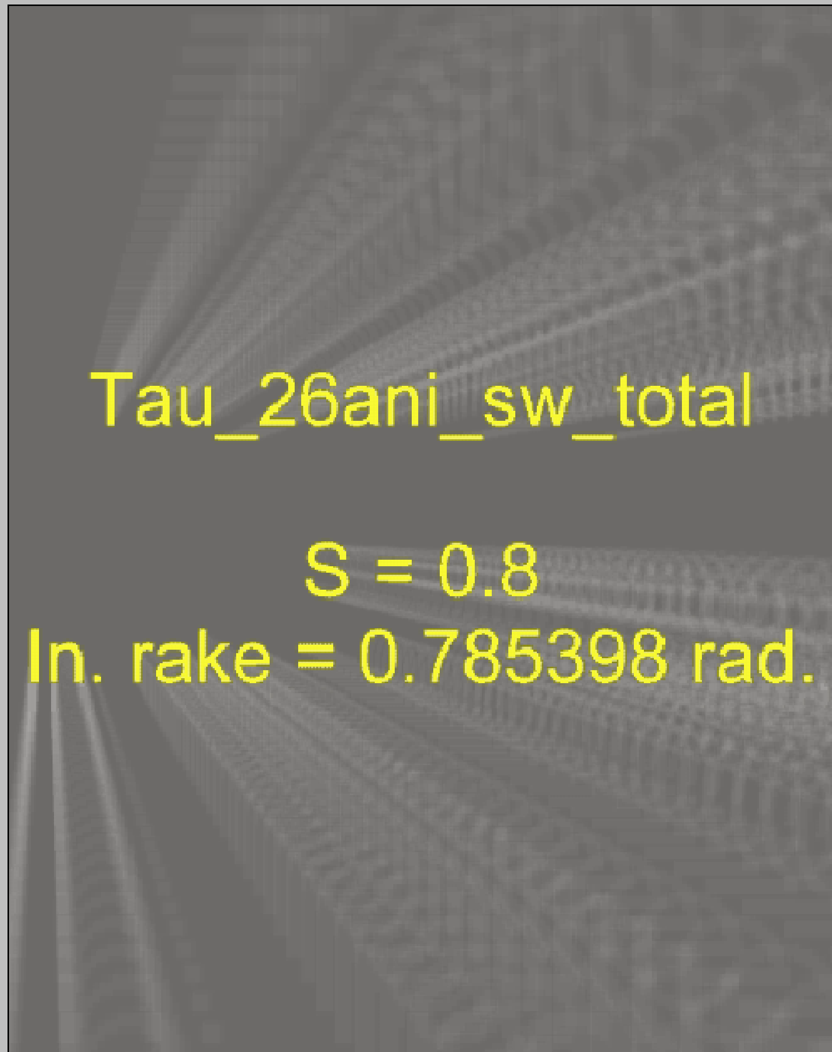
Reference Case

Slip



Anim_Slip_26ani_sw_total.avi

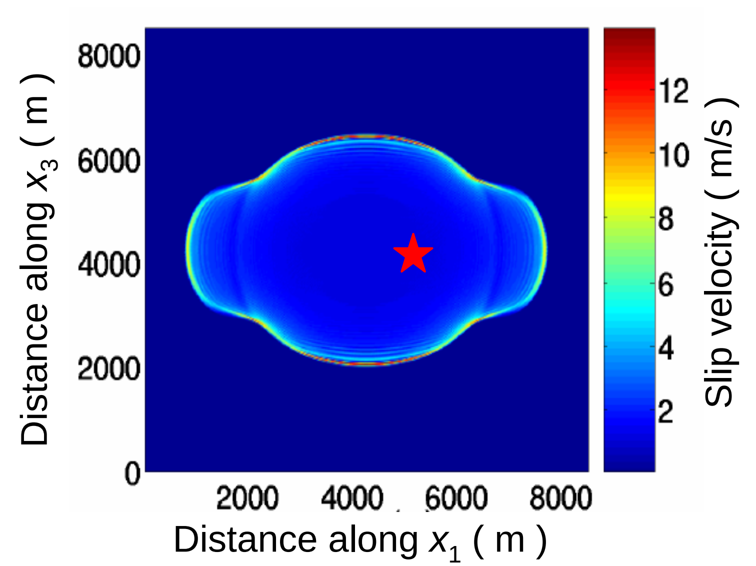
Traction



Anim_Tau_26ani_sw_total.avi

The cohesive zone

Time snapshot (t = 0.8 s) - SW law



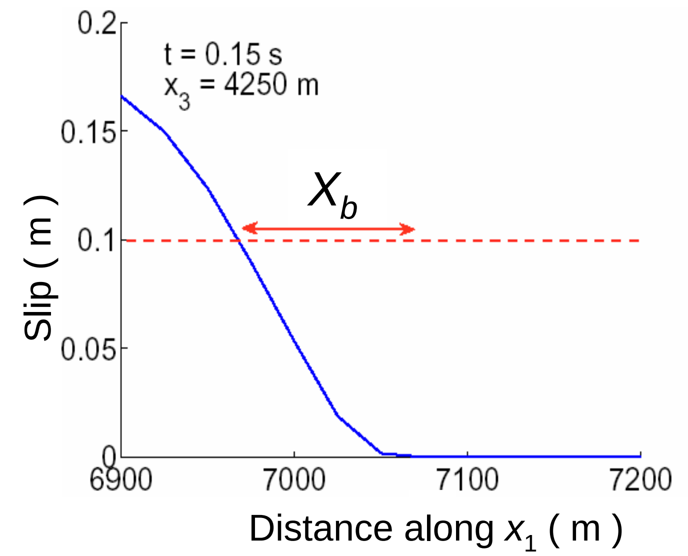
Local estimate

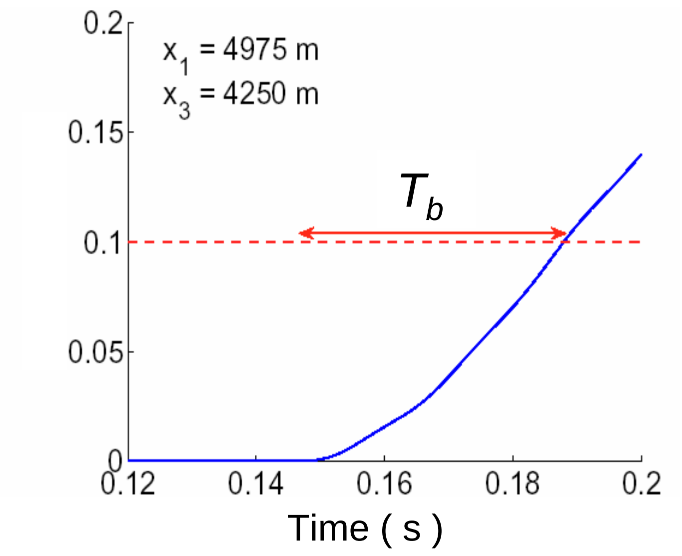
In the target location we can extimate:

X_b = 105 m T_b = 0.04 s

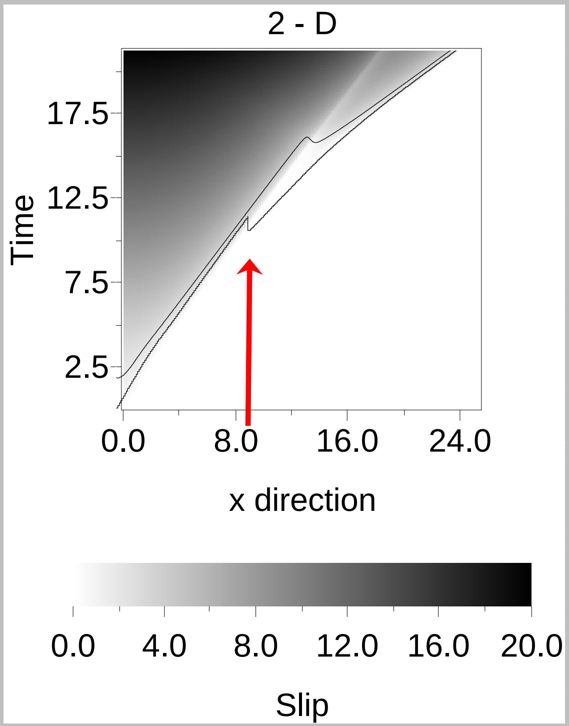
From these quantities:

$v_{rupt} = X_b/T_b$ = 2625 m/s

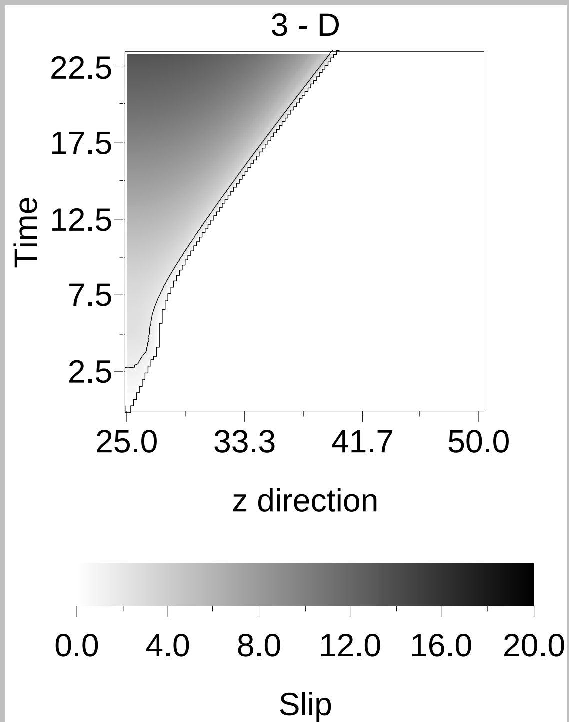




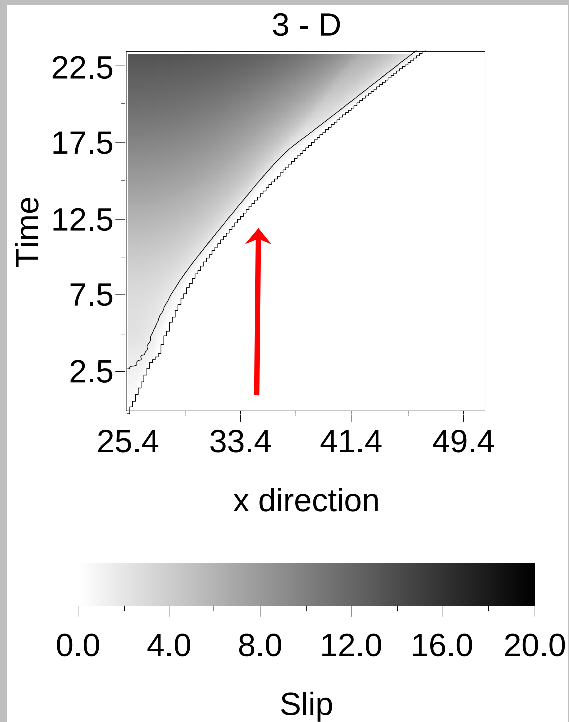
Comparision between 2 – D and 3 – D models #1



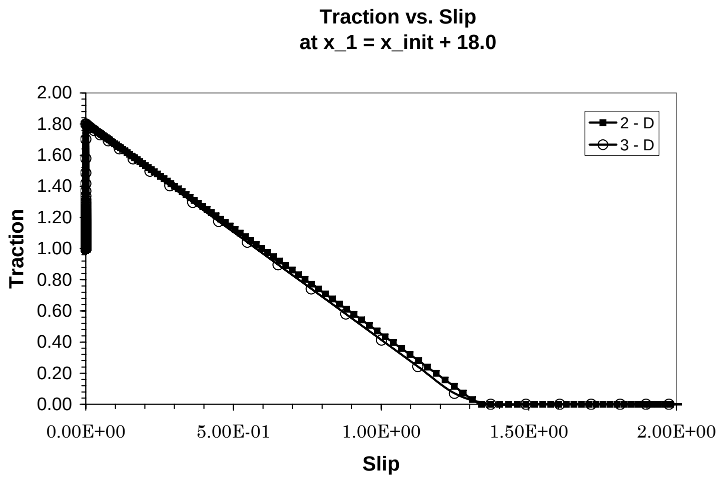
Fixed x_1 coordinate

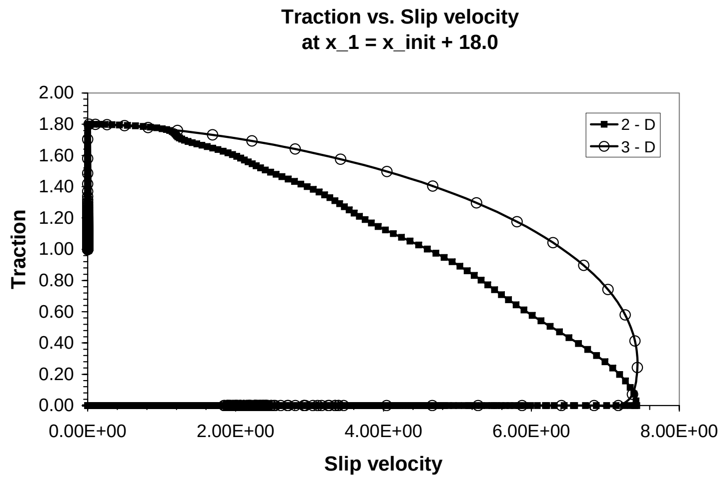


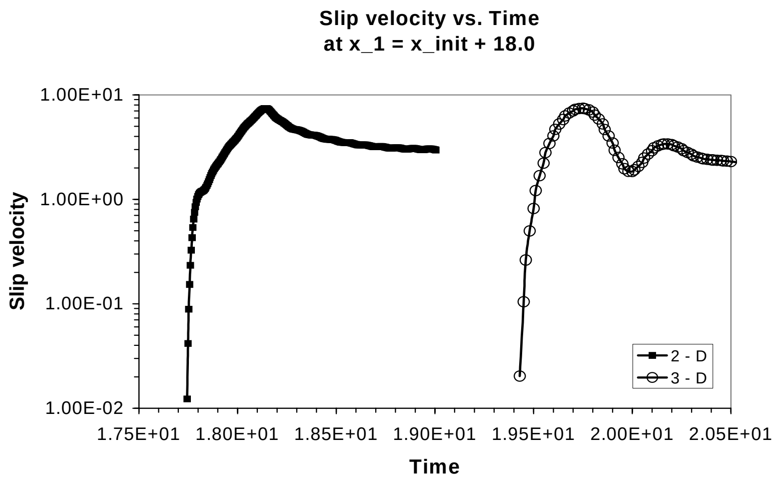
Fixed x_3 coordinate

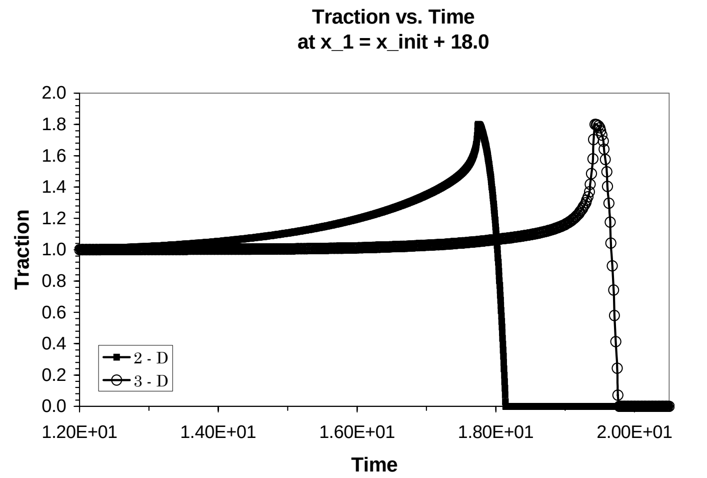


Comparision between 2 – D and 3 – D models #2

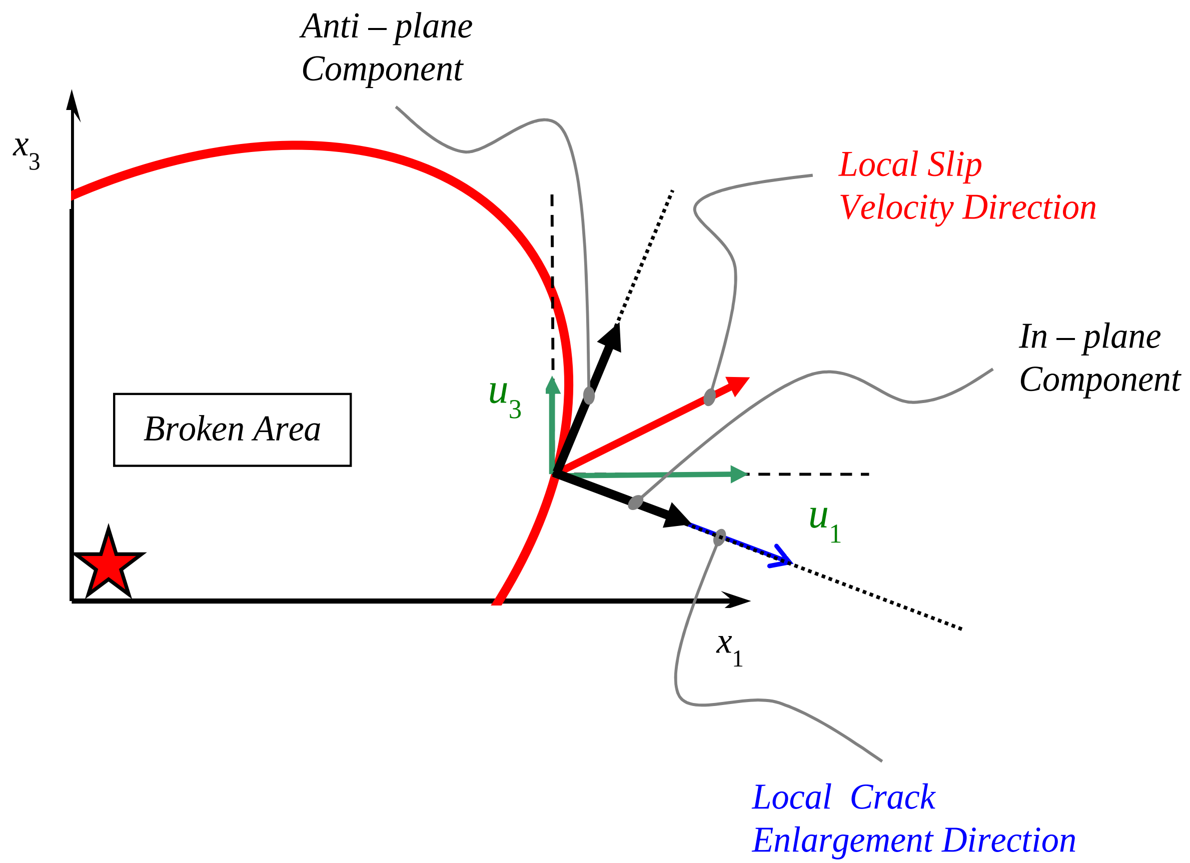








The rake rotation: the coupling of the two modes of propagation



Rake rotation #2: evidences

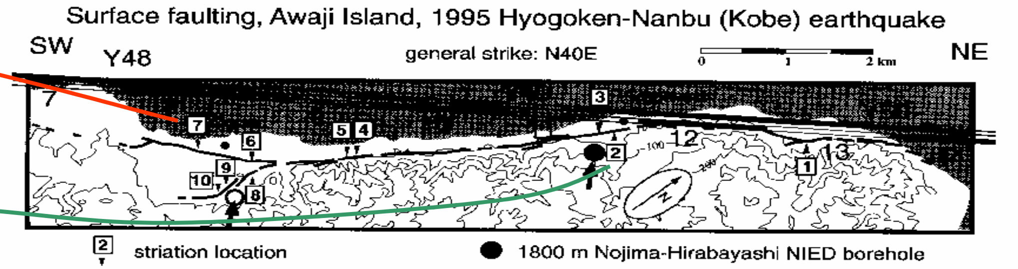


Figure 1. Map of Nojima fault on Awaji Island, showing elevation (m), surface faulting (heavy line), locations of fault striations (numbers in boxes), the Nojima-Hirabayashi NIED and the Nojima-Ogura boreholes, and the subfaults (numbered) in the original (Y48 to Y50) and interpolated (7 to 14) Yoshida slip models. Arrows show approximate direction of *SH* in boreholes.

From Spudich et al., (1998)

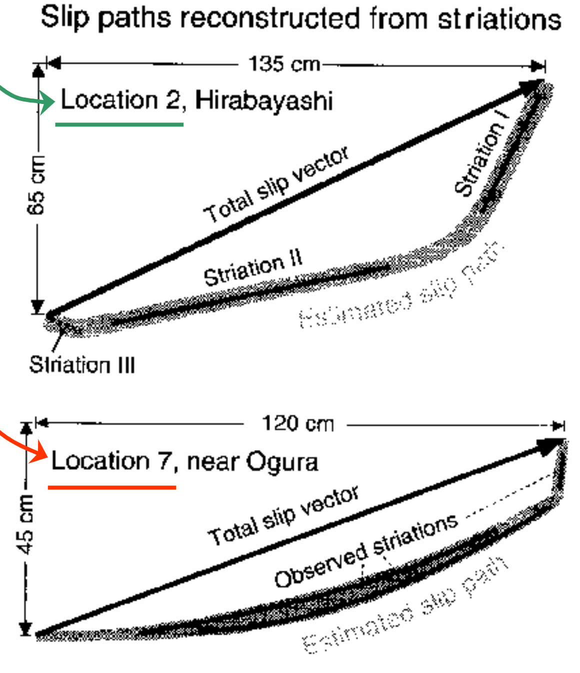


Figure 2. Black lines: striations observed at locations 2 and 7. Gray bands: slip paths inferred from striation locations 2 and 7. From Otsuki *et al.* (1997).

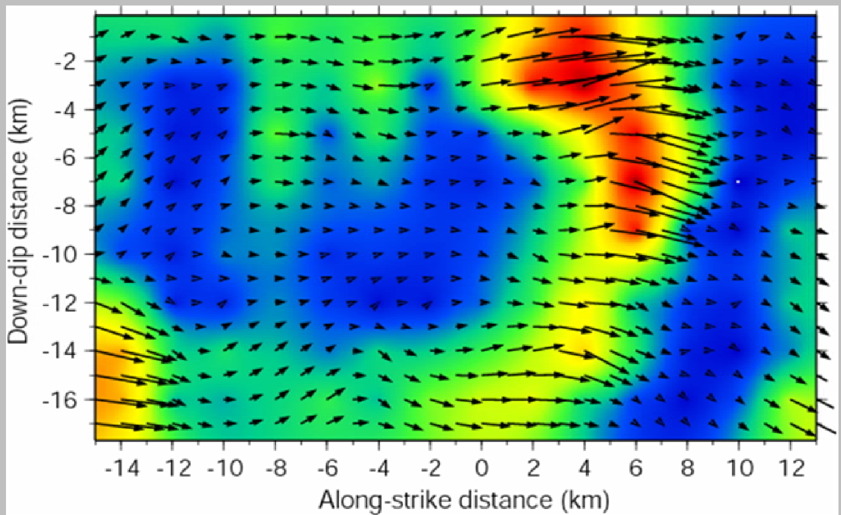
Etchecopar (1984), *Florensov and Solonenko (1965)*, *Kakimi et al. (1977)*, *Philip and Megard (1977)*.

More recently curved striations (also called slickenlines) were seen in the Denali earthquake (*Haeussler et al. 2004*).

Curved striations were observed in the 1971 San Fernando; 1999 Hector Mine EQ; the 1992 Landers EQ; the 1980 El Asnam, Algeria EQ, and on the San Andreas in the Mecca Hills.

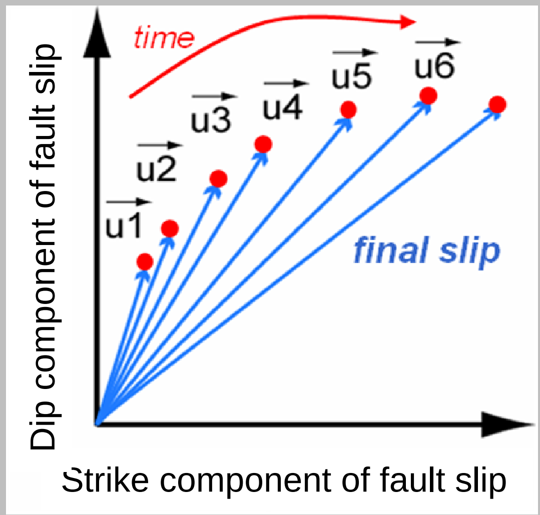
Rake rotation: a schematic example

Spatial heterogeneous rake

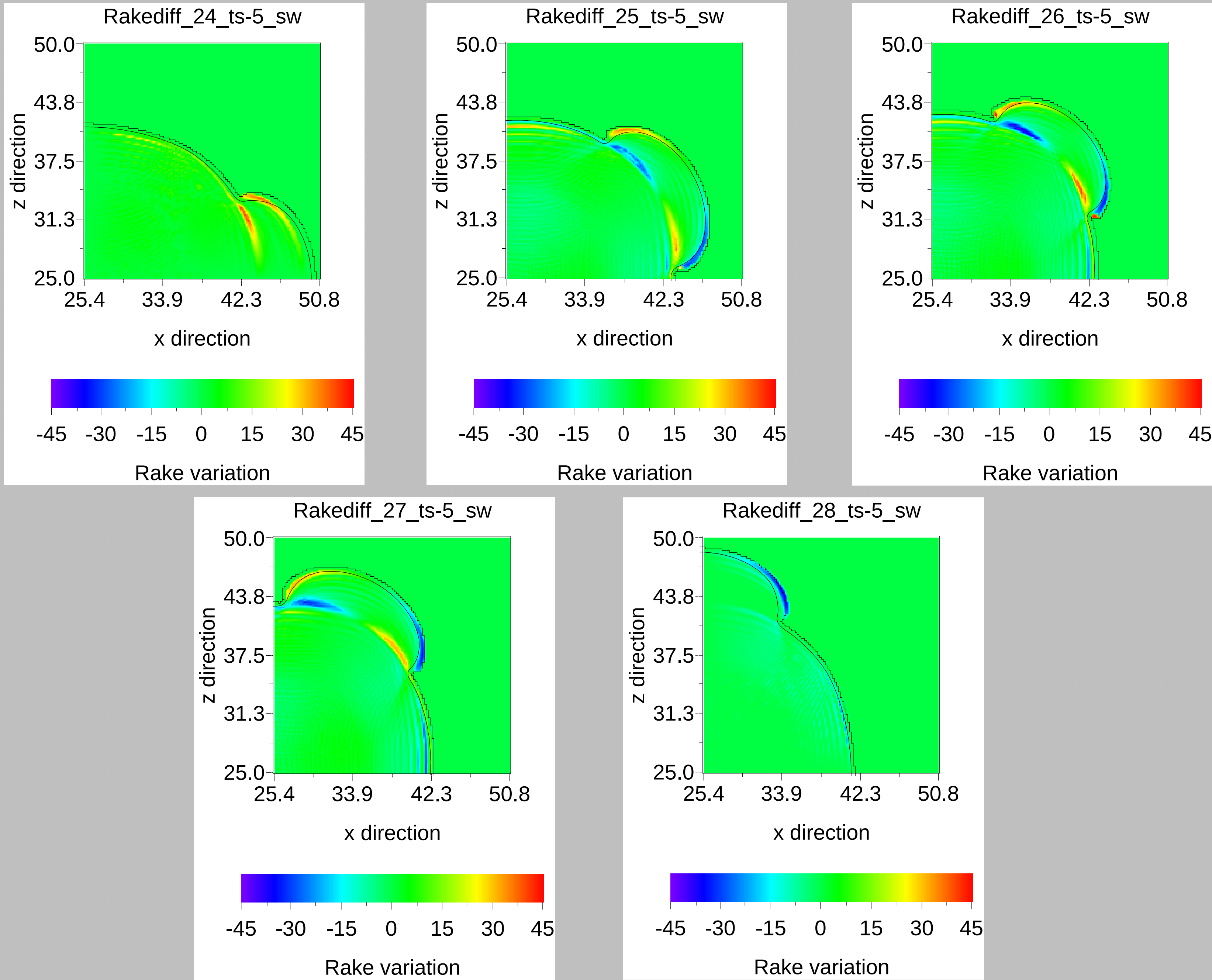


Slip distribution on the fault

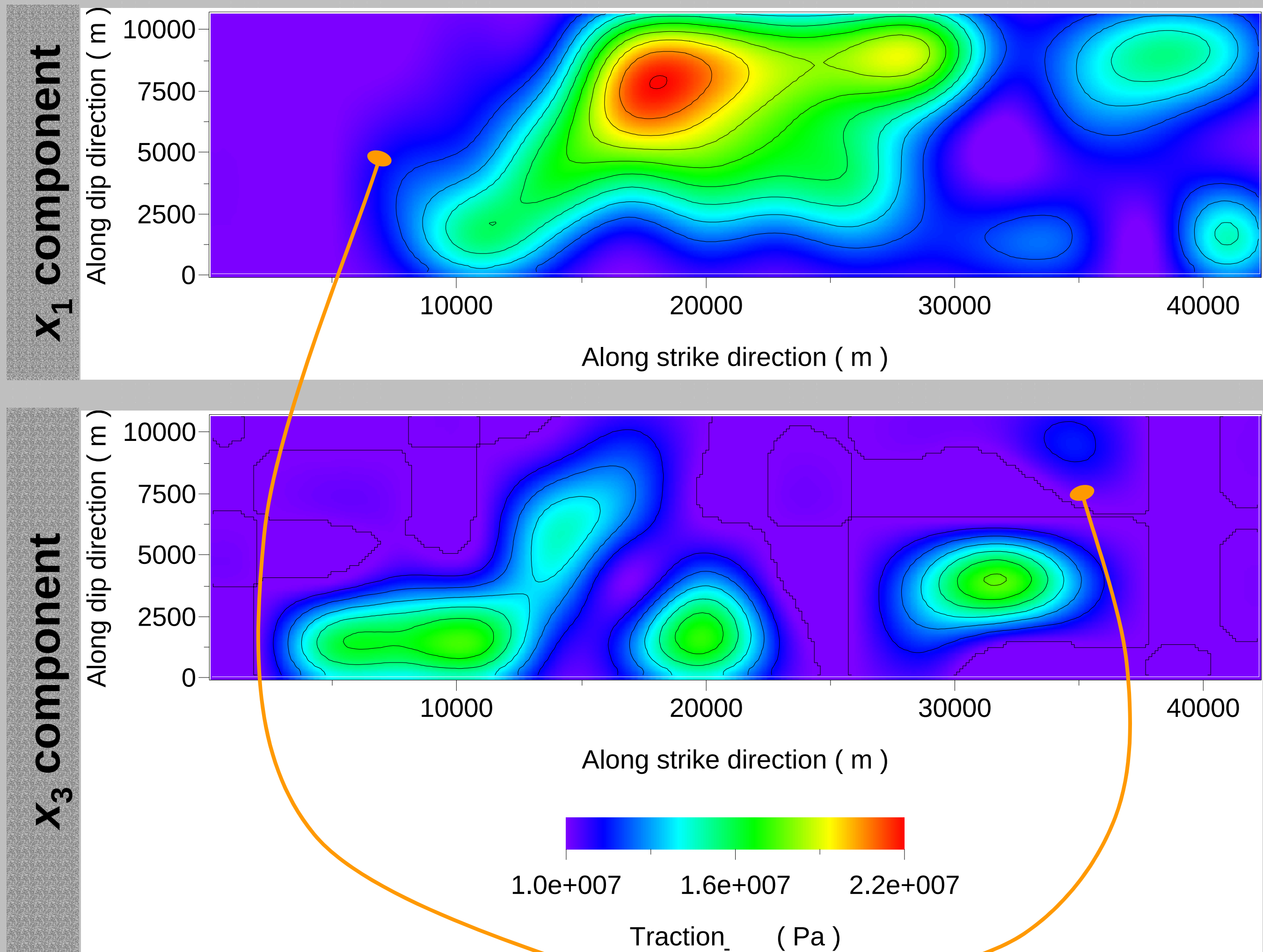
Temporal heterogeneous rake



Temporal evolution of slip for a target point


Rakediff_24_ts-5_sw
Rakediff_25_ts-5_sw
Rakediff_26_ts-5_sw
Rakediff_27_ts-5_sw
Rakediff_28_ts-5_sw
z direction
50.0
43.8
37.5
31.3
25.0
x direction
25.4
33.9
42.3
50.8
-45
-30
-15
0
15
30
45
Rake variation

The rake rotation #5: path / modulus



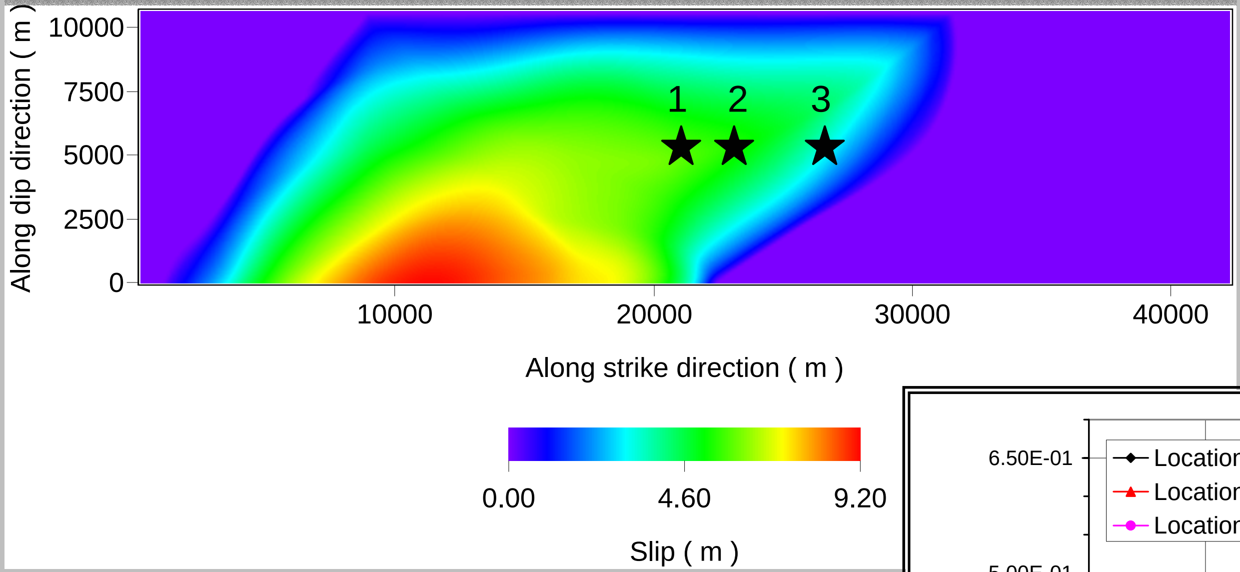
$$\mathrm{T}_0(x_1, x_3) \equiv \mathrm{T}(x_1, x_3, 0) = (T_1(x_1, x_3, 0), 0, T_3(x_1, x_3, 0))$$

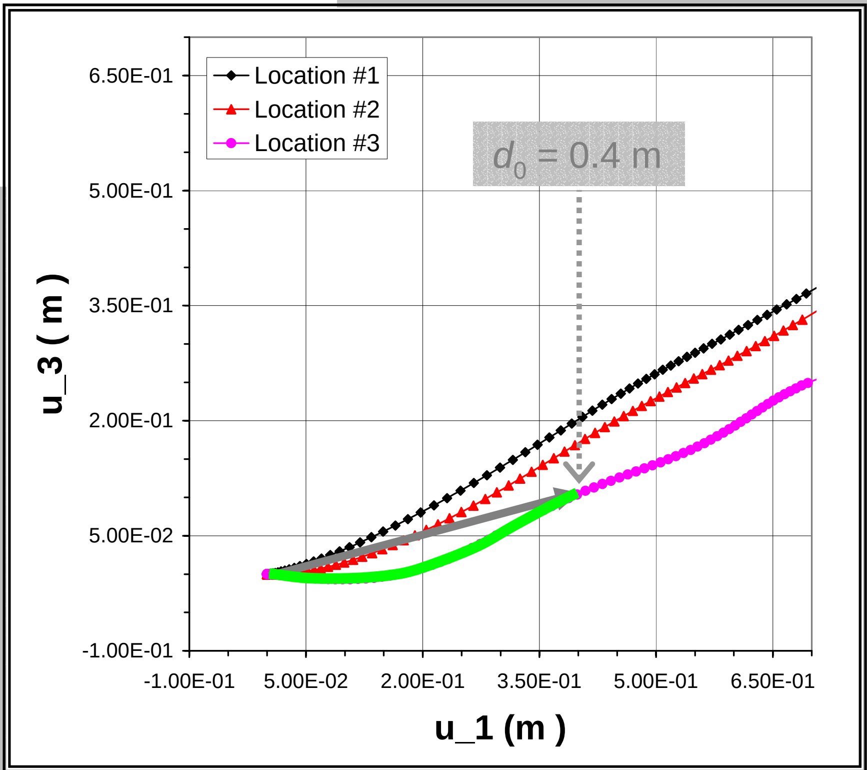
$$\mathcal{T}_0 = \mathrm{T}_0 + \Sigma_0$$

Normal Traction → $\Sigma_0(x_1, x_3) \equiv \Sigma(x_1, x_3, 0) = -\sigma_n^{eff}\,\hat{\mathbf{n}} = (0, -30\ \mathrm{MPa}, 0)$

Total Traction

Fault slip time snapshots – Linear SW assumed





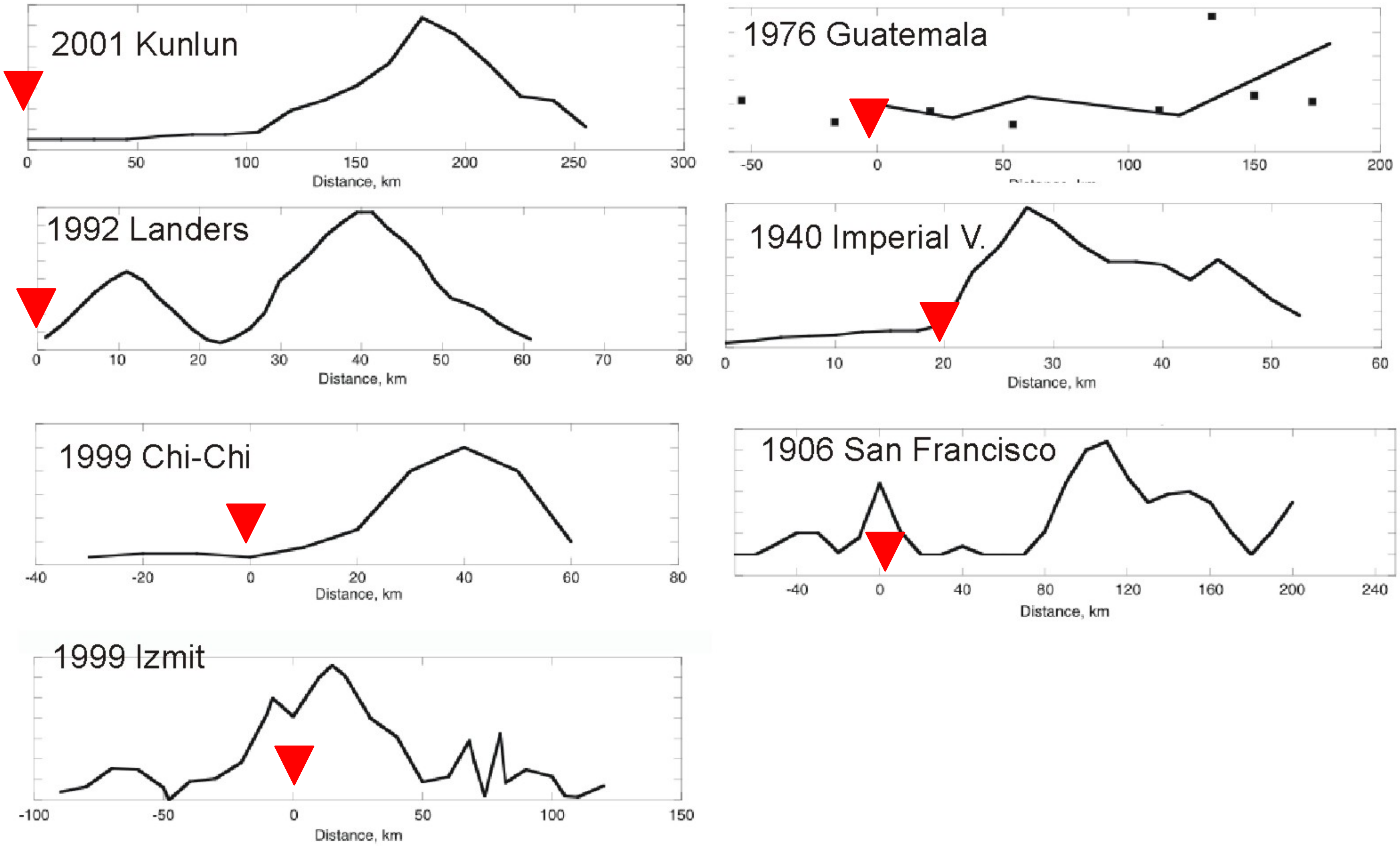
Slip modulus:

$$u = u^{(mod)}\left(x_1, x_3, t\right) \equiv \left\| \mathbf{u}\left(x_1, x_3, t\right) \right\|$$

Slip path:

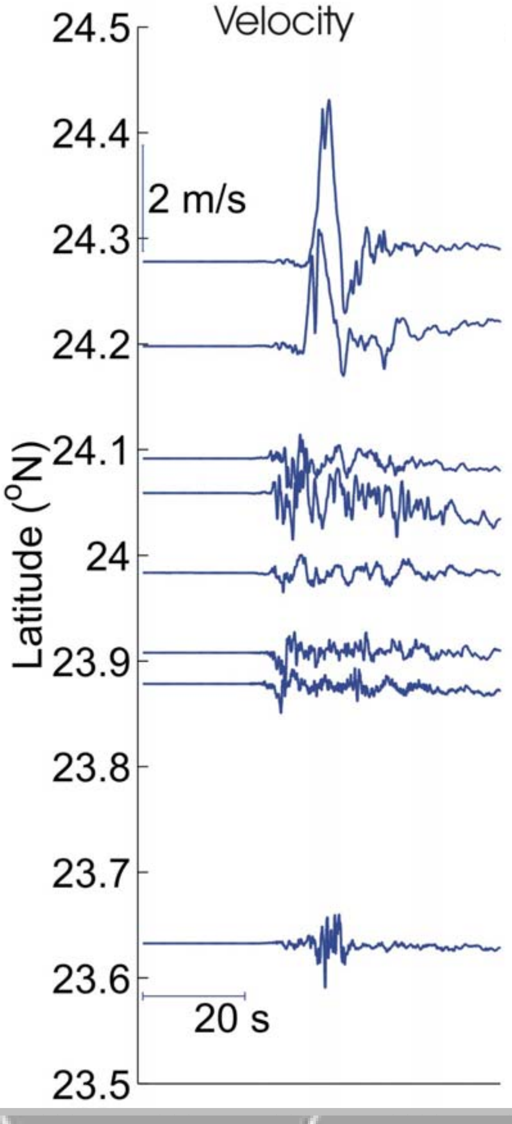
$$u = u^{(path)}\left(x_1, x_3, t\right) \equiv \int_0^t \left\| \mathbf{v}\left(x_1, x_3, t'\right) \right\| \mathrm{d}\, t'$$

Slip distribution of large earthquakes

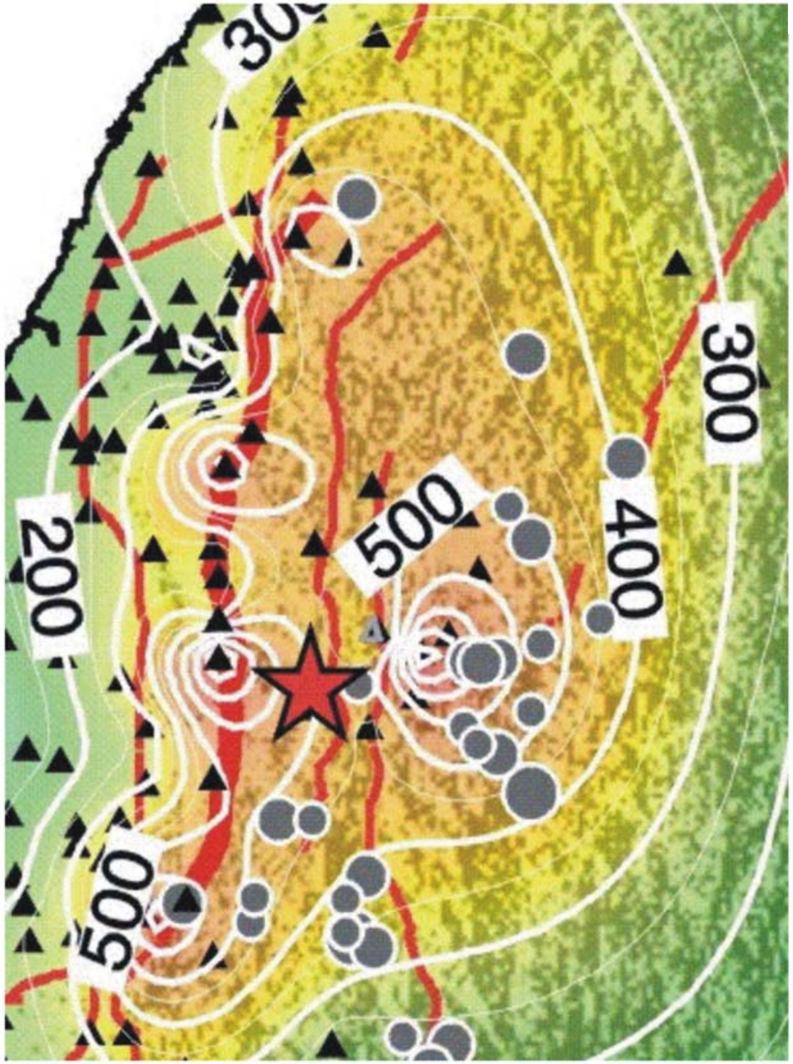


Ground motion from Chi – Chi, Taiwan, EQ

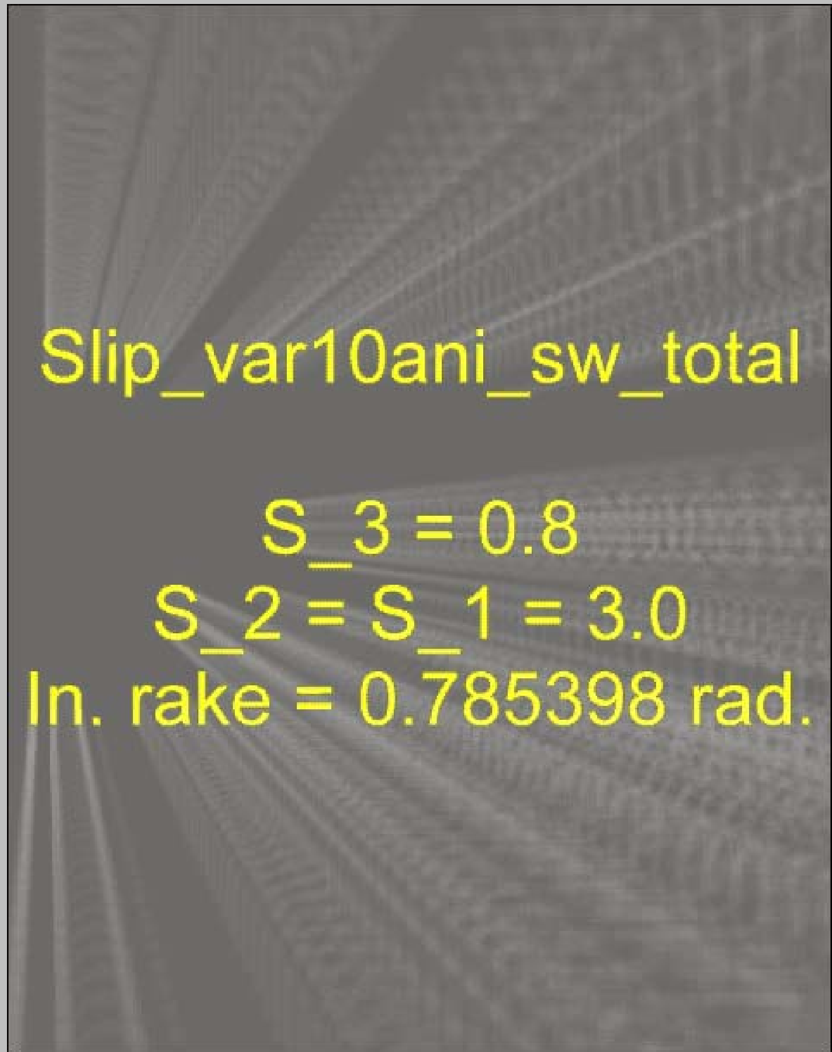
Brodsky and Kanamori (2001)



Ma et al. (1993)

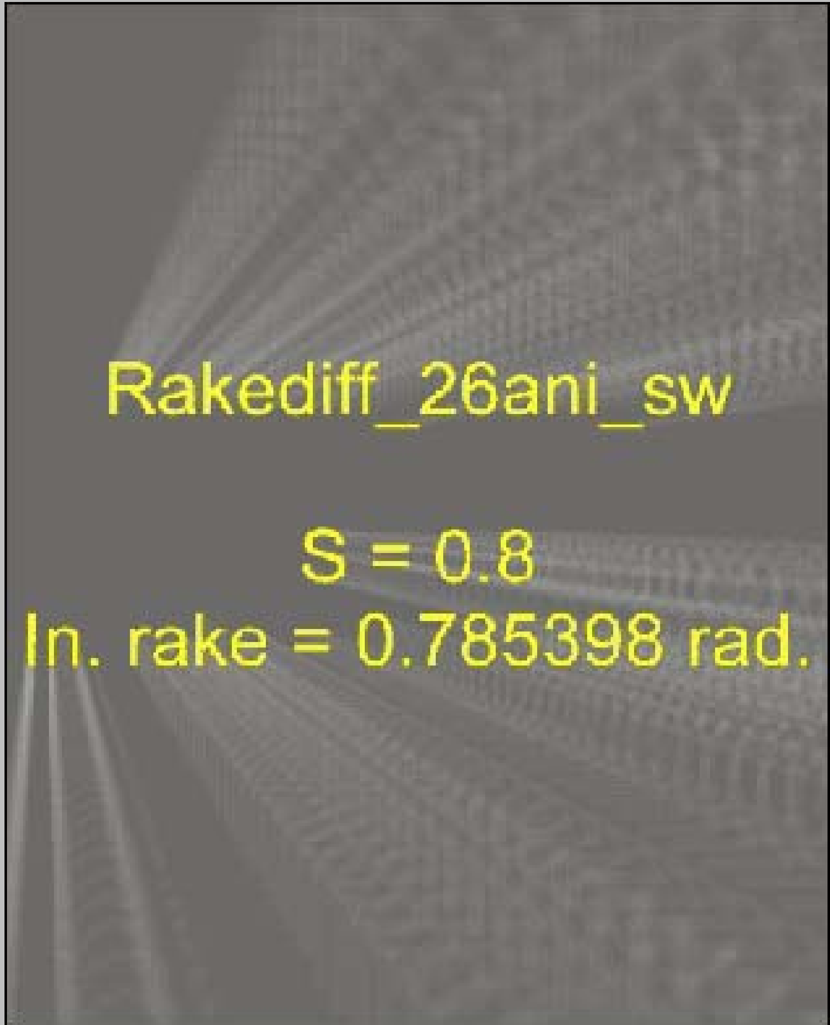


Effects of Strength Heterogeneity #1



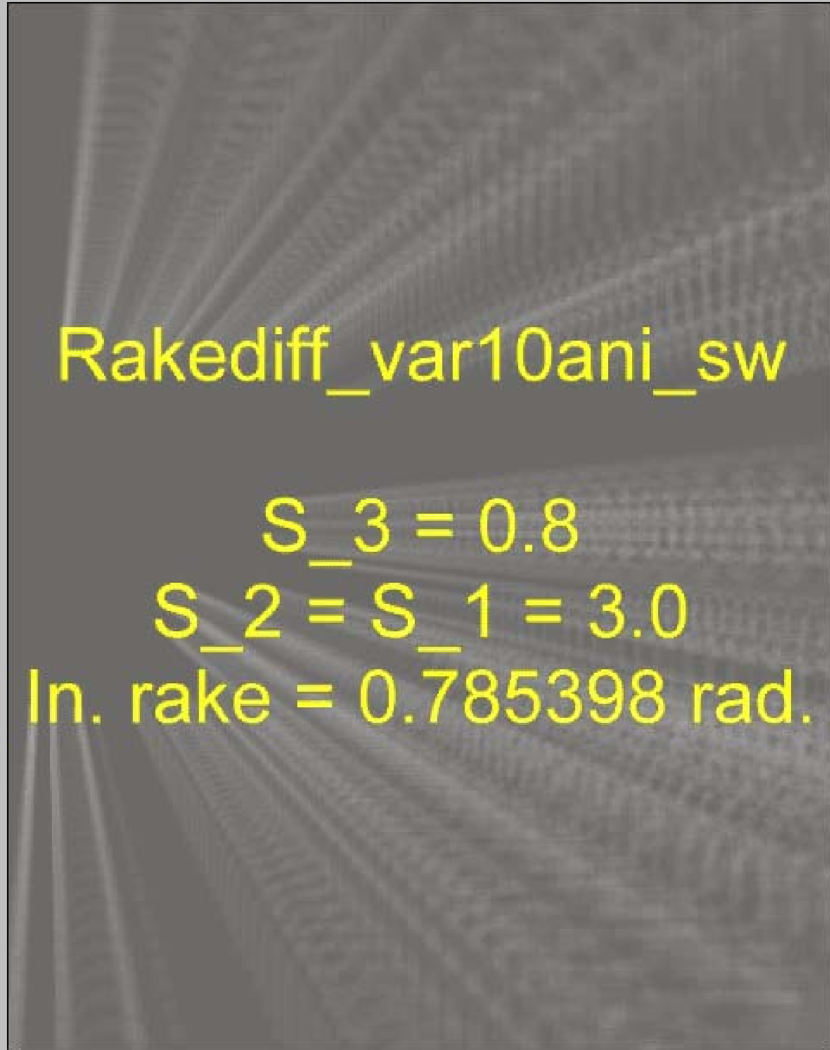
Anim_Slip_var10ani_sw_total.avi

Homogeneous



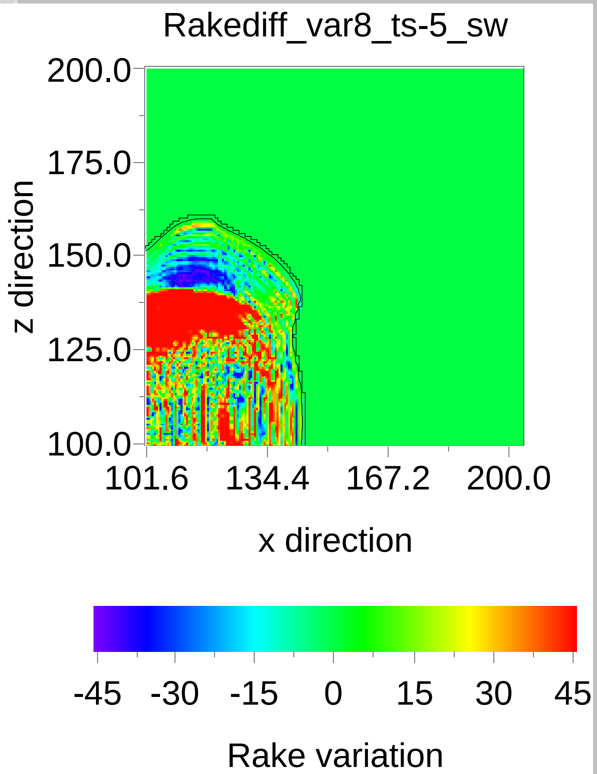
Anim_Rakediff_26ani_sw_total.avi

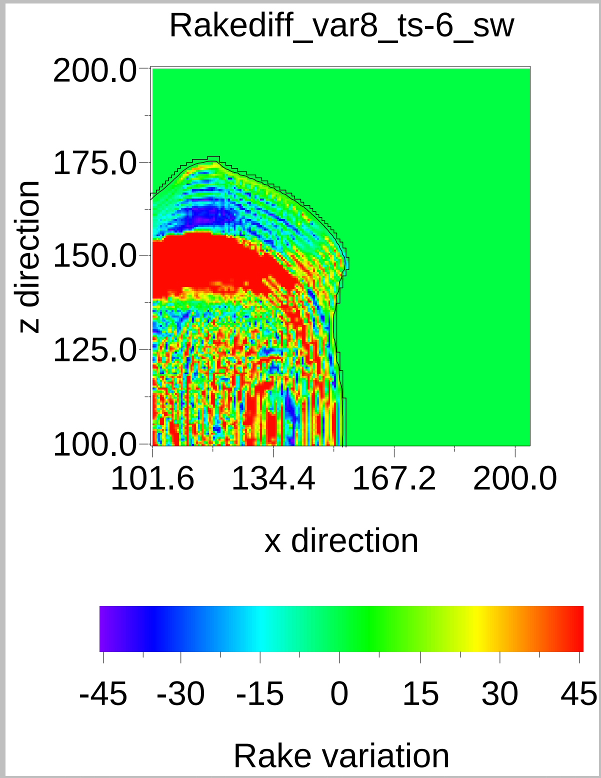
Heterogeneous

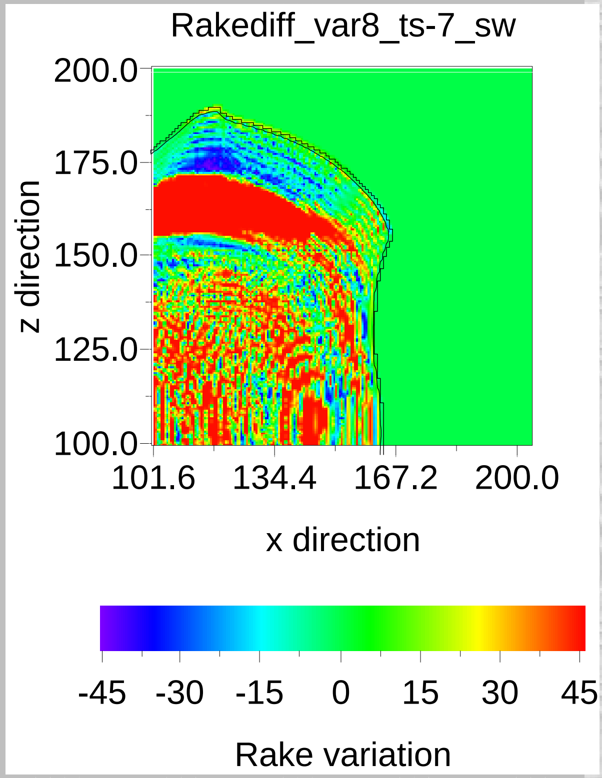


Anim_Rakediff_var10ani_sw_total.avi

Effects of Strength Heterogeneity #2

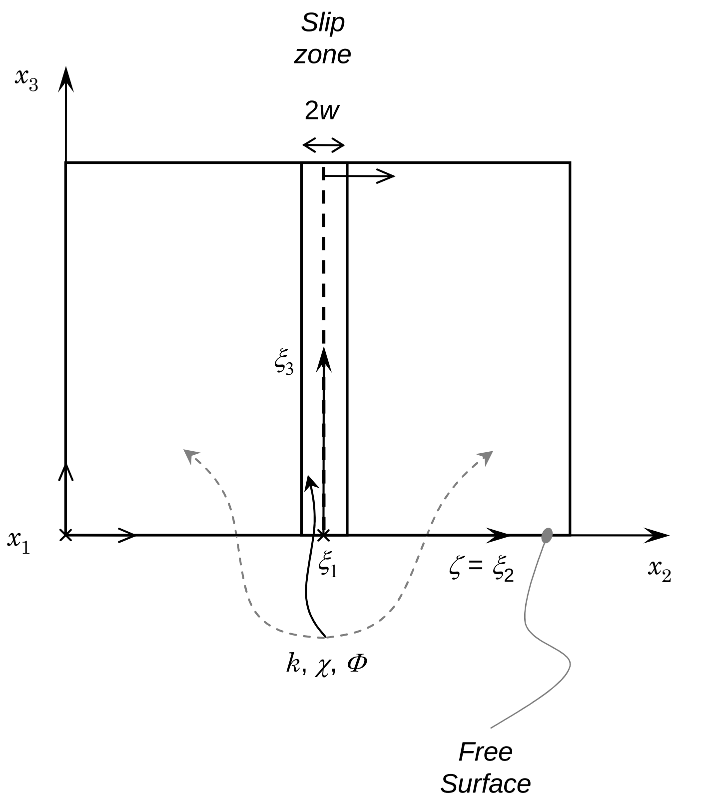






Thermal pressurization of pore fluids

Mathematical background



1 – D Fourier' s heat conduction equation:

$$\frac{\partial}{\partial t} T = \chi \frac{\partial^2}{\partial \zeta^2} T + \frac{1}{c} q$$

Coupling of temperature *T* with pore fluid pressure p_{fluid}:

$$\frac{\partial}{\partial t} p_{fluid} = \frac{\alpha_{fluid}}{\beta_{fluid}} \frac{\partial}{\partial t} T - \frac{1}{\beta_{fluid} \Phi} \frac{\partial}{\partial t} \Phi + \omega \frac{\partial^2}{\partial \zeta^2} p_{fluid}$$

where χ is the thermal diffusivity, *c* the heat capacity for unit volume, α_{fluid} the coefficient of thermal expansion, β_{fluid} the compressibility coefficient, Φ the porosity and $\omega = k/\eta_{fluid}\beta_{fluid}\Phi$ the hydraulic diffusivity (being k the permeability of the medium and η_{fluid} the dynamic fluid viscosity). Analytical solutions at $\zeta = 0$ are:

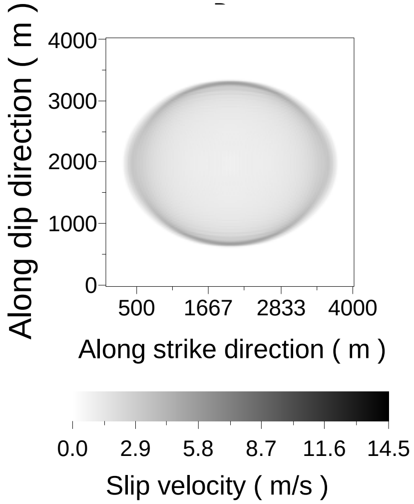
$$T^{w^f}(\xi_1,\xi_3,t) = T_0^f + \frac{1}{2cw(\xi_1,\xi_3)} \int_0^{t-\varepsilon} dt' \operatorname{erf}\left(\frac{w(\xi_1,\xi_3)}{2\sqrt{\chi(t-t')}}\right) \tau(\xi_1,\xi_3,t') v(\xi_1,\xi_3,t')$$

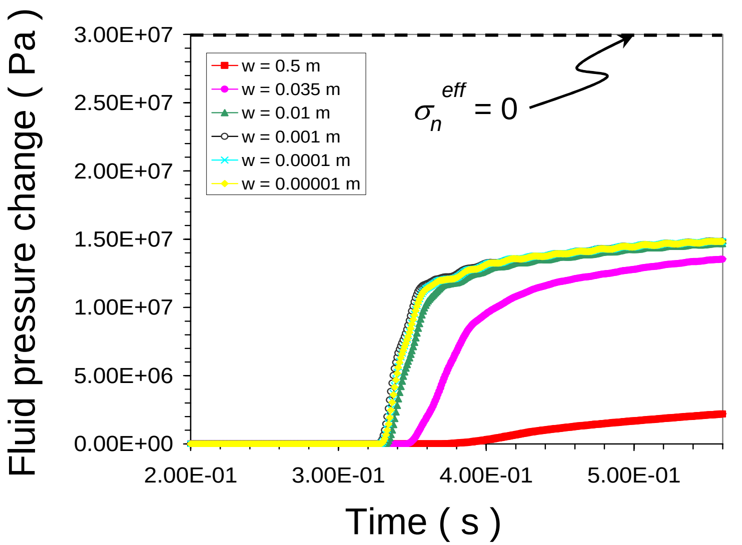
$$\tilde{p}_{fluid}{}^{w^f}(\xi_1,\xi_3,t) = p_{fluid_0}{}^f + \frac{\gamma}{2w(\xi_1,\xi_3)} \int_0^{t-\varepsilon} dt' \left\{ -\frac{\chi}{\omega-\chi} \operatorname{erf}\left(\frac{w(\xi_1,\xi_3)}{2\sqrt{\chi(t-t')}}\right) + \frac{\omega}{\omega-\chi} \operatorname{erf}\left(\frac{w(\xi_1,\xi_3)}{2\sqrt{\omega(t-t')}}\right) \right\}$$
$$\left\{ \tau(\xi_1,\xi_3,t') v(\xi_1,\xi_3,t') - \frac{2w(\xi_1,\xi_3)}{\gamma} \frac{1}{\beta_{fluid}\Phi(t')} \frac{\partial}{\partial t'} \Phi(\xi_1,0,\xi_3,t') \right\}$$

Bizzarri and Cocco (2006a, 2006b, *JGR*)

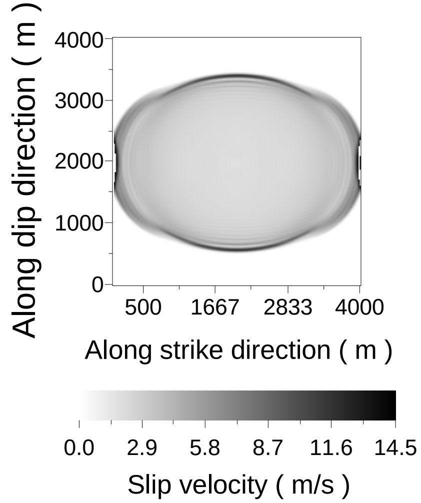
Results with SW law

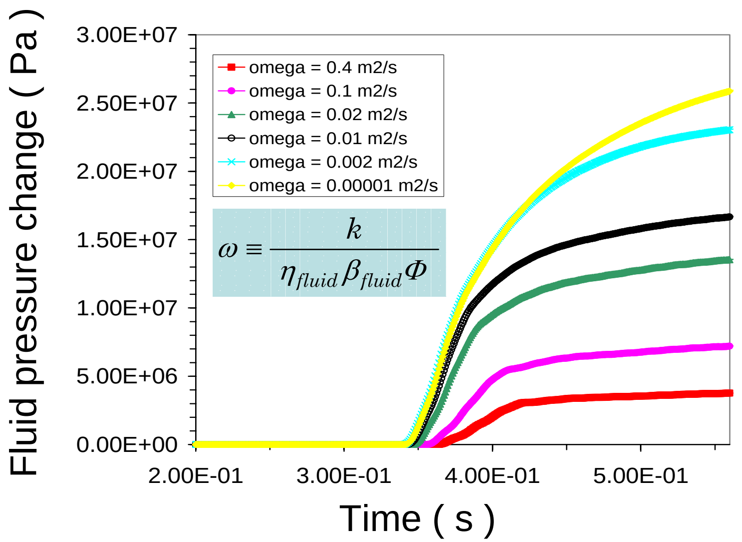
Dry fault (σ_n^{eff} = const)



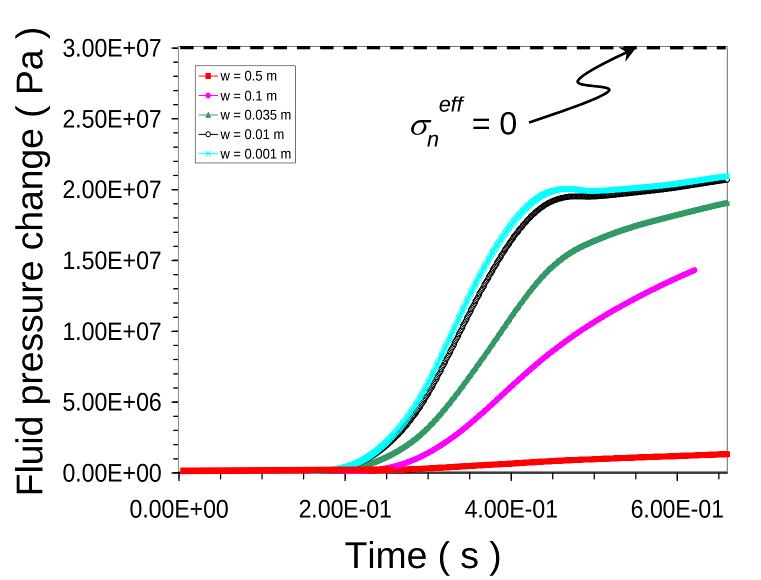


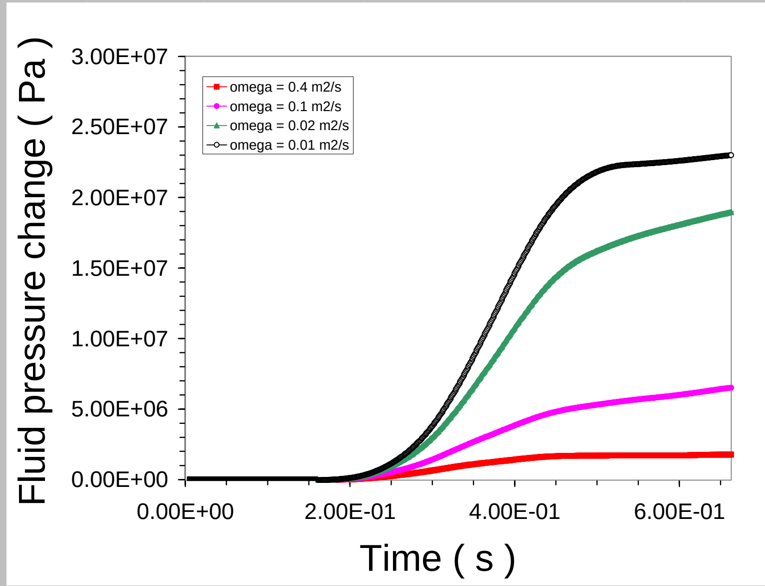
Wet fault (σ_n^{eff} varies)



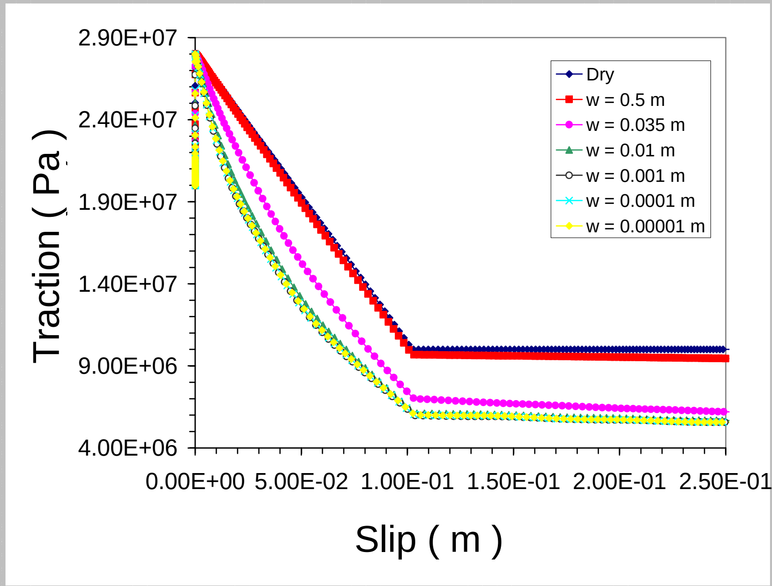


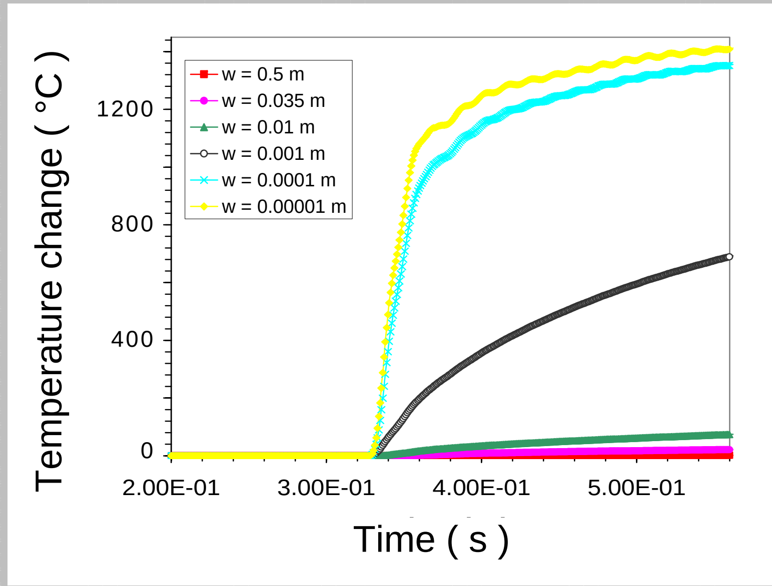
Results with DR law

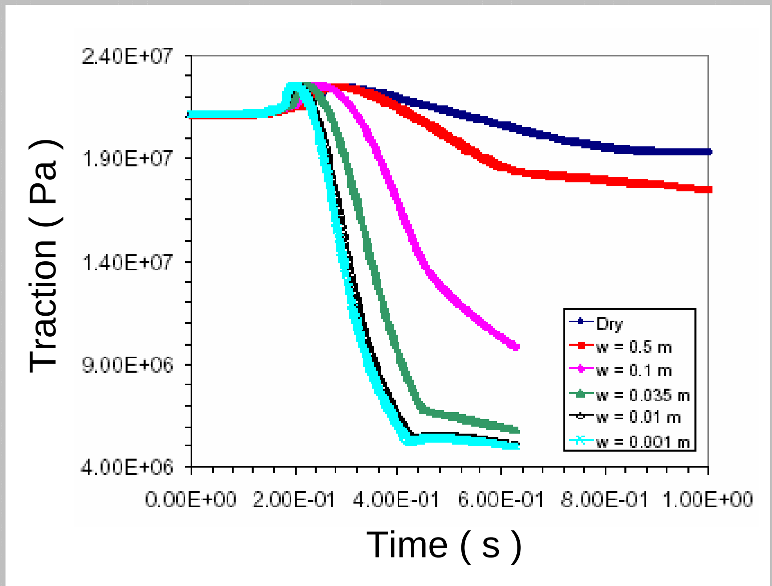


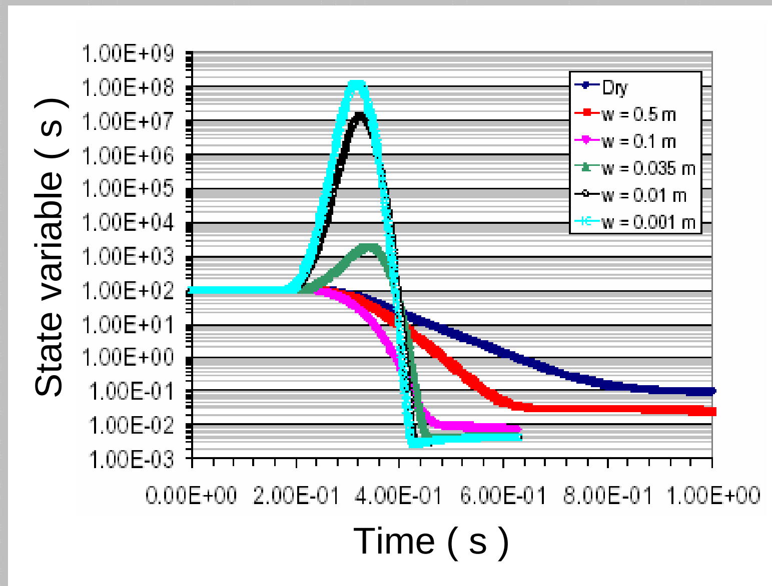


The breakdown zone









Thank you!

This slide is empty intentionally.

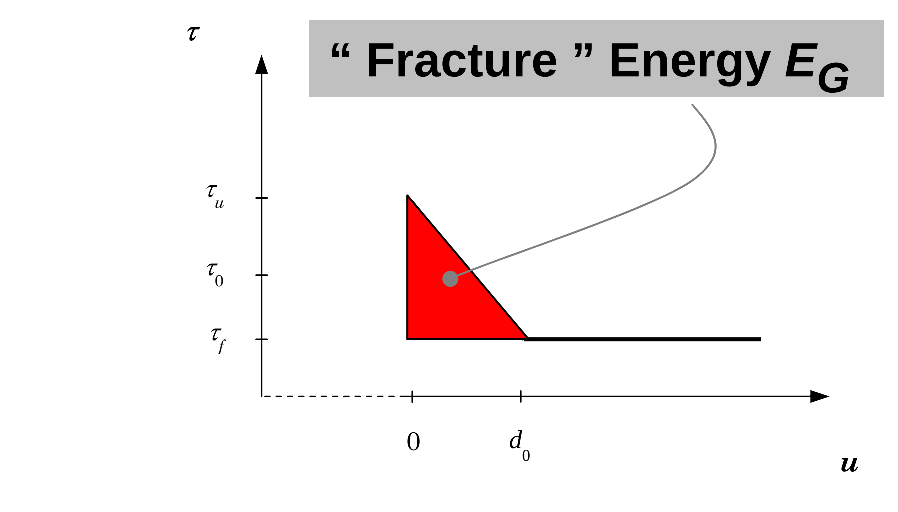
Support Slides:

Parameters, Notes, etc.

To not be displayed directly. Referenced above.

Slip - Weakening Friction Law

$$\tau = \begin{cases} \left[\mu_u - (\mu_u - \mu_f) \dfrac{u}{d_0} \right] \sigma_n^{\ eff} & , u < d_0 \\ \mu_f \sigma_n^{\ eff} & , u \geq d_0 \end{cases}$$



Barenblatt (1959a, 1959b), Ida (1972), Andrews (1976a, 1976b), and many authors thereinafter

d_0 is the characteristic slip – weakening distance

Rate - and State - Dependent

DIETERICH – RUINA WITH VARYING NORMAL STRESS

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\frac{v_*}{v}\right) + b \ln\left(\frac{\Psi v_*}{L}\right) \right] \sigma_n^{eff} \\ \frac{\mathrm{d}}{\mathrm{d}t}\Psi = 1 - \frac{\Psi v}{L} - \left(\frac{\alpha_{LD}\Psi}{b\sigma_n^{eff}}\right)\frac{\mathrm{d}}{\mathrm{d}t}\sigma_n^{eff} \end{cases}$$

Linker and Dieterich (1992), *Dieterich and Linker (1992)*, *Bizzarri and Cocco (2006a*, *2006b)*

Response to an abrupt jump in load