Fault constitutive relations inferred from the analysis of the slow slip events in Guerrero, Mexico

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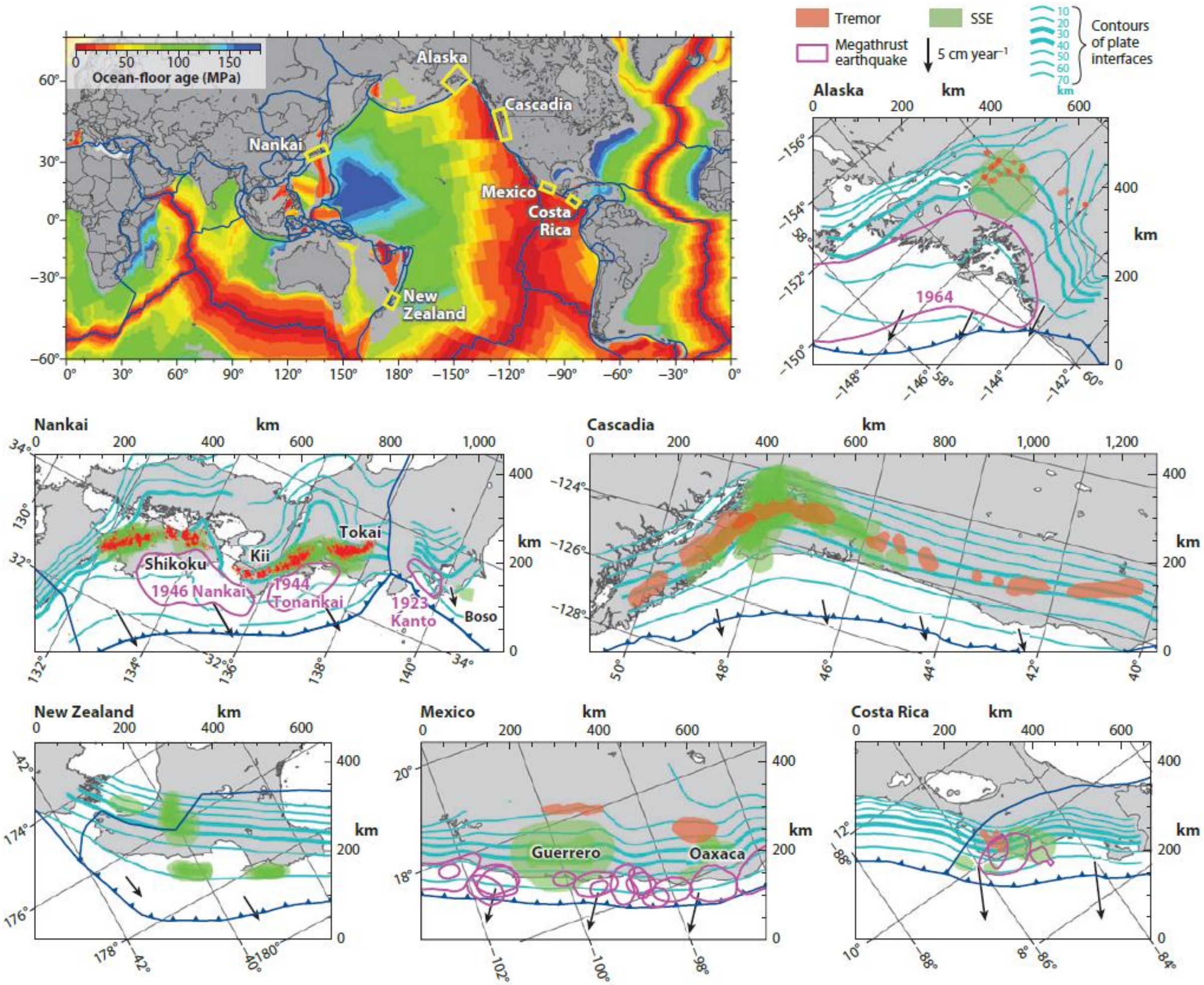
ANR-S4 Subduction: standard and slow seismology

INTRODUCTION

- Slow Slip Event (SSE): slip on a fault, no wave emission, takes a long time to happen i.e. a few days to a few years.
  - SSE in the transition zone (most common) or in the seismogenic zone (Boso, Japan, *Ozawa et al, 2003*; Costa Rica, *Protti et al, 2004*).

- Recurrence: months to years.
- Slip: a few cm
- Stress drop: ~ 0.1 Mpa
- Associated with tremors



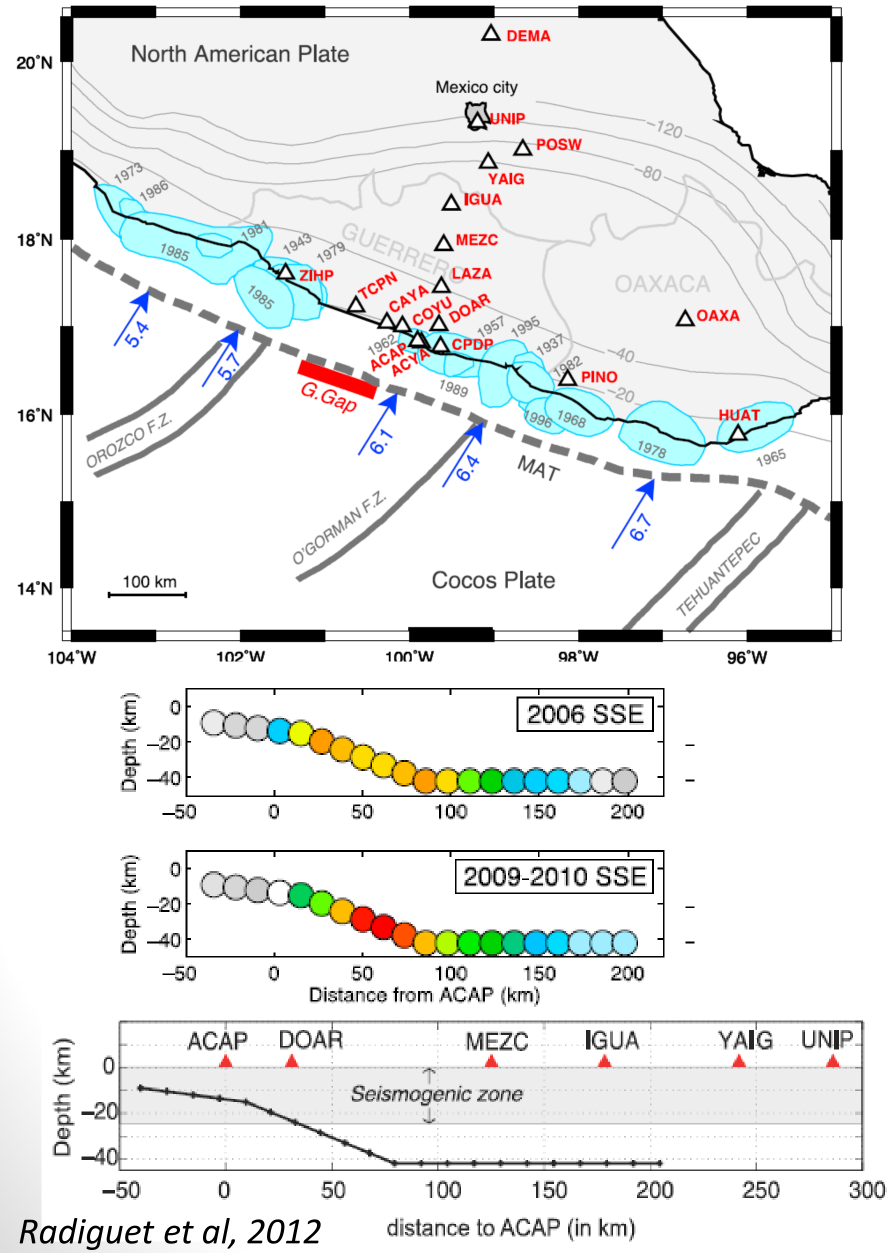
Beroza et Ide, 2011

AIM

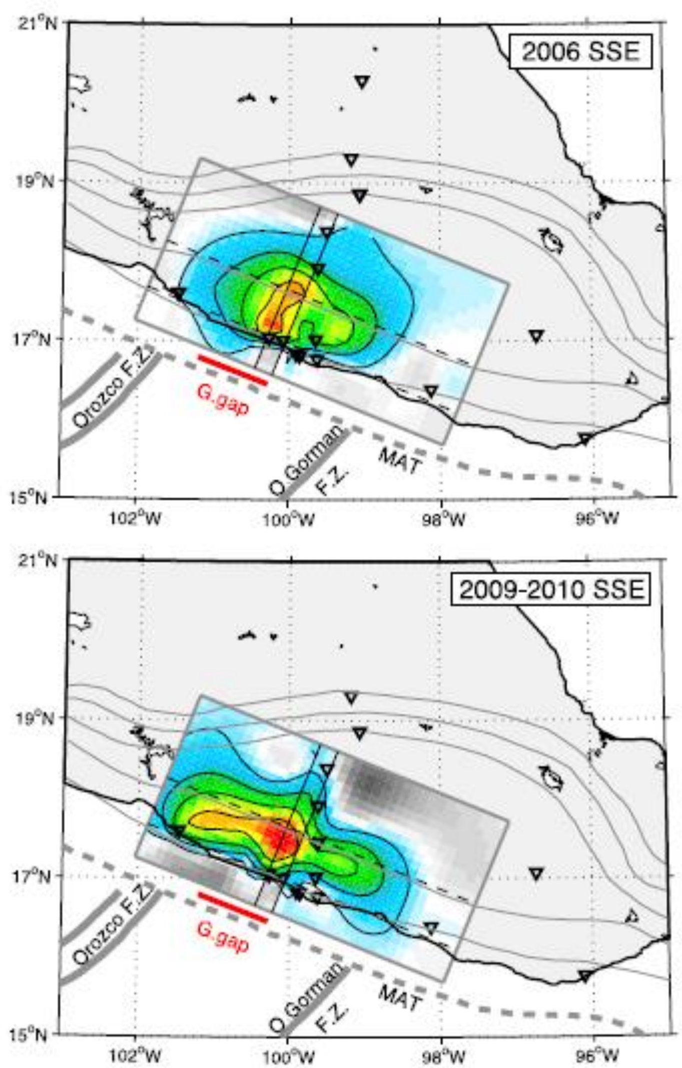
- Work already done: caracteristics and spatio-temporal evolution of slip during SSE *(Radiguet, 2011)*

- This work:
- Stress evolution has not been studied
- Evaluate the stress-slip or stress-slip rate relationship as is done for earthquake *(Ide and Takeo, 1997).*

INTRODUCTION



Radiguet et al, 2012

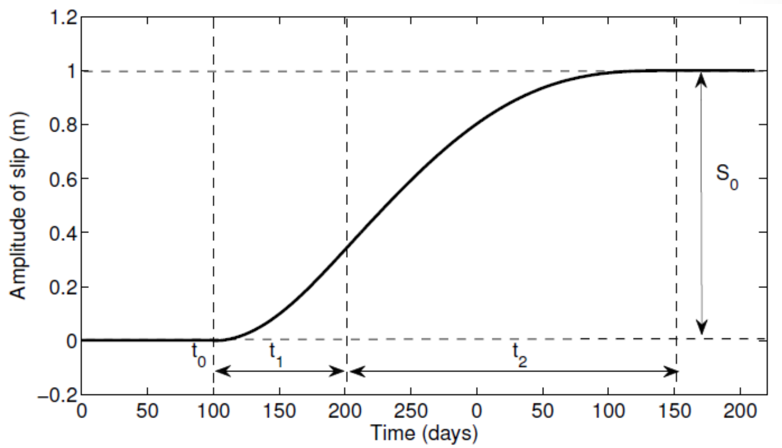


Radiguet et al, 2010

Introduction

SSE	Duration	Mean slip	Mw equiv
2006	1 year	5.7 cm	7.5
2009-2010	1 year (2 sub-events)	6.3 cm	7.5

- Slip model :
  - Fault decomposed in subfaults 12,5*13 km
  - Principal Component Analysis Model (PCAIM): GPS temp. series decomposed as sum of components and inversion of the displacement associated to each component (spatial eigenvectors). No a priori on slip evolution but spatial smoothing important
  - Parametric method: Slip on each subfault described by a slip function, inversion with a least square formulation. Simple source description but a priori on the slip evolution

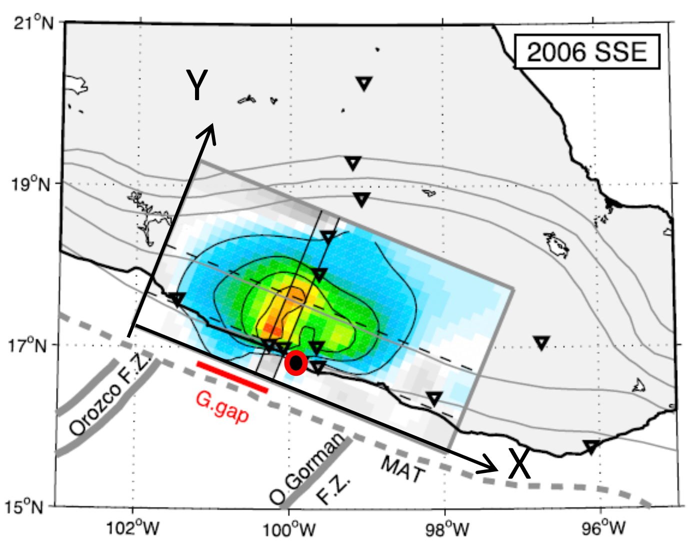


Stress determination method

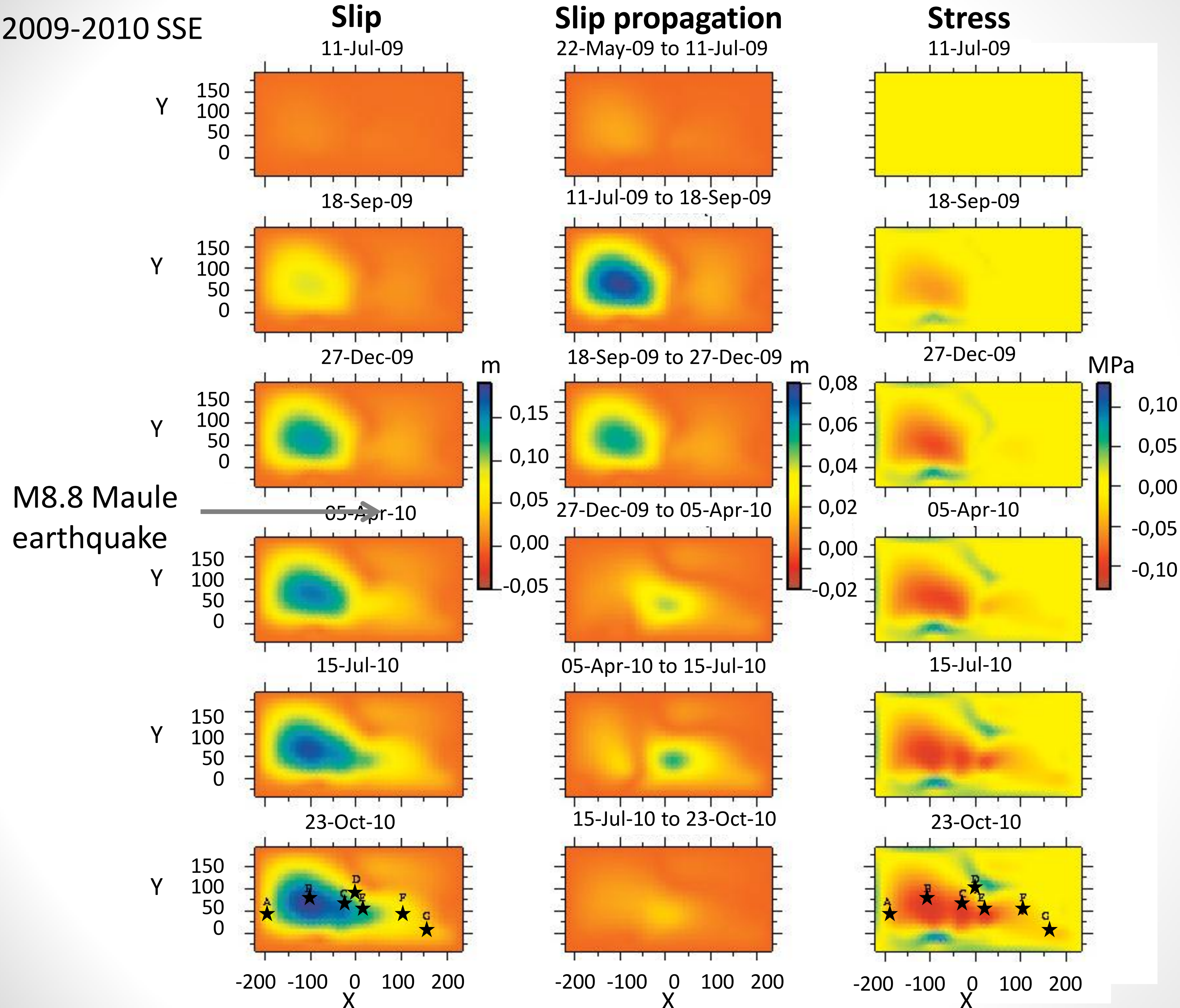
- Stress change on a fault plane: convolution of the causal fault slip and the medium response function over the slipping area

$$\Delta\boldsymbol{\tau}(\overrightarrow{\boldsymbol{X}}) = \int \boldsymbol{ker}(\vec{\boldsymbol{x}} - \vec{\boldsymbol{\xi}})\boldsymbol{\Delta u}(\vec{\boldsymbol{\xi}})\boldsymbol{d\Sigma}$$

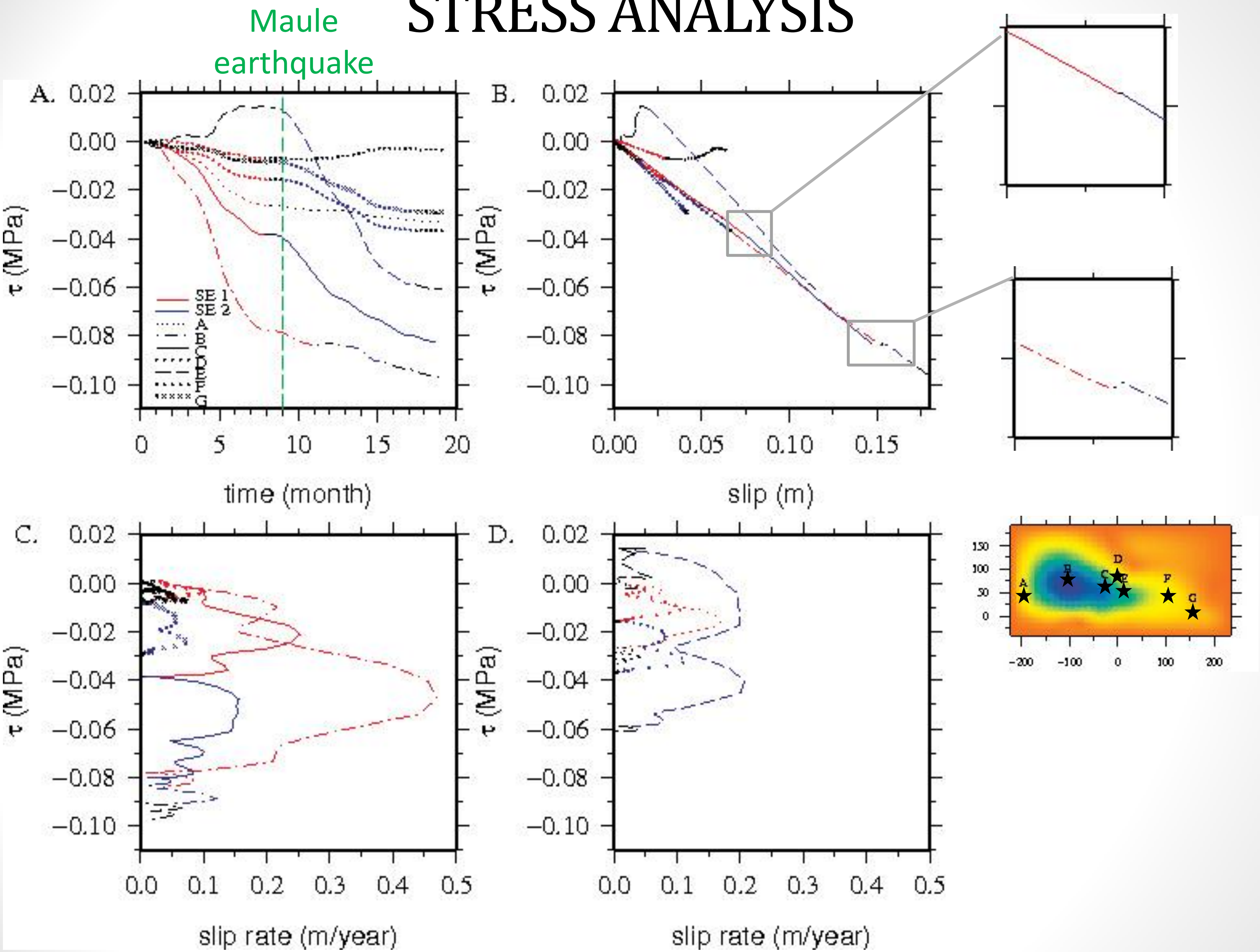
- Analytical Green function for an homogeneous, elastic, infinite space.



2009-2010 SSE



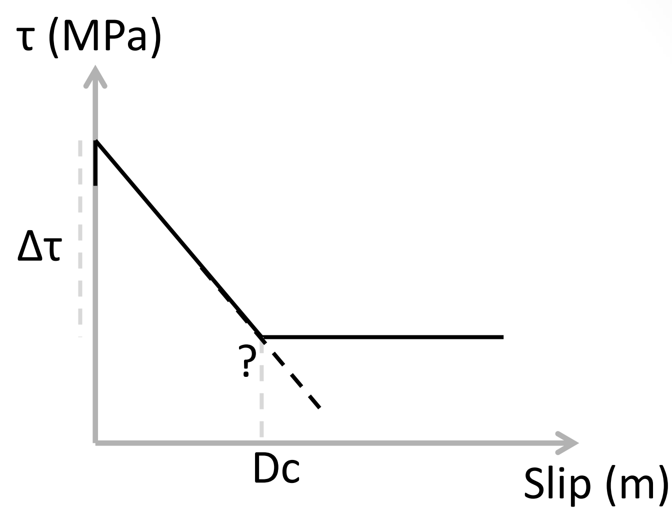
STRESS ANALYSIS

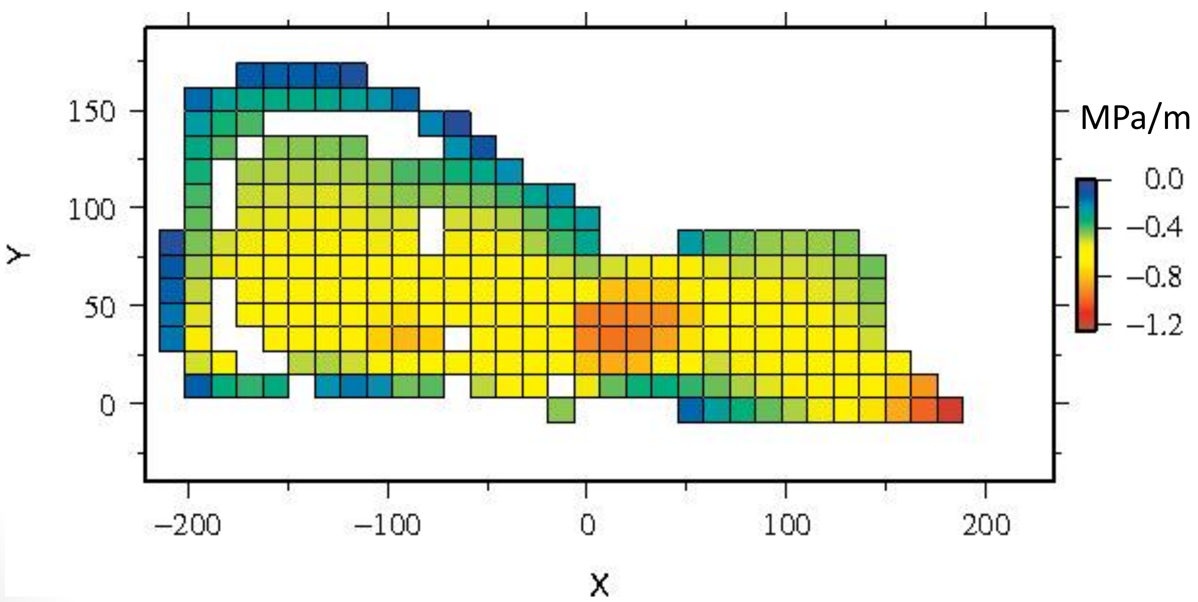


CONSTITUTIVES LAWS

Slip weakening law:
Mean slope -0,5 MPa/m

Δτ~ 0,03 MPa
Dc ~ 0,06 m





CONSTITUTIVES LAWS

- **Rate and state law:**

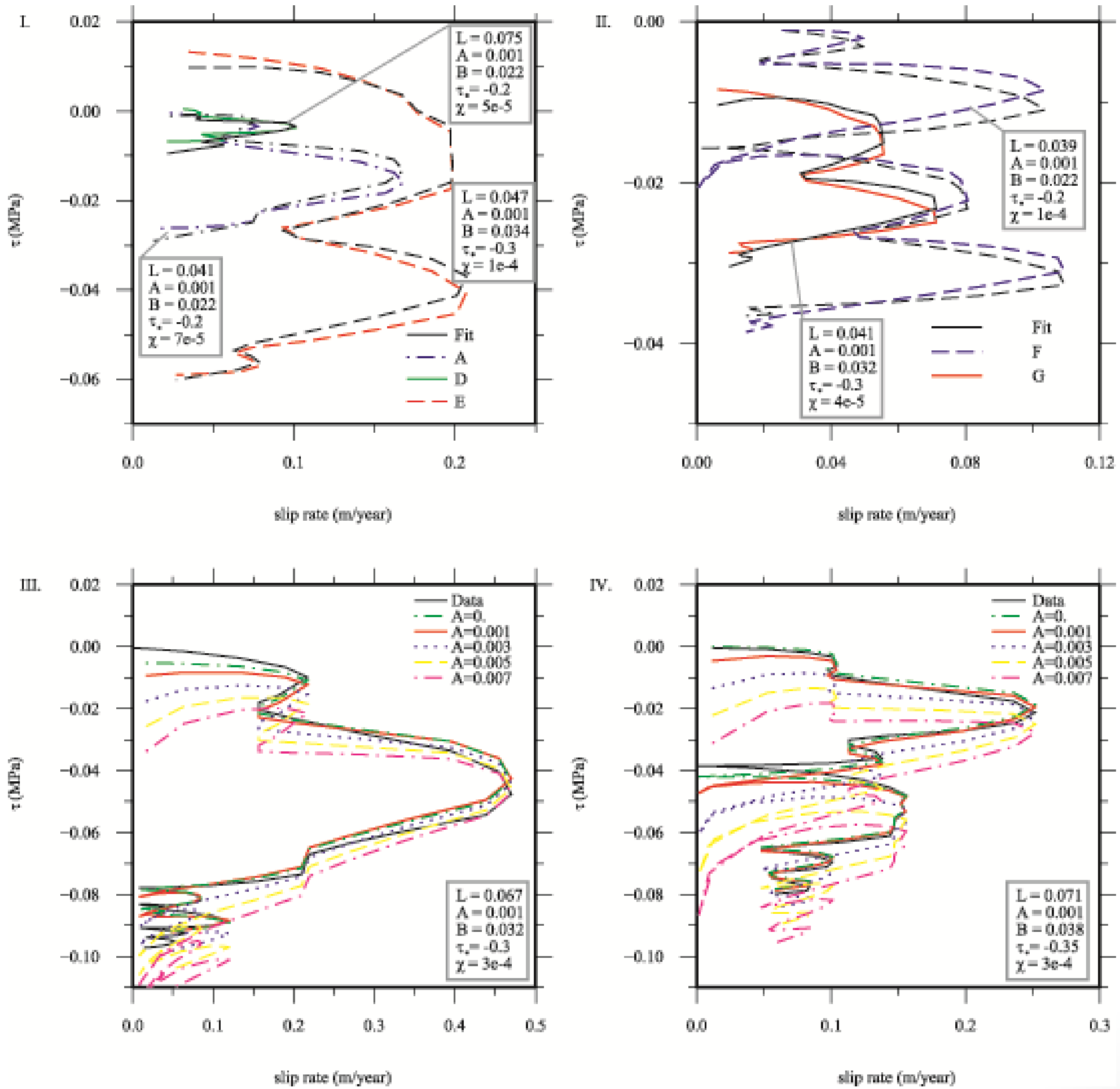
  Dieterich law

$$\begin{cases} \tau = se + A * \ln(V) + B * ln\left(\frac{\theta}{L}\right) \\ \frac{d\theta}{dt} = 1 - \frac{V\theta}{L} \end{cases}$$

- b-a>0: stable, velocity strengthening
- b-a<0: unstable, velocity weakening
- 4 unknowns: **A**=a*s_{neff}, **B**=b*s_{neff}, **L**, se
- Grid search: what is the best τ corresponding to V?
- Initial condition: fault in the steady state
- Misfit:

$$\chi = \sum (\tau_{calc} - \tau_{anal})^2$$

CONSTITUTIVES LAWS



CONSTITUTIVES LAWS

$$\tau = -0{,}2 + \underset{A}{0{,}001} * \ln(V) + \underset{B}{0{,}02} * ln\left(\frac{\theta}{0{,}04}\right)$$

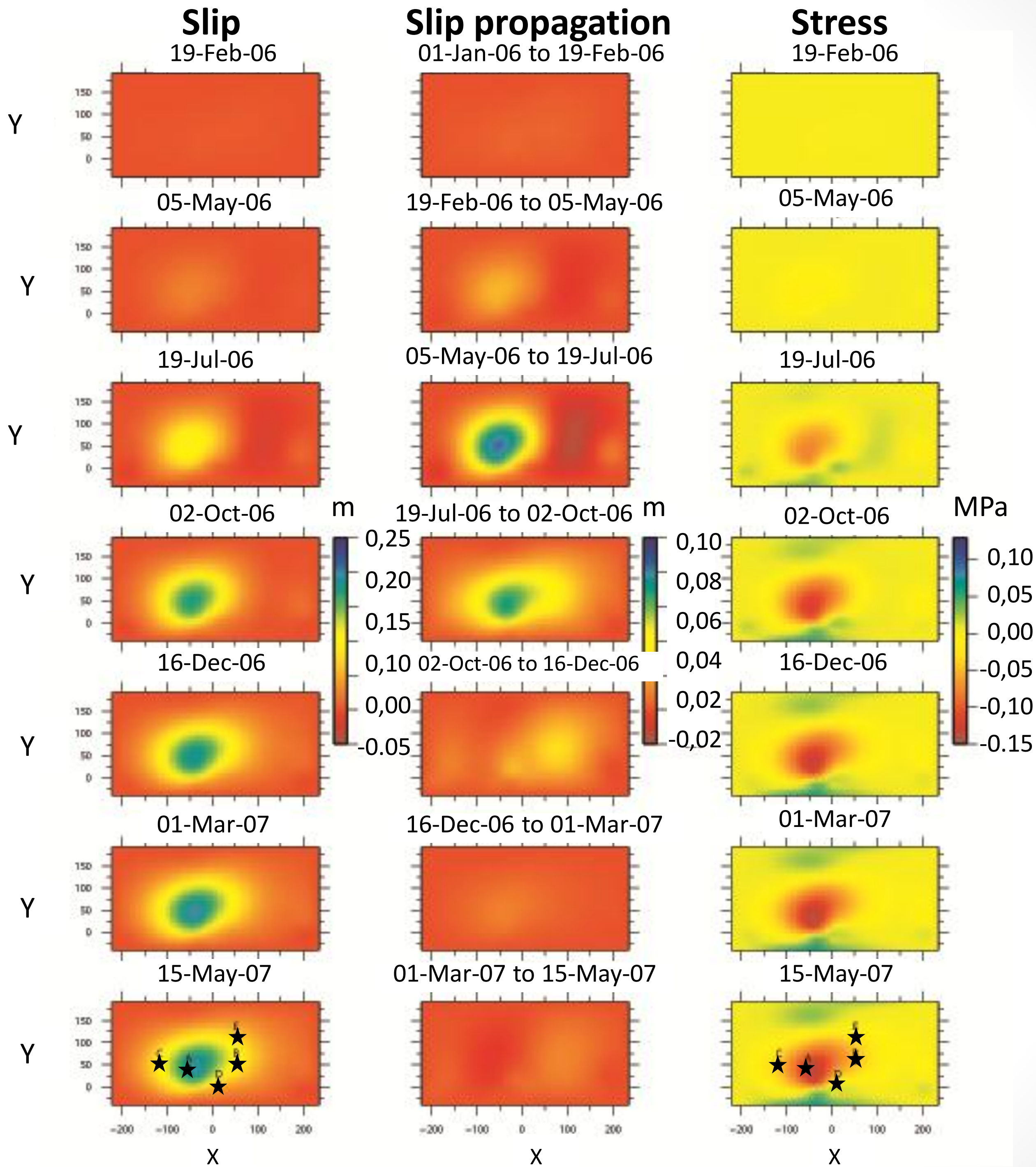
- L~cm; A term negligible compared to B term.

- 87% of the subfaults considered has a misfit lower than 0,005

- B-A = (b-a)s_n => if b-a=0,004 then **s_n=5 MPa**

  ↑ Normal effective stress

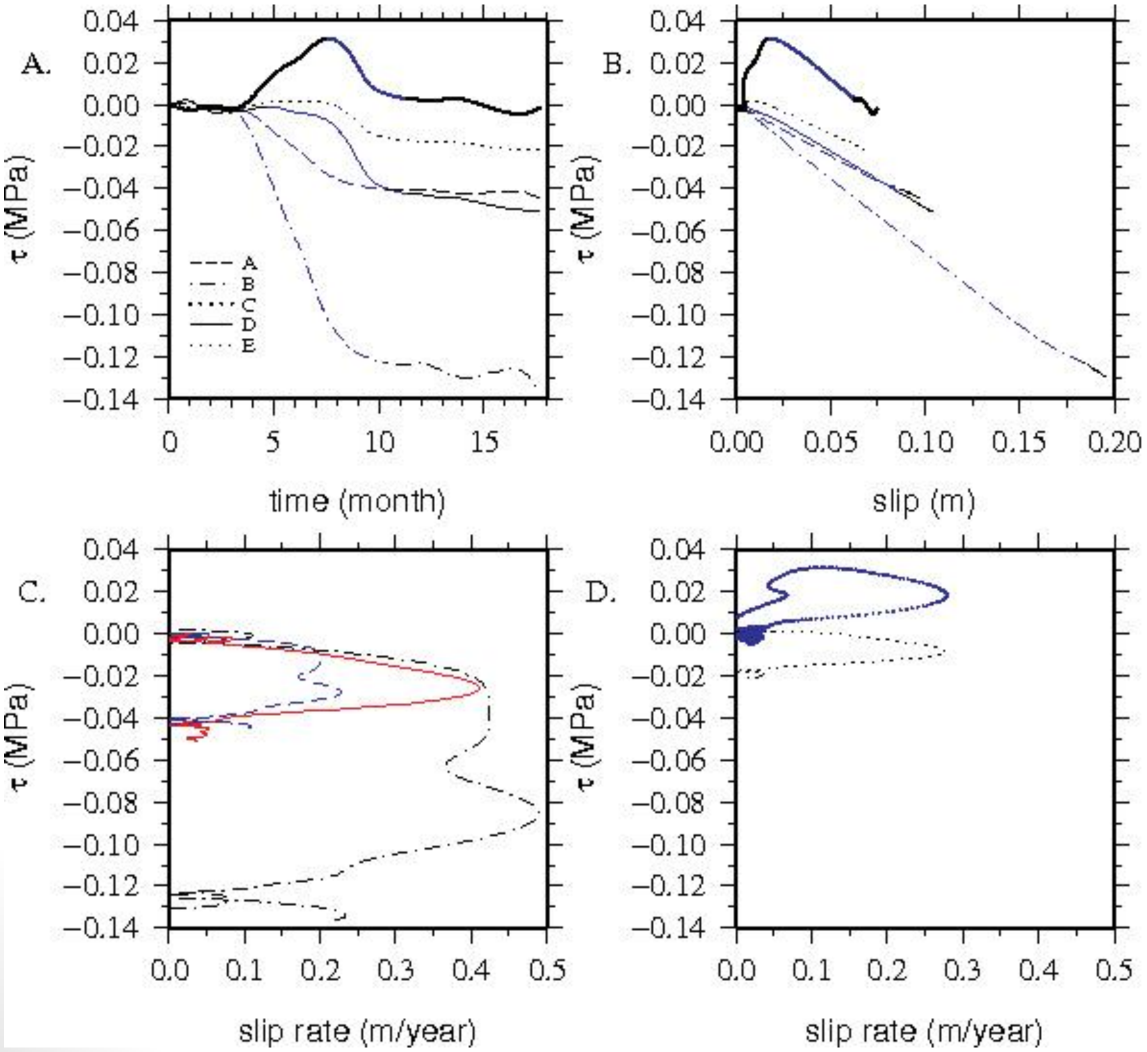
2006 SSE

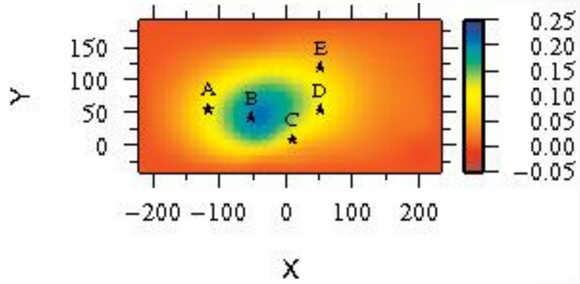


Slip
Slip propagation
Stress
19-Feb-06
01-Jan-06 to 19-Feb-06
19-Feb-06
05-May-06
19-Feb-06 to 05-May-06
05-May-06
19-Jul-06
05-May-06 to 19-Jul-06
19-Jul-06
02-Oct-06
19-Jul-06 to 02-Oct-06
02-Oct-06
16-Dec-06
02-Oct-06 to 16-Dec-06
16-Dec-06
01-Mar-07
16-Dec-06 to 01-Mar-07
01-Mar-07
15-May-07
01-Mar-07 to 15-May-07
15-May-07
m
0,25
0,20
0,15
0,10
0,00
-0.05
m
0,10
0,08
0,06
0,04
0,02
-0,02
MPa
0,10
0,05
0,00
-0,05
-0,10
-0.15
Y
X

2006 SSE

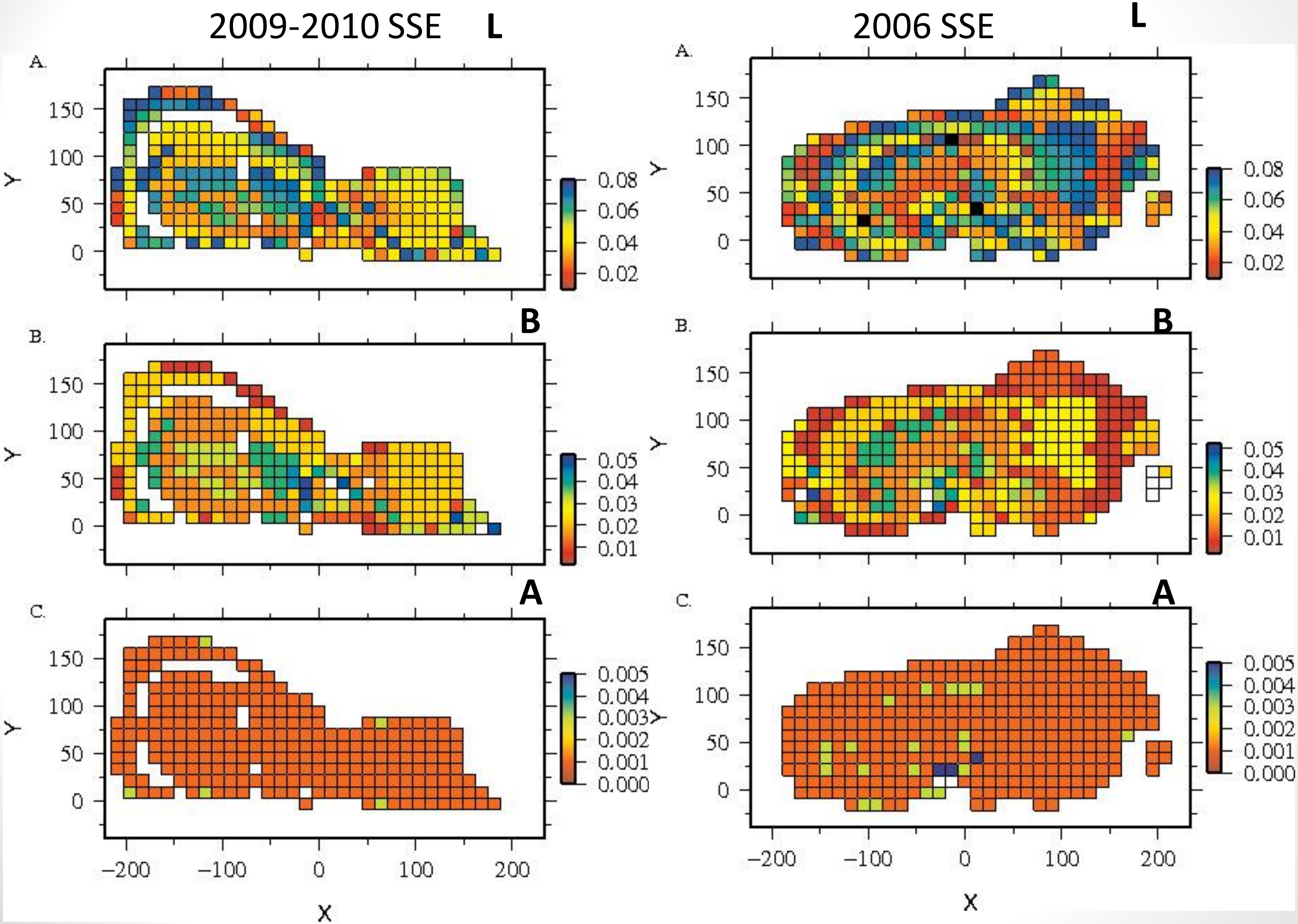
same observations





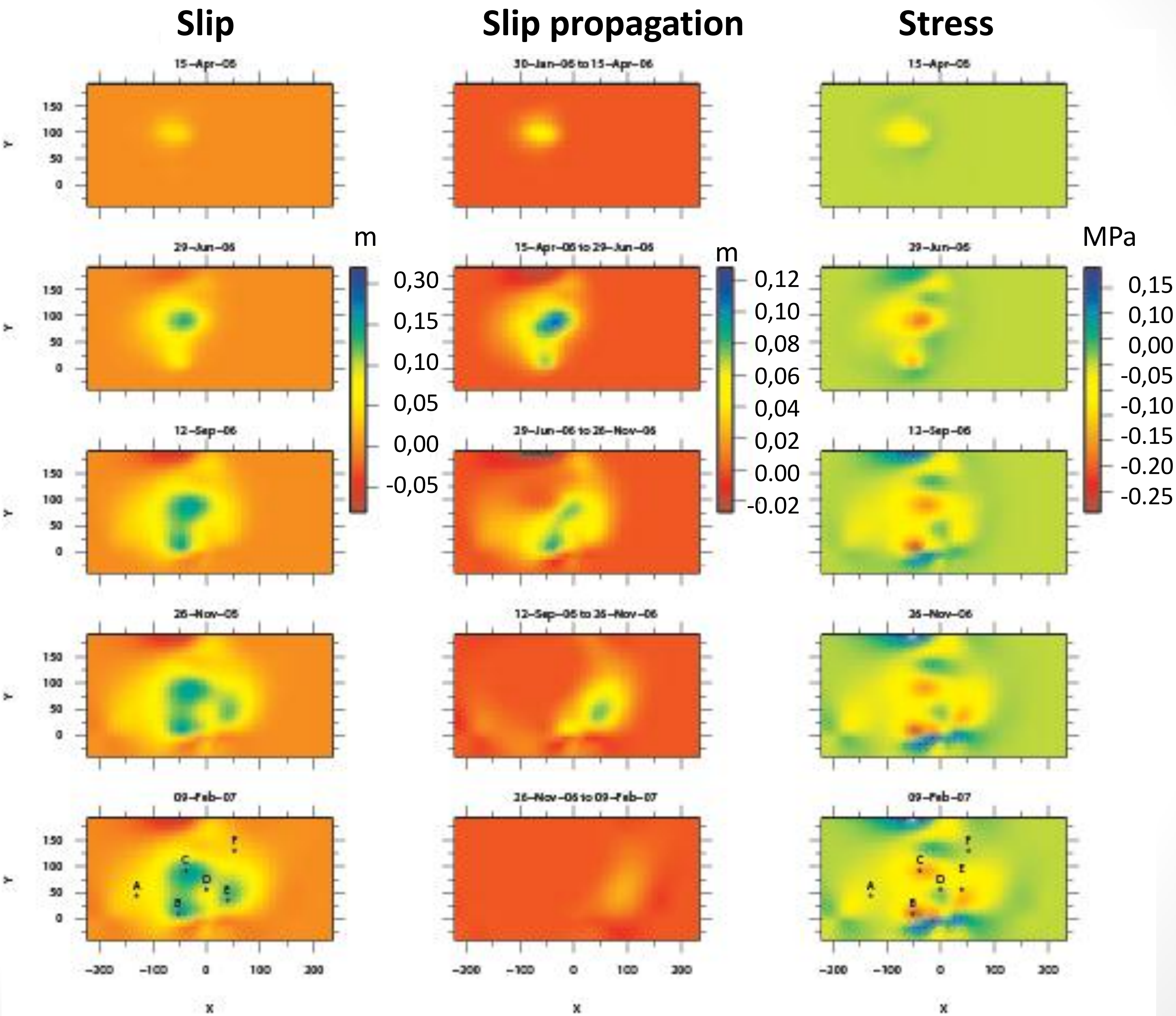
Slip weakening law:
Mean slope -0,5 MPa/m

2006 SSE


2009-2010 SSE
L
2006 SSE
L
A.
B.
C.
B
A
Y
X
150
100
50
0
−200
−100
0
100
200
0.08
0.06
0.04
0.02
0.05
0.04
0.03
0.02
0.01
0.005
0.004
0.003
0.002
0.001
0.000

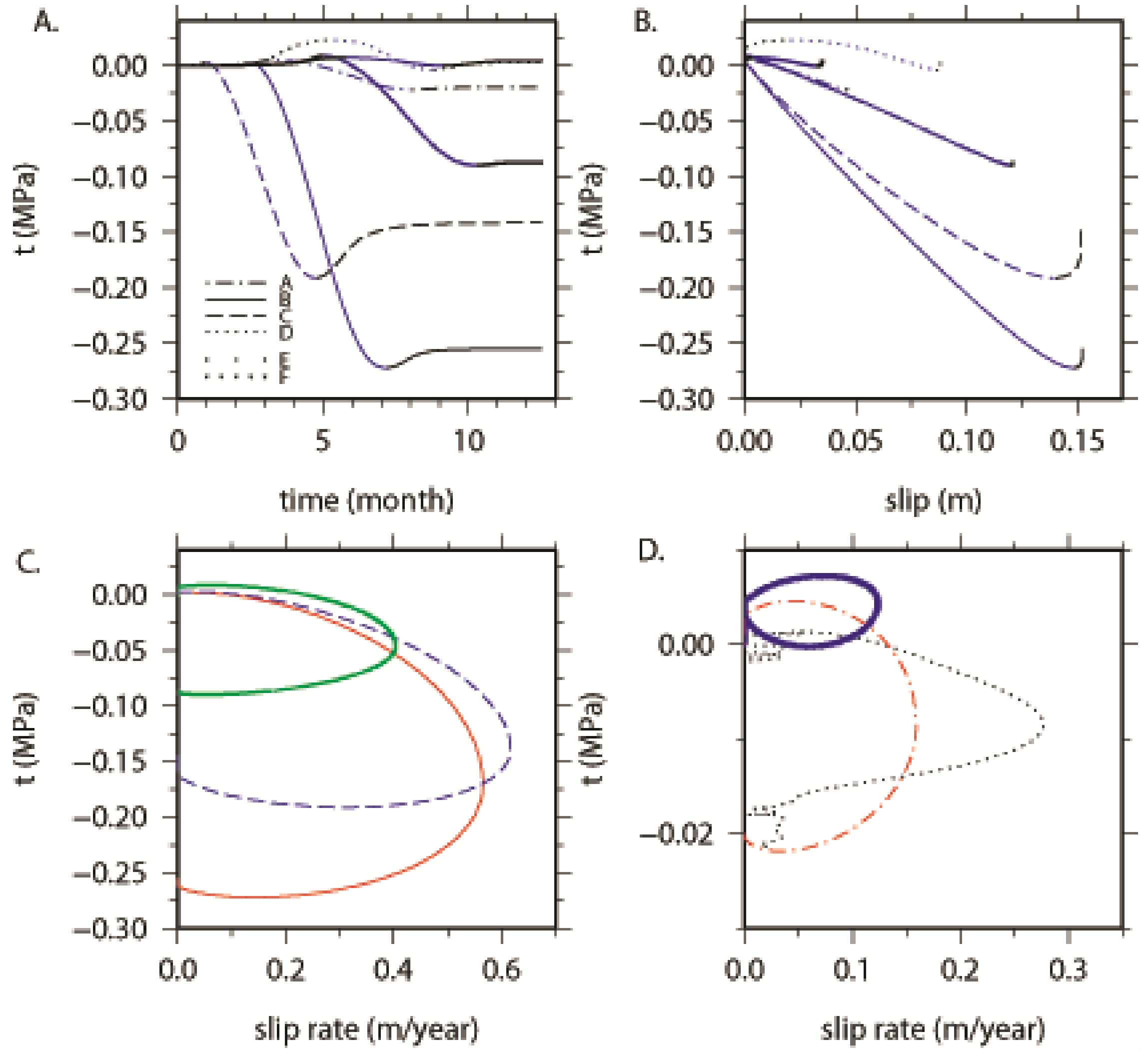
Parametric method

2006 SSE



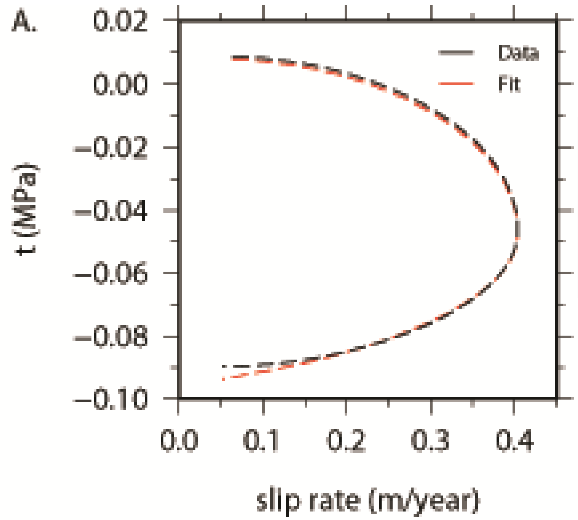
Parametric method

2006 SSE



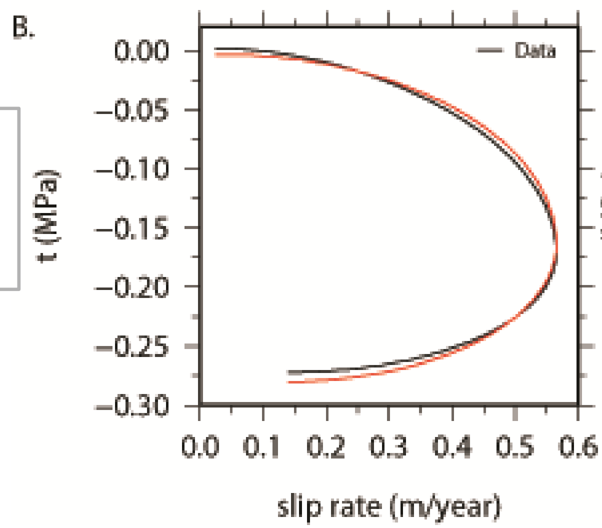
Parametric method

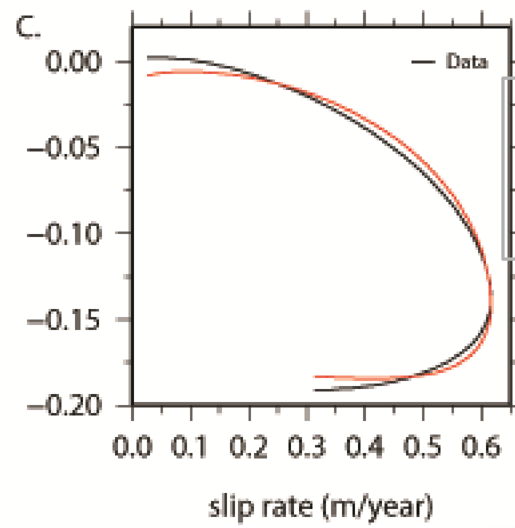
2006 SSE



L = 0,019 m
A = 0,001 MPa
B = 0,038 MPa

L = 0,013 m
A = 0,003 MPa
B = 0,022 MPa





L = 0,06 m
A = 0,001 MPa
B = 0,05 MPa

Conclusion

- Stress analysis of 2 SSEs: 2006 and 2009-2010
- Constitutive laws used for classical earthquakes are valid for SSE:
  - Slip weakening law emerges spontaneously
  - Confirm rate and state law explains behavior of SSEs
- Same mechanical behavior for both SSEs
- Parameters of the rate and state law can be retrieved:
  - L of the order of cm
  - Low effective normal stress
  - Kinetic term negligible compared to the evolution term
- The constitutive relations remain unchanged before and after the Maule earthquake.

THANK YOU!

PCAIM

- Principal Component Analysis Inversion Method

1. GPS temp. series decomposed as sum of components. A component is associated to a pattern of surface displacement and a time function.
2. Spatial displacements associated to each component are inverted to determine a principal slip distribution.
3. Fault slip distribution is derived by linear combination of the principal slip distribution (only 2 components necessary).

- Green function for a half space.
- Results filtered because of noise in the GPS time series
- No a priori on slip evolution, gap in time series not important but spatial smoothing important

Slip on the fault

Center matrix

$$X_0 = G * (L_{stationary} + \Delta L) \longrightarrow X(i,j) = X_0(i,j) - \frac{\sum_{k=1}^{m} X_0(i,k)}{m}$$

Row : temp. serie of a component
Column : data for a time period

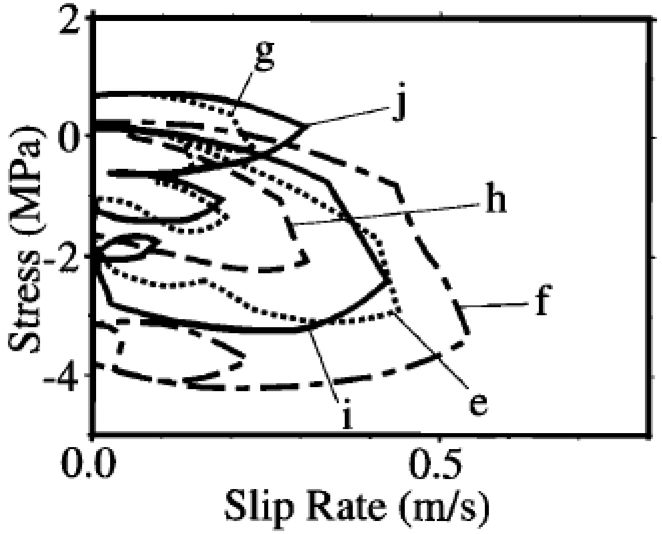
Spatial eigenvector

Singular values decomposition : $\mathrm{X} = \mathrm{U.S.}V^T$ *Temp. eigenvector*

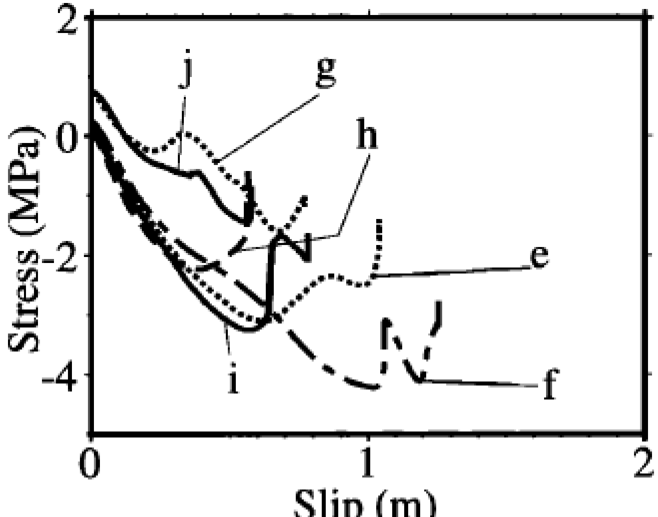
Spatial eigenvectors decomposition and linear combination of slip:

$$m = G^{-1}(X_0 - X) + G^{-1}U.S.V^T$$

$$\Delta\boldsymbol{\tau}(\overrightarrow{\boldsymbol{X}}) = -\frac{\boldsymbol{\mu}}{\mathbf{4}\boldsymbol{\pi}}\int_{\Sigma}\left[\mathbf{2}(\mathbf{1}-\boldsymbol{p}^{\mathbf{2}})\frac{\boldsymbol{\gamma}_{\mathbf{2}}}{\boldsymbol{r}^{\mathbf{2}}}\frac{\partial\Delta\boldsymbol{u}}{\partial\boldsymbol{y}}+\frac{\boldsymbol{\gamma}_{\mathbf{1}}}{\boldsymbol{r}^{\mathbf{2}}}\frac{\partial\Delta\boldsymbol{u}}{\partial\boldsymbol{x}}\right]\boldsymbol{d\Sigma}$$



2
0
-2
-4
0.0
0.5
Stress (MPa)
Slip Rate (m/s)
g
j
h
f
e
i



2
0
-2
-4
0
1
2
Stress (MPa)
Slip (m)
j
g
h
e
f
i