Mechanical Modeling of Lithospheric Strain with ADELI's Software

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Main purpose : model faults with consistent rheology

Mosha fault (Northern Iran)

Overview

1/ Practical use

general features
web site
write an input file

2/ Numerical Method

Space discretization
Constitutive laws
Contact and friction
Time discretization

3/ Fault Modeling examples

- Short term tectonics (0.1 Myr) : Oblique convergence in Zagros fault ; // faults in the Northern Cal. ; the North Anatolian fault
- Seismic cycle at 3D (0.01 Myr) : time-Space complexity
- Interseismic strain (10 yrs): impact of elastic thickness

General Features of ADELI

- Software history

2D code mostly written during 1991-1994 (PhD thesis of R. Hassani) + adds from M. Jean (CNRS), D. Demanets (Liège Univ.), F. Lucazeau (IPG Paris), R. Cattin (ENS Paris).

3D code mostly written during 1998-present (Chéry-Hassani)

- Capabilities

Large deformation, updated lagrangian, body forces, kinemati
+ static boundary conditions

- Availability

free Fortran 77 source code + documentation and examples or

http:// www.isteem.univ-montp2.fr/ PERSO/chery/Adeli_web/index.htm

(google adeli chery)

- Publications

about 40 (continental extension, subduction, fault slip rate, tectonic-erosion coupling, seismic cycle)

General Features

- Programs & Requirements

Operating system : Unix or Linux

Mesher + Solver at 2D : ea2d command line
Mesher + Solver at 3D : ea3d command line
only needs F77 compiler

Vizualisation at 2D : xadeli2d program
Vizualisation at 3D : p2x + xadeli3d program
needs C compiler + motif library + gmt software (postscript output)

Web site

- Software → download

- Documentation → user's guide (2D-3D)

- Benchmarks & experiments → quick start

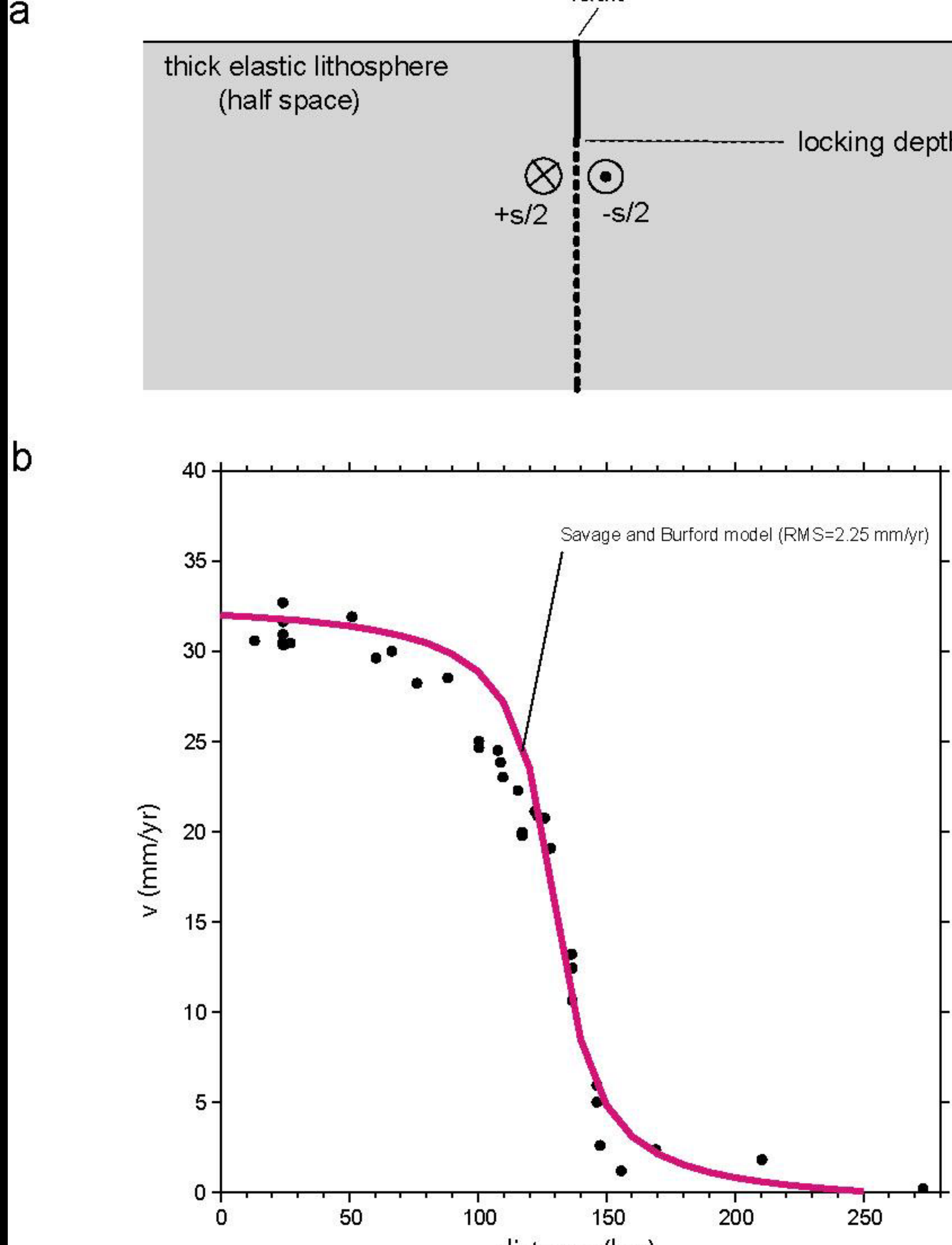
just ask for help…

How to design an input file ?

Example :

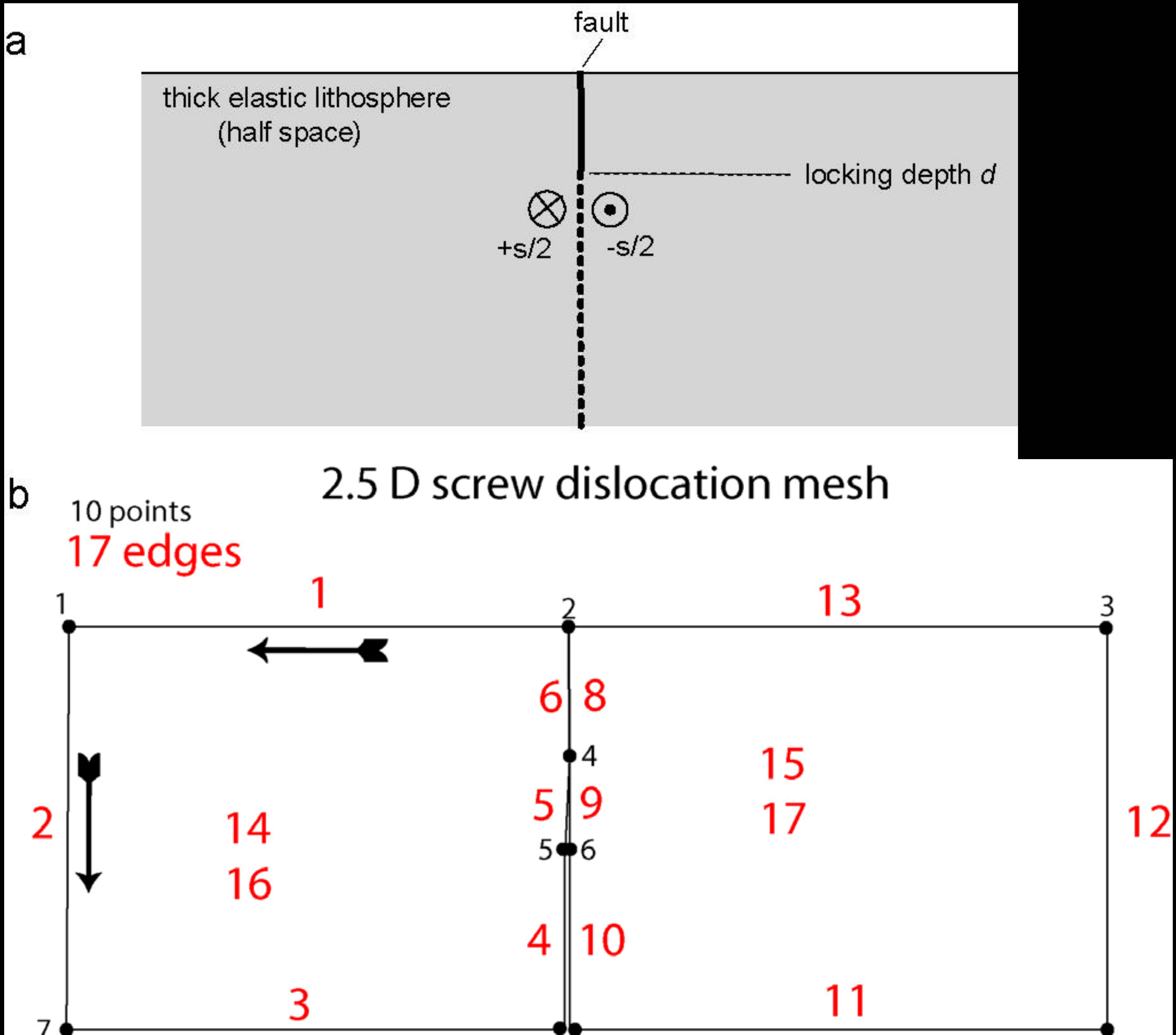
interseismic strain around a vertical strike-slip fault :

an antiplane problem with a 3D mesh



Setup the input file (i-file) :

mesh contour ; rheology ; boundary conditions



Running the code : 3 steps

1. Mesh generation + FE computation

command line : ***ea3d 3d4 lin f essai***

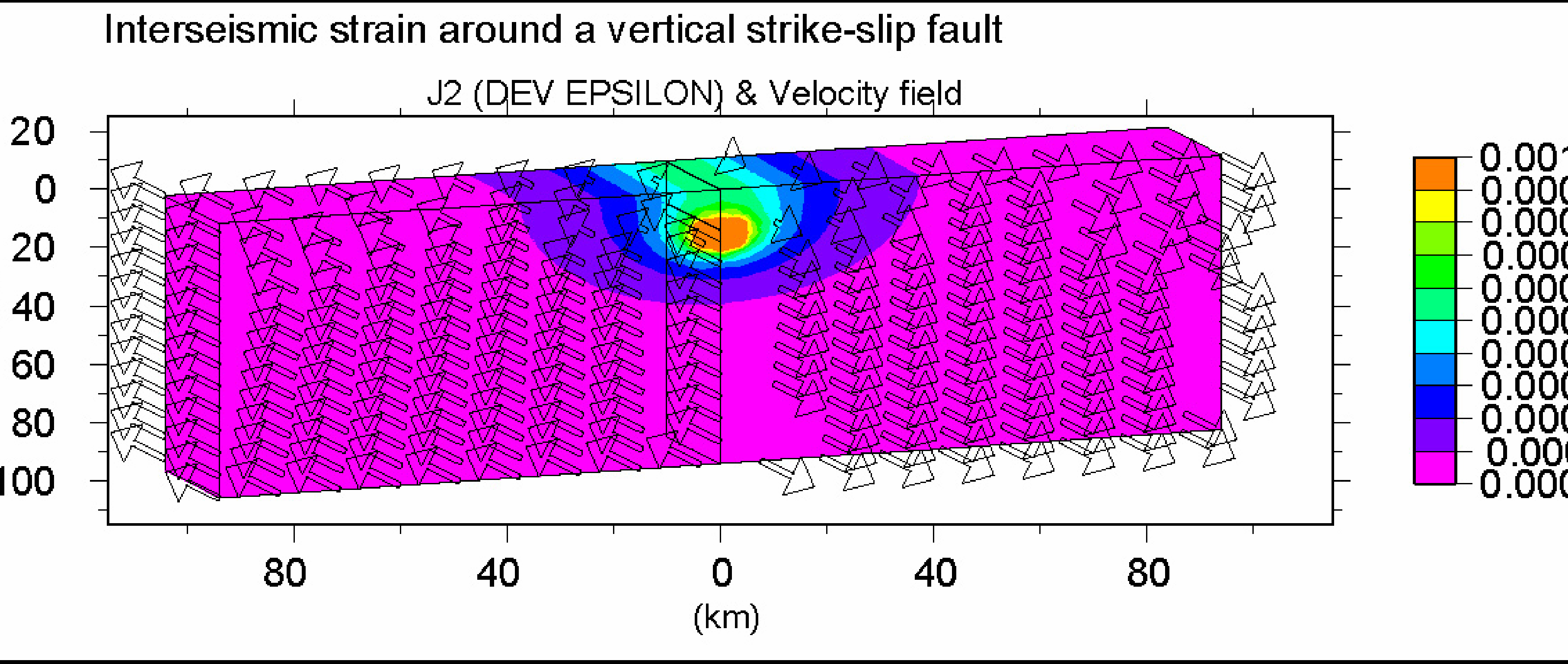
2. Creating graphic file (3D only)

command line : ***p2x***

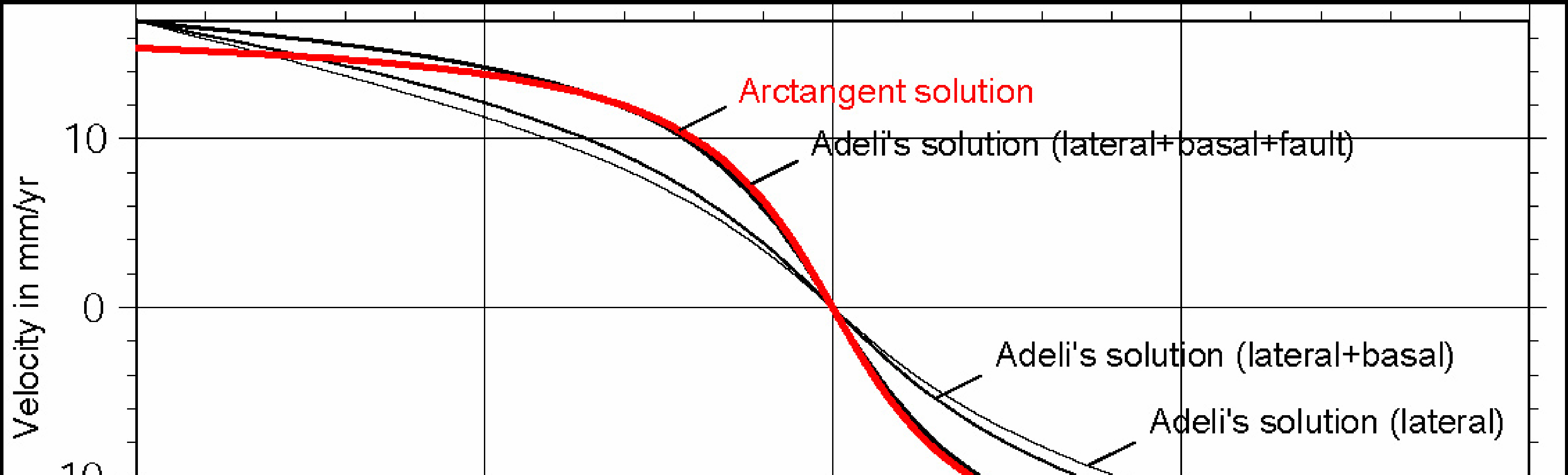
3. Visualizing graphic file

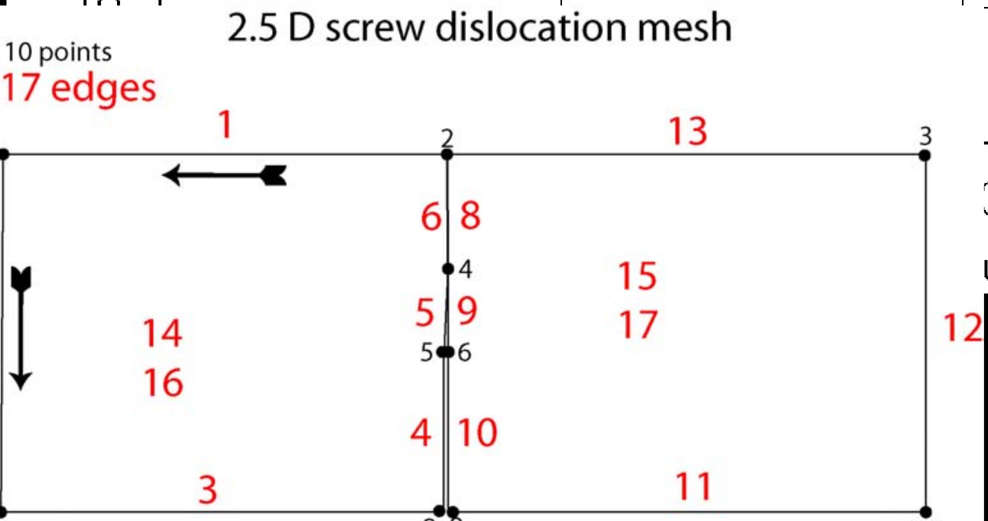
command line : ***xadeli2d / xadeli3d***

Strain


Interseismic strain around a vertical strike-slip fault
J2 (DEV EPSILON) & Velocity field
20
0
20
40
60
80
100
80
40
0
40
80
(km)

Surface velocity





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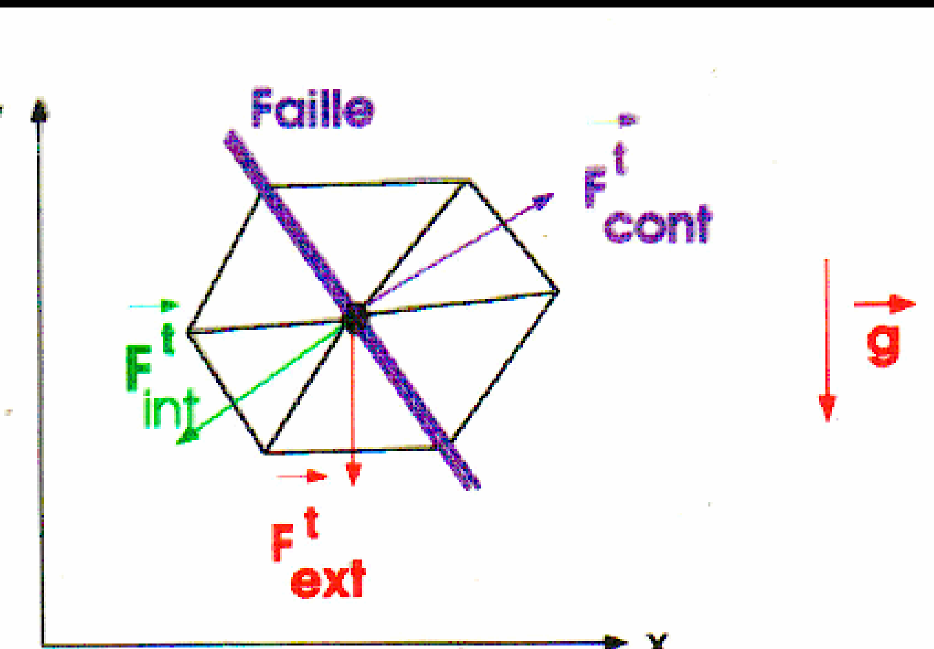
Space discretization

Built-in unstructured frontal mesh
2D : pair of triangles
3D : tetrahedrons (extrusion of 2D mesh)

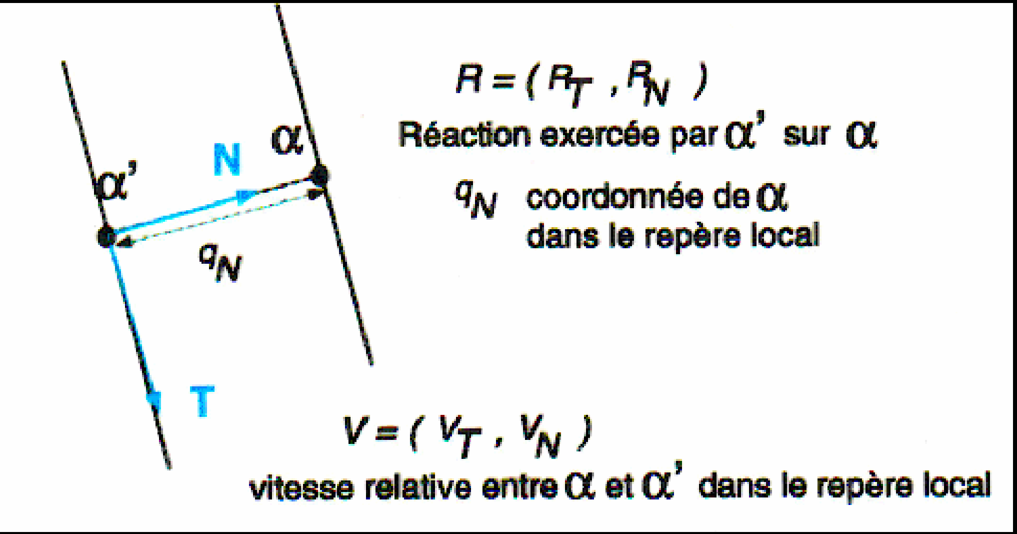


←Assembling forces (1 node)

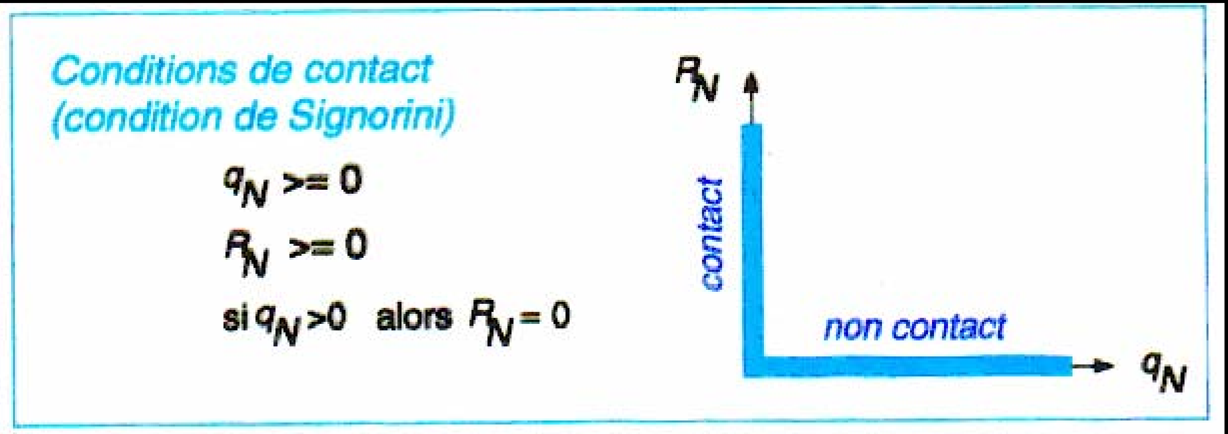
lobal force balance eq. in
ector mode (1 line / DOF) →

$$\vec{F}^{t}_{int} + \vec{F}^{t}_{ext} + \vec{F}^{t}_{cont} = M \vec{a}$$

Contact and friction (M. JEAN algorithm)

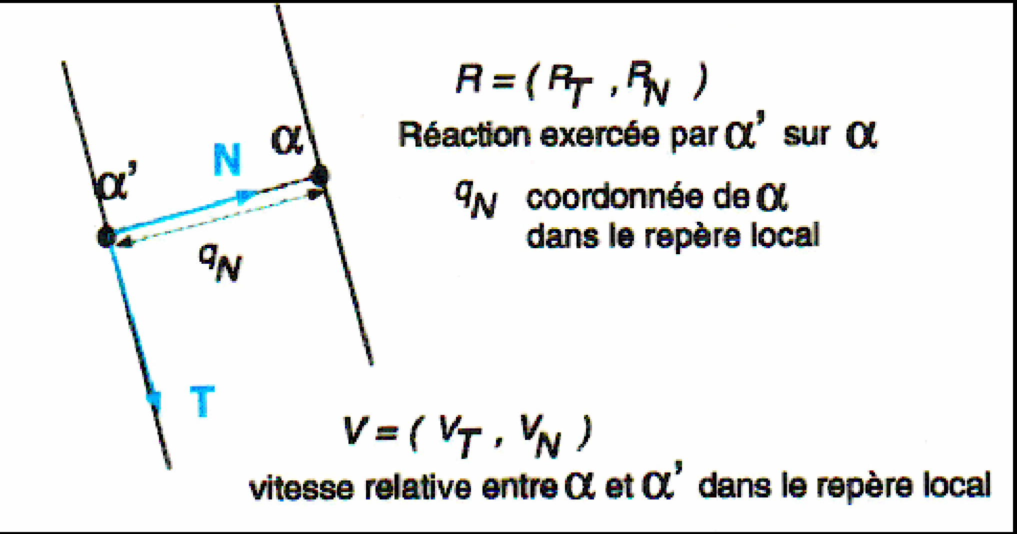


Local fault frame geometry (normal – tangential)



Signorini condition satisfied at end of timestep (implicit formulation)

Contact and friction (M. JEAN algorithm)



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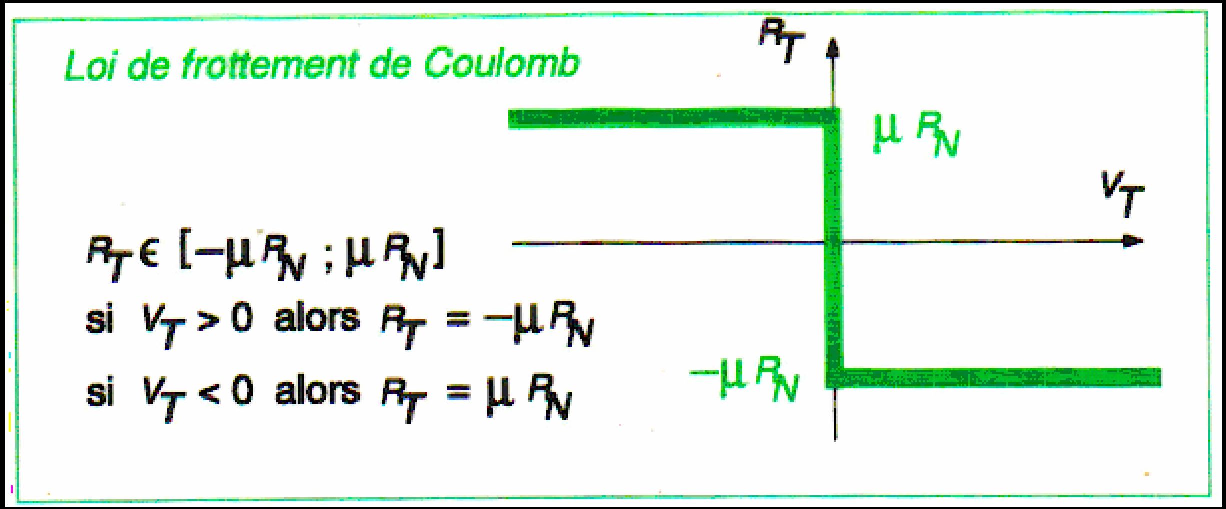


Coulomb law satisfied at end of timestep (implicit formulation)

Constitutive laws

Element by element stress integration in a rotating frame (Jaumann or Green-Naghdi derivative)

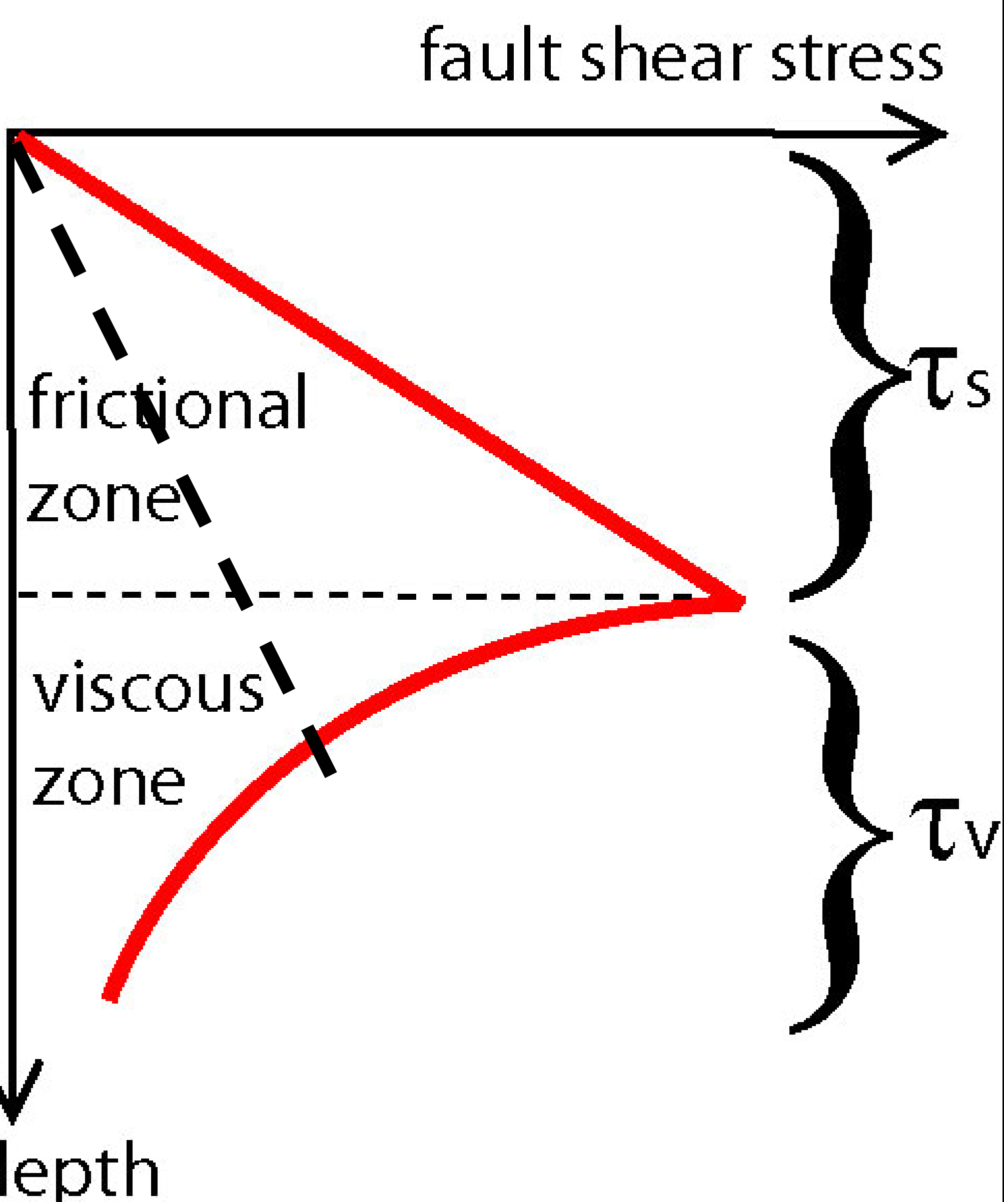
$$\sigma(\tau) = M(\sigma, \dot{\varepsilon}) \qquad \tau \in [t_n ; t_{n+1}]$$
$$\sigma(t_n) = \sigma_n$$

Four choices for stress-strain constitutive equations :

- **Linear elasticity**
- **Linear – non linear viscoelasticity (Maxwell rheology)**
- **Associated – non associated Drucker-Prager plasticity**
- **Von Mises plasticity**

One choice for thermal transfer : Fourier law

Crustal constitutive laws



Drucker-Prager : pressure dependent criterion

$$J_2(\hat{\sigma}) - \alpha\left[\bar{\sigma} + \frac{\tau_0}{\tan\phi}\right] = 0$$

$$\alpha = \frac{6\sin\phi}{3-\sin\phi}$$

Non linear viscoelasticity : temperature dependent fluidity

$$\dot{\varepsilon} = A_0(\sigma_1 - \sigma_3)^n \exp\left(-\frac{Q}{RT}\right.$$

Time discretization

Dynamic Relaxation Method (Otter et al. 1966 ; Cundall 1988)
Adapted from FLAC scheme. NO LINEAR SYSTEM SOLVING

For each DOF :

Compute
free acceleration,
free velocity,
free displacement

$$\ddot{u}_f^t = M^{-1}(F_{ext}^t + F_{\text{int}}^t + F_{damp}^t)$$

$$\dot{u}_f^{t+1/2} = \dot{u}^{t-1/2} + \Delta t \cdot \ddot{u}^t$$

$$u_f^{t+1} = u^t + \Delta t \cdot \dot{u}^{t+1/2} + \Delta t^2 / 2 \cdot \ddot{u}$$

Compute
contact forces

$$F_{cont}^{t+1} = F(\dot{u}_f^{t+1/2}, u_f^{t+1})$$

Correct
velocity,
displacement

$$\dot{u}^{t+1/2} = \dot{u}_f^{t+1/2} + \Delta t \cdot M^{-1} F_{cont}^{t+1}$$

$$u^{t+1} = u_f^t + \Delta t^2 / 2 \cdot M^{-1} F_{cont}^{t+1}$$

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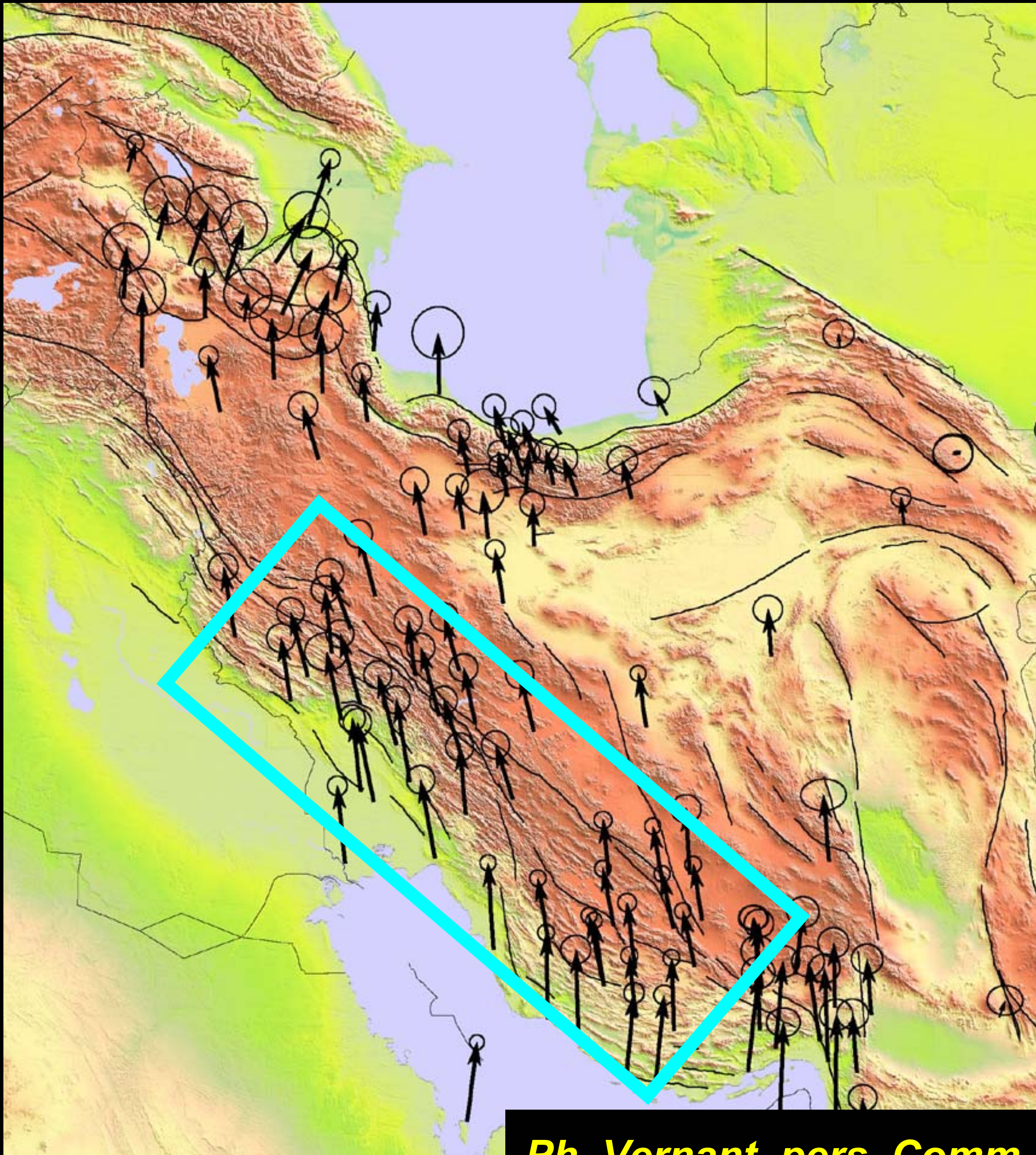
Oblique convergence in Zagros

Collision between
Arabian plate
and central Iran

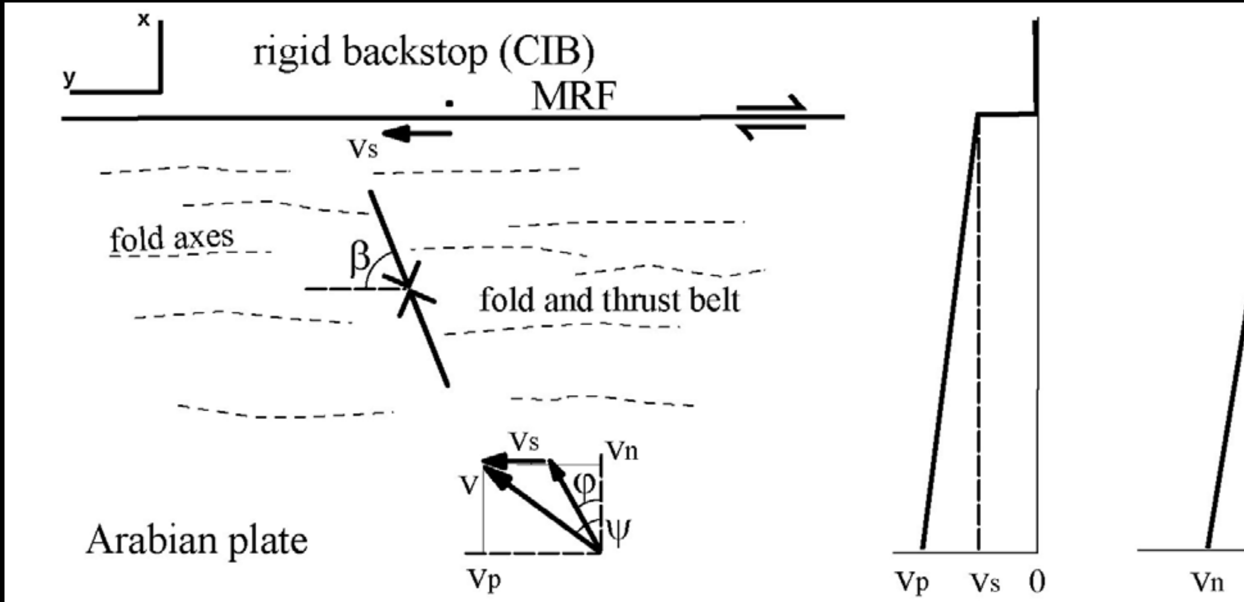
2.5 model



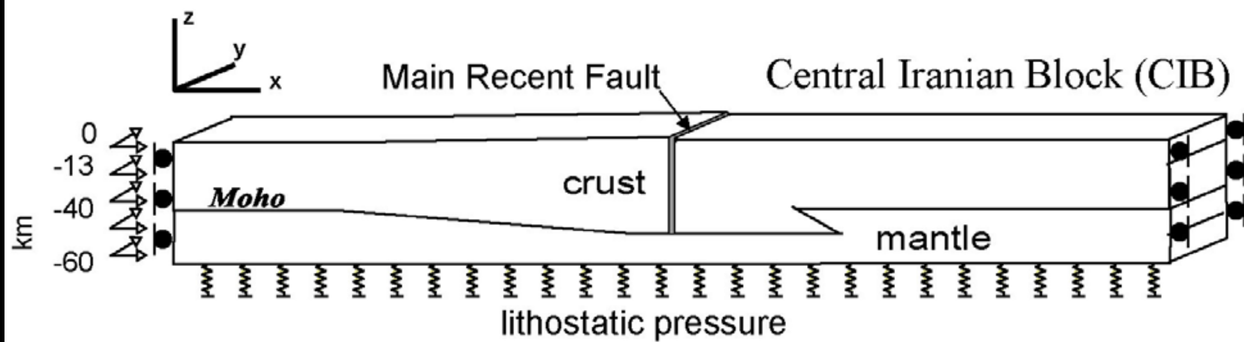
Ph. Vernant, pers. Comm.

Oblique convergence in Zagros

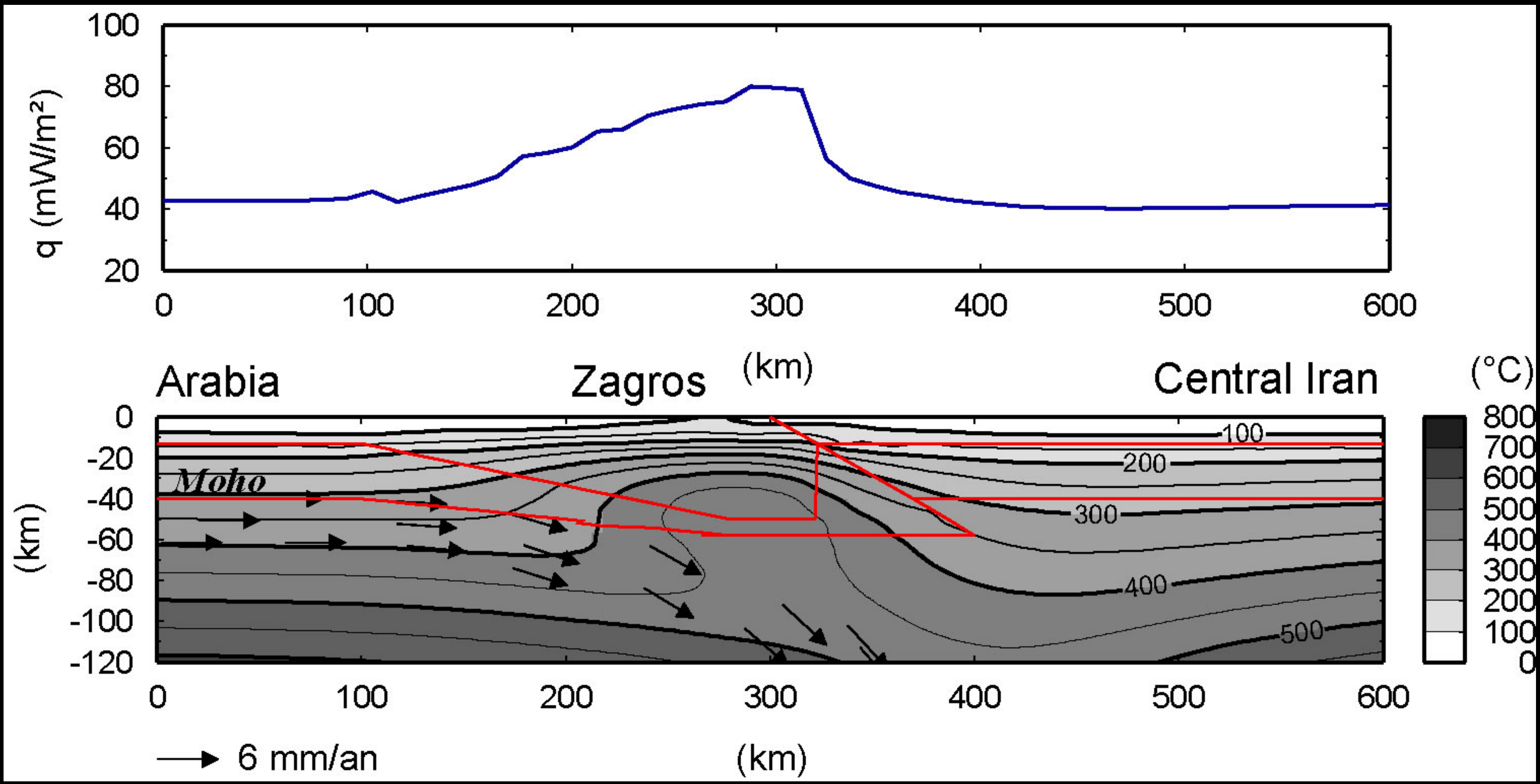
Map view :



Cross-section :

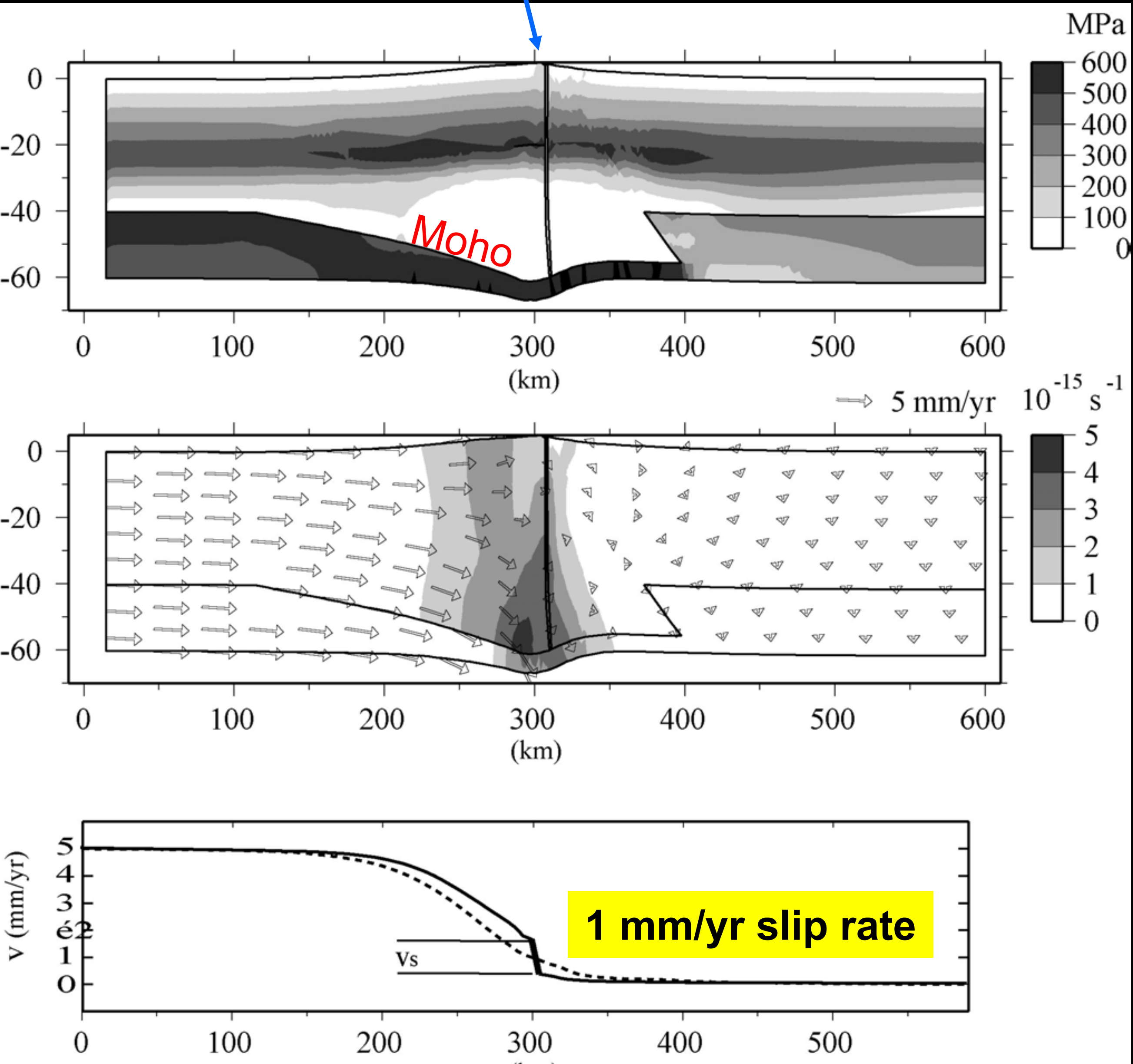


Step 1 : thermal model of Zagros with assumed mantle subduction (T output from 2D code, T input for 3D experiment)



Step 2 : Weak fault (low friction)

State after 10 Myrs of oblique shortening (45° obliquity)



Deviatoric stress:

Crust-mantle decoupling in Zagros

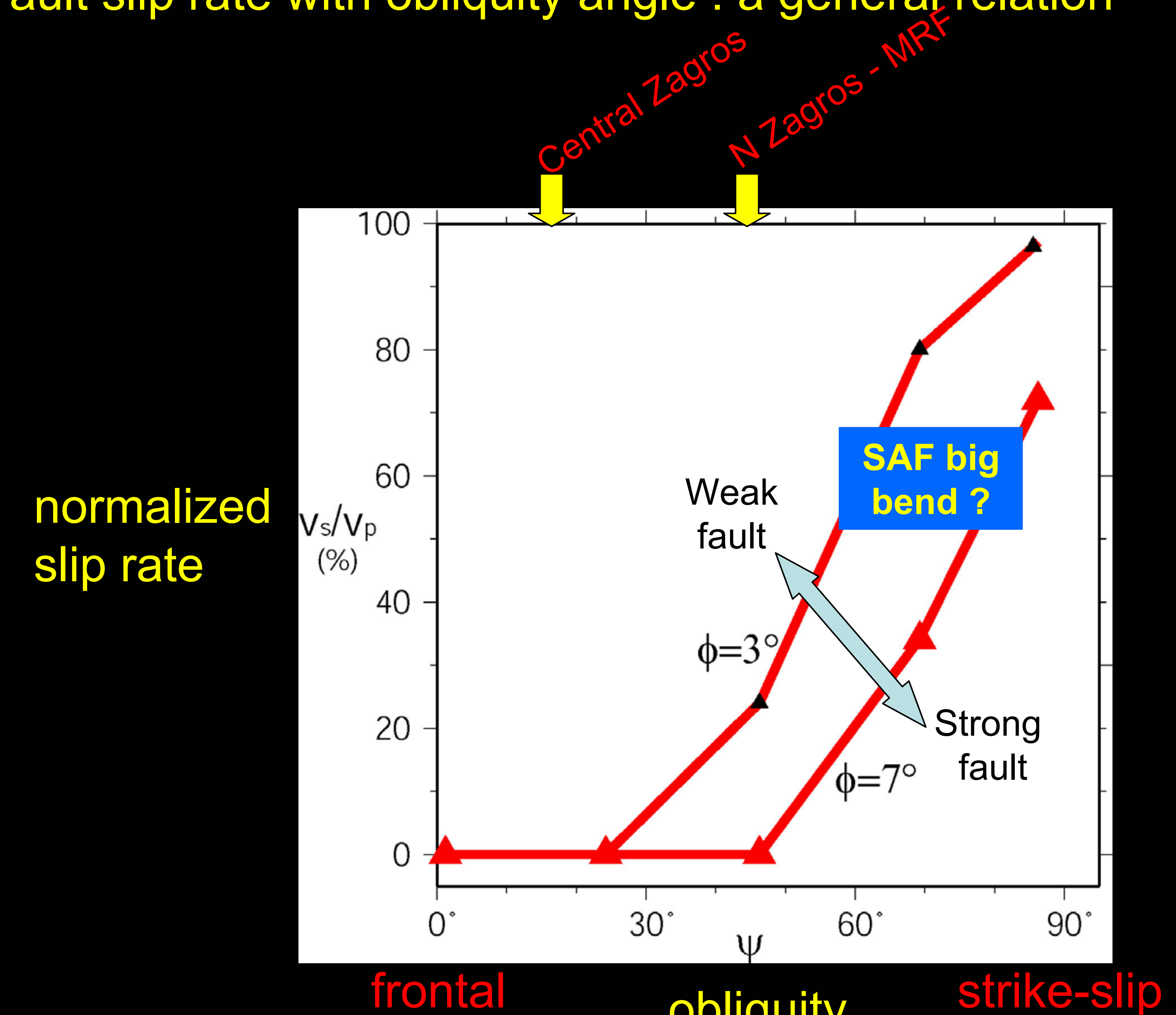
Shear strain rate:

Distributed strain in the orogen + localized strain on the strike slip fault

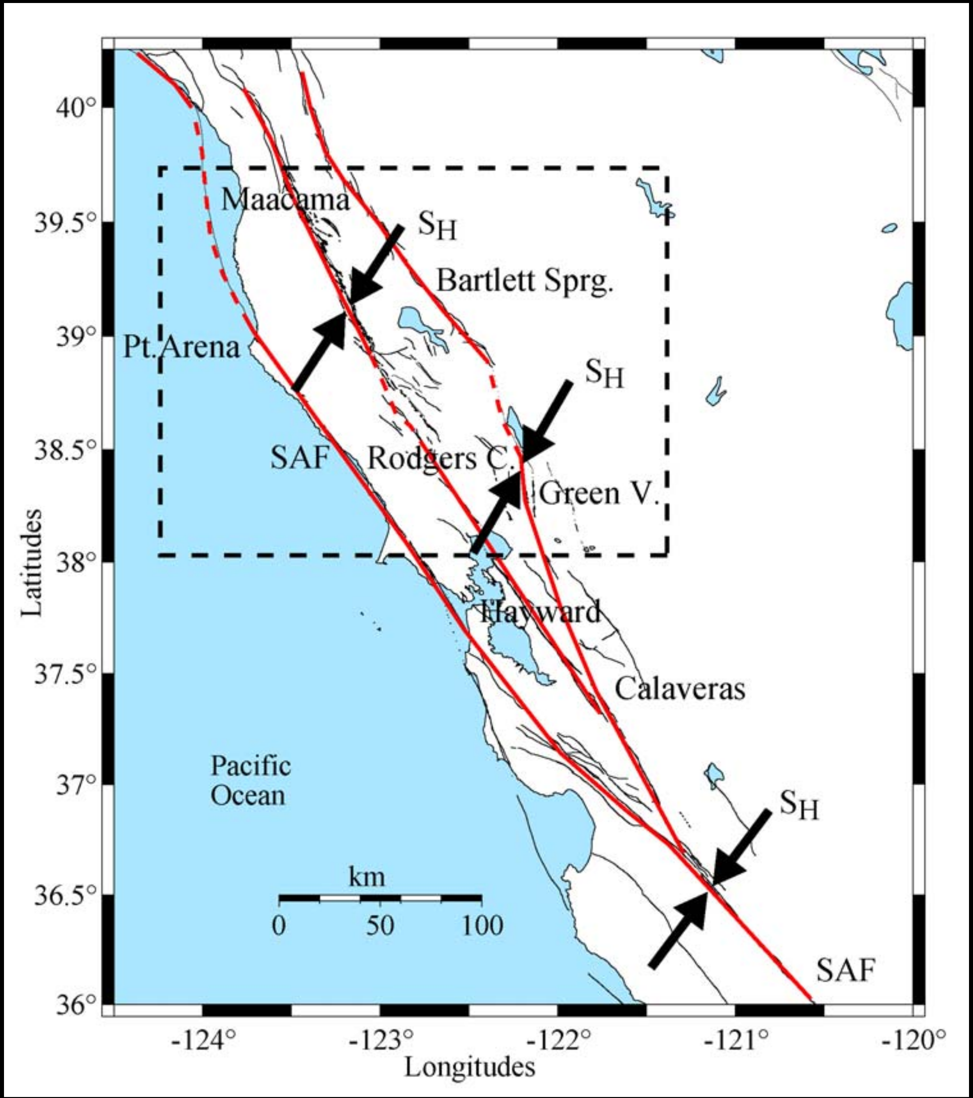
Surface velocity :

Smooth variation + jump accross the fault

Fault slip rate with obliquity angle : a general relation



Northern California : 3 // faults
San Andreas – Maacama – Bartlett Springs

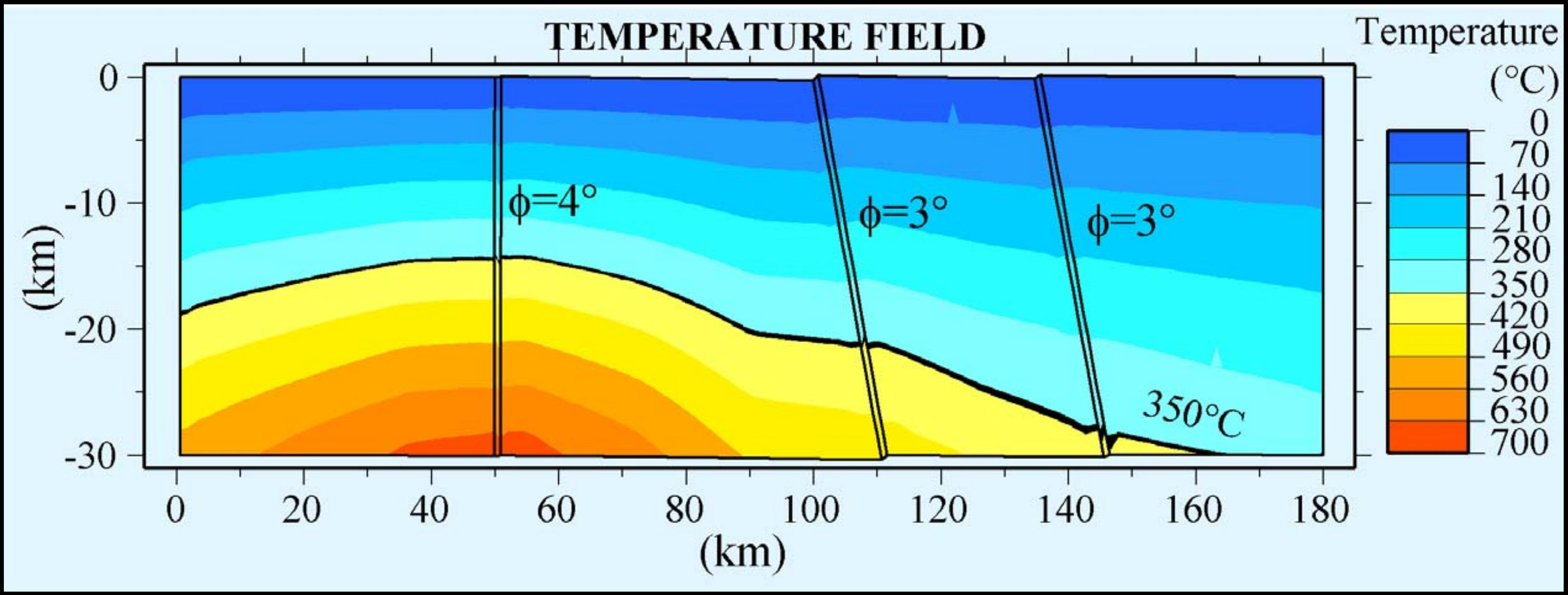


San Andreas = 21 mm/yr
Maacama = 10 mm/yr
Bartlett Springs = 6.5 mm/yr

Provost et Chéry, 200

Initial temperature field from heat flow measurements

40-80 mW/m2

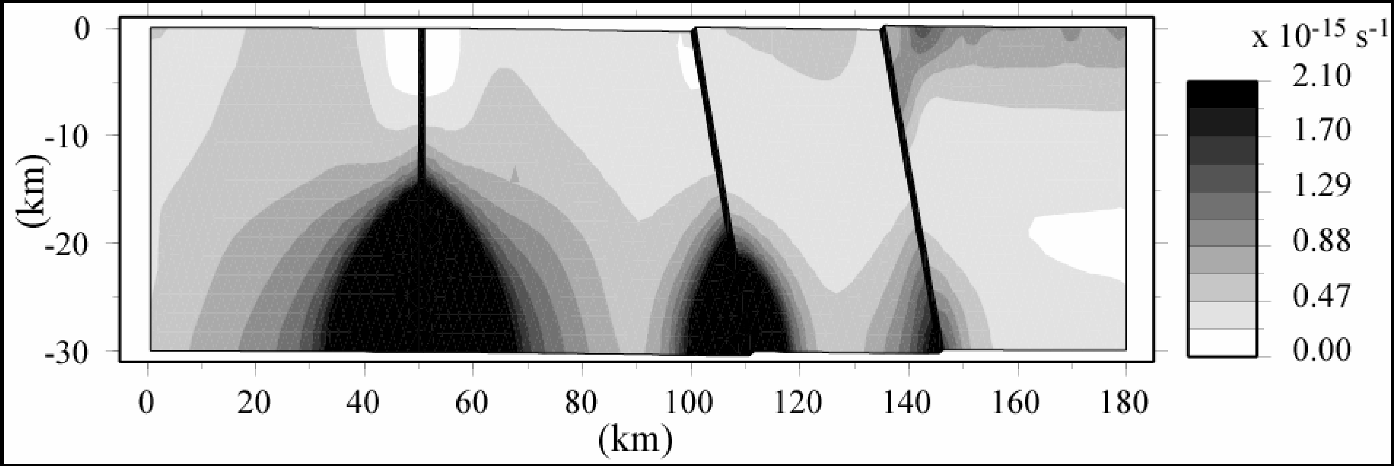


Provost et Chéry, 200

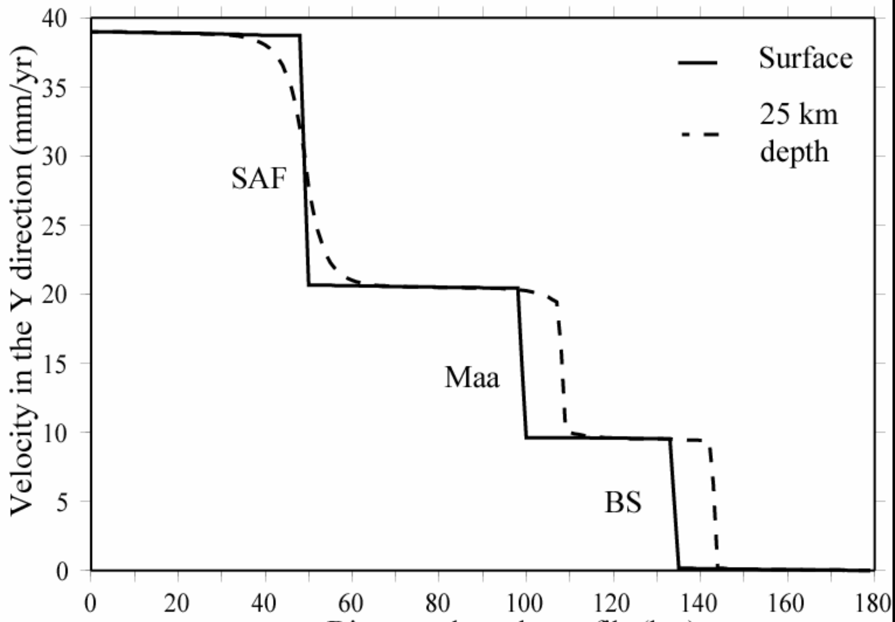
Transpressive mechanical model driven by the sides (Pac. – Sierra Nev.)

Best model (Vmodel = Vdata ; Shmax check)

Long term Strain rate



Slip rate



Provost et Chéry, 200

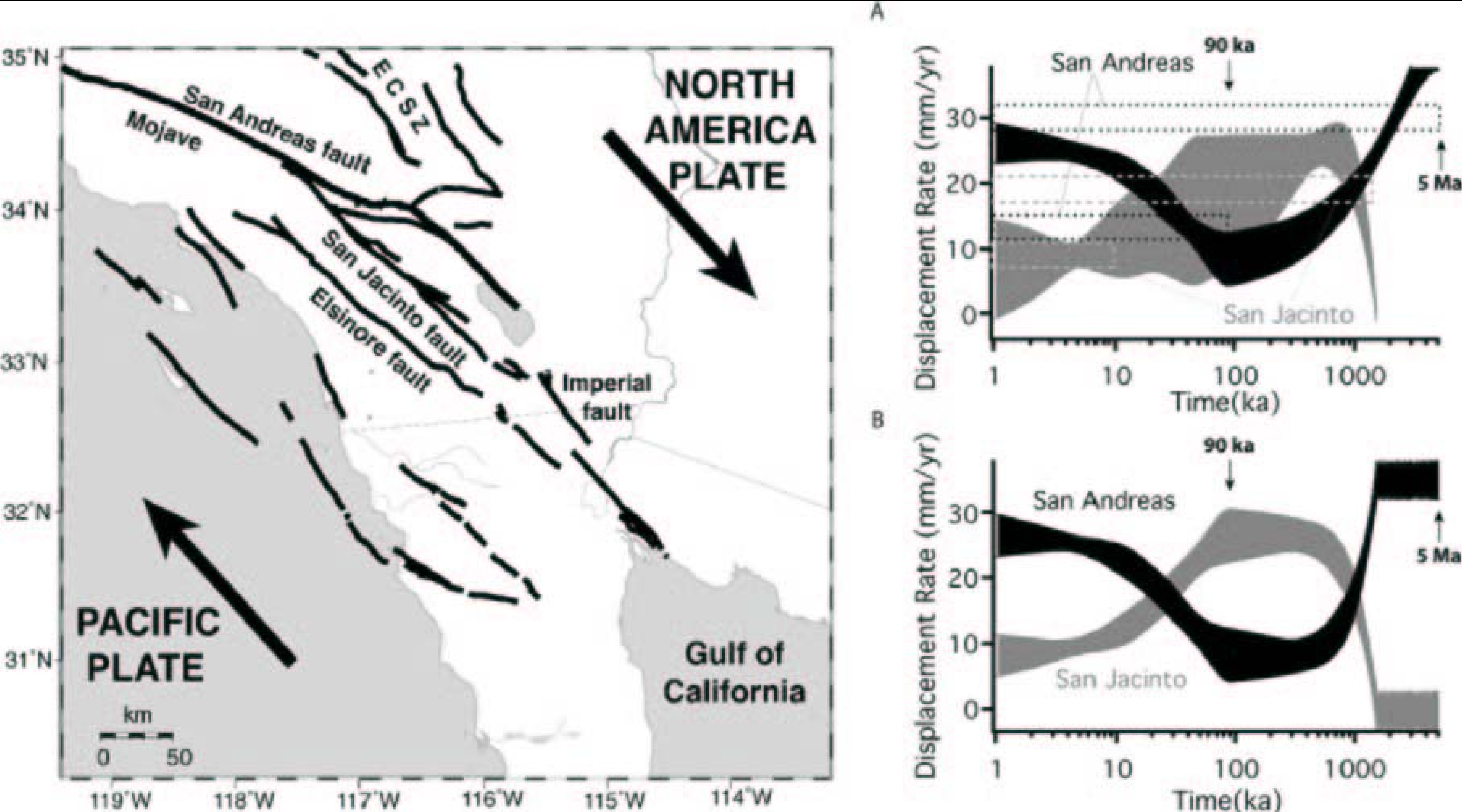
Parametric study of friction coefficients

$\phi_{SAF, Maa, BS}$	V_{SAF}	V_{Maa}	V_{BS}	$V_{off\text{-}faults}$ (%)
3, 3, 3	28.8	6.2	3.3	1.7
4, 3, 3	18.1	10.8	9.3	2.0

Slip rate very sensitive to friction

A small friction variation (~ 5 MPa) induces
a dramatic slip rate change (10 mm/yr)
(only true if 2 or more faults)

Effective friction variation : possible explanation for fault slip rate variation



Bennett et al, 2004

Conclusion from long term (10 Myrs) and short term (0.1 Myr) modeling

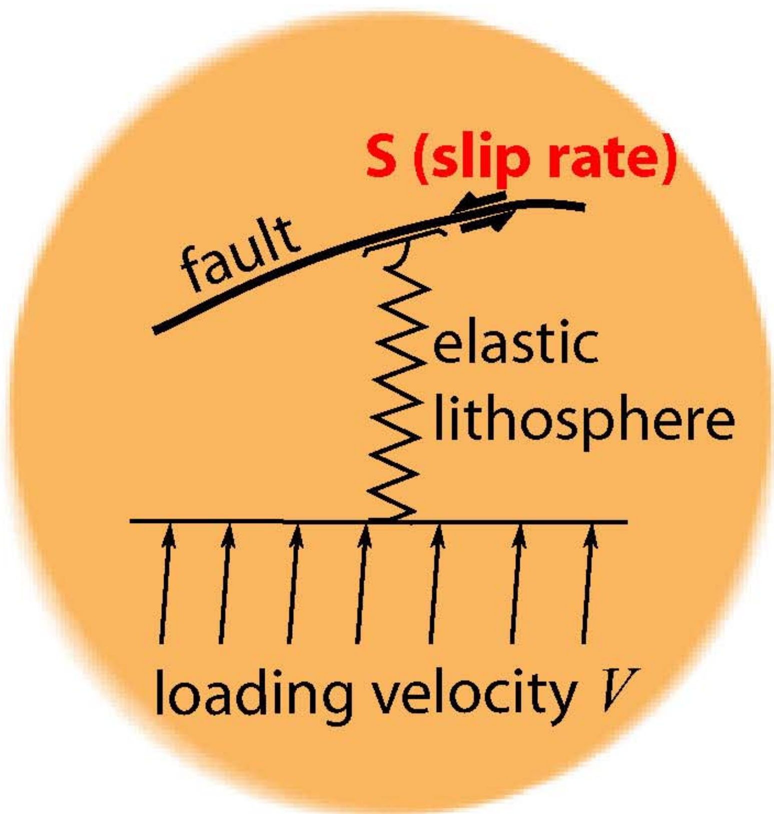
1) Experimentally controlled crust and mantle rheology + weak fault rheology + BC explain slip rate on major faults. Q : why faults are weak ?

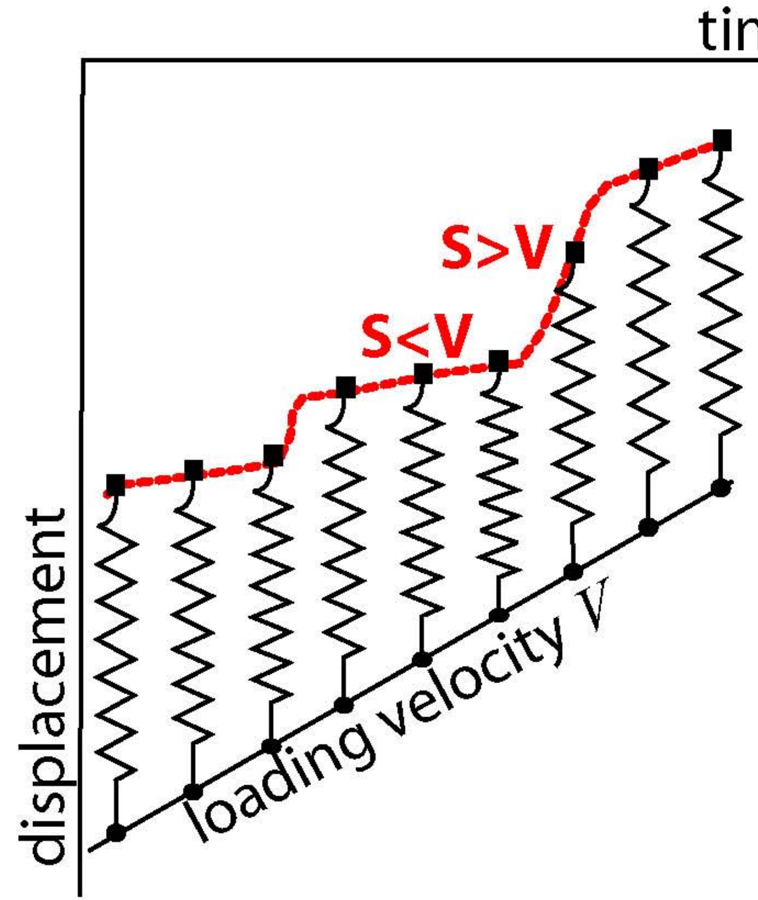
2) Fault slip rate variation (SJ vs. SAF) can be explained with effective friction variation

3) Elasticity (although included) does not matter too much for 1) and 2)

4) However, fault slip rate cannot exceed velocity boundary conditions (Wrightwood ?)

Wrightwood-type behavior (also exist along Dead Sea) requires 1) crustal elasticity 2) remote BC 3) variable friction





Chery et Vernant, EPSL 2006

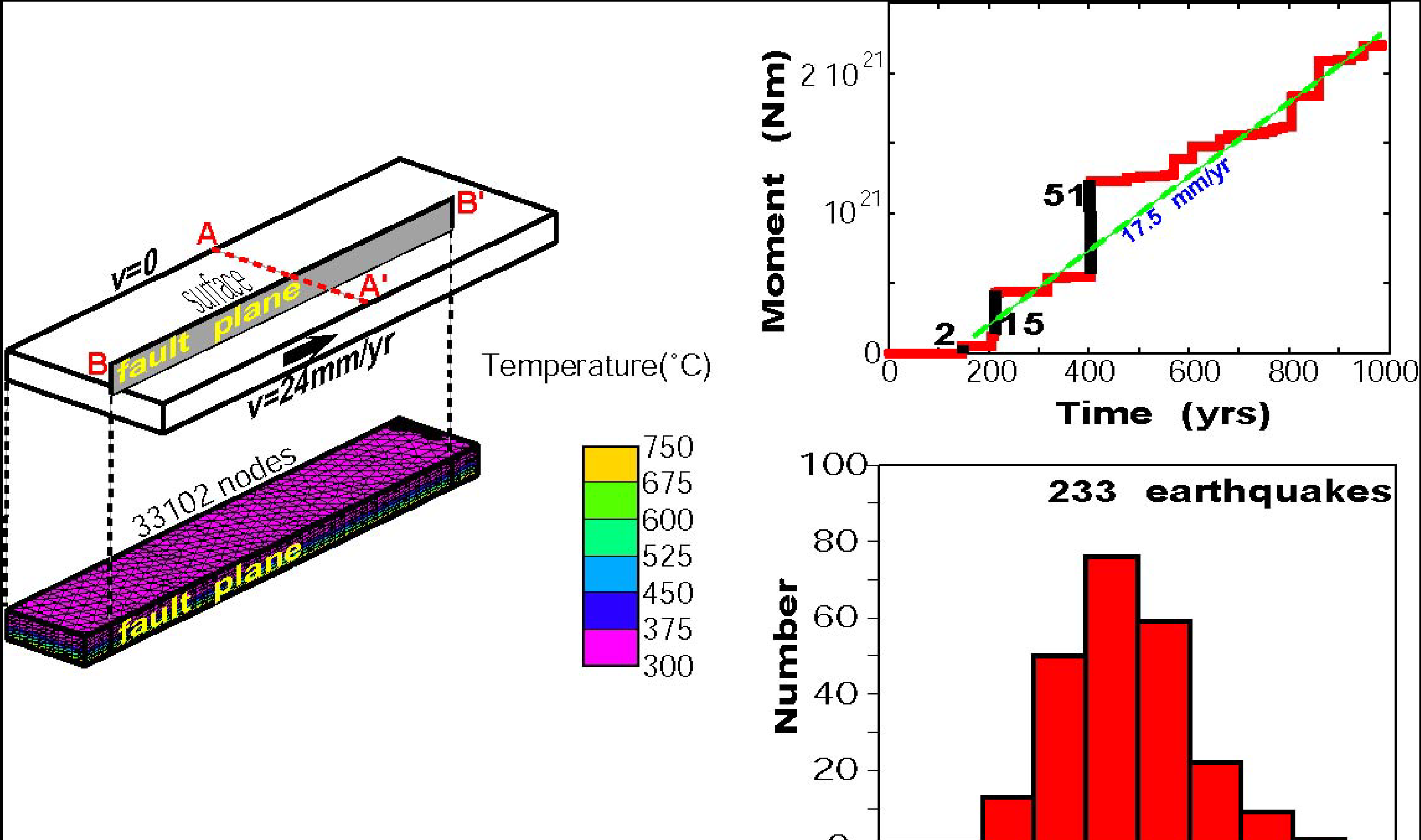
From short term (0.1 kyr) to seismic cycle Modeling : a generic attempt (QS)

Two-layer viscoelastic model
+ variable coulomb friction
+ remote and constant velocity BC

Coseismic phase : $\mu_s \rightarrow \mu_d$
when yield stress is reached on a fault point

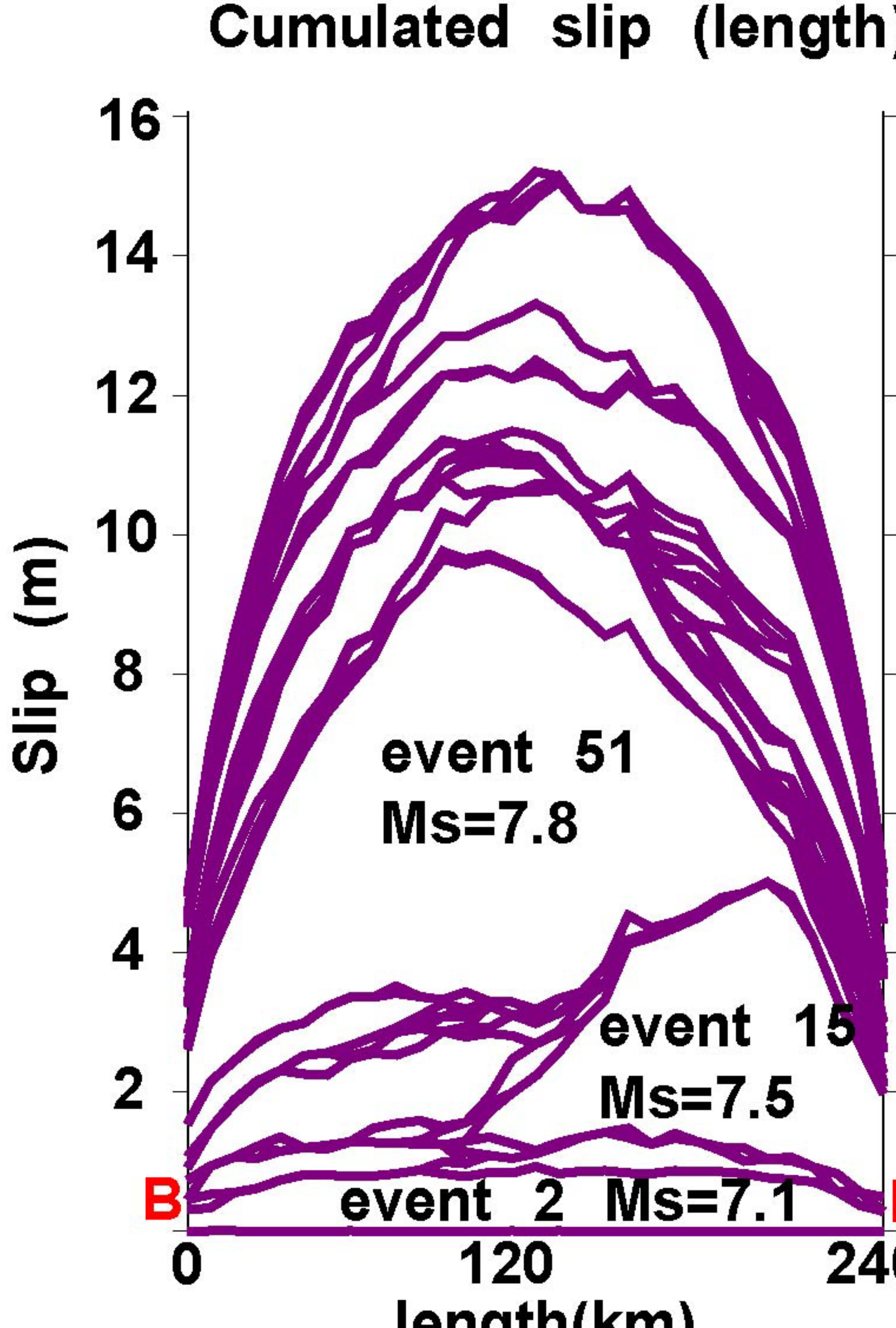
Interseismic phase : μ_s
when yield stress is not reached

Example of generic EQ's model : Viscoelastic crust + static-dynamic friction + BC

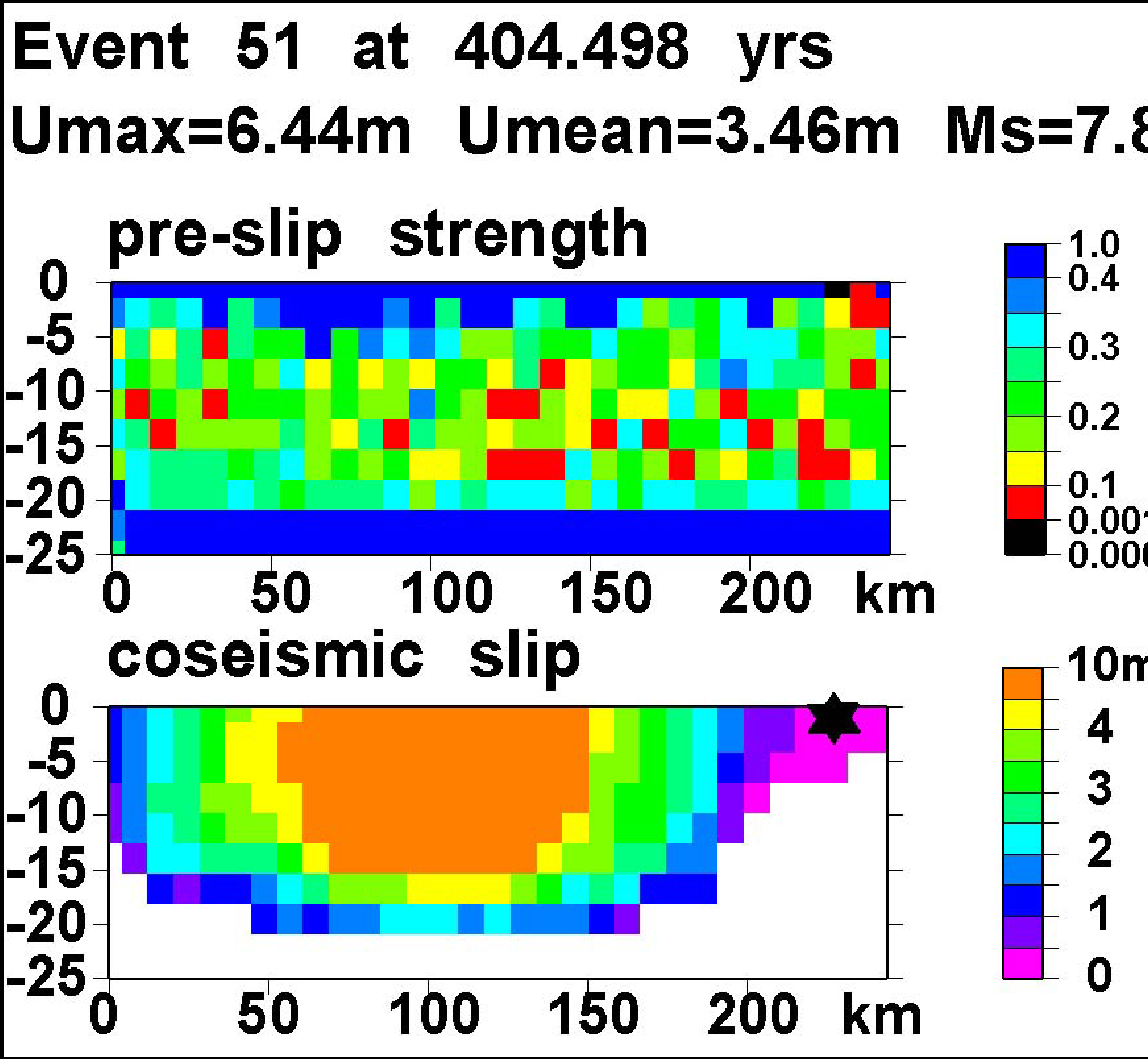


Chery et Provost, unpublished

Successive slip events :



Pre-stress and slip for EQ 51



Generic EQ cycle model : an endless quest ?

+ reproduce natural EQ sequences

- which friction law ?
- sensitive to mesh design
- sensitive to initial conditions
- adaptative time stepping with dynamic relaxation method

Interseismic strain modeling (1 yr-100 yrs)

GPS/InSAR data : a dense data set
(California, Japan, …)

Q : what interseismic geodetic strain tells us about
long term slip rate ?

A : The answer is model dependent…

Elastic half-space provides slip rate but assumes

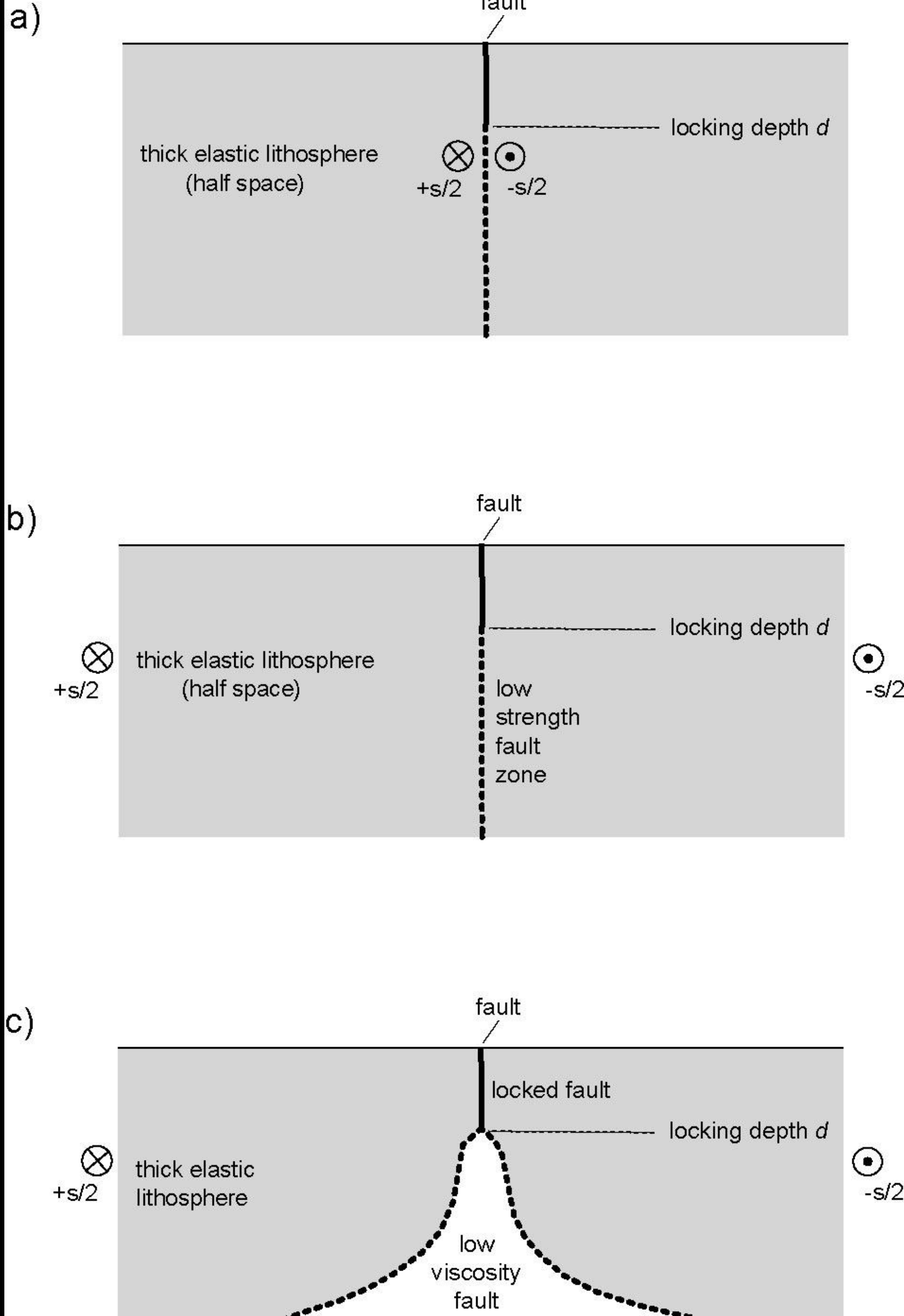
1) local drive

2) irrealistic rheology

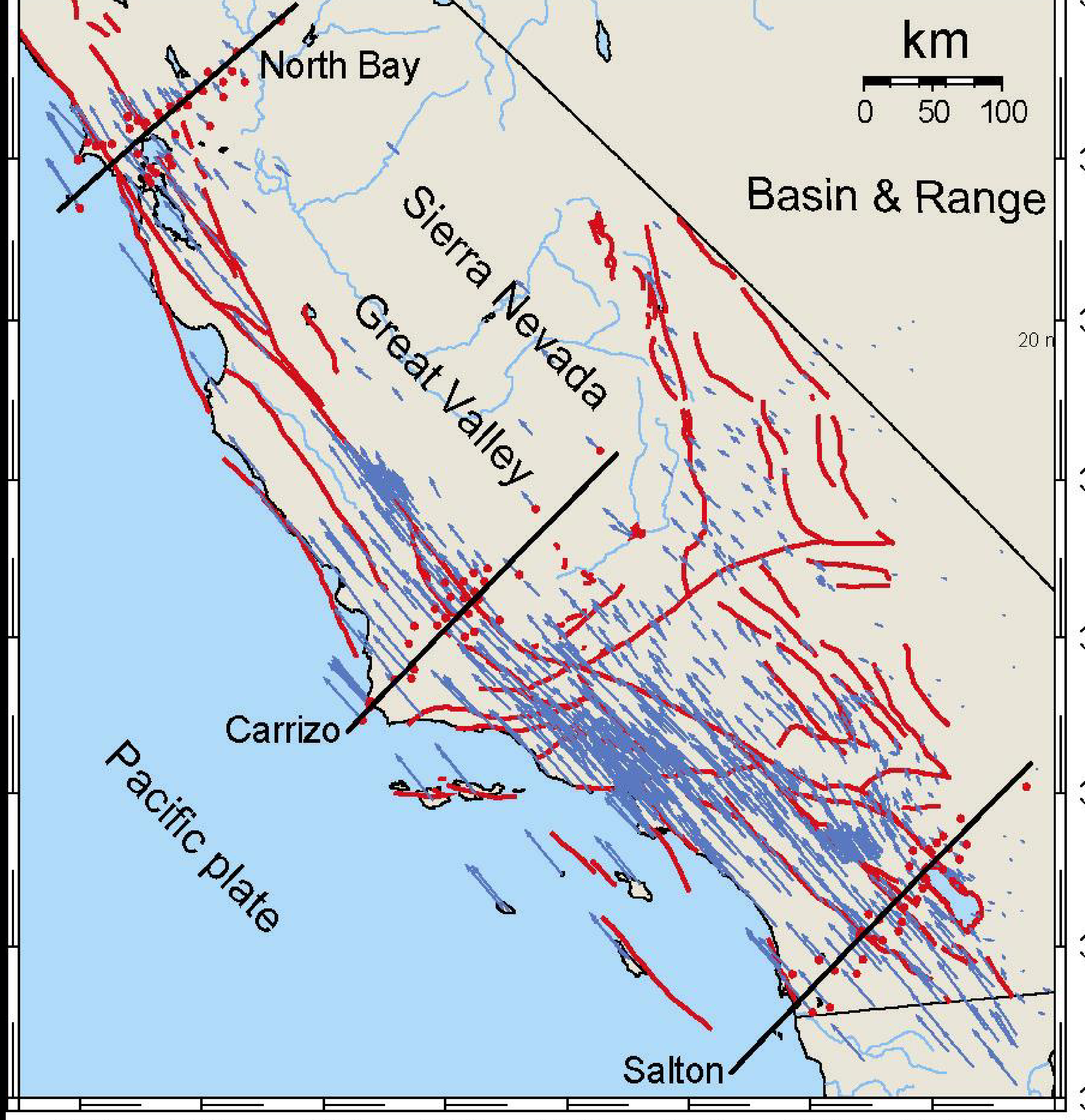
3) time extrapolation

(same for the block model)

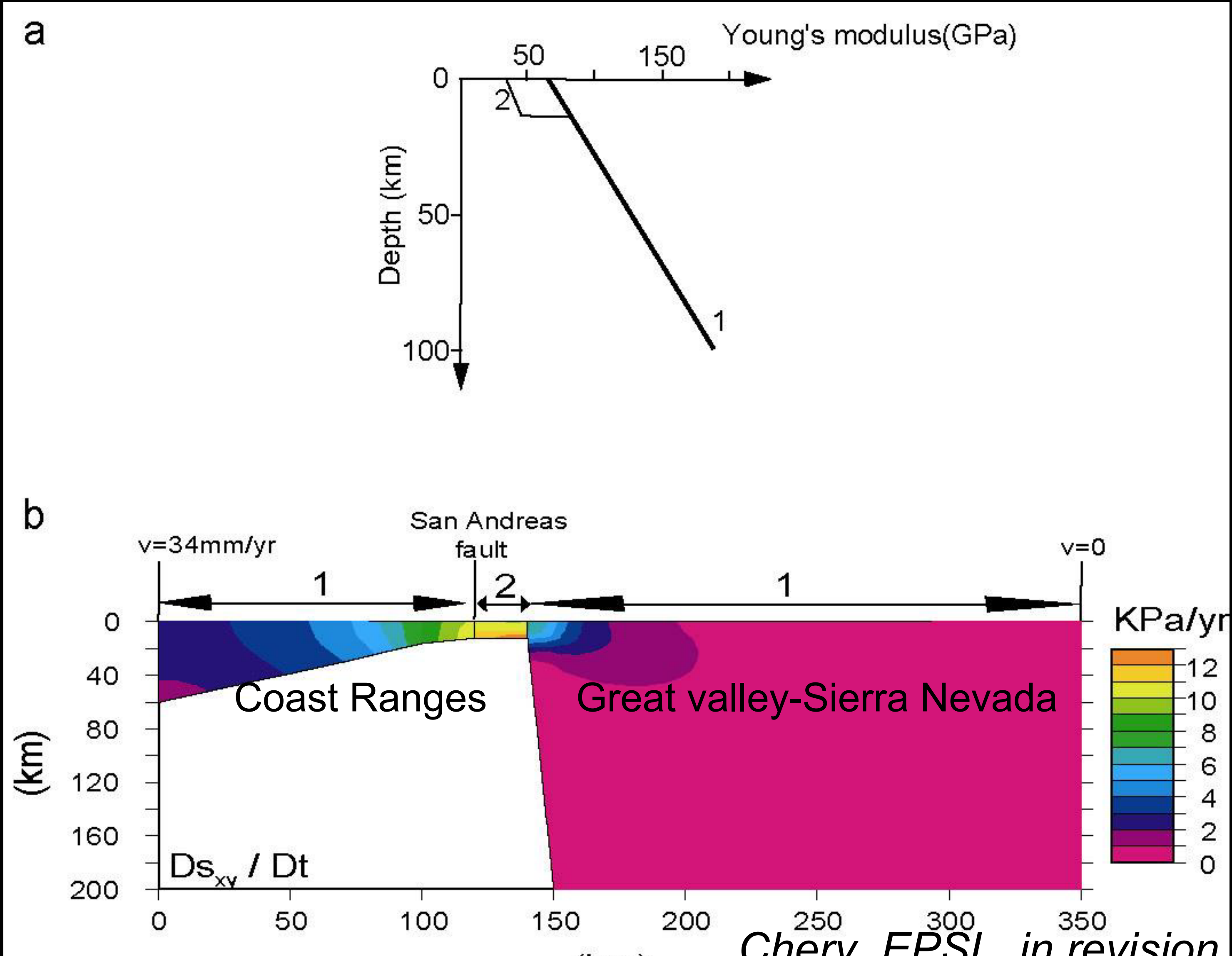
Remotely driven elastic plate is rheologically more consistant. It provides stress rate but not slip rate if more than 1 fault



CMM3
on
Carrizo

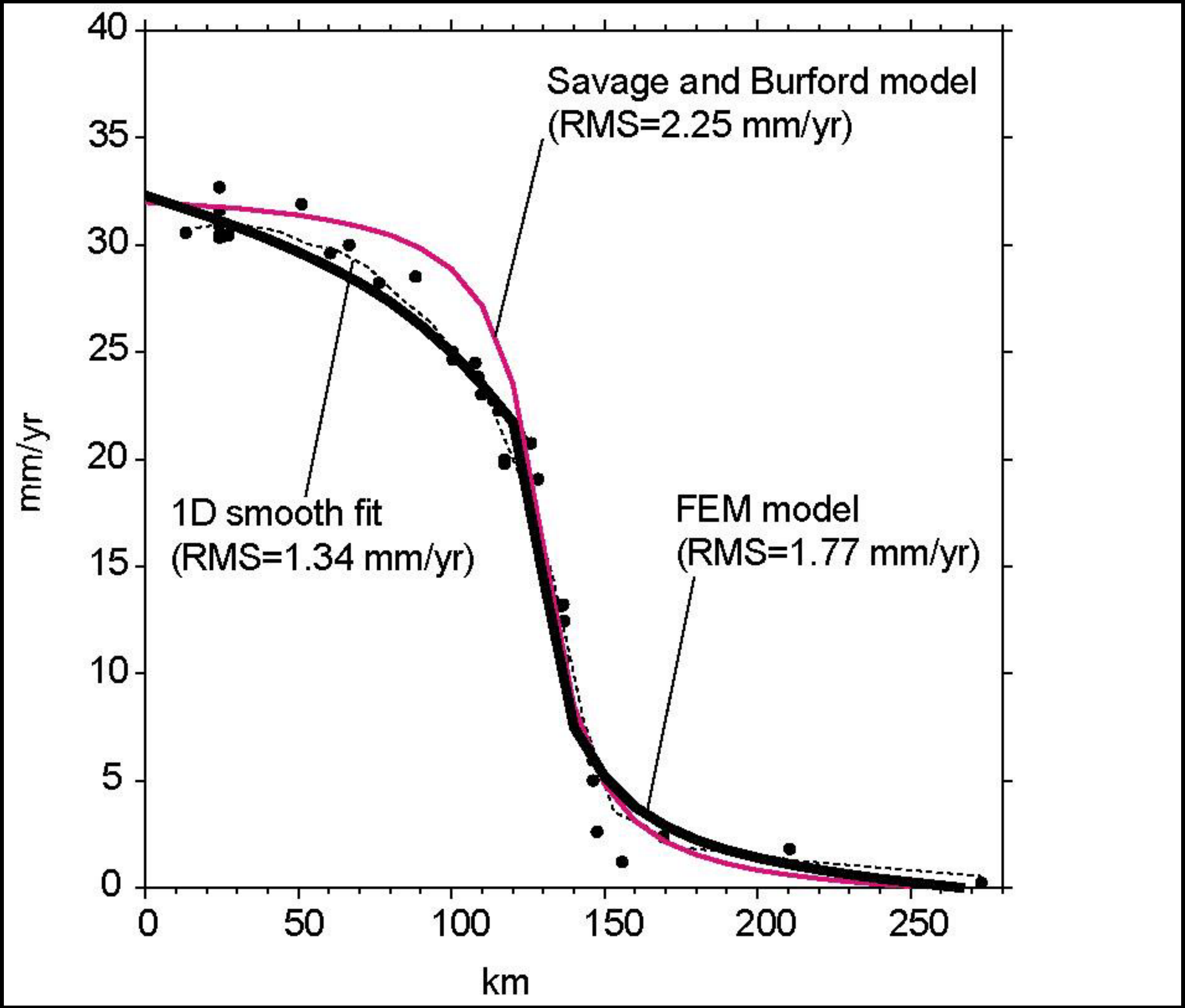


3D Finite Element Model of interseismic strain accross the SAF (Carrizo profile)



Chery, EPSL, in revision

Carrizo data fit : smoothed velocity, elastic dislocation and FEM model



Suggestions for future fault modeling

How to organize time scales, models, and data to provide an 3D integrated master EQ model ?

Time scales : coseismic, interseismic, postseismic, holocene

Model : a thermally controlled elasto-visco-plastic model with frictional interfaces

Data : heat flow, hypocenters, Vp-Vs, stress orientation, Moho depth, paleoearthquakes, geodetic velocity

How to organize time scales, models, and data to provide an 3D integrated master EQ model ?

Follow the strategy of meteorological forecasting :

- Acknowledge that long term prediction is impossible because of deterministic chaos (Lorenz, 1963)

- Concentrate on short term prediction (tomorrow's weather)

- Use false predictions to correct and improve the model (K. Popper)

- Use true predictions to get more money

Tentative strategy to compute time and location of the next EQ (not size)

Step 1 : use geophysical data (Moho depth, topography, fault trace, heat flow, seismology) to setup model geometry, temperature, lithostatic stress

Step 2 : run the model (velocity BC) in a locked fault mode (high friction) to check consistency with interseismic strain → interseismic stress rate

Step 3 : adjust effective fault friction μ_{eff} on fault segment to match holocene slip rate s and stress field

Step 4 ??? : Use past EQ's to correct stress field with respect to max. fault stress → $\sigma_{max} - \Delta\sigma$ (initial conditions)

Step 5 : run the model in the locked fault mode until reaching σ_{max} somewhere → T, lat, long