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MODELING INSTANTANEOUS DYNAMIC TRIGGERING IN A 3-D FAULT SYSTEM: THE CASE OF AN EALRY AND REMOTE AFTERSHOCK IN THE JUNE 2000 SOUTH ICELAND SEISMIC SEQUENCE

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Motivations and Goals

- Remote triggering is a case of dynamic triggering occurring at distances larger than the dimension of the causative fault;

- Since the M_w 7.7 1992 Landers EQ only a few examples of remote triggering have been observed; we consider the <u>early events in Reykjanes Peninsula on June 17, 2000</u>;

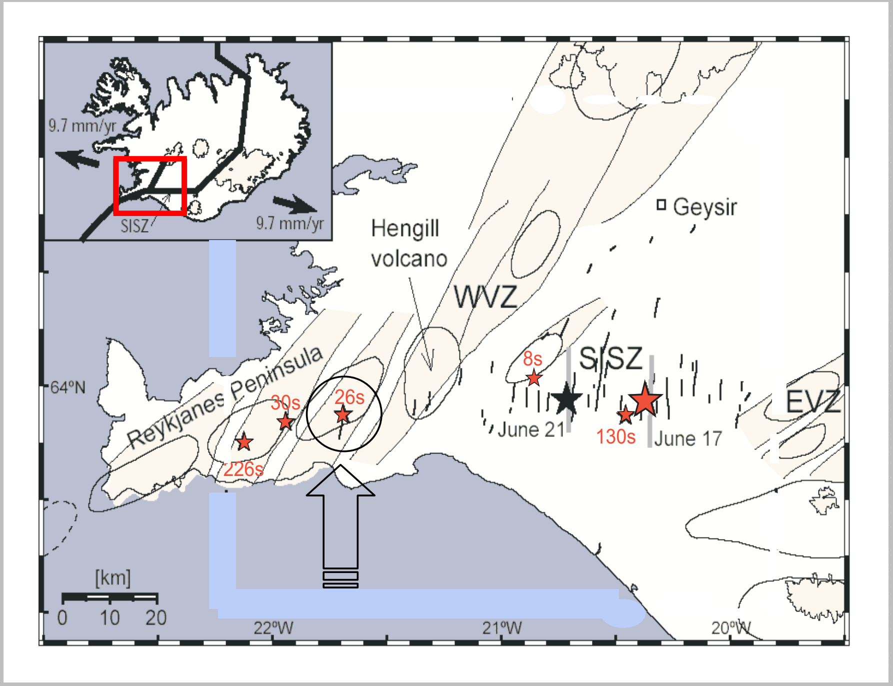
- We study the instantaneous remote triggering of a fault of finite extension, considering a realistic 3–D fault model, including heterogeneities in the crustal profile and in the fault rheology;

- We generalize the conclusions obtained in a previous paper on the basis of a simple 1–D spring–slider analog system;

- We study the response of the triggered fault as depending on the assumed constitutive relation: rate– and state–dependent governing laws and slip–dependent law.

The June 2000 seismic sequence in the South Iceland Seismic Zone

The sequence started on June 17, at 15:40:41 UTC, with an event of magnitude M_S = 6.6 (*Pedersen et al., 2001*), with hypocenter located at (63.973 °N, 20.367 °W, 6.3 Km) (*Stefansson et al., 2003*; *Arnadottir et al., 2006*).



- The largest events (M~5) occurring in the first five minutes are:

  8s, 26s, 30 s, 130s, 226s

- In intermediate–far field:

  26s, 30 s, 226s

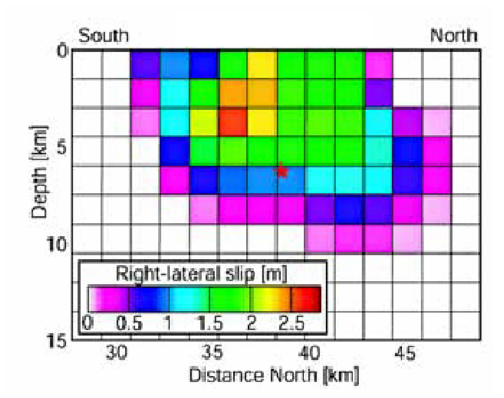
- Reasonably are not secondary aftershocks:

  26s, 30 s.

- The 30 s event is affected by the mainshock and also by the 26 s aftershock.

The numerical approach

For the June 17 2000 mainshock we assume:



1) The slip distribution retrieved by a joint inversion of GPS and InSAR data (*Arnadottir et al., 2003*) →

2) A bilateral Haskell model, with a rupture velocity v_r = 2500 m/s

3) A Bouchon ramp source time function (*Bouchon, 1981*) with a rise time t_0 equal to 1.6 s

4) 7°, 88° and 180° for the strike, the dip and the rake angles, respectively (i. e. right–lateral strike slip mechanism), on the basis of the aftershock distribution (*Stefansson et al., 2003*)

Using the discrete wavenumber and reflectivity code developed by *Cotton and Coutant (1997)* we compute the resulting stress field variations $\Delta\sigma_{ij}(\mathbf{x},t)$

The values of the tensor $\Delta\sigma_{ij}$ are calculated on the 26 s fault plane up to 2.78 Hz, in a total of 12 × 8 "receivers", located in nodes uniformly spaced 1650 m in the strike direction and at depths of 0 m, 1650 m, 3300 m, 4950 m, 6550 m, 8100 m, 9900 m and 11550 m.

The spatial sampling of the receiver grid is <u>not</u> sufficient to correctly resolve the dynamic processes occurring during the rupture nucleation and propagation (*Bizzarri and Cocco, 2003; 2005*), as well as the temporal discretization.

We develop an algorithm that employs a $\mathcal{C}^2$ cubic spline to interpolate $\Delta\sigma_{ij}$ in space and in time.

In the numerical code presented by *Bizzarri and Cocco (2005)* at time t and in each fault node, the dynamic load is: $\mathcal{L}_i = f_{ri} + T_{0i} + \Delta\sigma_{2i}$ (i = 1 and 3).

T_{0i} are the components of the initial traction ($\mathrm{T}_{\mathbf{0}}(x_1, x_3) = \tau_0(x_1, x_3)(\cos(\varphi_0), 0, \sin(\varphi_0))$)

f_{ri} are the components of the load (namely the contribution of the restoring forces, $\mathbf{f}_{\mathbf{r}}$) exerted by the neighbouring points:

$$f_{ri} = (M^- f_i^+ - M^+ f_i^-)/(M^+ + M^-),$$

where M^+ and M^- are the masses of the "+" and "–" half split–node of the fault plane Σ and $\mathbf{f}^+$ is the force acting on partial node "+" caused by deformation of neighbouring elements located in the "–" side of S (and viceversa for $\mathbf{f}^-$).

$\{\Delta\sigma_{2i}\}$ are coupled to the components of the fault friction T_i via

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2} u_1 = \alpha[\mathcal{L}_1 - T_1]$$
$$\frac{\mathrm{d}^2}{\mathrm{d}t^2} u_3 = \alpha[\mathcal{L}_3 - T_3]$$

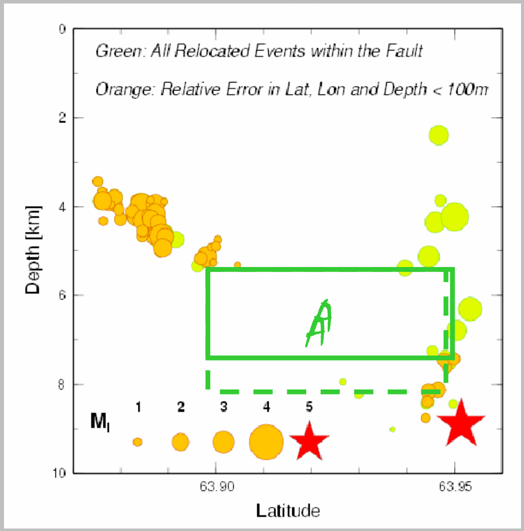
where $\alpha \equiv \mathcal{A}\,((1/M^+) + (1/M^-))$, $\mathcal{A} = \Delta x_1 \Delta x_3$. T_i express on the governing law.

Observational constraints

1) Perturbed rupture time t_r = 25.9 ± 0.1 s

2) Hypocenter (63.951 ± 0.004 °N, 21.689 ± 0.008 °W, 8.9 ± 1.3 Km) ↔ on fault coordinates of (16500 ± 450, 8900 ± 1300) m (*Antonioli et al., 2006*)

3') From the aftershocks distribution shown in *Hjaltadottir and Vogfjord (2005)* we consider the seismic part of the fault ($\mathcal{A}$) limited in latitude between 63.890 °N and <u>63.947</u> °N (in the case of North–South fault this corresponds to <u>[9700, 16050]</u> m in strike direction) and limited in depth between 5400 m and <u>8100</u> m



Upper bound estimates':

$M_0 = 1.23 \times 10^{15}\, \mathcal{A}^{3/2} = 8.73 \times 10^{16}$ Nm;

Av. fault slip: $\langle u \rangle_{\mathcal{A}} = M_0/(\rho\, v_S^2 \mathcal{A}) = 0.14$ m;

Av. stress drop: $\langle \Delta\tau \rangle_{\mathcal{A}} = 2M_0/(\pi W_{\mathcal{A}} L_{\mathcal{A}}) = 1.62$ MPa

4) $M_w \geq 5$ (*Arnadottir et al., 2006; Vogfjord, 2003*) ⇒ $M_0 \cong 3.2 \times 10^{16}$ Nm

Results with DR law – homogeneous

Dieterich – Ruina governing law

$$\tau = \mu(v,\Psi)\,\sigma_n^{eff} = \left[\mu_* + a\,\ln\left(\frac{v}{v_*}\right) + b\,\ln\left(\frac{\Psi\, v_*}{L}\right)\right]\sigma_n^{eff}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\Psi = 1 - \frac{\Psi\, v}{L}$$

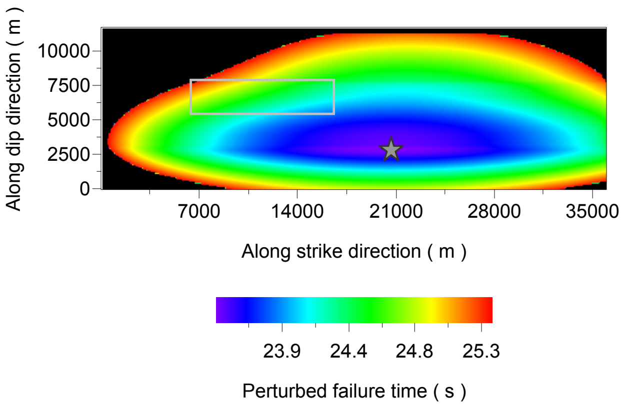
Can be neglected (see *Antonioli et al., 2006*)

Perturbed rupture times

$v(x_1,x_3,t) \geq v_l \;\Rightarrow\; t_p(x_1,x_3) = t$

v_l = 0.1 m/s, in agreement with *Belardinelli at al. (2003)*; *Antonioli et al. (2005)*; *Rubin and Ampuero (2005)*; *Ziv and Cochard (2006)*

σ_n^{eff} = 2.5 MPa everywhere; acting only $\Delta\sigma_{21}$



t_p^{min} = 23.47 s @ (20700,2900) m

M_0 = 2.37 x 10^{19} Nm

Whole fault

From Bizzarri and Belardinelli (Nov. 2006; subm. to JGR)

Results with DR law – homogeneous

Dieterich – Ruina governing law

$$\tau = \mu(v,\Psi)\,\sigma_n^{eff} = \left[\mu_* + a\,\ln\left(\frac{v}{v_*}\right) + b\,\ln\left(\frac{\Psi\,v_*}{L}\right)\right]\sigma_n^{eff}$$

$$\frac{d}{dt}\Psi = 1 - \frac{\Psi\,v}{L}$$

Can be neglected (see *Antonioli et al., 2006*)

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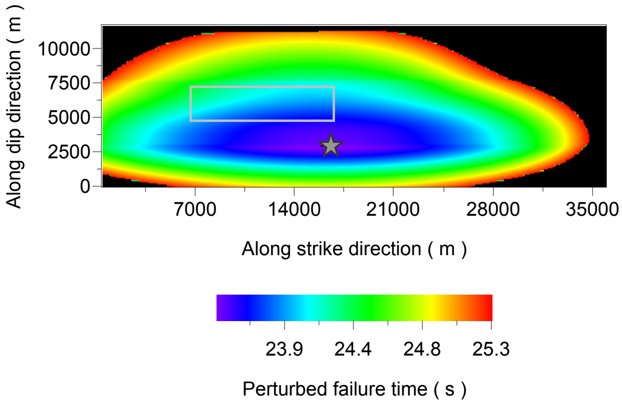
σ_n^{eff} = 2.5 MPa everywhere; acting also $\Delta\sigma_{22}$



t_p^{min} = 23.47 s @ (16500,2900) m

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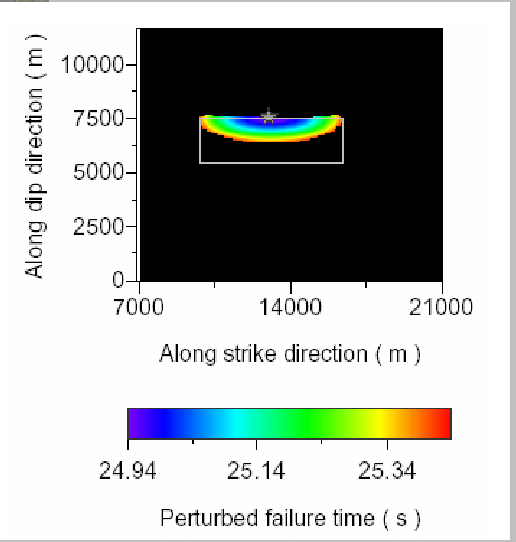
Whole fault

From Bizzarri and Belardinelli (Nov. 2006; subm. to JGR)

Results with DR law – heterogeneous



Velocity strengthening behavior ($a > b$) for $x_1 < 9700$ m, $x_1 > 16500$ m, $x_3 > 8800$ m

Effective normal stress profile

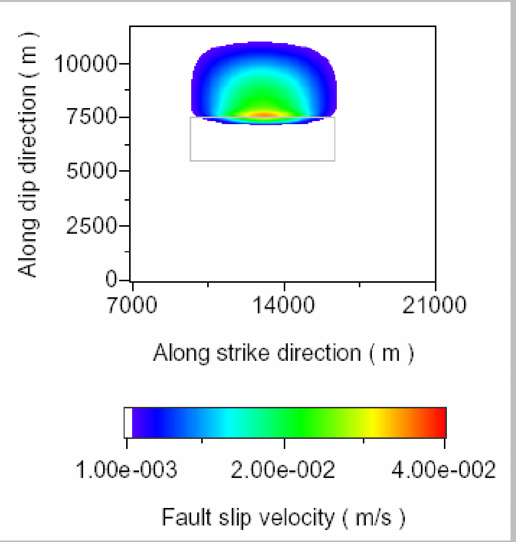
$t_p^{min} = 24.94$ s @ (13200,7500) m

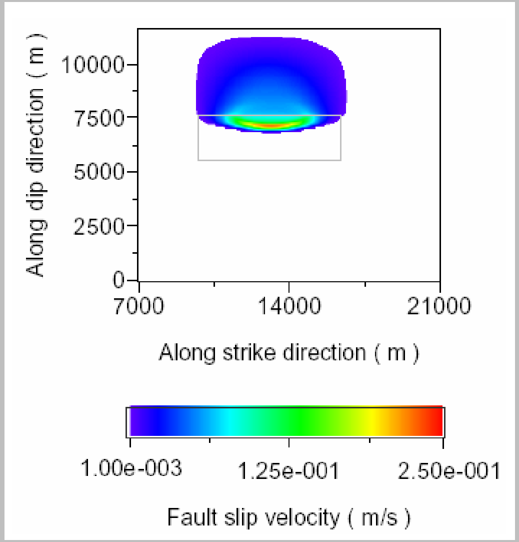
$M_0 = 2.27 \times 10^{16}$ Nm

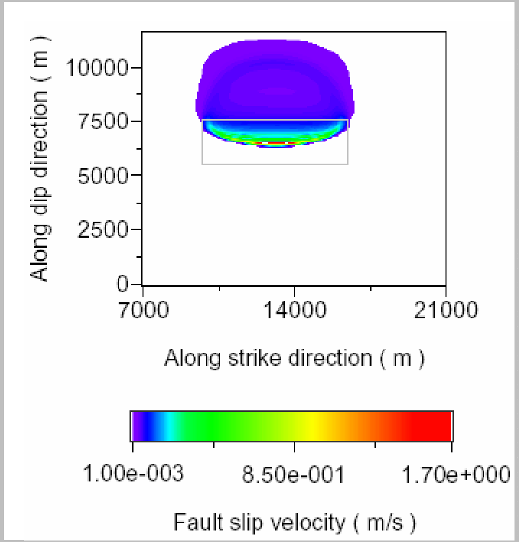
[9700,16500] m in strike direction

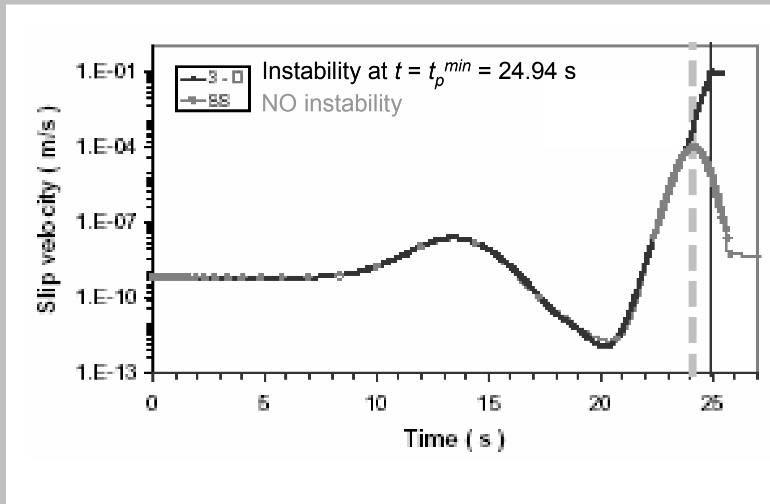
[6400,7500] m in dip direction

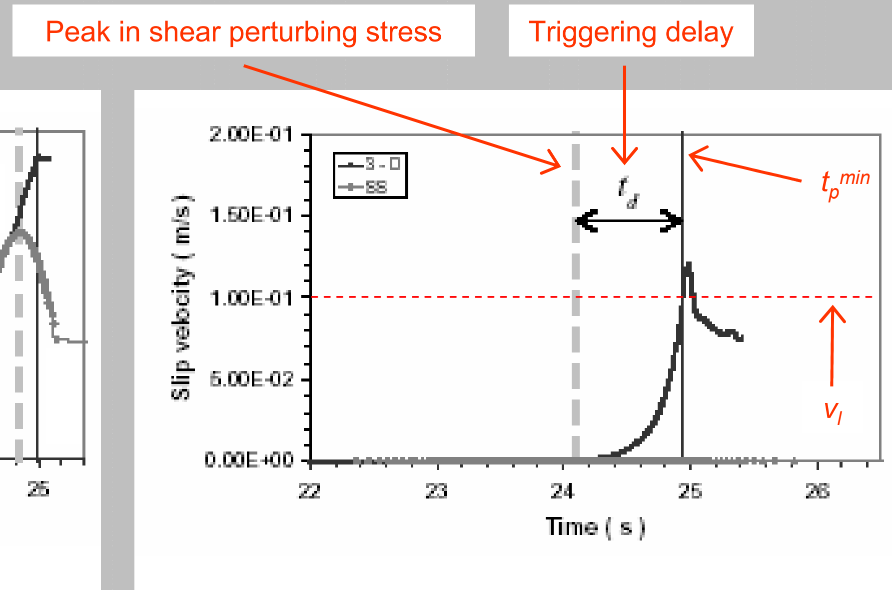
From Bizzarri and Belardinelli (Nov. 2006; subm. to JGR)

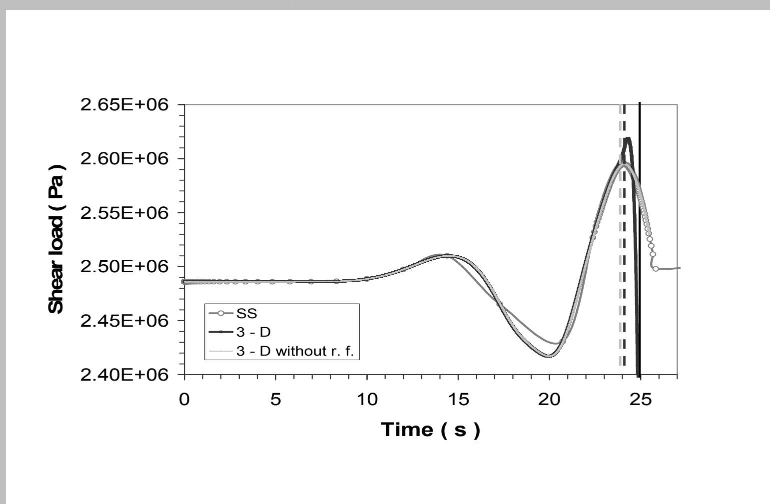


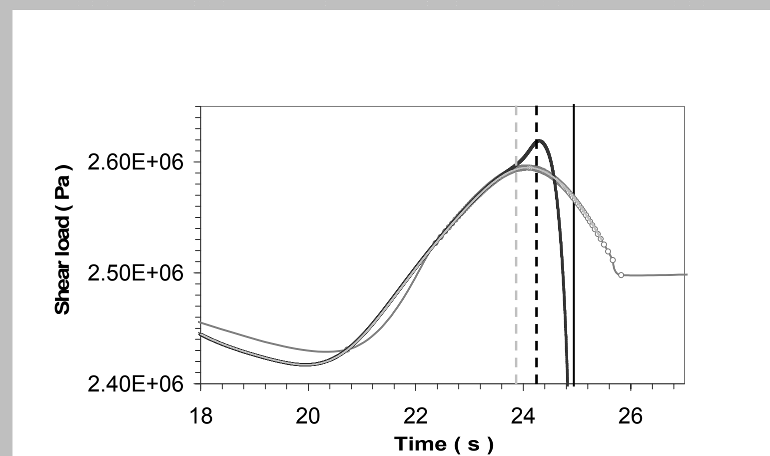












From Bizzarri and Belardinelli (Nov. 2006; subm. to JGR)

Results with RD law – heterogeneous

Ruina – Dieterich governing law

$$\tau = \left[\mu_* + a \ln\left(\frac{v}{v_*}\right) + b \ln\left(\frac{\Psi v_*}{L}\right)\right] \sigma_n^{\ eff}$$

$$\frac{d}{dt}\Psi = -\frac{\Psi v}{L} \ln\left(\frac{\Psi v}{L}\right)$$

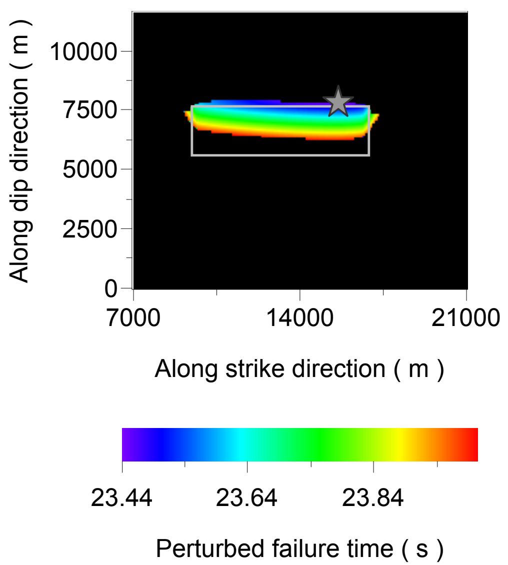
Can be neglected

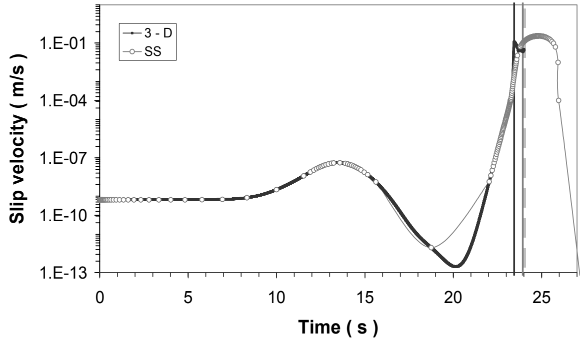
t_p^{min} = 23.44 s @ (15700,7900) m

M_0 = 2.02 x 10^{16} Nm

[9000,17300] m in strike direction

[6300,8000] m in dip direction

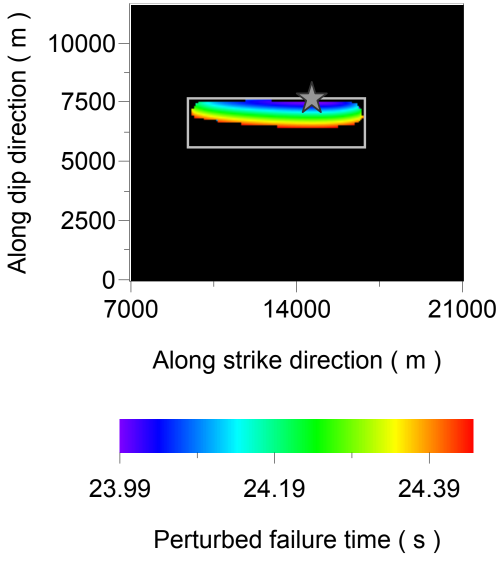




From Bizzarri and Belardinelli (Nov. 2006; subm. to JGR)

Different values of *L* in the RD law

L = 5 mm	**L = 10 mm**
t_p^{min} = 23.99 s @ (14600,7600) m	t_p^{min} = 24.72 s @ (13300,7300) m
M_0 = 1.27 x 10^{16} Nm	M_0 = 2.17 x 10^{16} Nm
[9500,16800] m in strike direction	[9500,16700] m in strike direction
[6500,7700] m in dip direction	[6000,7400] m in dip direction



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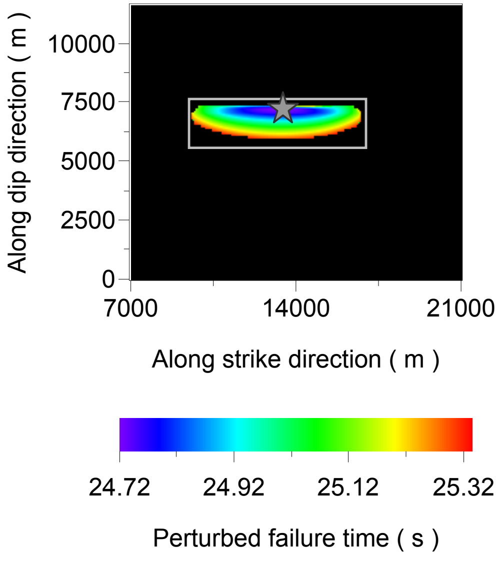
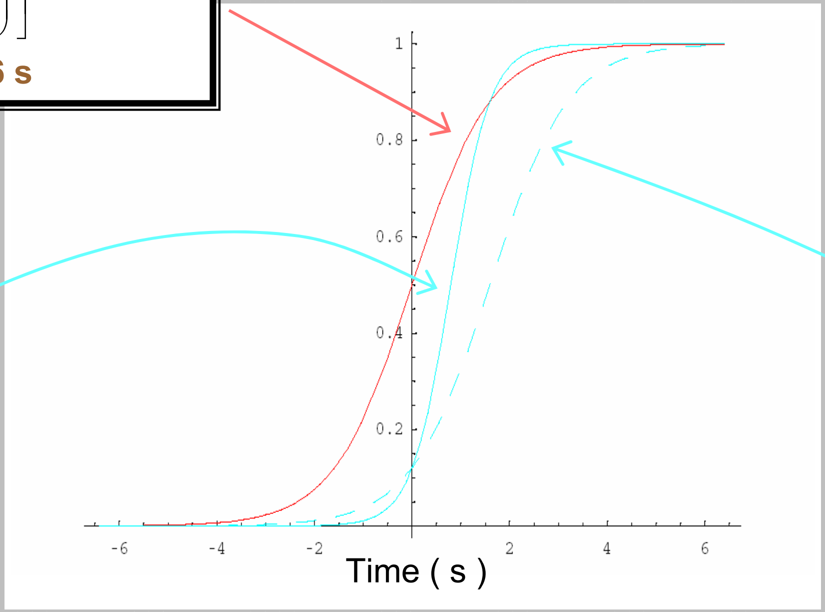


Alternative source time functions #1

Bouchon source time function:

$$f(t)=\frac{1}{2}\left[1+\tanh\left(\frac{t}{t_0}\right)\right]$$

Bouchon, 1981; t_0 **= 1.6 s**



Modified Bouchon source time function:

$$f(t)=\frac{1}{2}\left[1+\tanh\left(\frac{t-\frac{t_0}{2}}{\frac{t_0}{2}}\right)\right]$$

corrected from *Cotton and Campillo, 1995*; t_0 **= 1.6 s**. Increased amplitudes in $\Delta\sigma_{21}$ peaks.

Modified Bouchon source time function:

$$f(t)=\frac{1}{2}\left[1+\tanh\left(\frac{t-\frac{t_0}{2}}{\frac{t_0}{2}}\right)\right]$$

corrected from *Cotton and Campillo, 1995*; t_0 **= 3.2 s**. Only a temporal shift.

Alternative source time functions #2

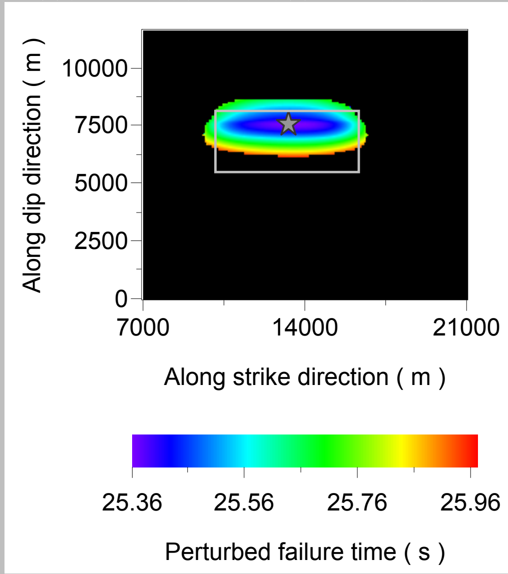
Modified Bouchon, t_0 = 1.6 s;
σ_n^{eff*} = 4.2 MPa – DR law

t_p^{min} = 25.36 s @ (13500,7600) m

$M_0 = 2.59 \times 10^{16}$ Nm

[9500,16700] m in strike direction

[6200,8700] m in dip direction



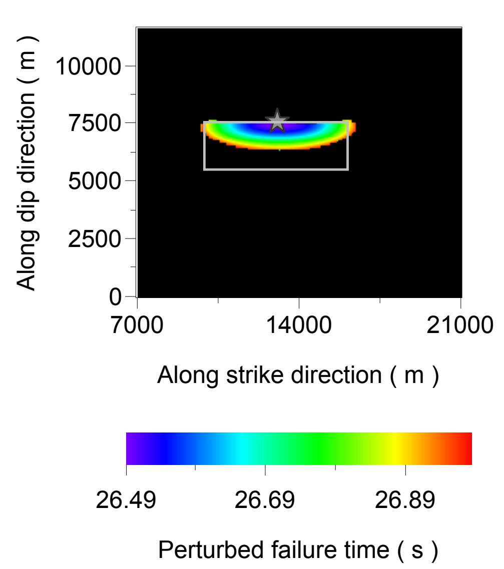
Modified Bouchon, t_0 = 3.2 s
DR law

t_p^{min} = 26.49 s @ (13000,7500) m

$M_0 = 2.30 \times 10^{16}$ Nm

[9700,16500] m in strike direction

[6400,7600] m in dip direction



Conclusions

- ✓ We simulate the remote triggering in a *truly* 3–D fault model with different governing laws;
- ✓ We generalize the results of *Antonioli et al. (2006)*, providing additional details of the 26 s event: the location of the hypocenter, its failure time, the rupture area and the seismic moment;
- ✓ The effective normal stress and the pre–stress are heterogeneous;
- ✓ The spring–slider and the 3–D model are intrinsically different, but we observe an excellent agreement during the slow nucleation phase…
- ✓ … during the acceleration, in the 3–D model the dynamic load of the slipping points further decrease the perturbed failure time;

- ✓ The agreement with observations increases considering a modified (and more causal) source time function;
- ✓ If detailed informations of the initial state of the fault, potentially highly heterogeneous, were available the agreement with observations will be even better.

Case	***Constitutive law***	***Rupture extension along strike*** (m)	***Rupture extension along dip*** (m)	***Hypocenter location*** (m)	***Origin time*** (s)	***Total seismic moment*** M_0 (Nm)
F	DR	[9700, 16500]	[6400, 7500]	(13200,7500)	24.94	2.27×10^{16}
L	RD (L = 10 mm)	[9500, 16700]	[6000, 7400]	(13300,7300)	24.72	2.17×10^{16}
O	DR	[9700, 16500]	[6400, 7600]	(13000,7500)	26.49	2.30×10^{16}
P	DR	[9500, 16700]	[6200, 8700]	(13500,7600)	25.36	2.59×10^{16}
Observational constraints		**[9700, 16500]**	**[5400, 7400]**	**(16500 ± 450, 8900 ± 1300)**	**25.9 ± 0.1**	$\cong \mathbf{3.2 \times 10^{16}}$

Thank you!

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Support Slides:
Parameters, Notes, etc.

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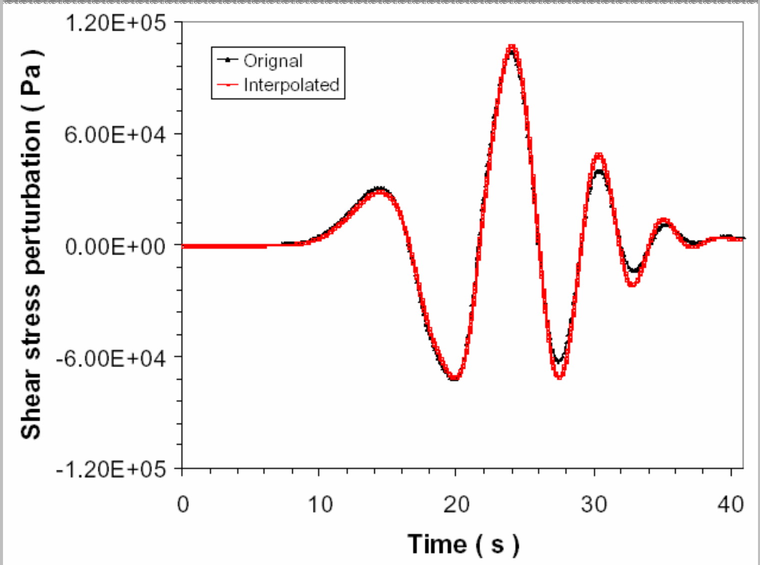
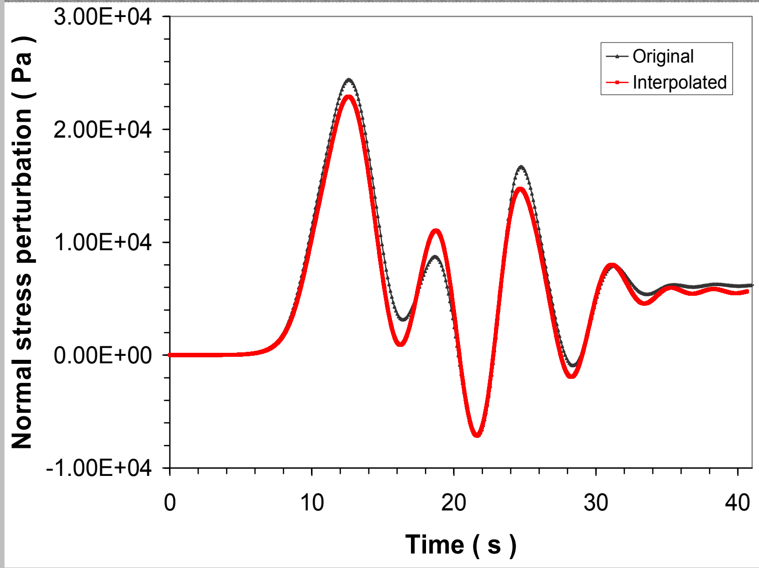
The spatial sampling of the receiver grid is <u>not</u> sufficient to correctly resolve the dynamic processes occurring during the rupture nucleation and propagation (*Bizzarri and Cocco, 2003*; *2005*), as well as the temporal discretization.

We develop an algorithm that employs a $\mathcal{C}^2$ cubic spline to interpolate $\Delta\sigma_{ij}$ in space and in time.

In the hypocenter at *t* = 26.37 s



In the hypocenter at *t* = 26.37 s



Parameter	*Value*
$\mathcal{D}$	parallelepiped that extends $x_{1_{end}} = 36.5$ Km along x_1, $x_{2_{end}} = 10$ Km along x_2 and $x_{3_{end}} = 11.6$ Km along x_3
$\Sigma = \mathcal{C}\mathcal{S}$	$\{ \mathbf{x} \mid x_2 = x_2^f = 5000 \text{ m} \}$
$\Delta x_1 = \Delta x_2 = \Delta x_3 \equiv \Delta x$	100 m [a]
Number of nodes	4,289,571
Δt	1.27×10^{-3} s [a]
Number of time levels	33,650
v_l	0.1 m/s
$\sigma_n^{eff^*}$	2.5 MPa
$\varphi(x_1, x_3, 0)$	$\varphi_0 = 180°$
$v(x_1, x_3, 0)$	$v_{init} = 6.34 \times 10^{-10}$ m/s (= 20 mm/yr)
$\Psi(x_1, x_3, 0)$	$\Psi^{ss}(v_{init}) = 1.577 \times 10^6$ s ($\cong$ 18.25 d)
$\sigma_n^{eff}(x_1, x_3, 0)$	See Table 3
$\tau_0(x_1, x_3)$	$\mu^{ss}(v_{init})\sigma_n^{eff}(x_1, x_3, 0)$
a	0.003 [b]
b	0.010
L	1×10^{-3} m
μ_*	0.7
v_*	v_{init}
α_{LD}	0

Crustal profile (from *Vogfjord et al., 2002*; *Antonioli et al., 2006*)

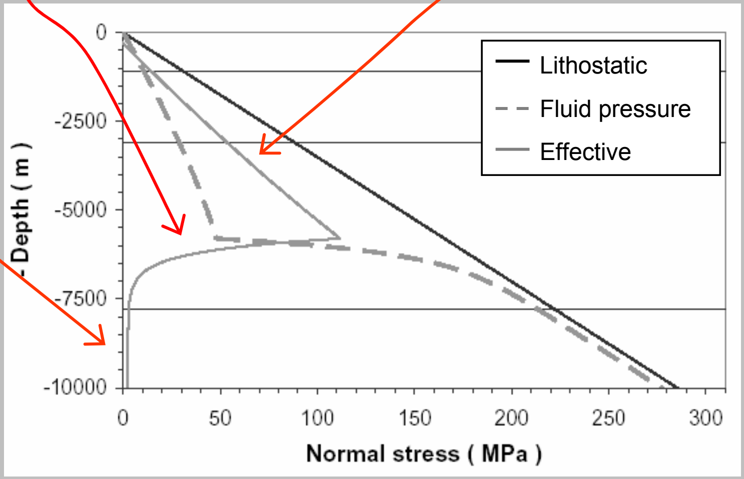
***Layer* # k**	v_{P_k} (m/s)	v_{S_k} (m/s)	ρ_{rock_k} (Kg/m^3)	***Up do depth of* x_{3_k} (m)**
1	3200	1810	2300	1100
2	4500	2540	2540	3100
3	6220	3520	3050	7800
4	6750	3800	3100	11600

Initial effective normal stress

$$\sigma_{n_0}^{eff}(x_3) \equiv \sigma_n^{eff}(x_1,x_3,t) =$$

$$\begin{cases} \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - p_{fluid}^{(hydro)}(x_3) & , x_3 \le x_3^* = 5800\ \text{m} \\ \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - \Big[\, \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - \sigma_n^{eff^*} \\ \qquad - \Delta P_2\, e^{-\frac{x_3 - x_3^*}{h^*}} + \sigma_n^{eff^*} e^{-\frac{x_3 - x_3^*}{h^*}} \Big] & , x_3^* < x_3 < x_3^* + D^* \\ \sigma_n^{eff^*} = 2.5\ \text{MPa} & , x_3 \ge x_3^* + D^* = 8800\ \text{m} \end{cases}$$

$$\Delta P_2 \equiv \hat{p}^{(litho)}(x_3^*) - \Delta\sigma^{(dev)} - p_{fluid}^{(hydro)}(x_3^*)$$



Support Slides 2: Parameters, Notes, etc.

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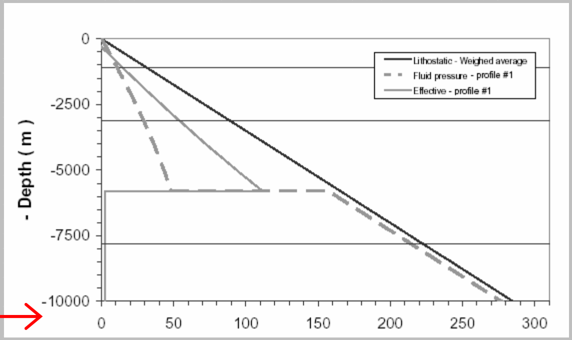
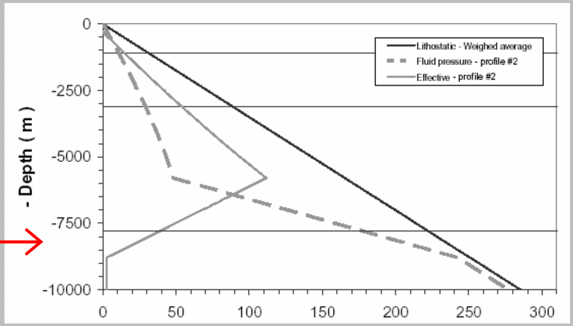
Initial effective normal stress

Profile #	$\sigma_{n_0}^{eff}(x_3) \equiv \sigma_n^{eff}(x_1,x_3,t) =$
1	$\begin{cases} \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - p_{fluid}^{(hydro)}(x_3) & , x_3 \le x_3^* \\ \sigma_n^{eff*} & , x_3 > x_3^* = 5800 \text{ m} \end{cases}$



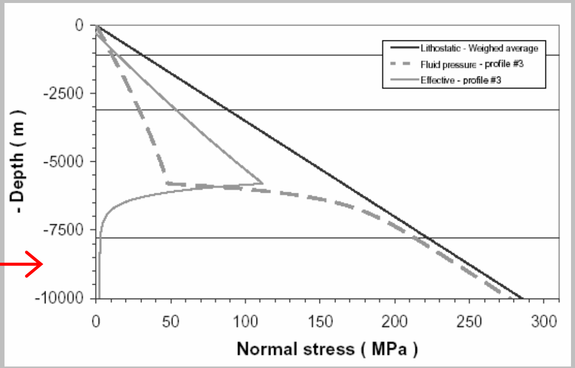
Initial effective normal stress

Profile #	$\sigma_{n_0}^{eff}(x_3) \equiv \sigma_n^{eff}(x_1,x_3,t) =$
2	$\begin{cases} \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - p_{fluid}^{(hydro)}(x_3) & , x_3 \le x_3^* \\ \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - \Big[\hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - \sigma_n^{eff^*} + \Delta P_2 \frac{(x_3 - x_3^* - D^*)}{D^*} - \sigma_n^{eff^*} \frac{(x_3 - x_3^* - D^*)}{D^*} \Big] & , x_3^* < x_3 < x_3^* + D^* \\ \sigma_n^{eff^*} & , x_3 \ge x_3^* + D^* = 8800 \text{ m} \end{cases}$ where: $\Delta P_2 \equiv \hat{p}^{(litho)}(x_3^*) - \Delta\sigma^{(dev)} - p_{fluid}^{(hydro)}(x_3^*)$



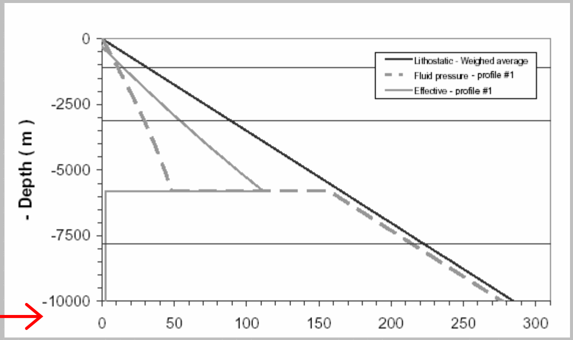
Initial effective normal stress

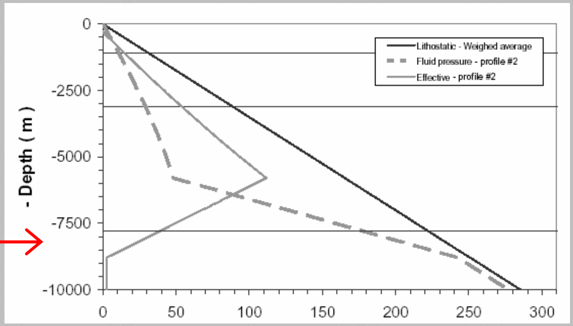
Profile #	$\sigma_{n_0}^{eff}(x_3) \equiv \sigma_n^{eff}(x_1,x_3,t) =$
3	$\begin{cases} \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - p_{fluid}^{(hydro)}(x_3) & , x_3 \le x_3^* \\ \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - \left[\hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - \sigma_n^{eff^*} - \Delta P_2\, e^{-\frac{x_3 - x_3^*}{h^*}} + \sigma_n^{eff^*}\, e^{-\frac{x_3 - x_3^*}{h^*}} \right] & , x_3^* < x_3 < x_3^* + D^* \\ \sigma_n^{eff^*} & , x_3 \ge x_3^* + D^* \end{cases}$

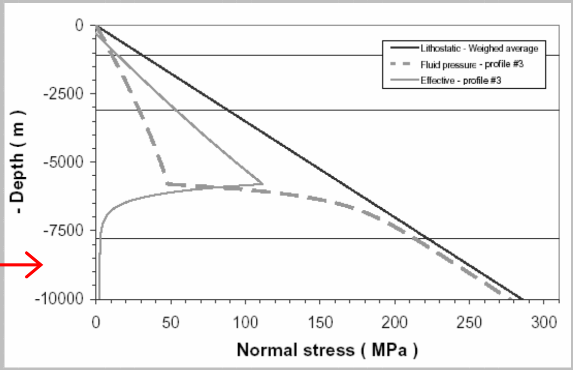


Initial effective normal stress

Profile #	$\sigma_{n_0}^{eff}(x_3) \equiv \sigma_n^{eff}(x_1,x_3,t) =$
1	$\begin{cases} \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - p_{fluid}^{(hydro)}(x_3) & , x_3 \le x_3^* \\ \sigma_n^{eff^*} & , x_3 > x_3^* = 5800 \text{ m} \end{cases}$
2	$\begin{cases} \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - p_{fluid}^{(hydro)}(x_3) & , x_3 \le x_3^* \\ \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - \left[\hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - \sigma_n^{eff^*} + \Delta P_2 \dfrac{(x_3 - x_3^* - D^*)}{D^*} - \sigma_n^{eff^*} \dfrac{(x_3 - x_3^* - D^*)}{D^*} \right] & , x_3^* < x_3 < x_3^* + D^* \\ \sigma_n^{eff^*} & , x_3 \ge x_3^* + D^* = 8800 \text{ m} \end{cases}$ where: $\Delta P_2 \equiv \hat{p}^{(litho)}(x_3^*) - \Delta\sigma^{(dev)} - p_{fluid}^{(hydro)}(x_3^*)$
3	$\begin{cases} \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - p_{fluid}^{(hydro)}(x_3) & , x_3 \le x_3^* \\ \hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - \left[\hat{p}^{(litho)}(x_3) - \Delta\sigma^{(dev)} - \sigma_n^{eff^*} - \Delta P_2 \, e^{-\frac{x_3 - x_3^*}{h^*}} + \sigma_n^{eff^*} e^{-\frac{x_3 - x_3^*}{h^*}} \right] & , x_3^* < x_3 < x_3^* + D^* \\ \sigma_n^{eff^*} & , x_3 \ge x_3^* + D^* \end{cases}$

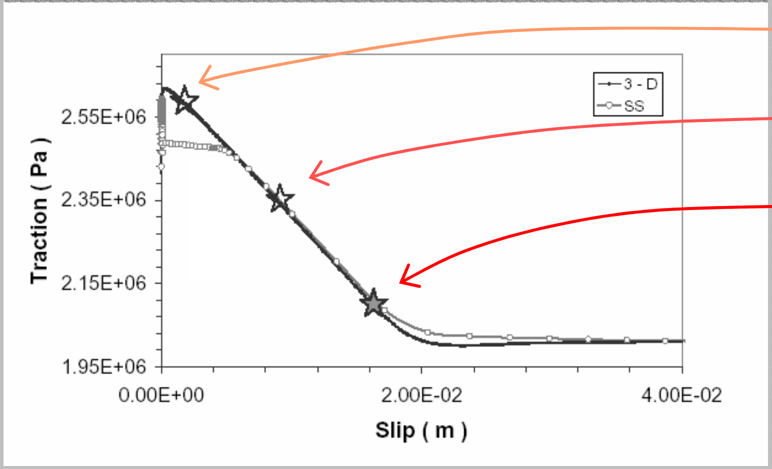






Effect of different v_l

Dieterich – Ruina governing law



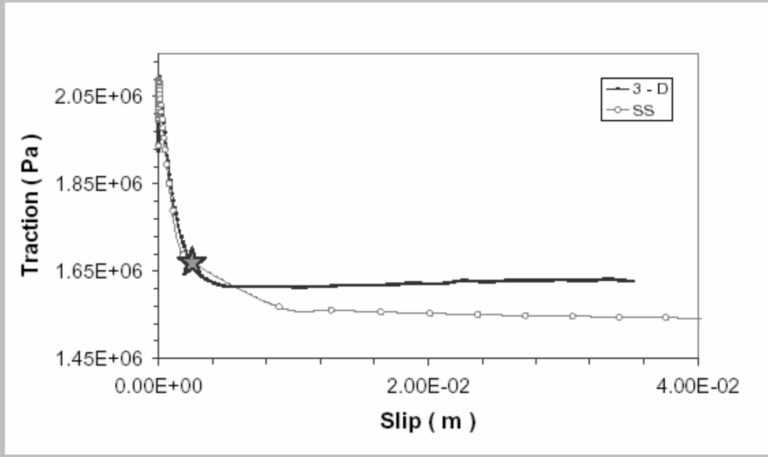
v^H = 0.01 m/s (t = 24.56 s)

v^H = 0.05 m/s (t = 24.84 s)

$v^H = v_l$ = 0.1 m/s ($t = t_p$ = 24.94 s)

Failure occurs before traction reaches the residual level.

Ruina – Dieterich governing law



From Bizzarri and Belardinelli (Nov. 2005; subm. to JGR)