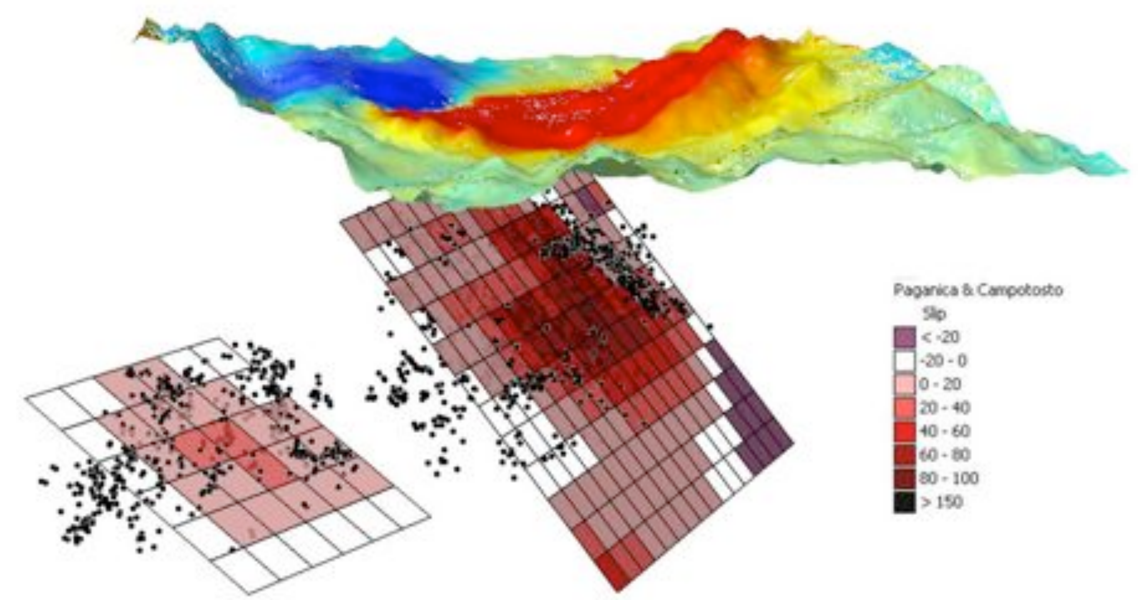
INGV



The M_w 6.3 April 2009 L'Aquila earthquake

Massimo Cocco INGV Rome

TRANSIENT SLIP VELOCITY: FROM SLOW PROCESSES TO EARTHQUAKE DYNAMICS

The First EarthScope Institute on the Spectrum of Fault Slip Behaviors
October 11-14, 2010, Portland, Oregon

MODE OF SLIP

- Natural faults can relieve the accumulated stress in very different ways, not limited to continuous aseismic sliding and earthquakes (Peng & Gomberg, 2010)
- The mode of slip depends on the intrinsic constitutive processes governing faulting episodes

$$g(\vec{\xi},t,\chi_i)$$

- The physical interpretation of modern observations of slip episodes (tremors, slow slip, earthquakes, afterslip, etc...) requires the understanding of the state of stress and constitutive properties of fault zones as well as the stress evolution caused by tectonic processes and stress perturbations

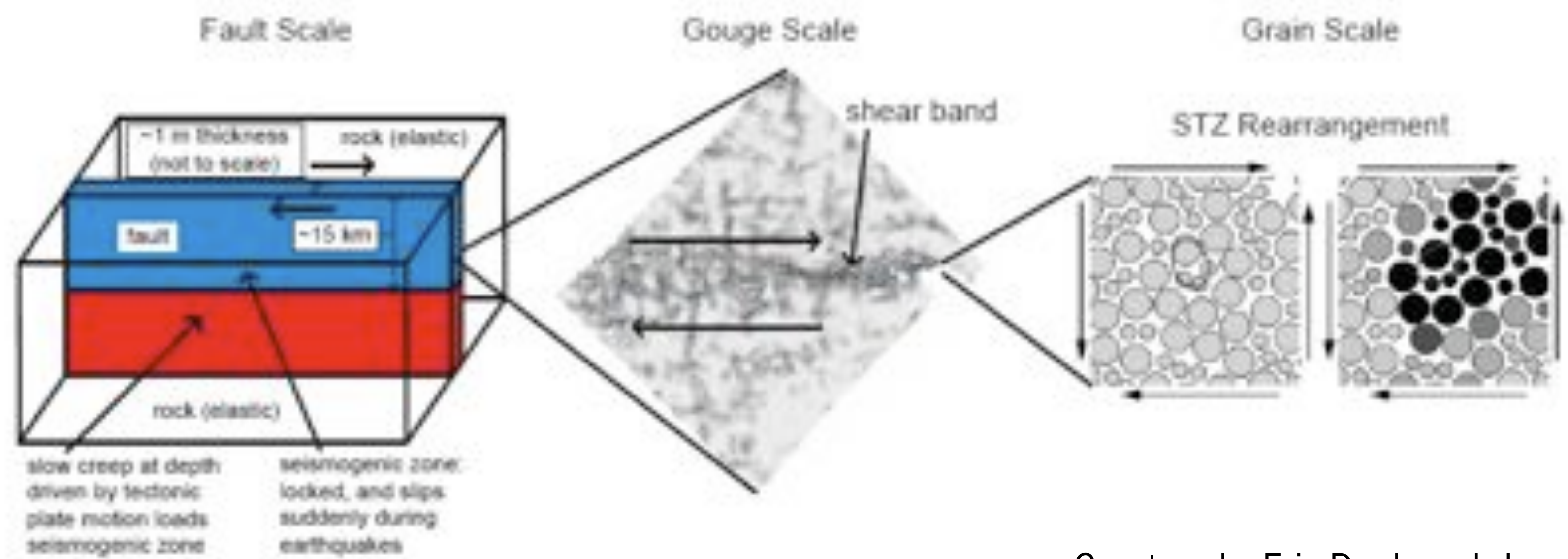
FAULT SYSTEMS

- A key general issue:
  - The need to reconcile geological observations of natural faults and seismological & geodetic data with laboratory tests on experimental faults

geology

seismology

Laboratory



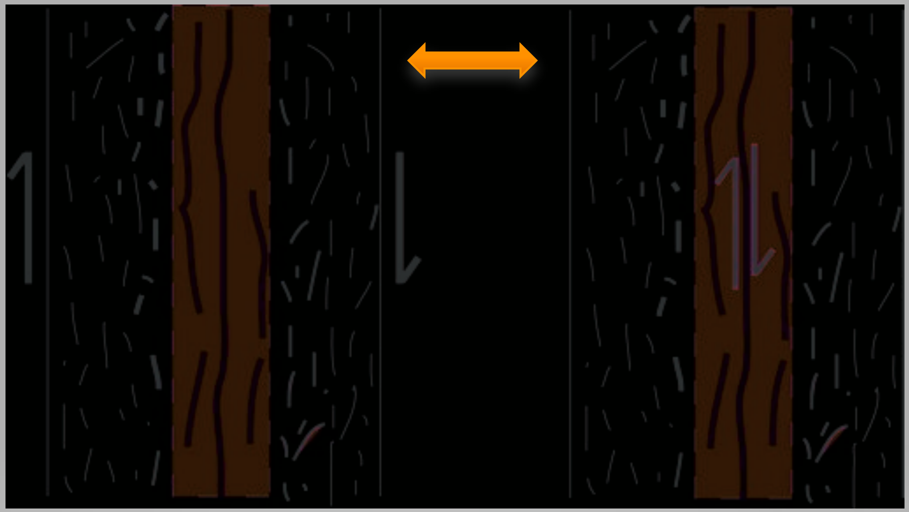
Courtesy by Eric Daub and Jean Carlson

Daub, E. G., and J. M. Carlson, Friction, Fracture, and Earthquakes, Ann. Rev. Cond. Matter Phys. 1, 397-418 (2010).

Geological Observations

- Geological observations reveal that faulting and earthquakes occur in a complex volume, named the fault zone.
- Despite extremely thin, Principal Slipping Zones have a finite thickness

Shear zone where strain is localized. Fluid flow & porosity evolution

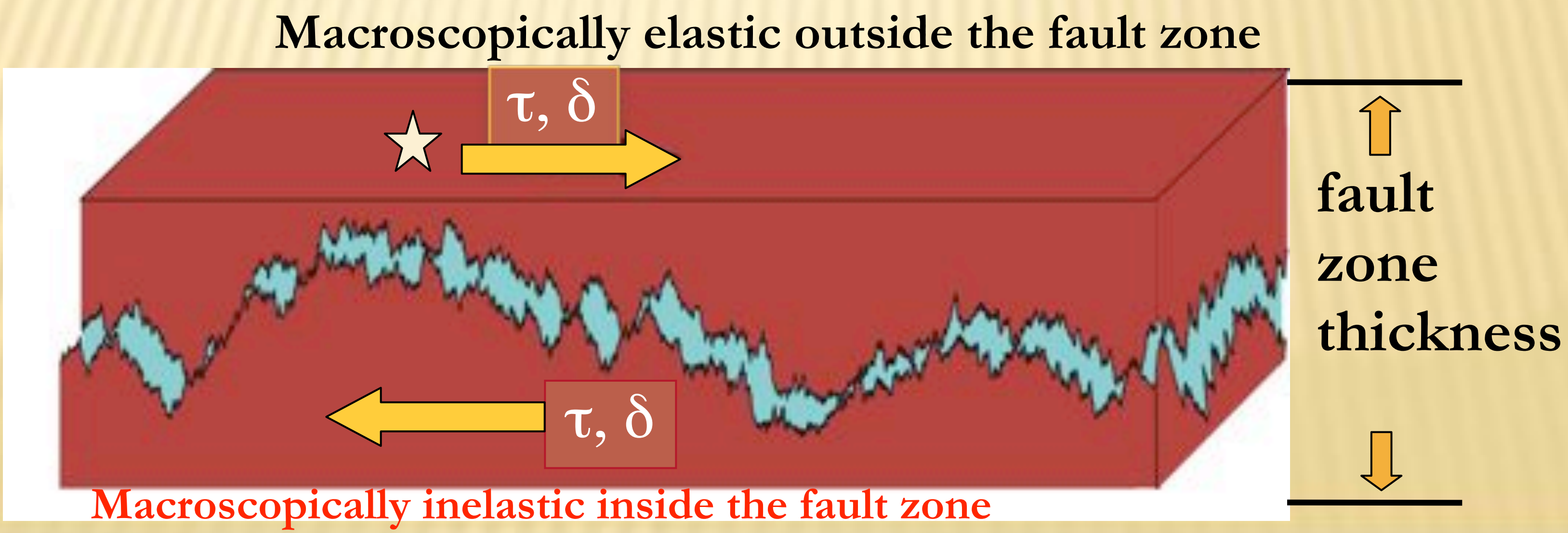


dynamic coseismic slip episodes and other transients

- Damage zone structure is extremely variable
- Fault core properties are poorly known

SELECT A SCALE OF MACROSCOPICITY

- Definition of macroscopic physical quantities (slip, slip-rate, stress,...) on a virtual mathematical plane of zero thickness
- Conscious adoption of a phenomenological description
- Friction should be considered in a macroscopic sense
- Shear traction (i.e., stress) is friction
- Macroscopic frictional work contains all the mechanical energy absorbed within the fault zone



A PHENOMENOLOGICAL CONTACT LAW

- In this framework a constitutive law is a phenomenological contact law

$$\tau = \mu\,(u, v, \Psi_i, T, \Phi, \lambda_c, h, \omega, C_e)\,\sigma_n^{eff}(\sigma_n, p_{fluid})$$

- It should contain a memory of previous slip episodes, as the R&S evolution law $\frac{d\Psi_i}{dt} = f\left(\Psi_i, u, V, \Phi, \chi_i\right)$

- It should explicitly contain length and/or time scale parameters

- We can use Rate & State Friction with this meaning

SPRING SLIDER SIMULATIONS

- Boatwrigth & Cocco JGR 1996

$$\tau = \tau_* + \vartheta + A \ln\left(\frac{V}{V_*}\right)$$

$$\dot{\vartheta} = -\frac{V}{L}\left[\vartheta + B \ln\left(\frac{V}{V_*}\right)\right]$$

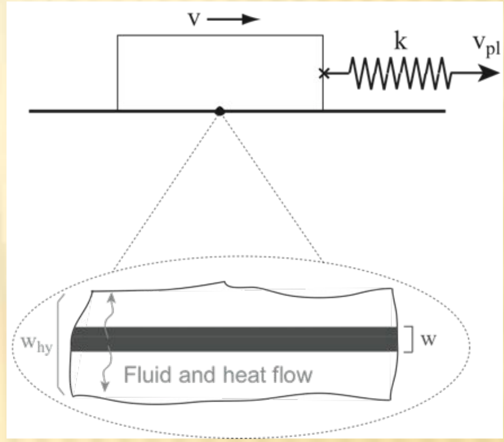


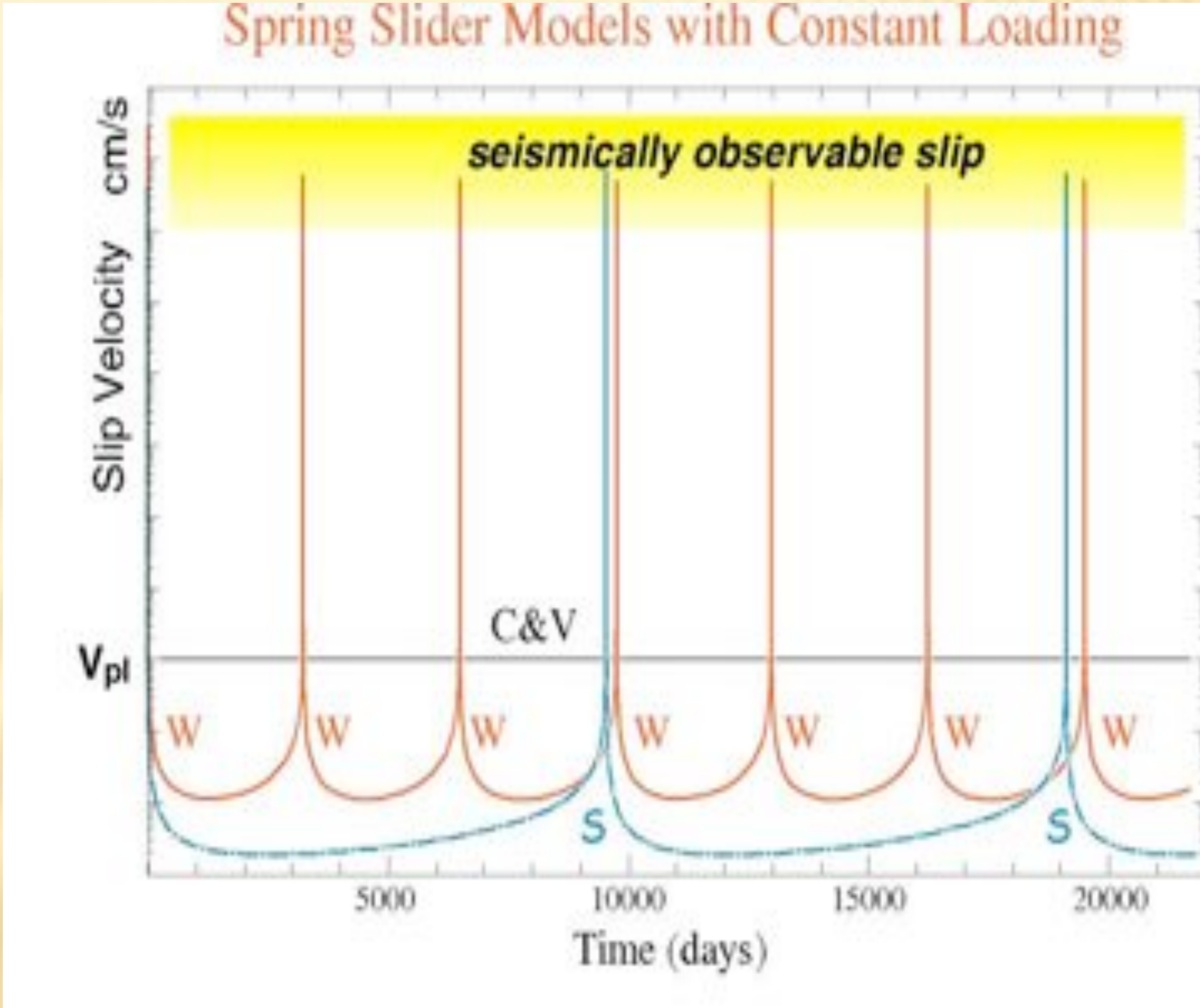
Table 1. Frictional behaviors proposed by Boatwright and Cocco (1996). $A = a\sigma_n^{eff}$ and $B = b\sigma_n^{eff}$.

Regime	Description	A and B	Seismicity	Strain Release
Velocity Weakening (VW)	Strong Seismic (S-VW)	$B >> A$	Main shocks and some aftershocks	Episodic dynamic slip
	Weak Seismic (W-VW)	$B - A > 0$ $B - A \leq 0.05$ MPa	Interseismic, foreshocks, main shocks and aftershocks	Creep and intermittent dynamic slip
Velocity Strengthening (VS)	Compliant (aseismic)	$B - A > 0$ $B - A \leq 0.1$ MPa	Some aftershocks	Creep and forced dynamic
	Viscous (aseismic)	$A >> B$	None	Stable sliding

FRICTIONAL CONSTRAINTS TO FAULTING

FRICTIONAL CONSTRAINTS TO FAULTING

Spring slider simulations under a constant tectonic loading
A=0.5 MPa, L=1 mm
k=5.0 MPa/m
V_o = 32 mm/y

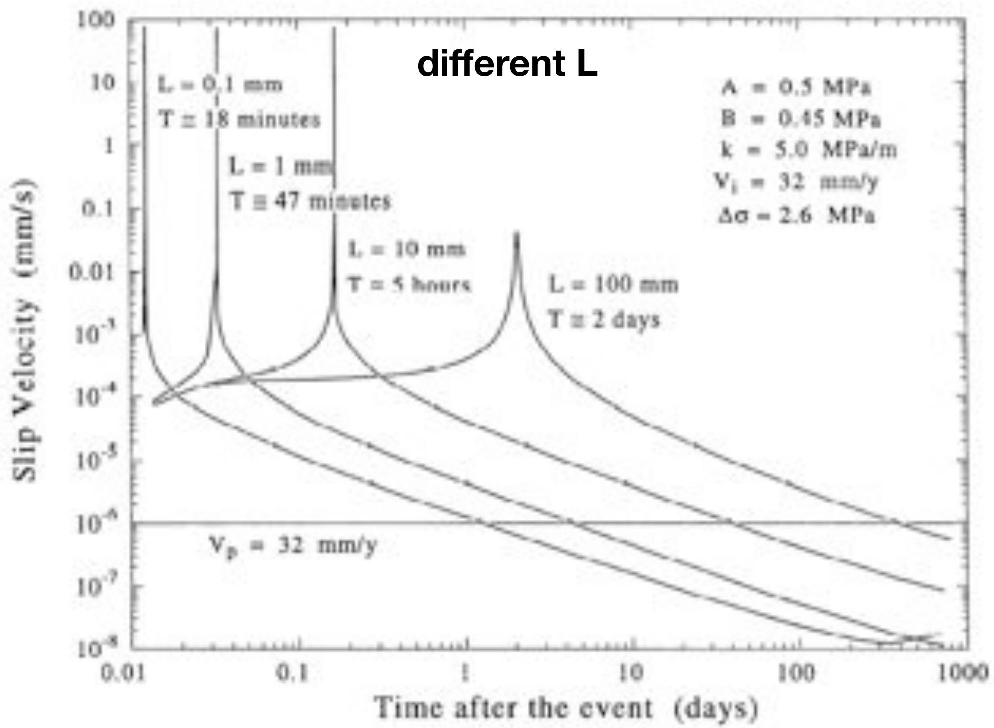


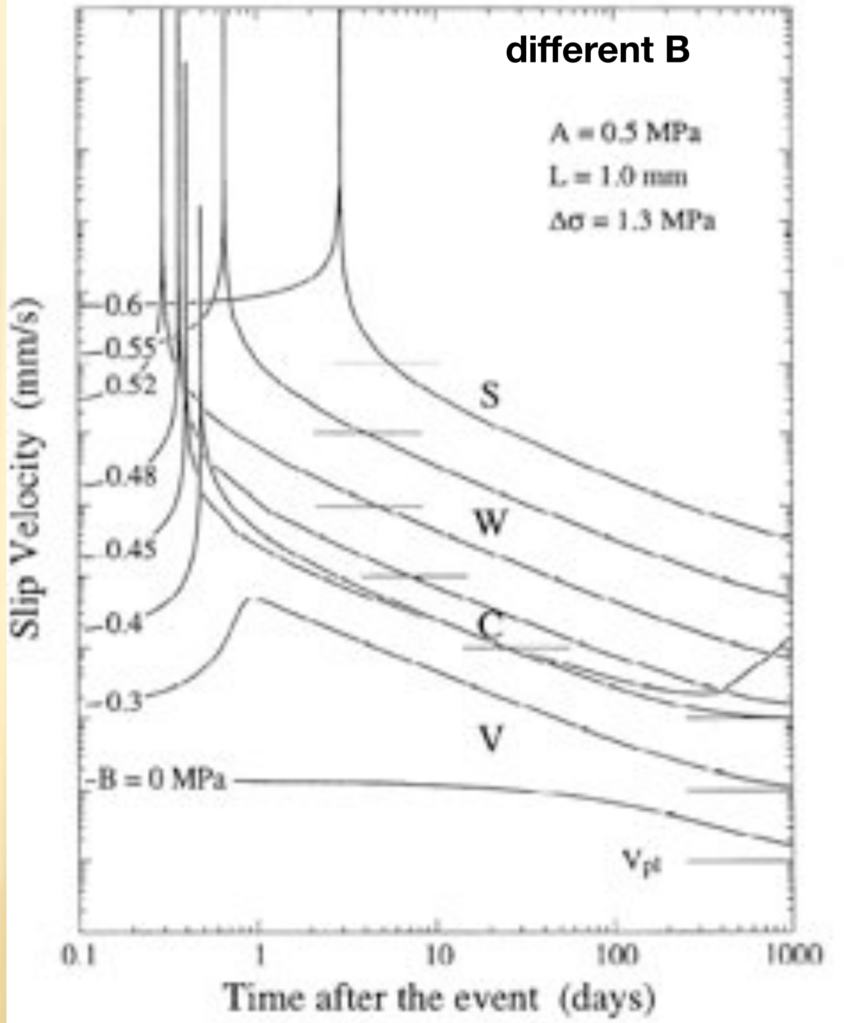
FRICTIONAL CONSTRAINTS TO FAULTING

FRICTIONAL CONSTRAINTS TO FAULTING

Spring slider simulations under an abrupt applied load

BOATWRIGHT AND COCCO: FRICTIONAL CONSTRAINTS ON FAULTING



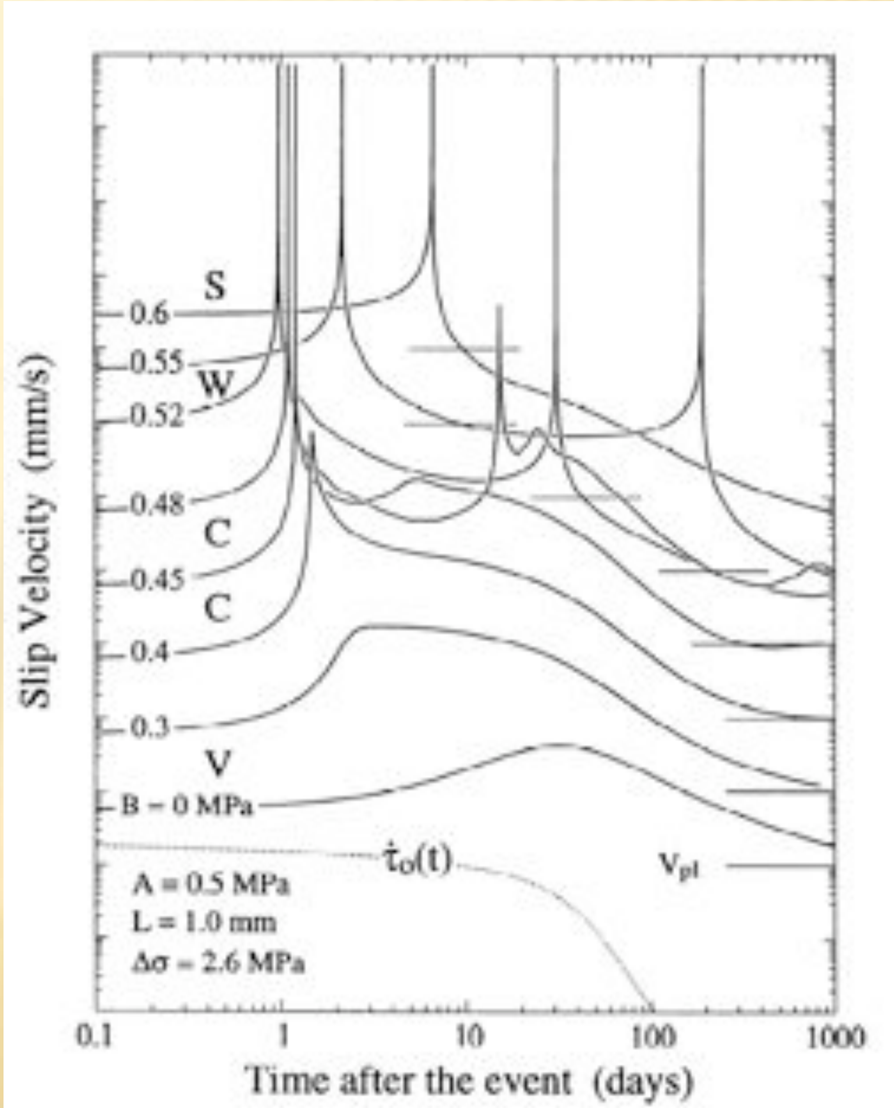


FRICTIONAL CONSTRAINTS TO FAULTING

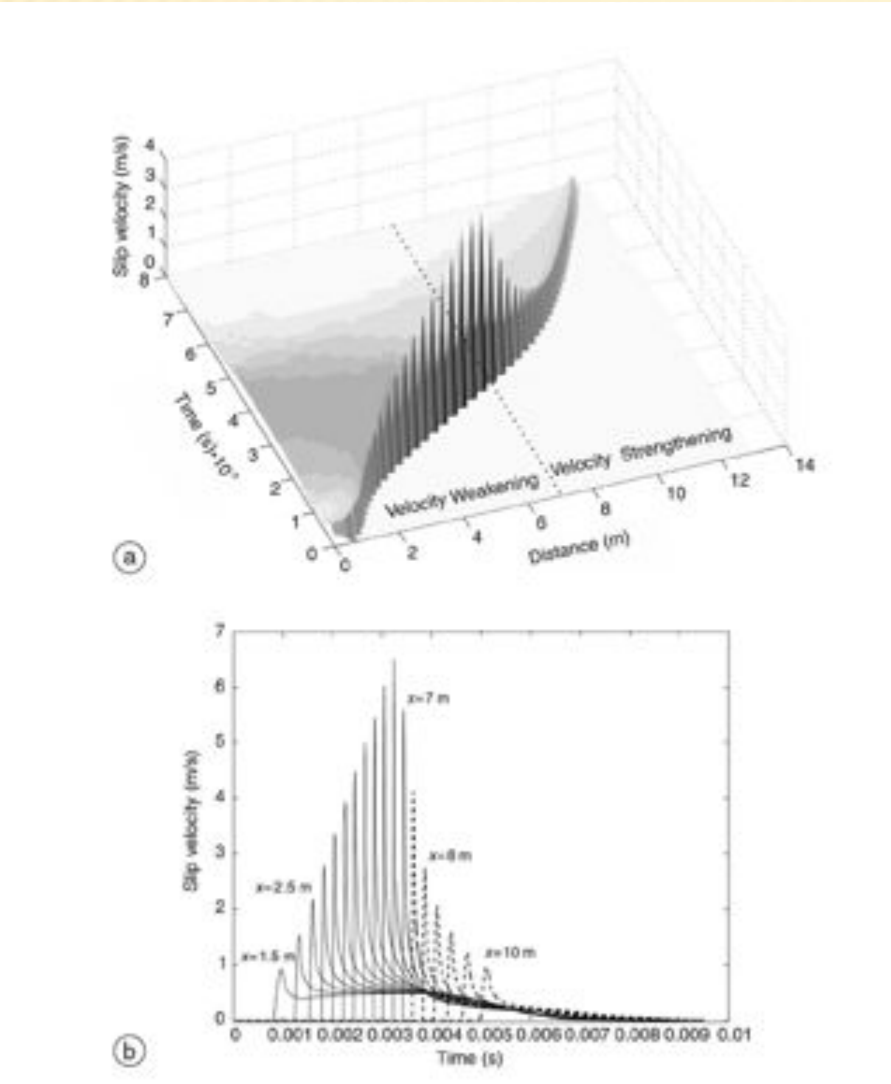
FRICTIONAL CONSTRAINTS TO FAULTING

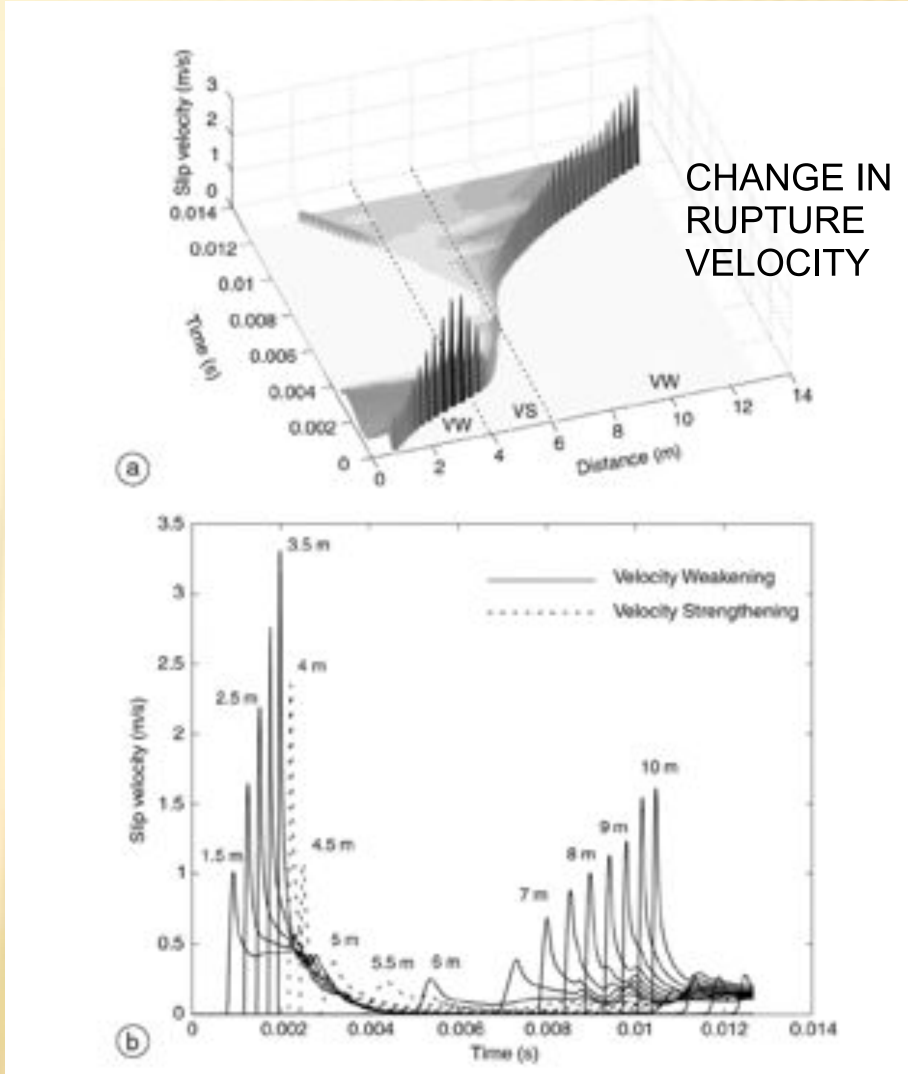
Spring slider response under
an abrupt and continued loading
(30 days)

This confirms that we have many different sliding behaviours determined by the local frictional properties



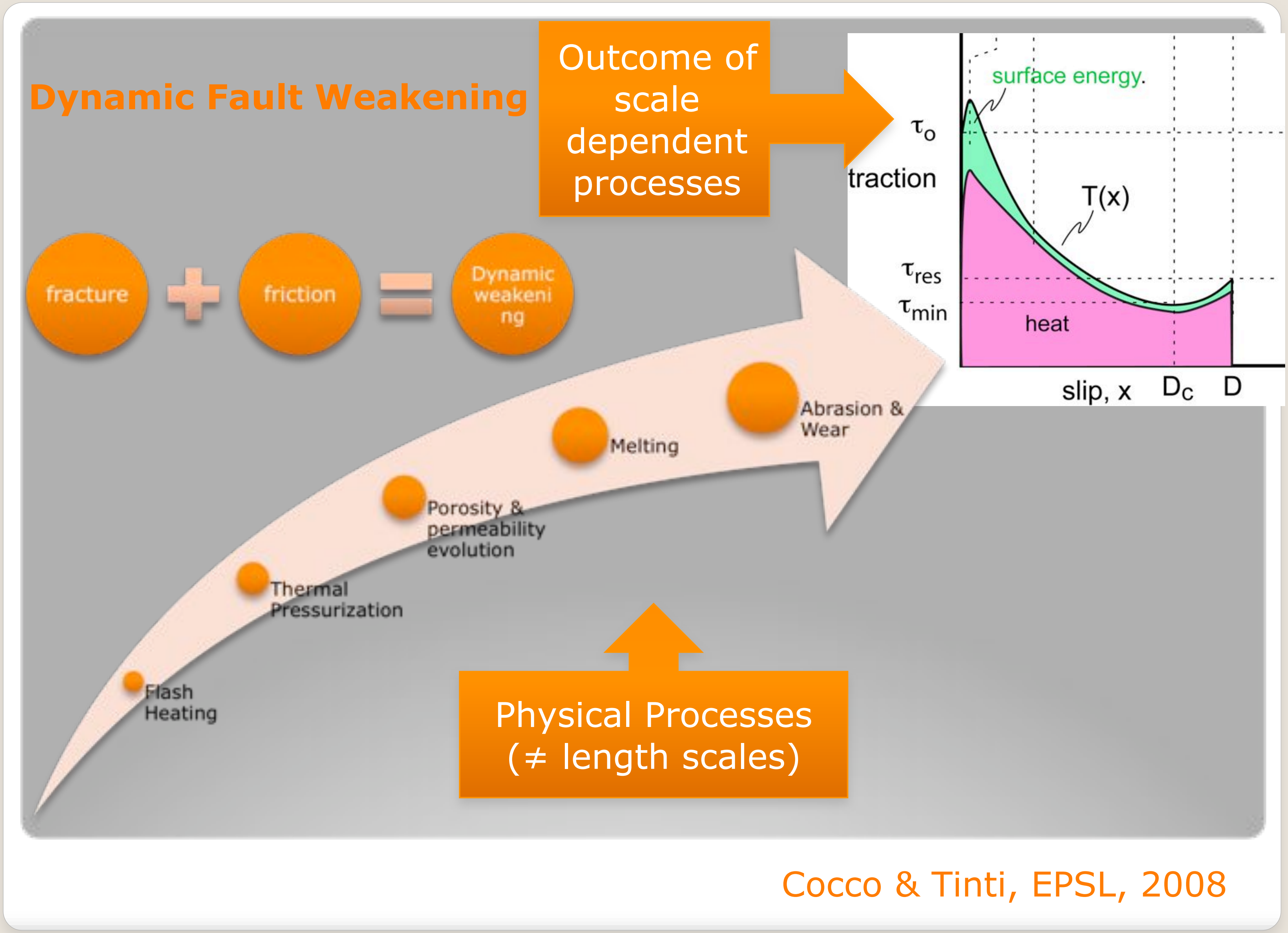
RUPTURE PROPAGATION ON A HETEROGENEOUS FAULT





Elisa Tinti, Andrea Bizzarri and Massimo Cocco

ANNALS OF GEOPHYSICS, VOL. 48, N. 2, April 2005


Dynamic Fault Weakening
Outcome of scale dependent processes
fracture
friction
Dynamic weakening
Flash Heating
Thermal Pressurization
Porosity & permeability evolution
Melting
Abrasion & Wear
Physical Processes (≠ length scales)
surface energy.
τo
traction
T(x)
τres
τmin
heat
slip, x
Dc
D
Cocco & Tinti, EPSL, 2008

CONSTRAINING DYNAMIC FAULT WEAKENING

This means:

- to infer the stress evolution as a function of time and slip at single points on the fault, to determine maximum slip, peak slip-rate, duration of slip episodes, ...
-
- to image the distribution on the fault plane of the main physical quantities to constrain the slip histories and the local rupture velocity characterizing the spatial propagation

. ... at least for earthquakes

Earthquake models

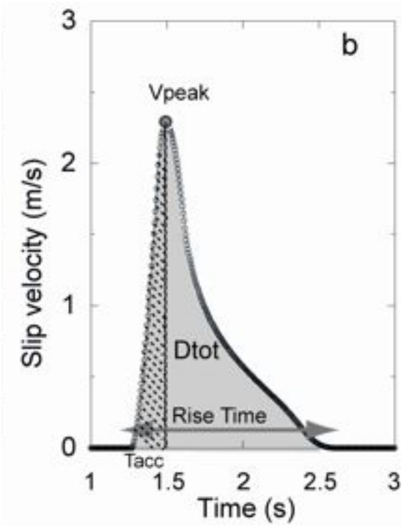
KINEMATIC MODELS ⟷ **DYNAMIC MODELS**

- Slip
- Rupture Time
- Rise Time
- Rake angle
- Source Time Function

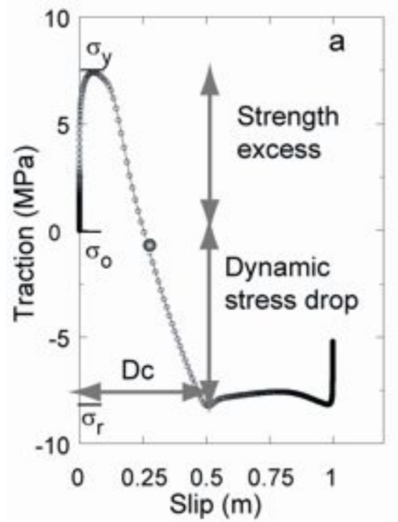
⟷

- Traction Evolution
- Strength Excess
- Dynamic Stress Drop
- Breakdown work
- Dc

Yoffe function



Tinti et al., BSSA 2005



Tinti et al., JGR 2005

IMPORTANCE OF SLIP RATE

By means of slip velocity history we can infer the traction change evolution on the fault plane

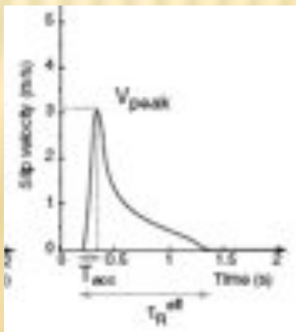
We solve the Elastodynamic equation using the rupture history as a boundary condition on the fault

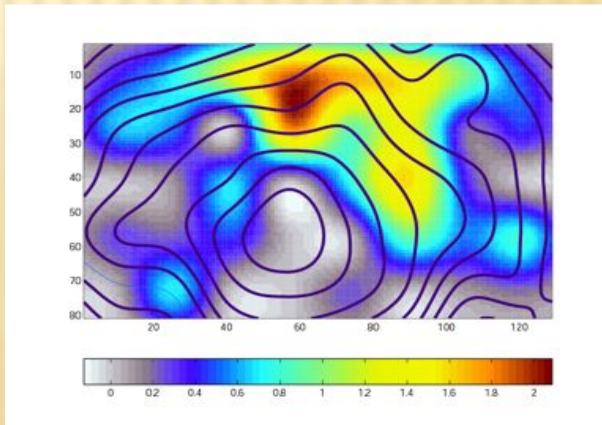
$$\sigma(x,t) = -\frac{\beta}{2\mu}\Delta\dot{u}(x,t) + \iiint \Delta\dot{u}(\xi,\tau)\mathrm{K}(x-\xi,t-\tau)\,d\xi\,d\tau$$

Fukuyama and Madariaga (1998)

$$\Delta\dot{u}(\hat{\mathbf{i}},t) = \dot{f}(t-t_r(\hat{\mathbf{i}}))\times d(\hat{\mathbf{i}})$$

Slip Velocity time history on the fault





example: Slip distribution and rupture time from kinematic inversion

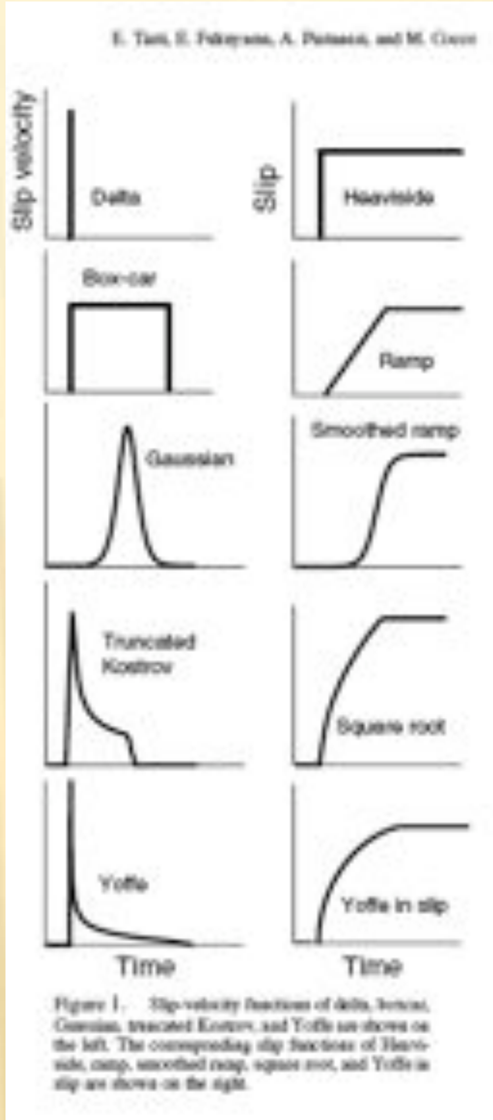
ADOPTED SOURCE TIME FUNCTIONS

Different source time functions are currently adopted in the literature to solve both the forward and the inverse problem and to model recorded waveforms.

If we limit our tasks to fitting observed ground motions and geodetic data, this choice is quite arbitrary and allows the achievement of good modelling results.

However, if the inferred rupture histories are used to constrain or determine dynamic source parameters, this choice can heavily affect the results.

Thus, a key issue in modelling ground motion waveforms to image earthquake ruptures and determine source parameters is the adoption of dynamically consistent source time functions.



A synthetic test: two models computed from spontaneous dynamic calculations

Tinti et al., 2009, GJI

A synthetic test: two models computed from spontaneous dynamic calculations

Model Constant D_c

Model Constant D_c/D_{tot}

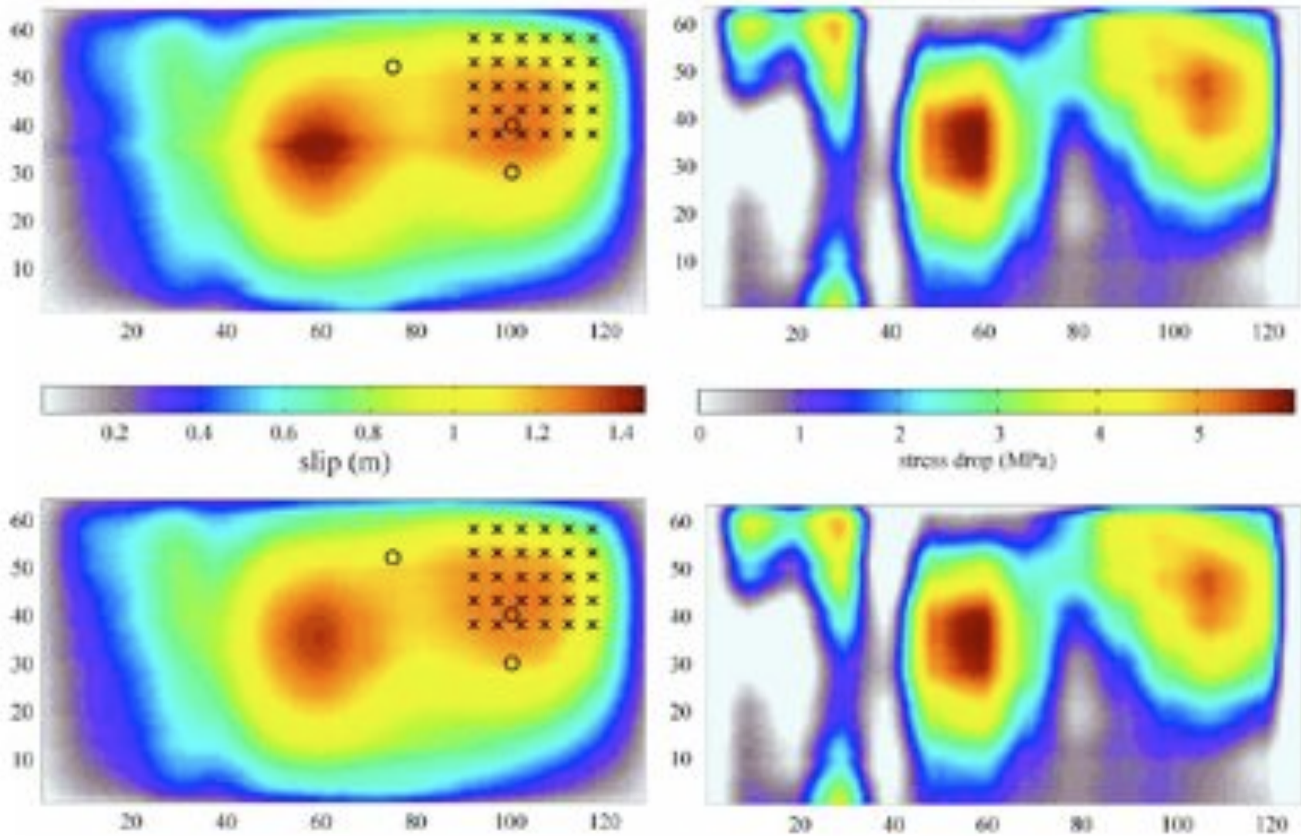


Figure 2: Slip and stress drop distributions on the fault plane for the two target dynamic models (top *Model 2* and bottom *Model 3*).

Tinti et al., 2009, GJI

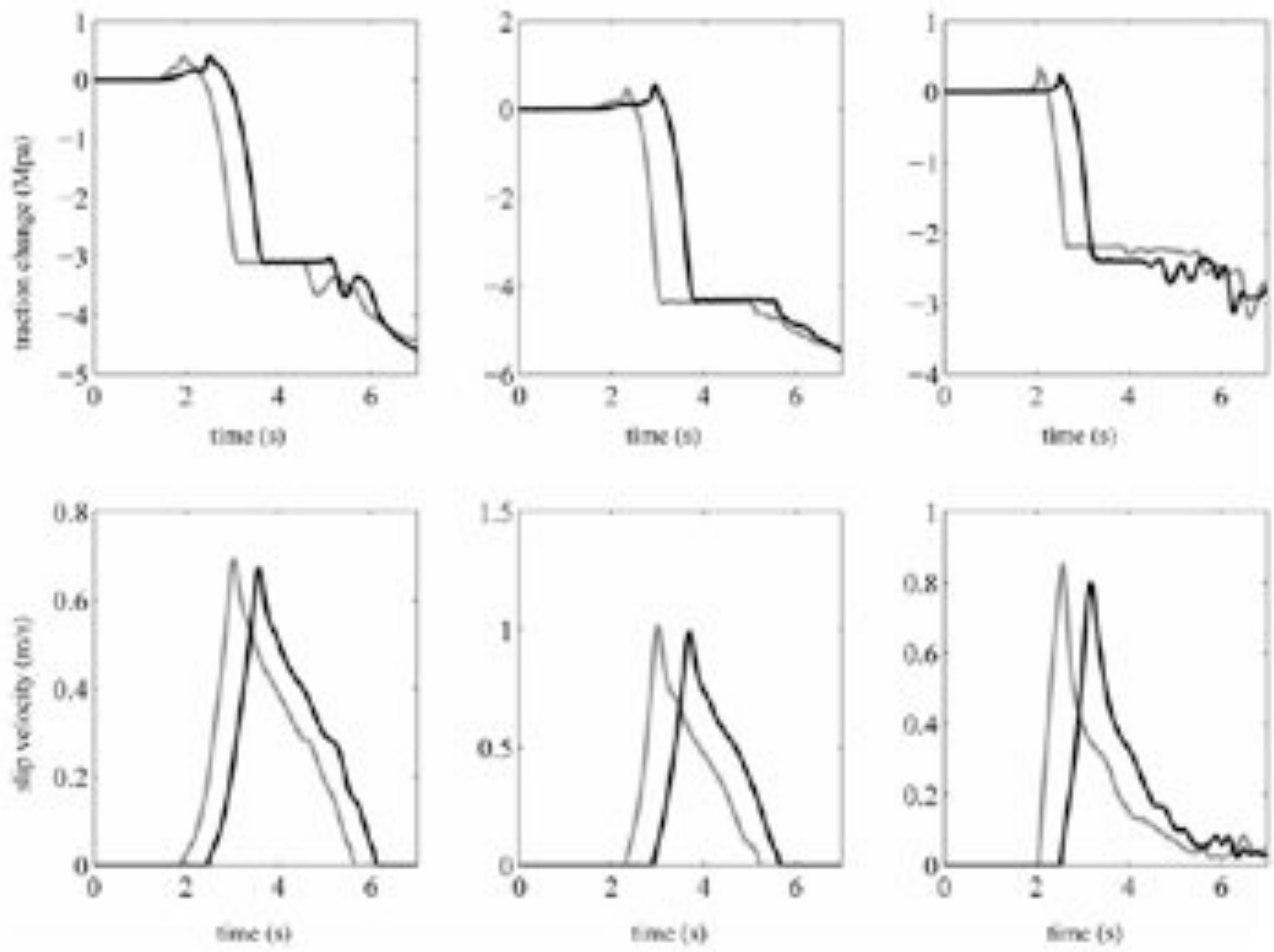
A synthetic test: two models computed from spontaneous dynamic calculations

Tinti et al., 2009, GJI

A synthetic test: two models computed from spontaneous dynamic calculations

Traction

Slip rate



Tinti et al., 2009, GJI

Results of the numerical test: if we know perfectly the STF we can reconstruct the traction evolution

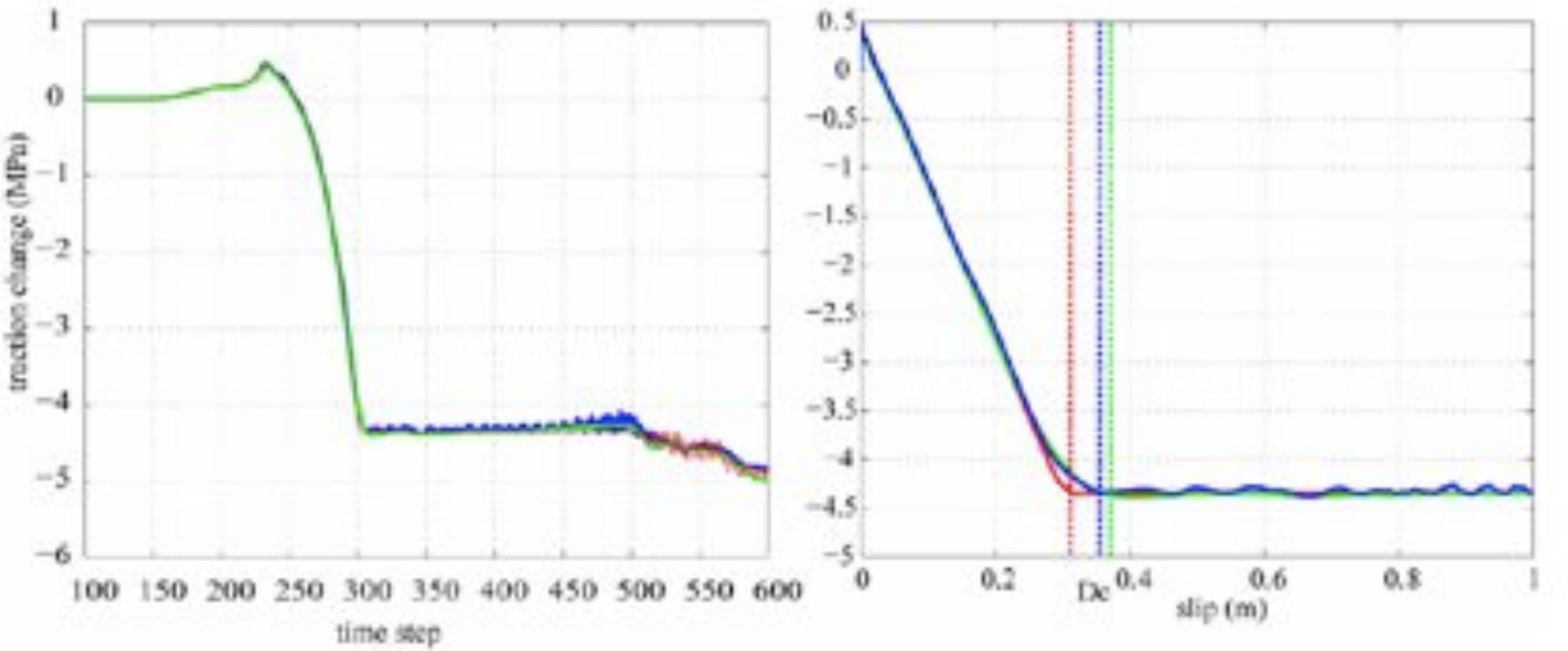


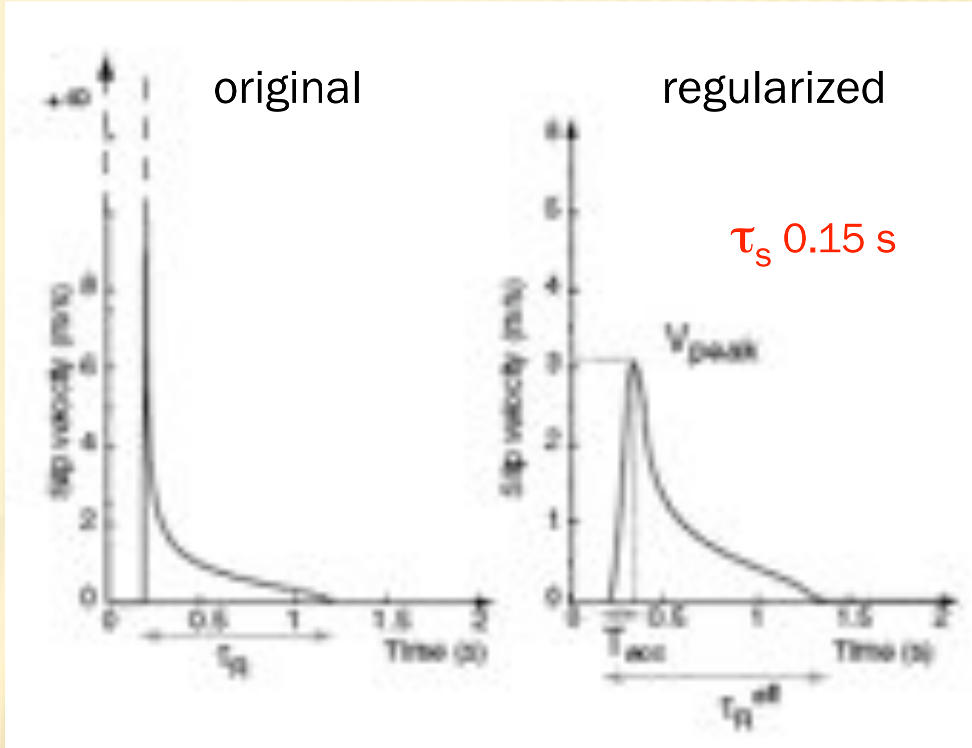
Figure 5: Comparison at a specific point of the traction time histories and traction versus slip curves for: the original dynamic model (red line), the two inferred dynamic tractions (blue and green) using two differently smoothed versions of the original target slip velocity.

Tinti et al., 2009, GJI

THE YOFFE FUNCTION

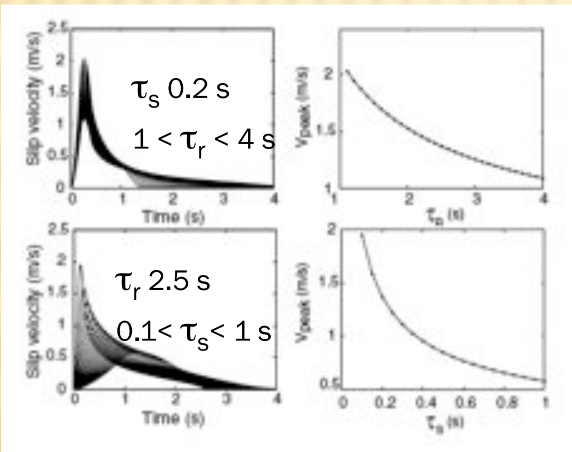
Nielsen & Madariaga (2000)

We have adopted the Yoffe function in our modelling results and we have proposed a regularized version of the original function.



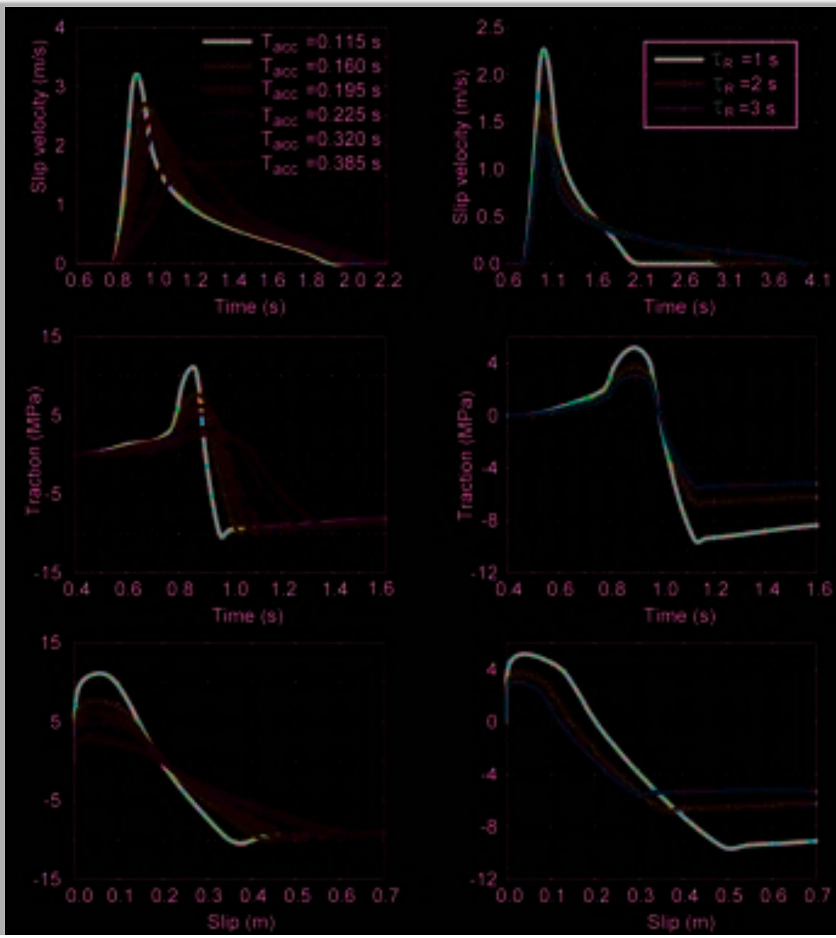
$$\tau_R^{\,eff} = \tau_R + 2\tau_S$$

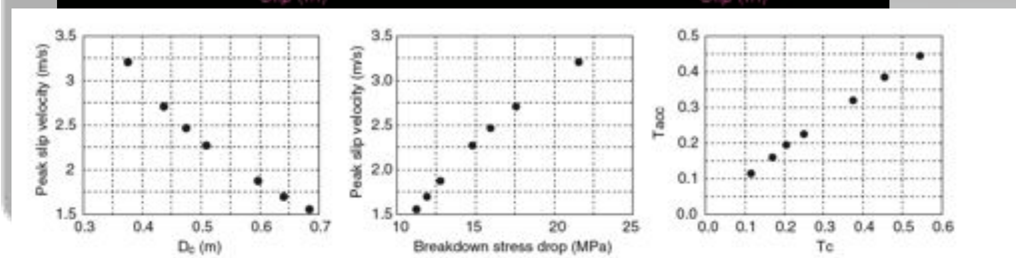
The regularization consists in convolving the original Yoffe function with a triangular function of given duration (τ_s).



$$\mathbf{V}_{\mathbf{peak}} \approx C \frac{D_{\max}}{\sqrt{T_{acc}\,\tau_R}}$$

Tinti e al. BSSA (2005)





Effects of STF on D_c/D_{tot}

D_c estimates depend on T_{acc}.

This means that inverting waveforms with a limited temporal resolution overestimates the real T_{acc} and therefore D_c.

D_c estimates depend on rise time

Using different values of rise time also affects D_c and peak slip velocity, they both ... e times.

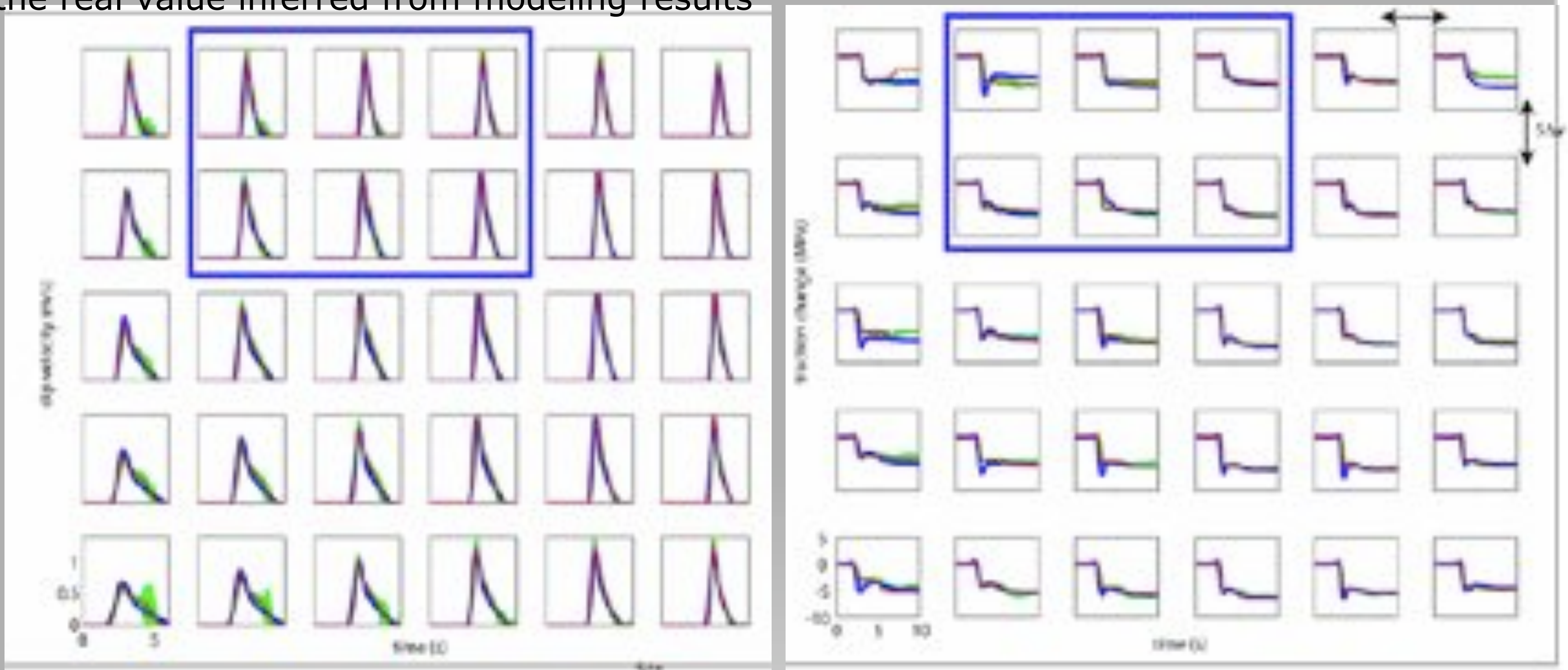
$$D_c \propto \sqrt{\frac{T_{acc}}{T_R}} D_{tot}$$

$$V_{peak} \propto \Delta\sigma_b$$

Tinti et al., 2005; Cocco et al., 2009

A good fit to slip velocity does not imply a good fit in traction evolution & slip weakening curves

Fit with a Yoffe function and T_{acc} equal to the real value inferred from modeling results



Tinti et al., 2009, GJI

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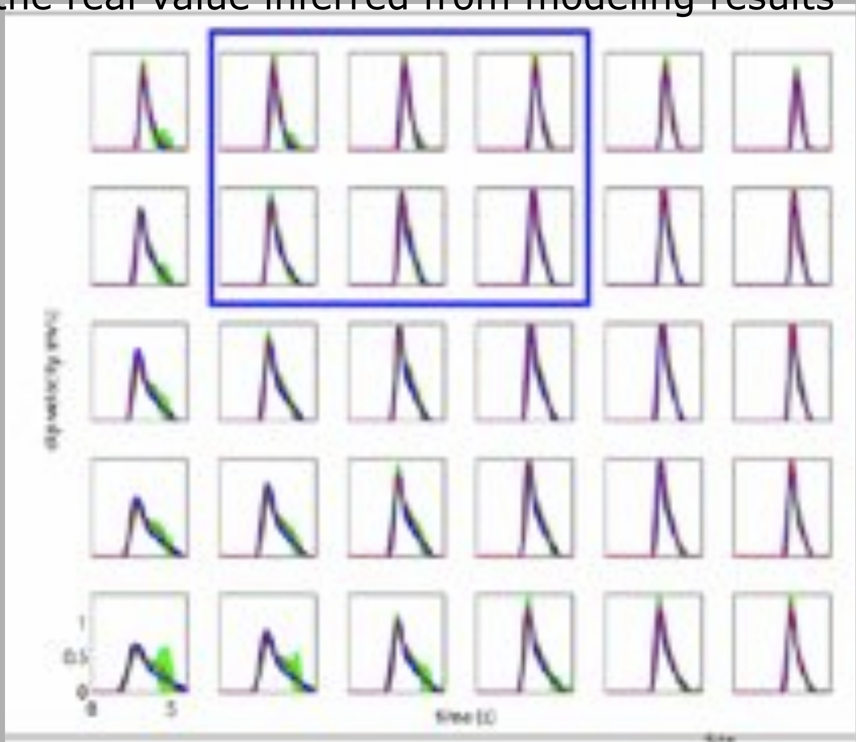

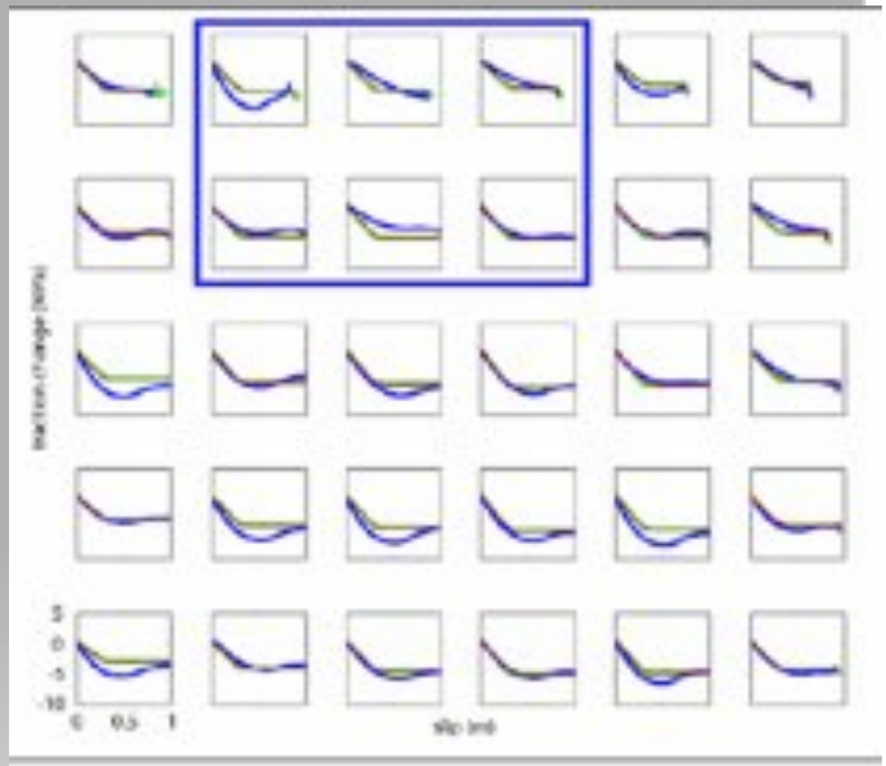

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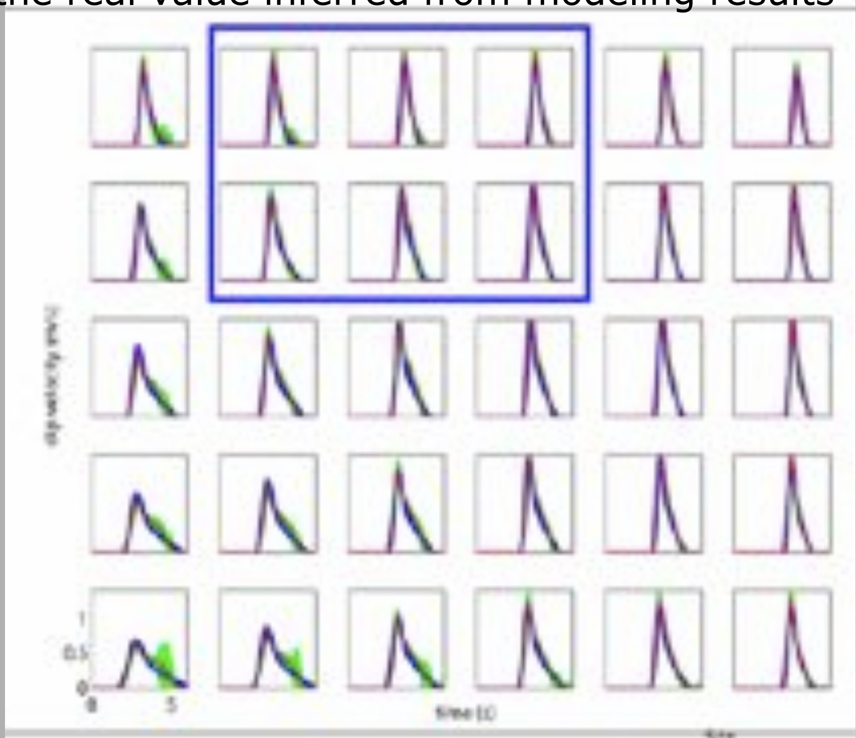
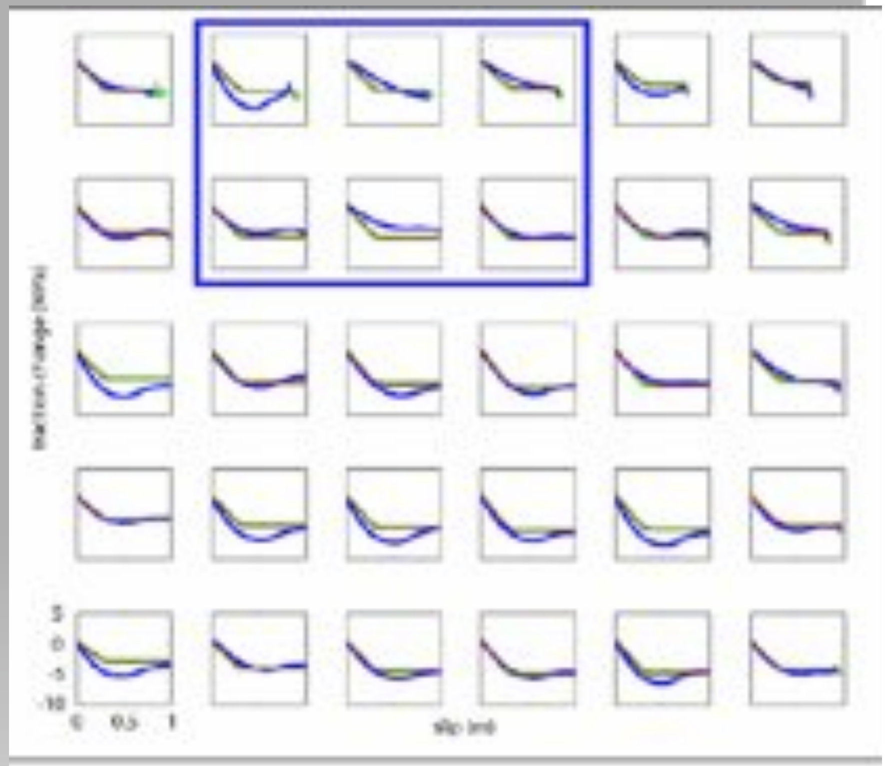




$$\sigma(x,t) = -\frac{\beta}{2\mu}\Delta\dot{u}(x,t) + \iiint \Delta\dot{u}(\xi,\tau)\mathrm{K}(x-\xi,t-\tau)d\xi d\tau$$

Tinti et al., 2009, GJI

A RELEVANT OUTCOME

- This results has been inferred for earthquake slip histories
- However, it might be significant for all those processes involving extended sources and a propagating perturbative front
- We have also to remind that, in such a phenomenological approach, rupture velocity is a macroscopic parameter

IMPACT ON GEOPHYSICAL DATA INVERSION

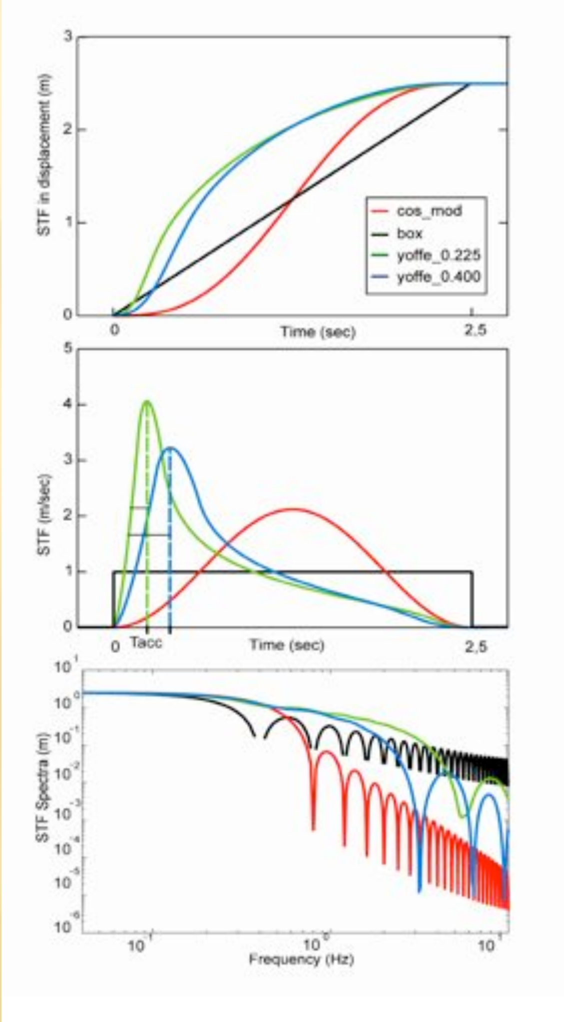
- We have used the non-linear inversion approach proposed by Piatanesi et al. (2007)

  I Stage: building-up the model ensemble by sampling the model space through the simulated annealing algorithm

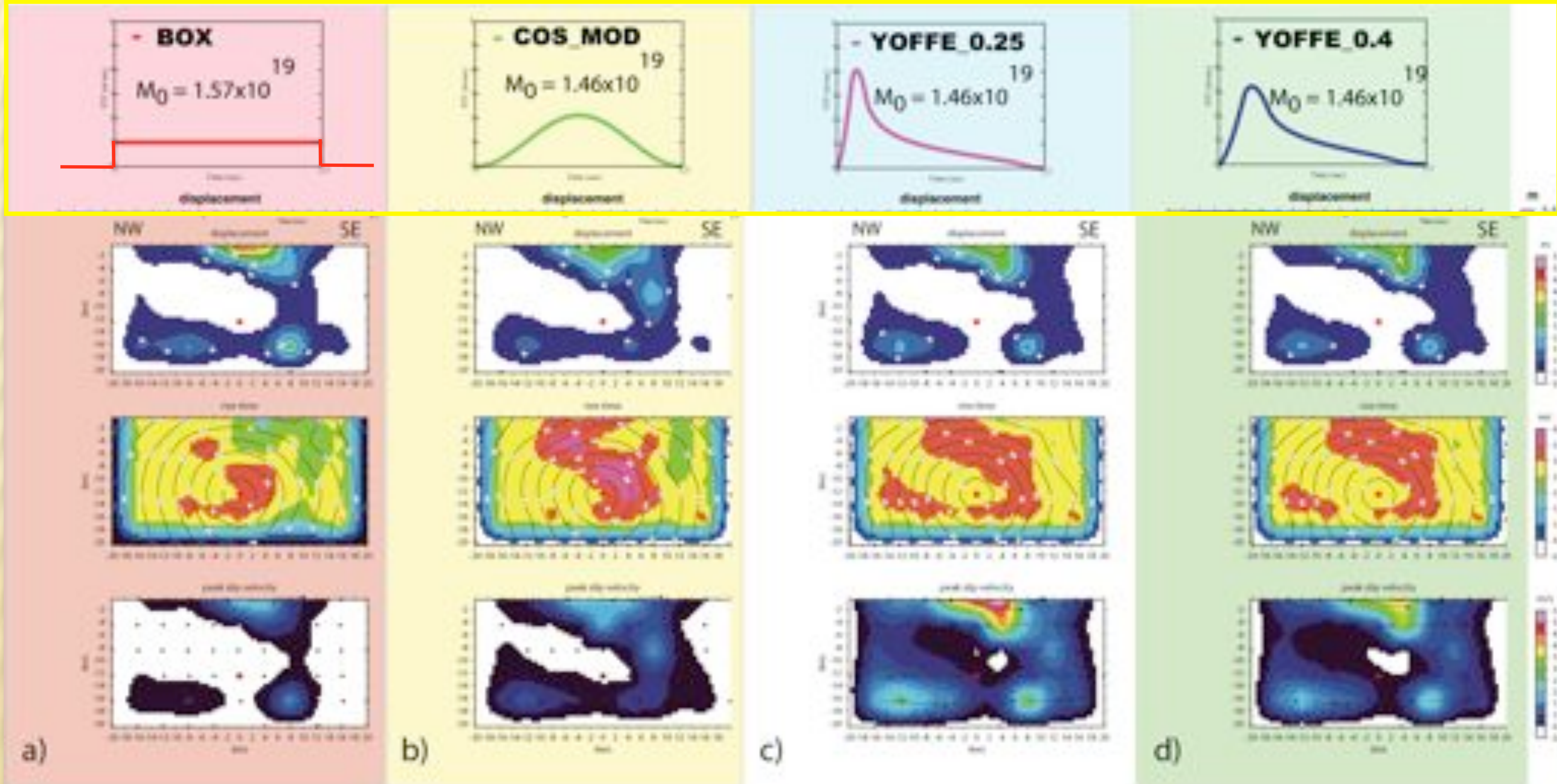
  II Stage: ensemble inference (weighted average model, standard deviation)

- This method don't look only at the best model (usually an extreme model) but it tries to extract the most stable features of the rupture process

- The slip velocity history on each point on the fault is determined by the shape of the a priori assumed source time function (single window approach)



STF: Kinematic Parameters



E(m)=0.26	E(m)=0.23	E(m)=0.24	E(m)=**0.21**

Cirella et al., 2010, in preparation

2000 TOTTORI EARTHQUAKE JAPAN

SOME PRELIMINARY OUTCOMES

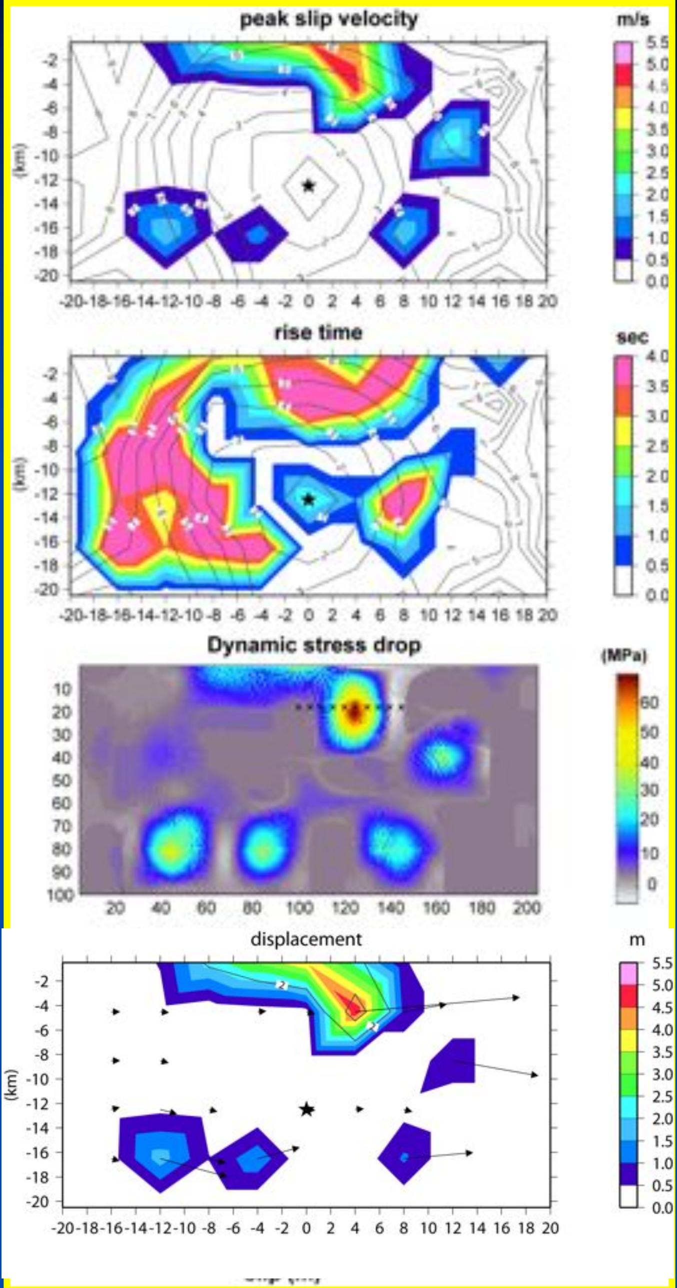
- The adoption of the STF does matter !
  - Implications for dynamic parameters
- Determining uncertainties of inverted model parameters is mandatory
  - More efforts needed to improve the statistical analysis of the ensemble inference

    (Bayesian approach, etc….)
- Kinematic inversions require the use of physically consistent STFs

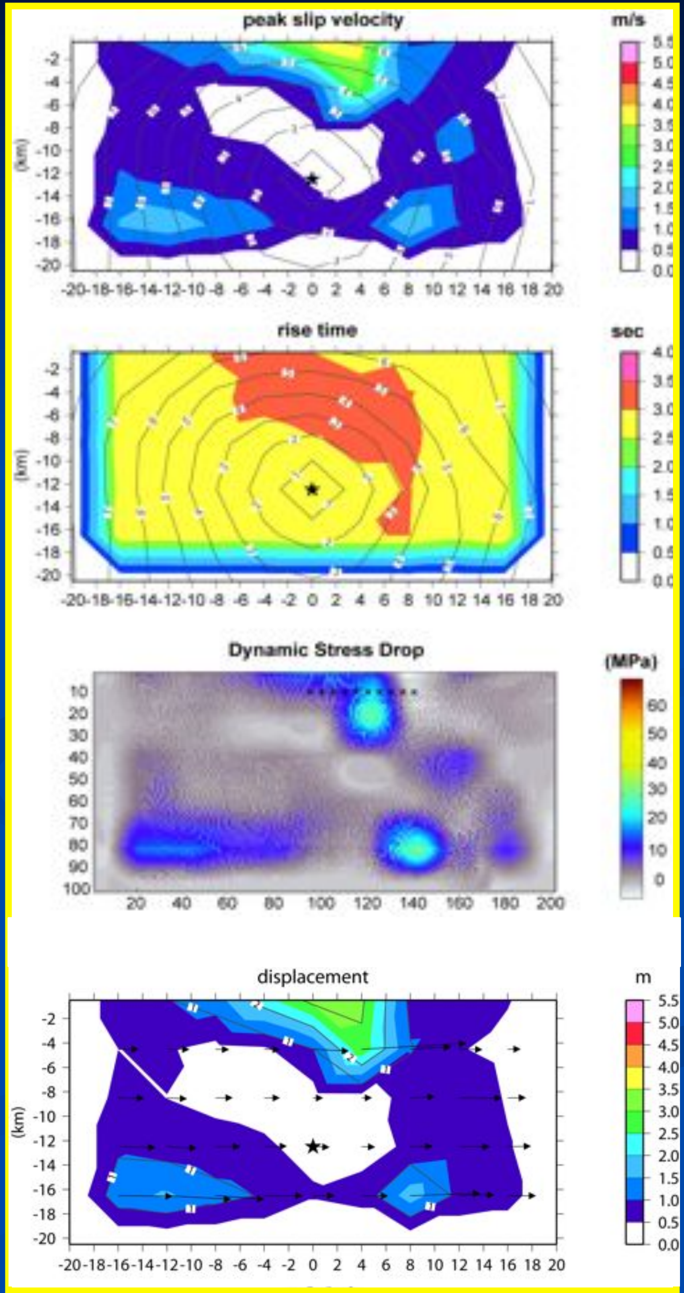
Best model

Inversion of recorded data

Average model



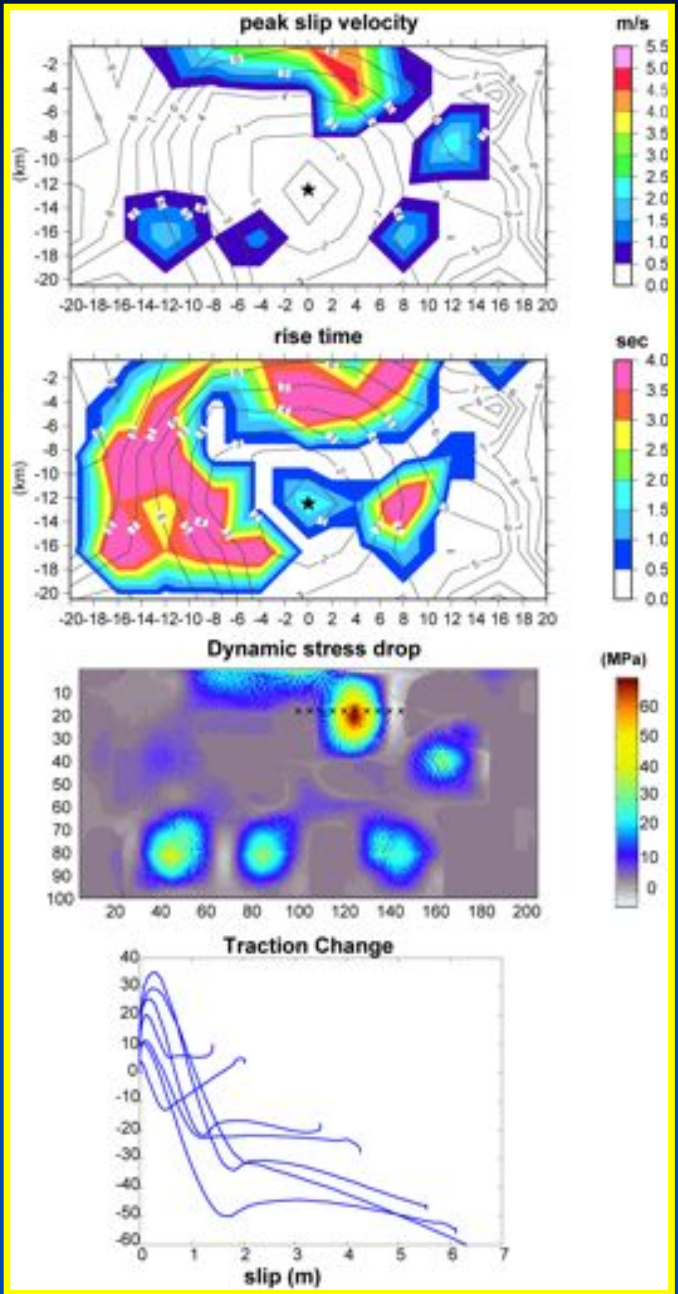
Tottori
Earthquake



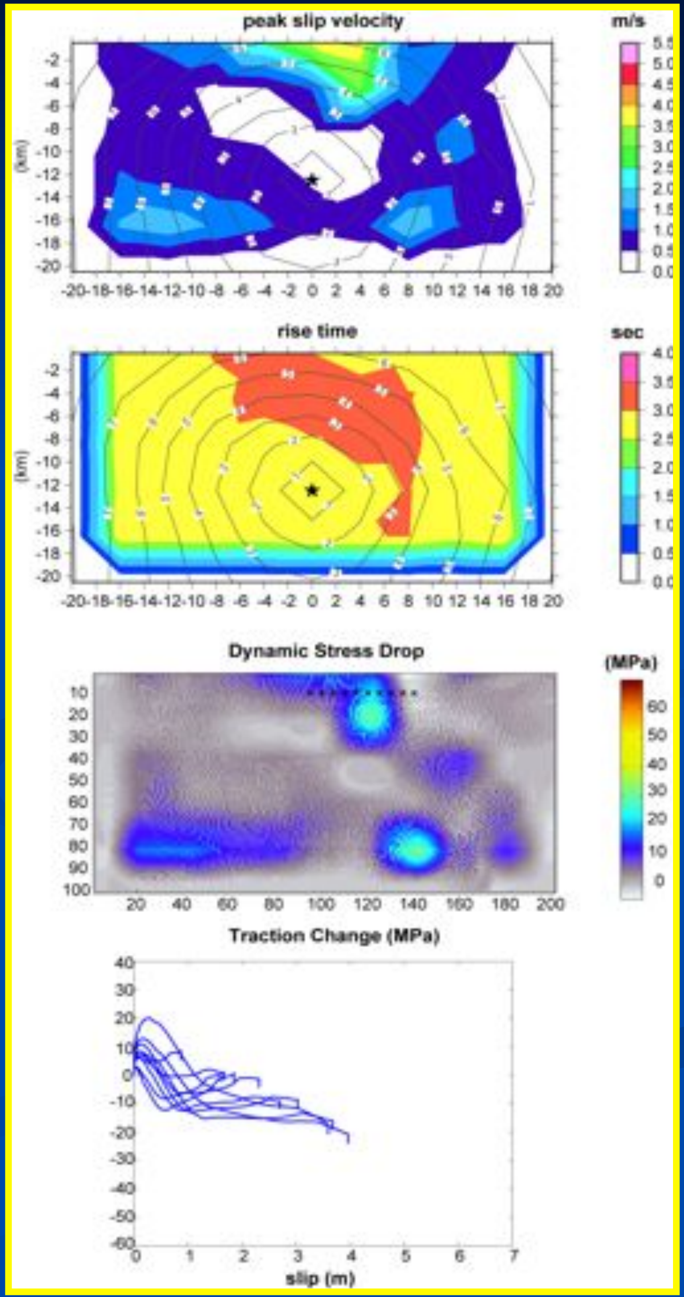
Best model

Inversion of recorded data

Average model

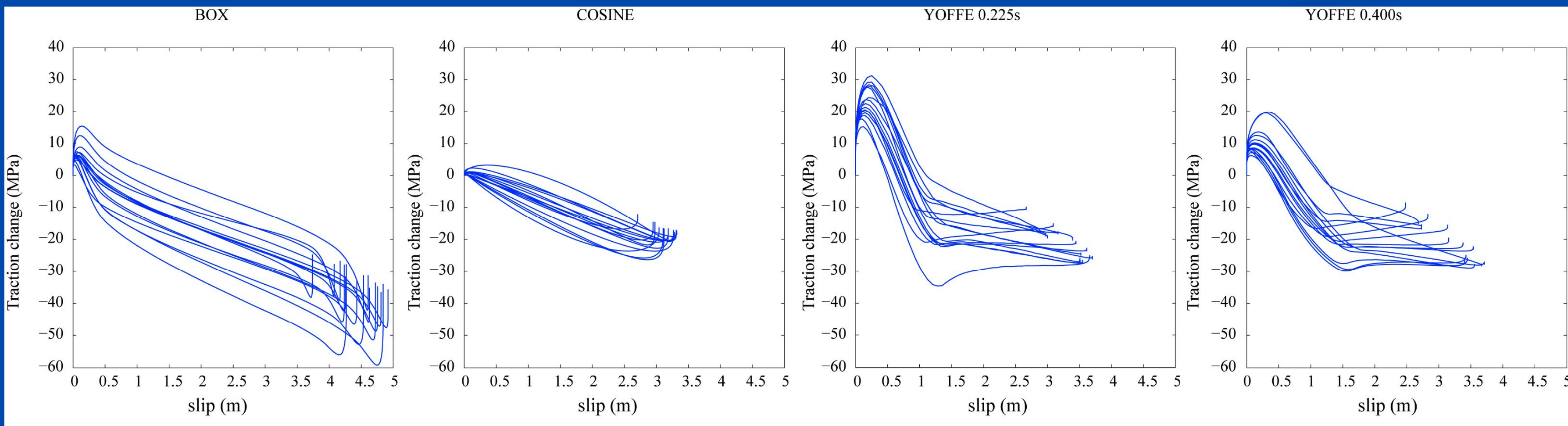


Tottori Earthquake



Dynamic traction evolution

- Traction evolution is calculated from rupture histories imaged by inverting recorded data, but using different STF to solve the forward problem



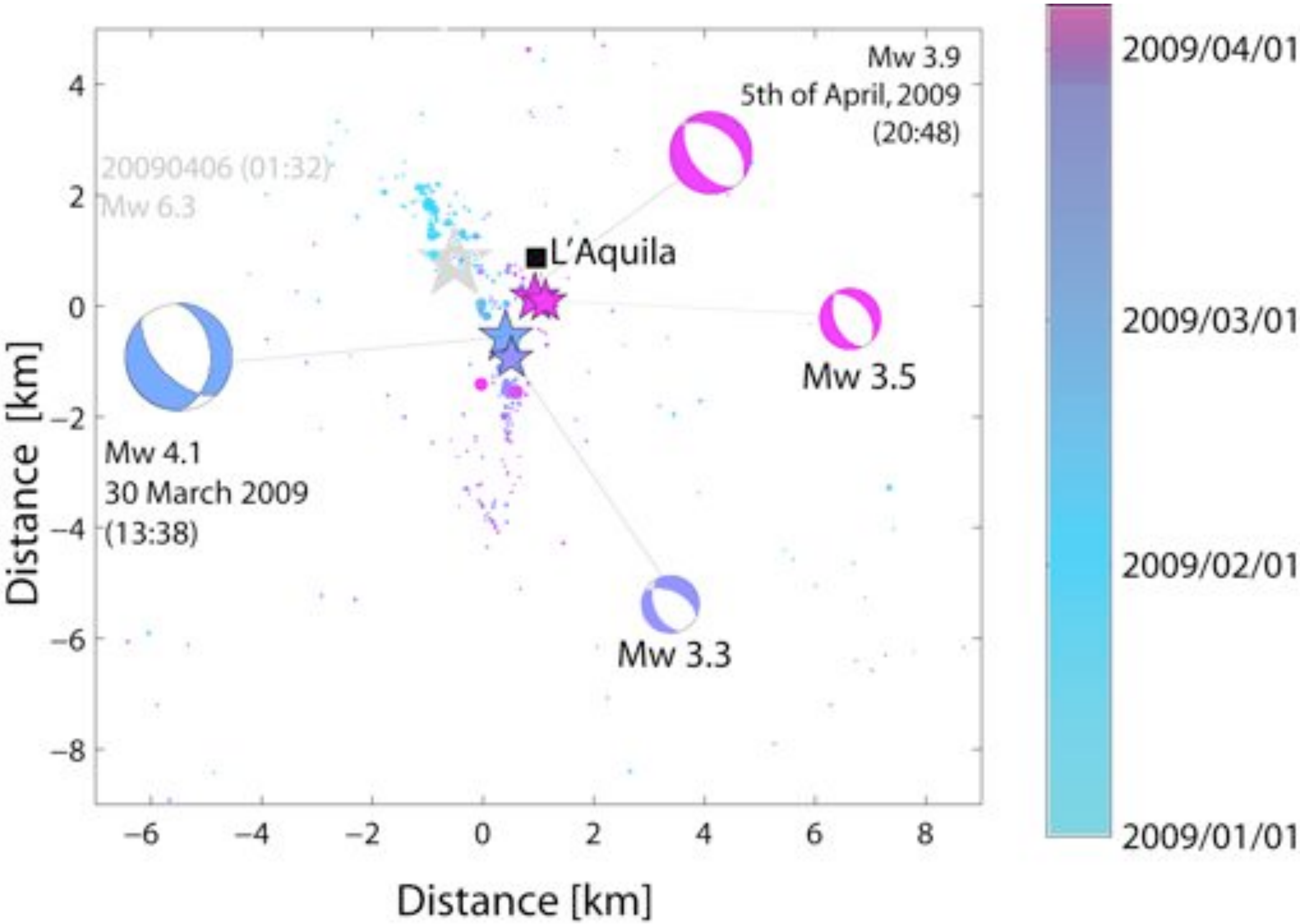
Cirella et al., 2010, in preparation

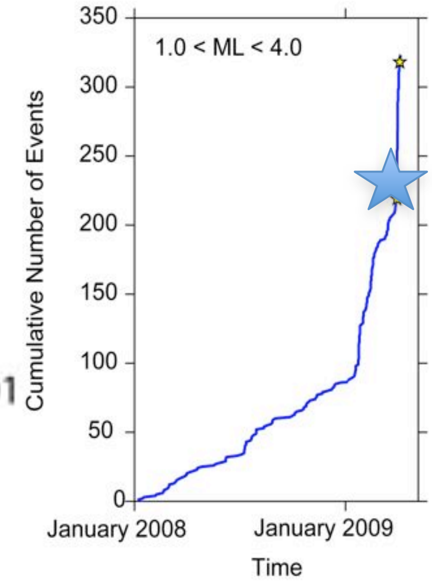
CONCLUSIONS & KEY QUESTIONS #1

- Need to reconcile geological, geophysical and laboratory observations
- Our phenomenological approach does not allow us to distinguish the meso- & micro-scale processes controlling dynamic fault weakening
- The complexity of fault zones and the diversity of frictional behaviours can explain the variability of the mode of slip
- Slip velocity contains many info of the traction evolution and dynamic fault weakening, but unfortunately it is poorly known
- This lack of knowledge also depends on the poor control on spatial resolution, slip gradients and neighbours interactions

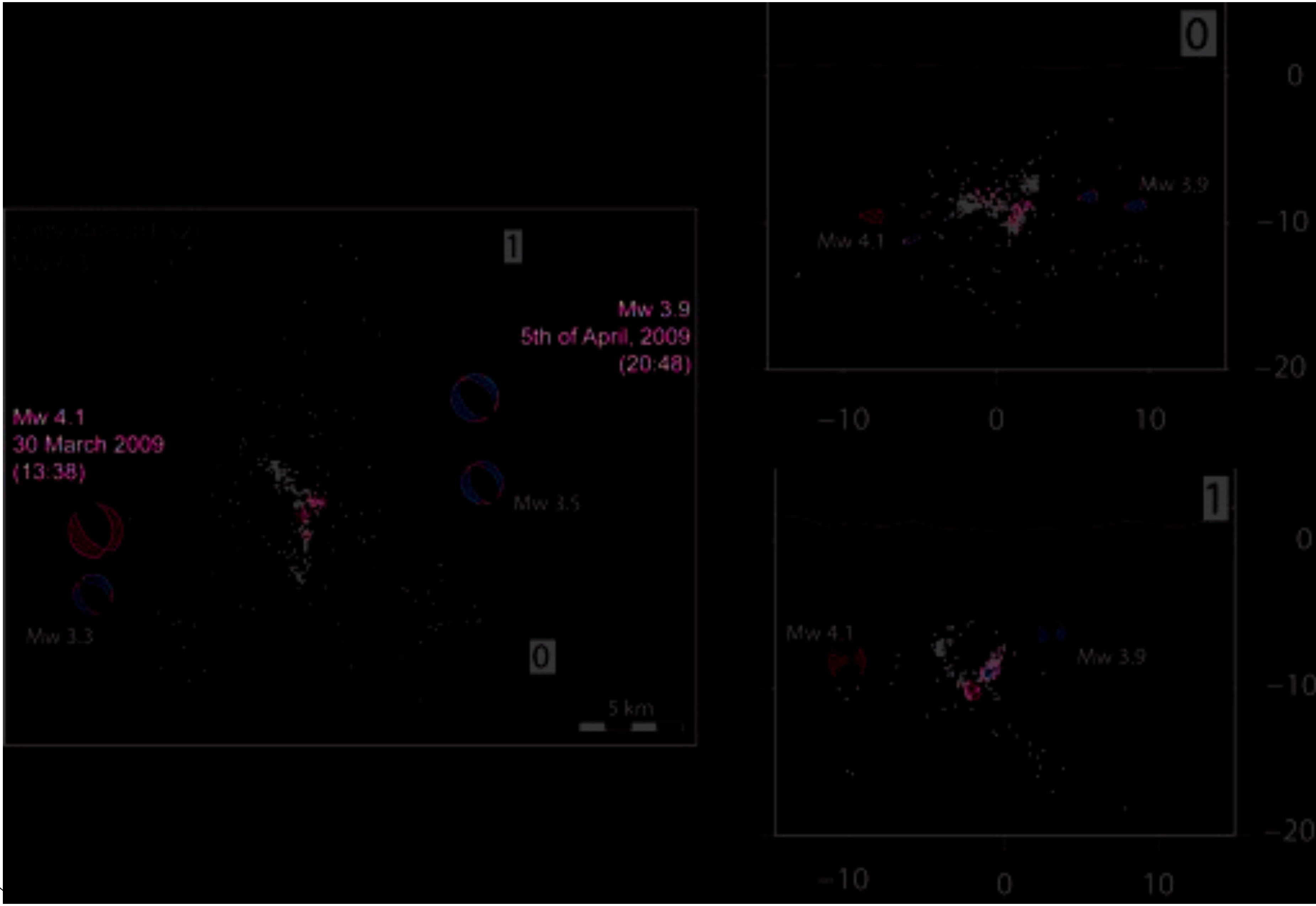
The 2009 Mw 6.3 L'Aquila earthquake - The Foreshock Sequence

Seismicity **m**igration **a**long **s**trike

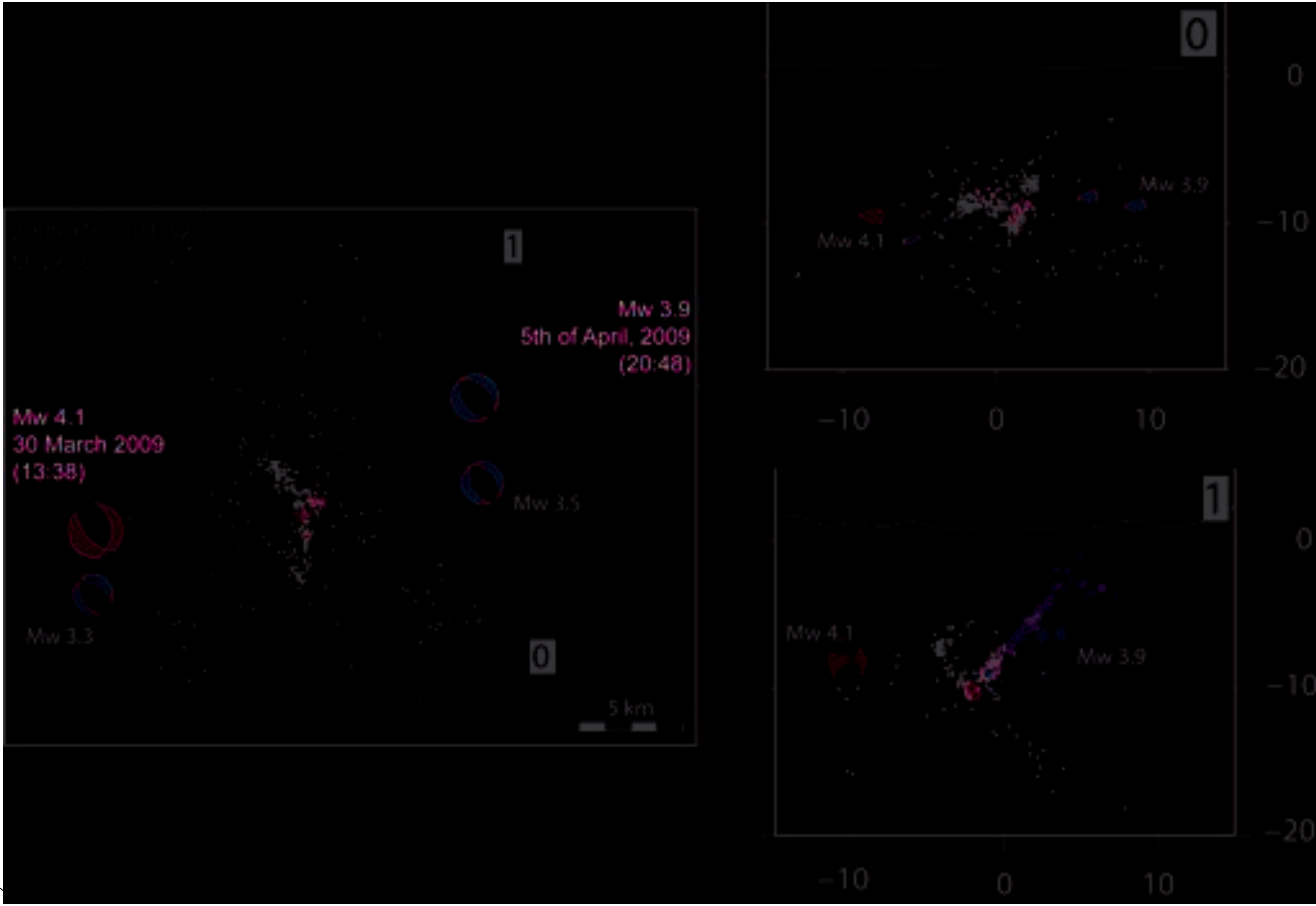




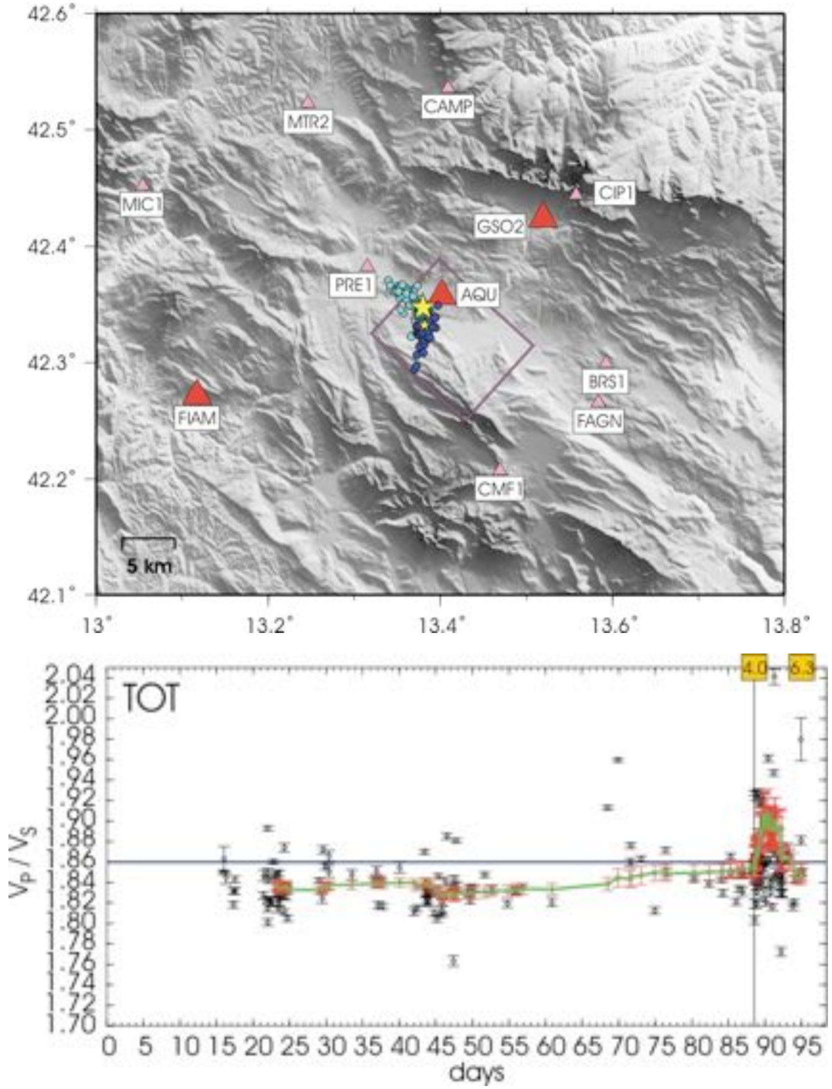
- Foreshock Sequence

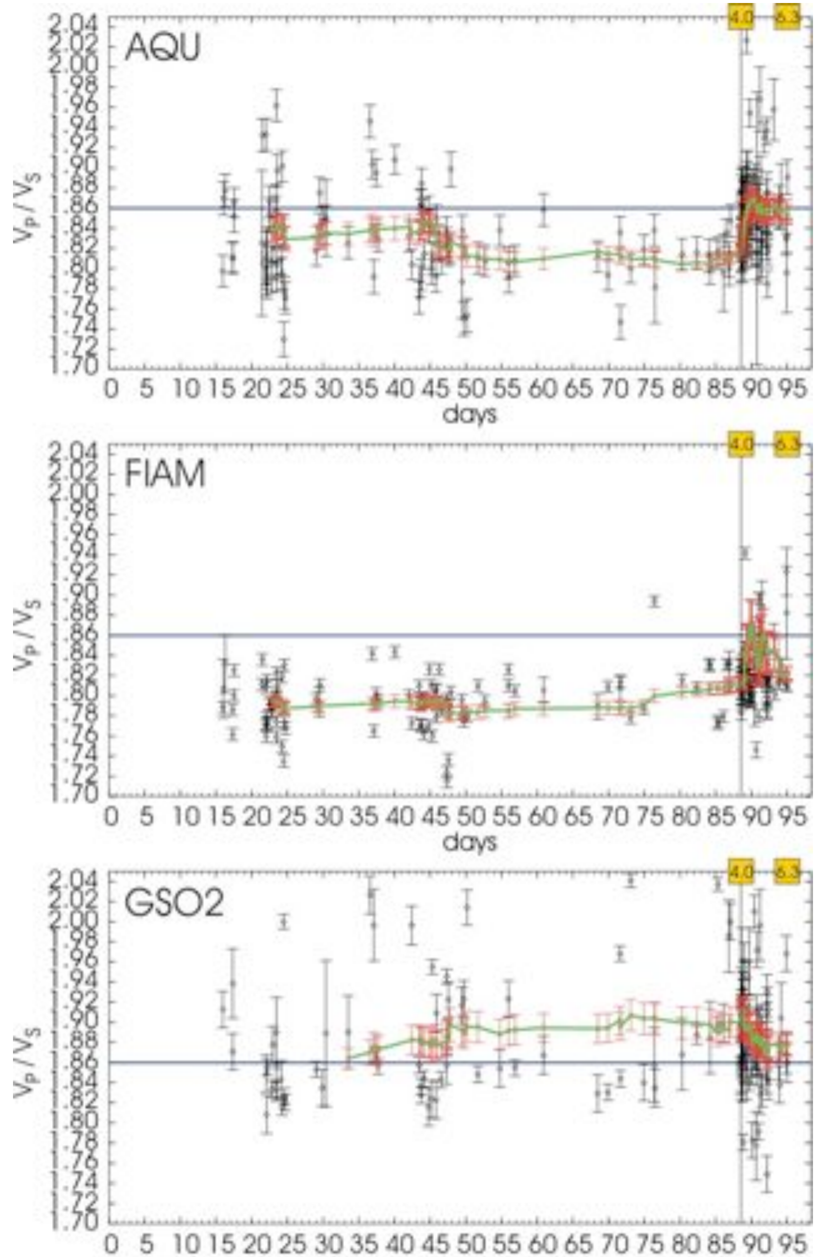


- Foreshock Sequence



Time series of V_P/V_S values for from January 2009 to April 6th 2009

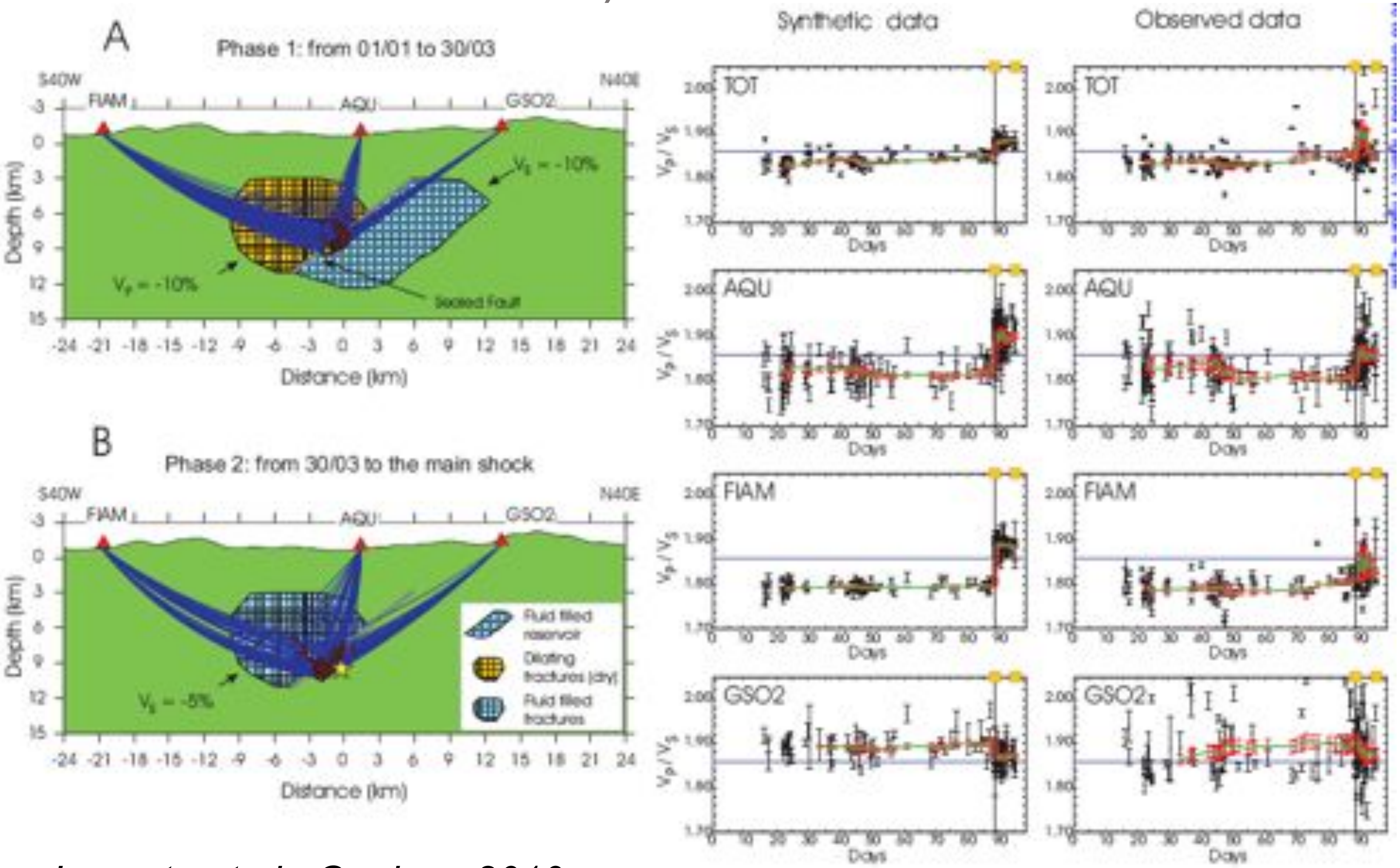




- Individual determinations of V_P/V_S are represented by black circles with black vertical bars indicating the errors in the measurement.
- Red circles are the mean values calculated on running windows of 20 samples with one sample step; red vertical bars indicate the standard deviation of the mean.
- Green lines are the mean values interpolating functions

Lucente et al., Geology 2010

Vp/Vs variations in 2009 around L'Aquila (before the main shock)



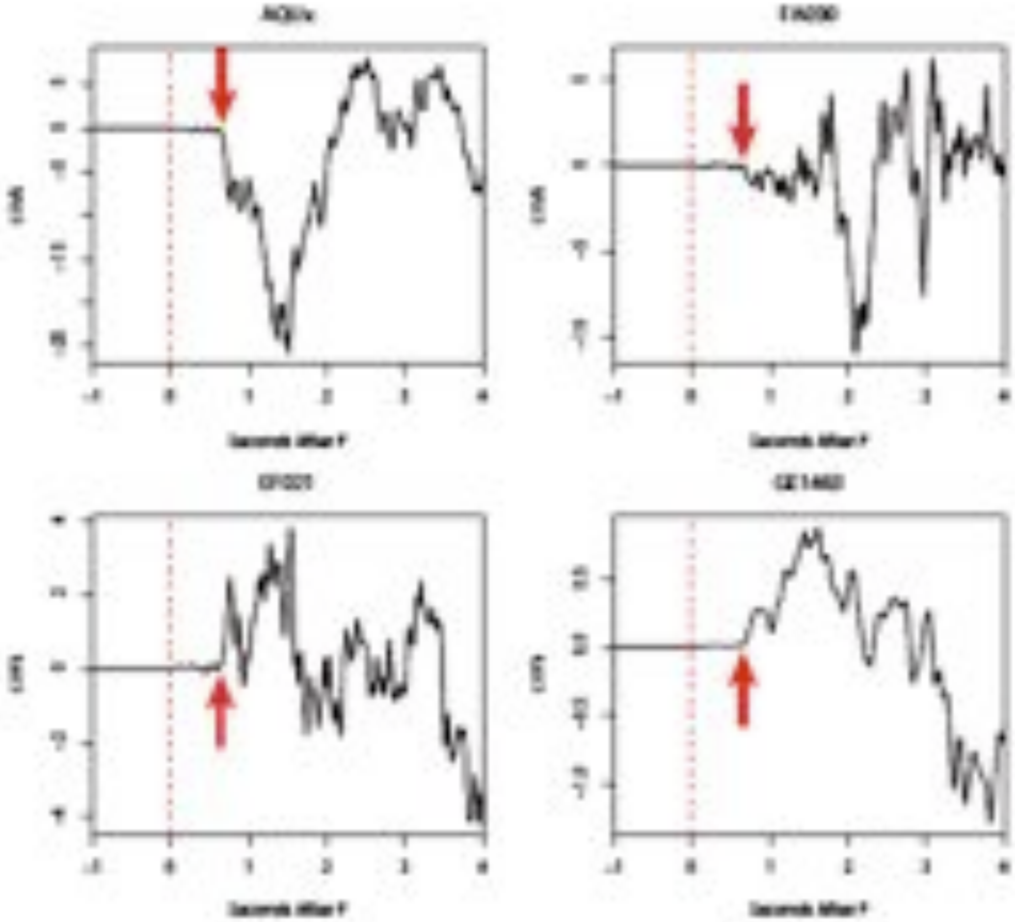
Lucente et al., Geology 2010

The earthquake initiation

The earthquake has a weak initiation with a nucleation phase followed by a strong "breakaway" phase (Beroza & Ellsworth, 1996).

The duration of the slow initial moment release process is nearly 0.8-0.9 sec and agrees with the scaling proposed by Beroza & Ellsworth.

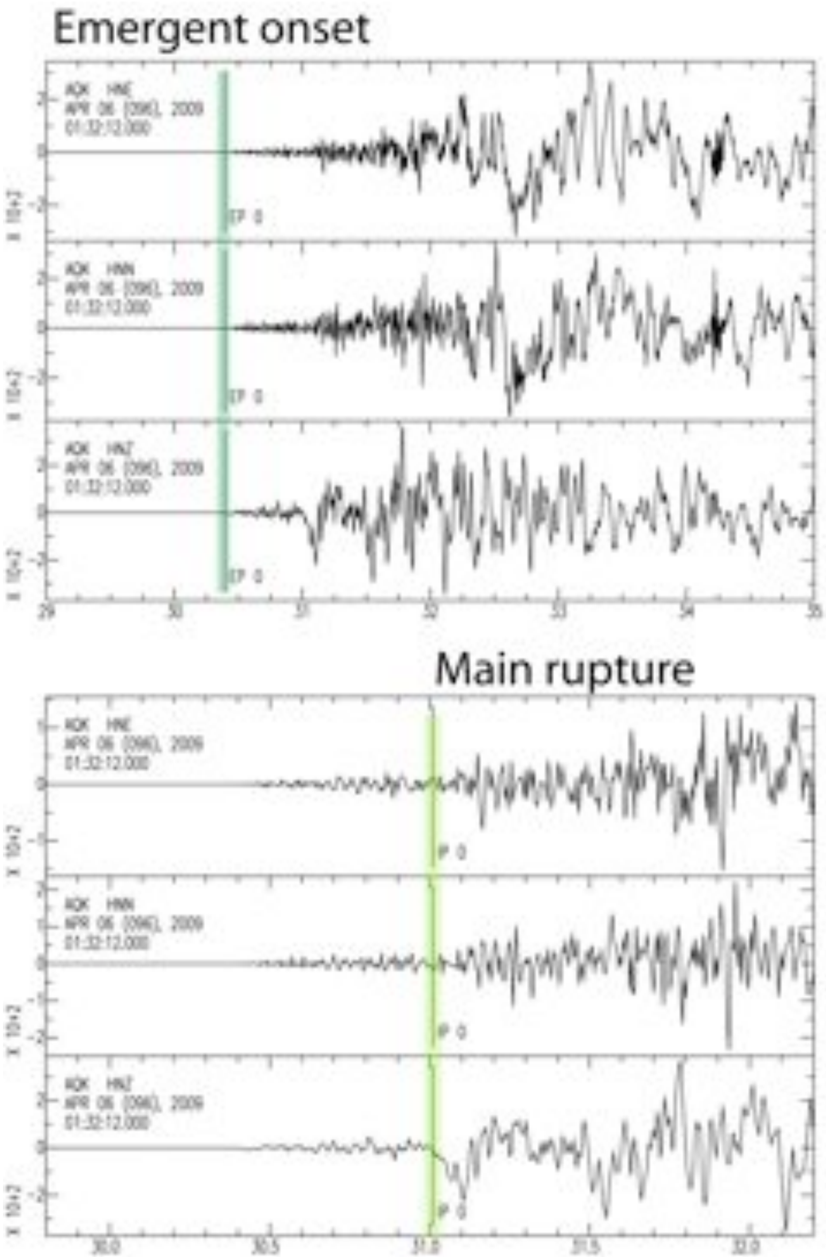
The onset of the impulsive "breakaway" phase (IP) is located nearly 2 km up-dip from the nucleation point (EP).



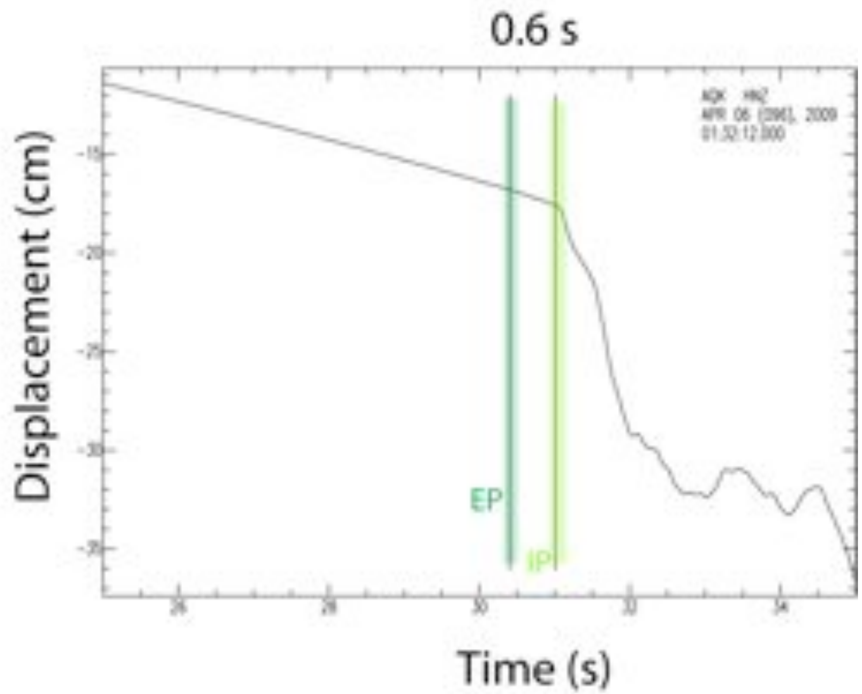
Displacement seismograms for four stations near the epicenter. The initial P-wave arrival marked by dashed red line. Strong arrival marked with arrow at about +0.6 s is the "breakaway" phase. The S-wave at the nearest station, AQU arrives at 1.0 s.

Elaborated by Bill Ellsworth, USGS, Menlo Park

Complex Rupture Initiation

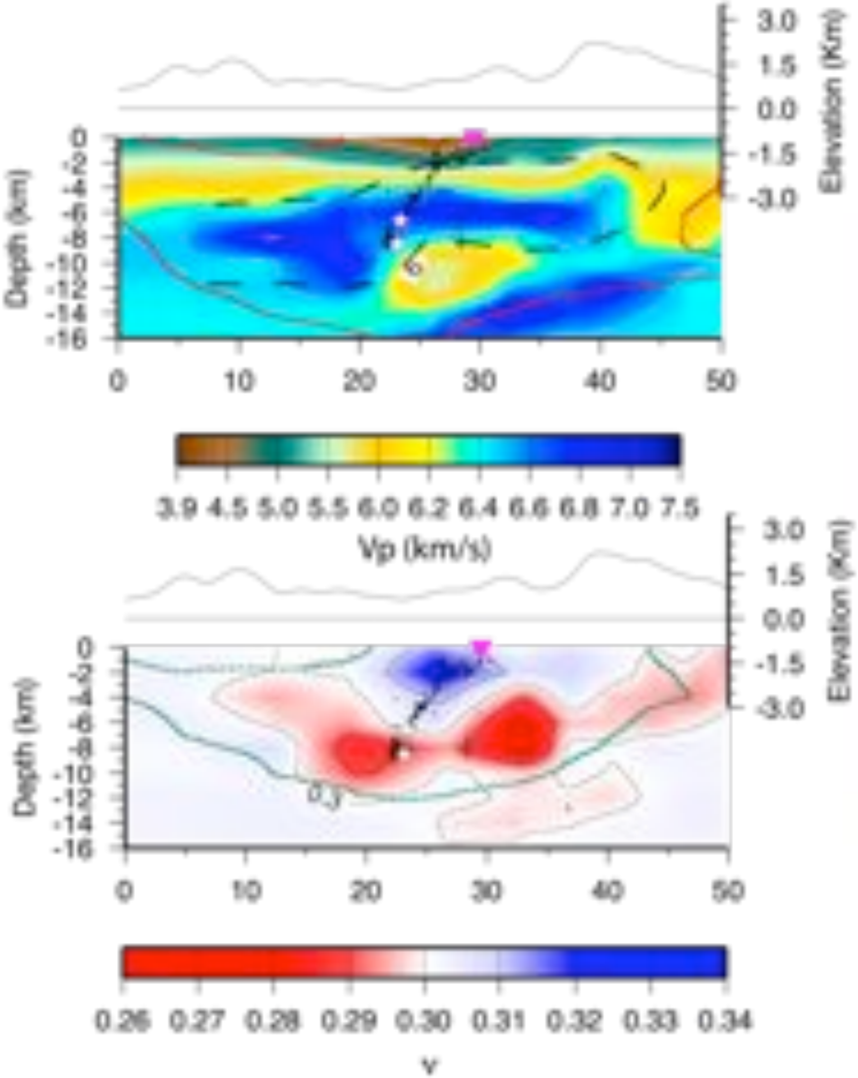


The 6th of April 2009 mainshock waveform shows a complex rupture onset: the figure highlights the *emergent (EP)* phase preceding the *impulsive (IP)* arrival.

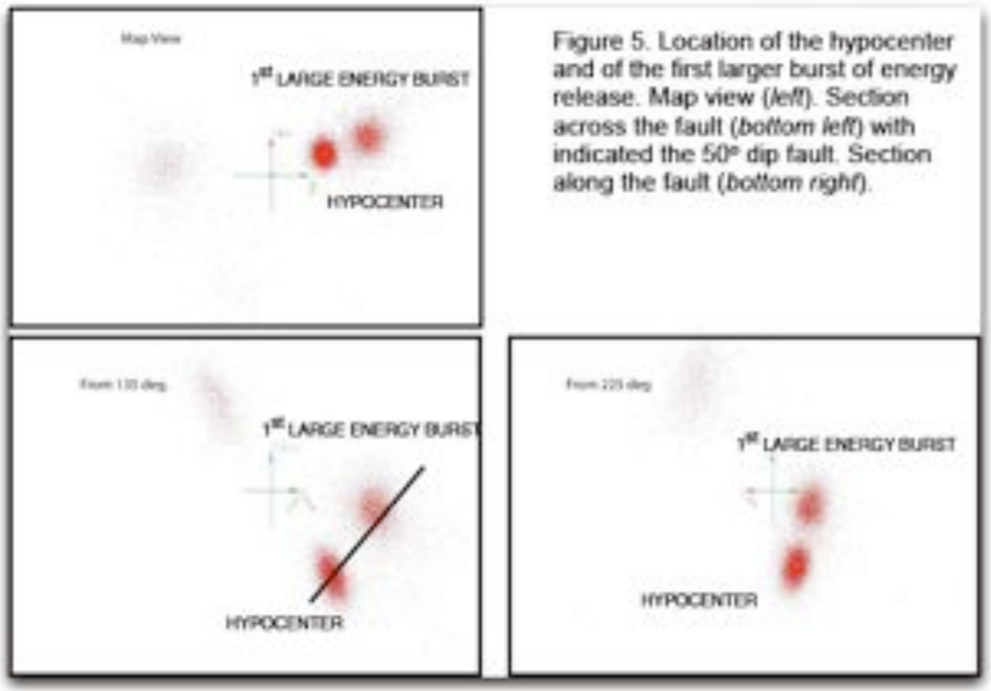


Station **AQK** (near field)

Location of the EP and IP hypocenters

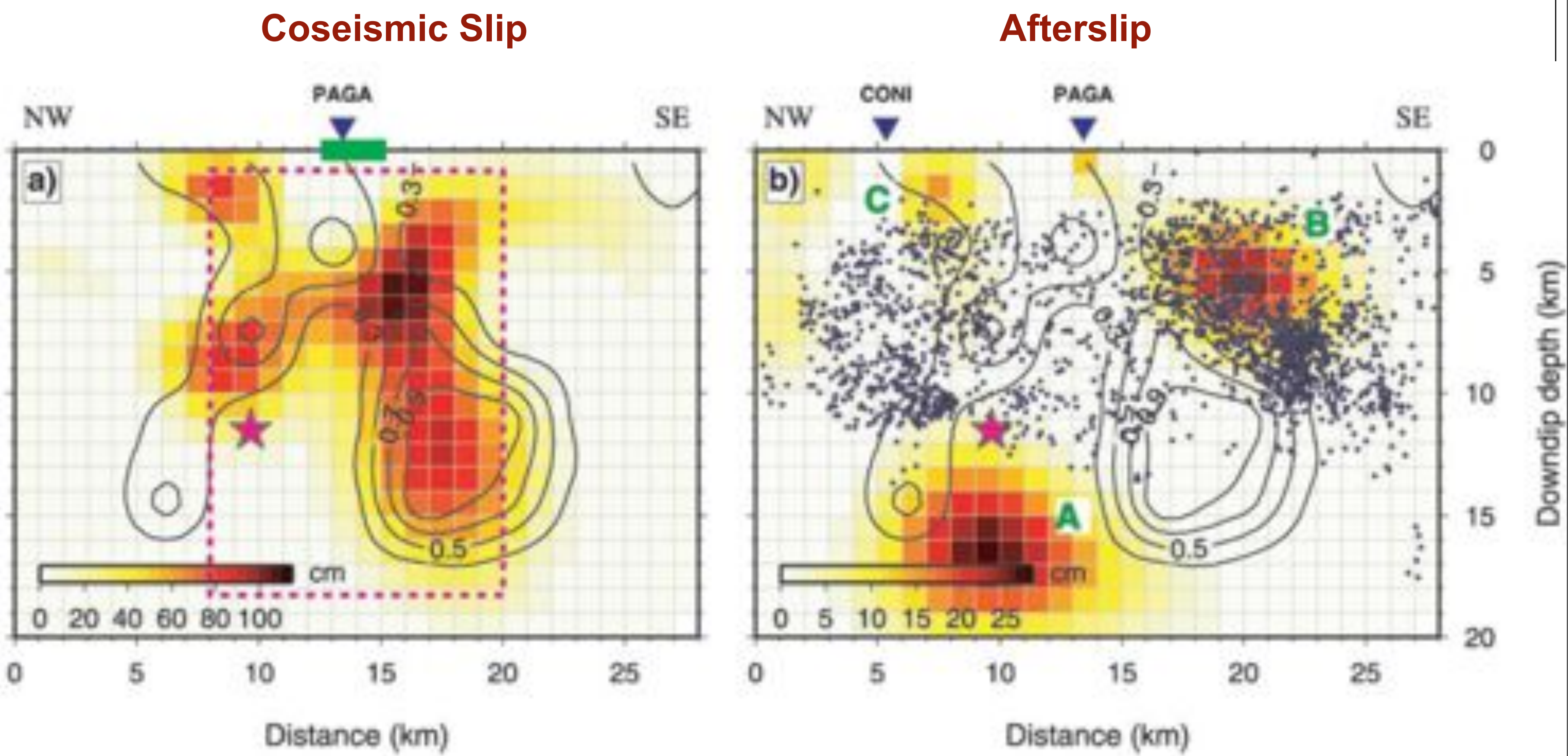


Di Stefano et al., 2010, submitted

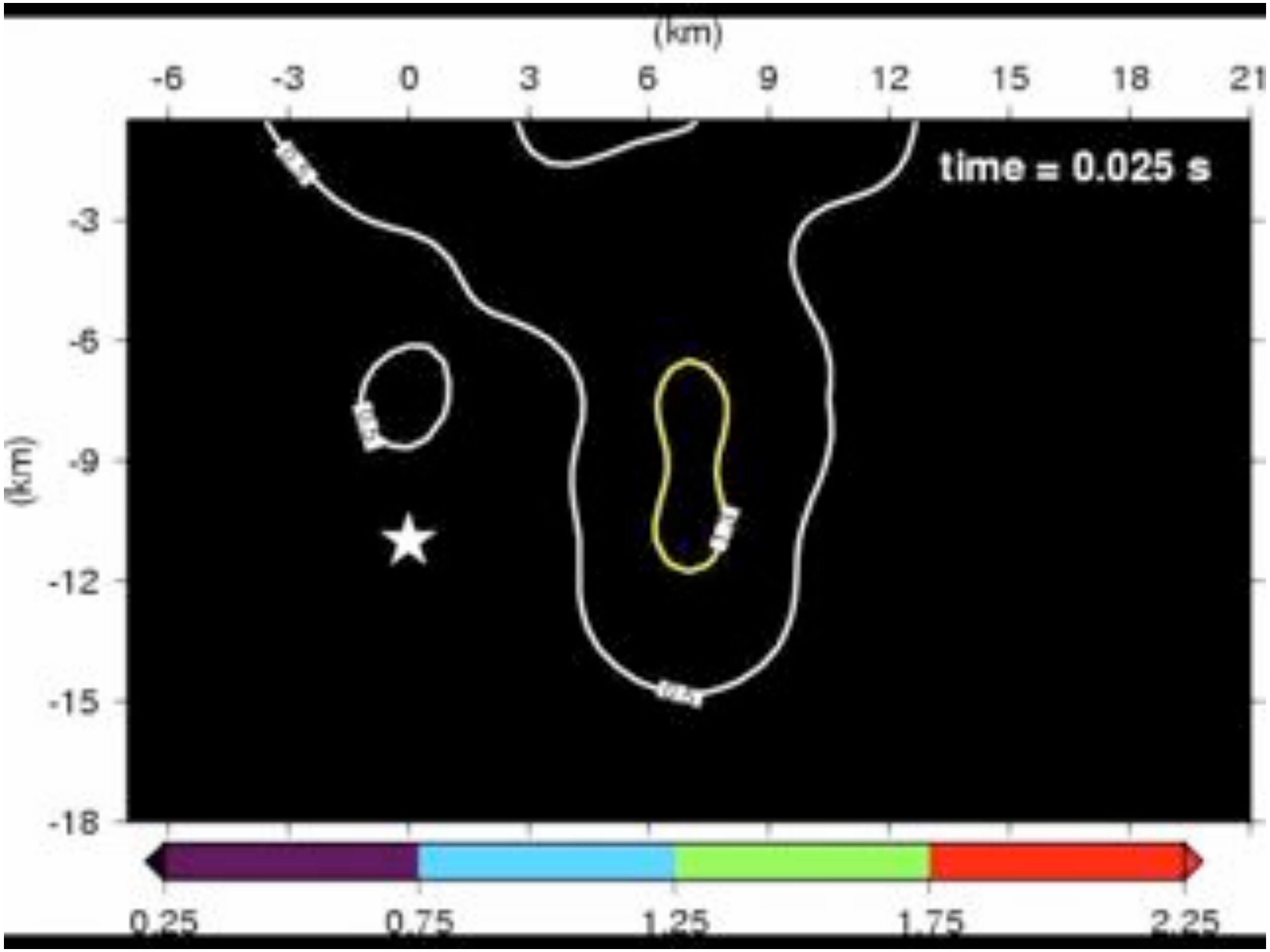


Michelini et al., 2009, AGU Fall Meeting

CO- and POST-seismic slip on the main-shock fault
(Cheloni et al., .G.JI, 2010, & Cirella et al., GRL, 2009)

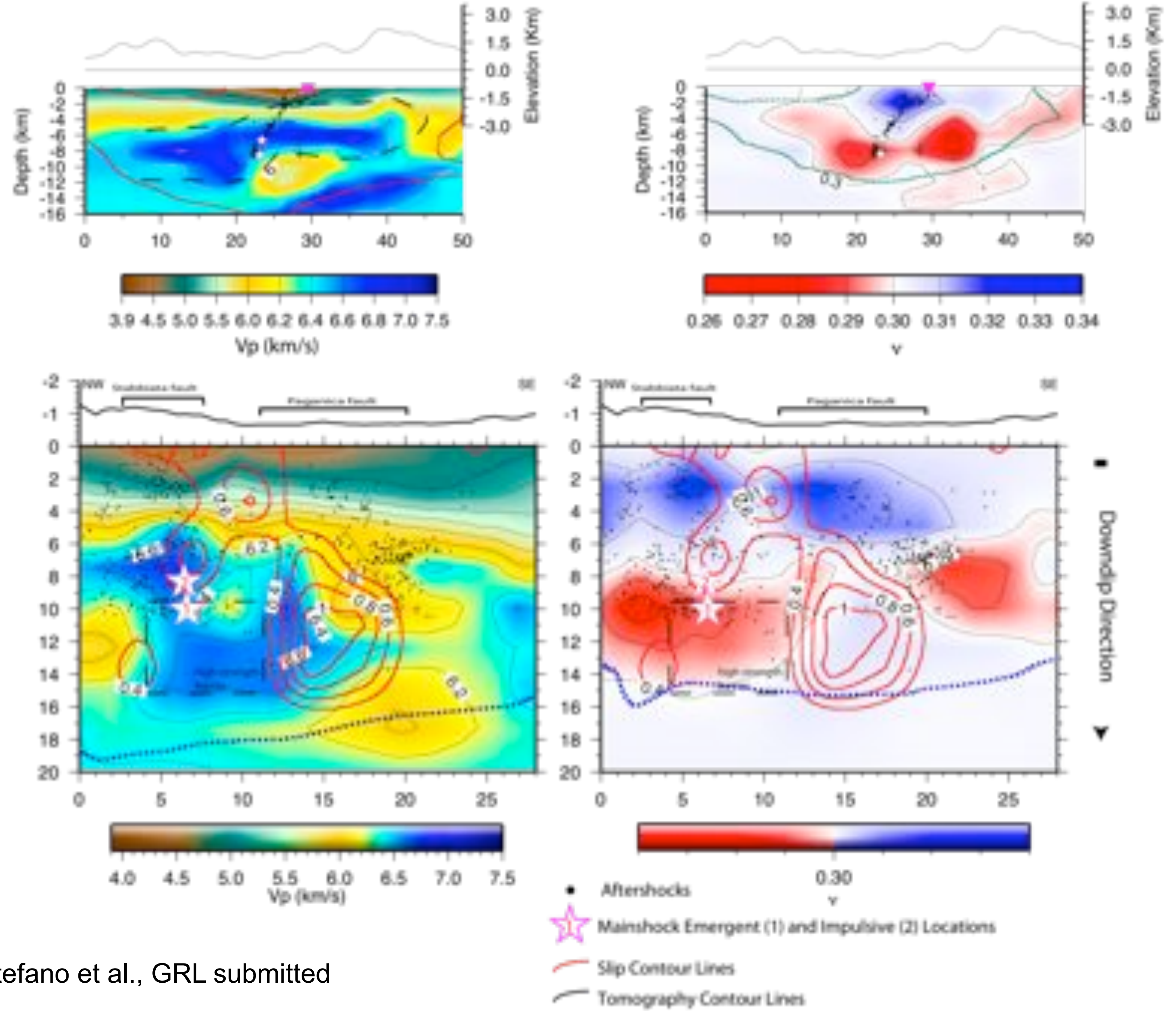


Afterslip occurred at the edges of the main coseismic patches releasing, in the first 60 d after the main shock, a postseismic moment of 6.5 × 10^{17} Nm, equivalent to a *Mw 5.8 earthquake.*


(km)
-6
-3
0
3
6
9
12
15
18
21
time = 0.025 s
-3
-6
-9
-12
-15
-18
(km)
0.25
0.75
1.25
1.75
2.25

Cross section

Along the fault



Di Stefano et al., GRL submitted

CONCLUSIONS & KEY QUESTIONS #2

- Need to adopt dynamic constrains, to model high-frequency waves, to adopt dynamically consistent STFs in waveform inversions as well as to develop new inversion algorithms, which are independent of the adoption of a particular source time function
- Can we model transients with STFs differing from those of earthquakes only for long durations and small V_{peak}?
- The 2009 L'Aquila earthquake displays a complex initiation and rupture propagation, with afterslip and postseismic effects,
- High rupture speed (super-shear?) in the up-dip propagation ($\approx$ 4÷4.4 km/s)
- No precursory signals have been observed. No evidence so far of tremors and slow slip events.