

Studium ohniskového procesu ničivého zemětřesení L'Aquila, Itálie 2009

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Jiří Zahradník

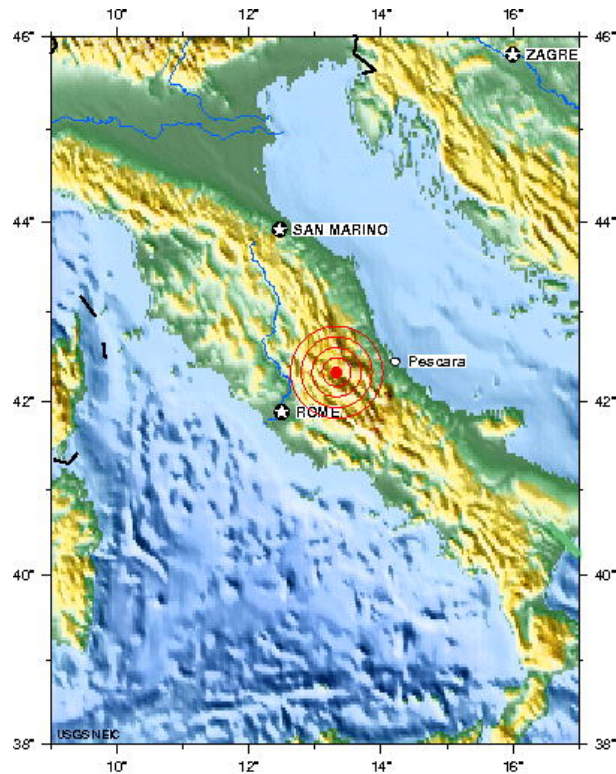
Matematicko-fyzikální fakulta, UK

Katedra geofyziky

Předměstí L'Aquily



2009 L'Aquila Mw 6.2



CENTRAL ITALY

2009 04 06 01:32:39 UTC 42.33N 13.33E Depth: 9 km, Magnitude: 6.3

Earthquake Location

USGS

- 6. dubna 2009, 3:32 místního času
- Oblast Abruzzo, Itálie
- Apeniny, extenzní režim (norm. zlom vedoucí přímo pod městem)
- 300 obětí, 28000 lidí bez domova

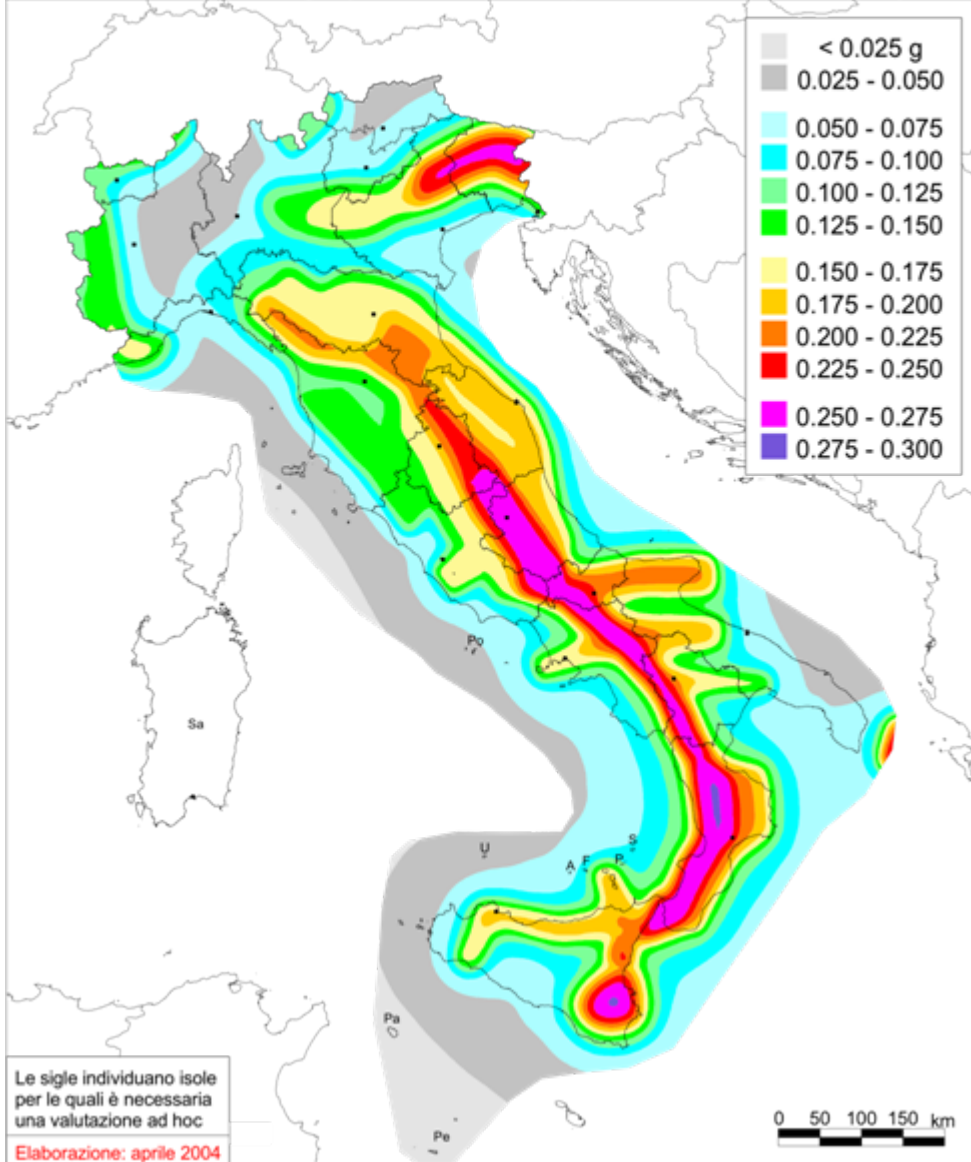


Mapa di pericolosità sismica del territorio nazionale

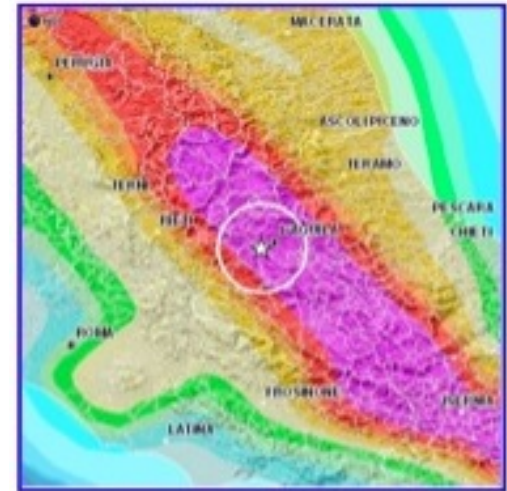
(riferimento: Ordinanza PCM del 28 aprile 2006 n.3519, All.1b)

espressa in termini di accelerazione massima del suolo
con probabilità di eccedenza del 10% in 50 anni

referita a suoli rigidi ($V_{s30} > 800$ m/s; cat.A, punto 3.2.1 del D.M. 14.09.2005)

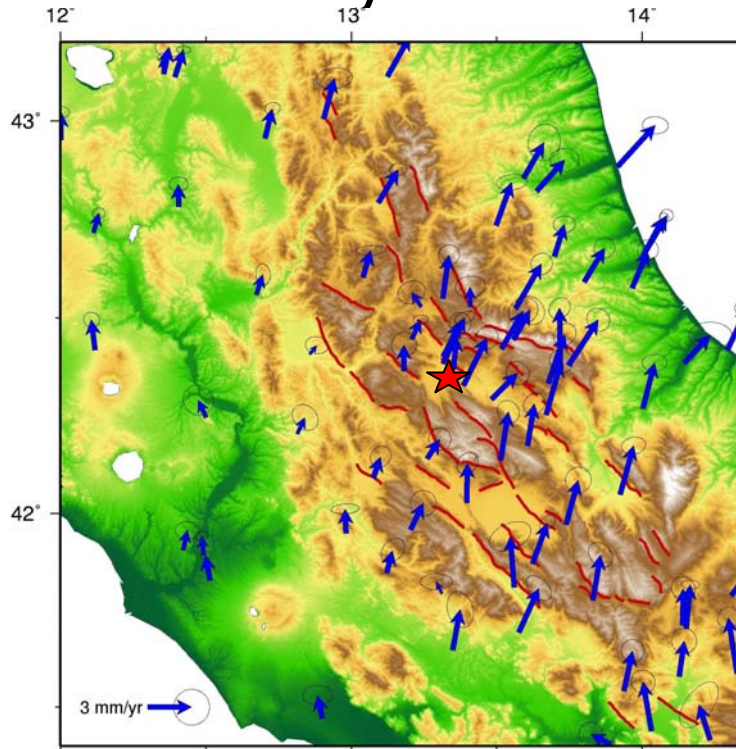


The seismic hazard map of Italy (2004)

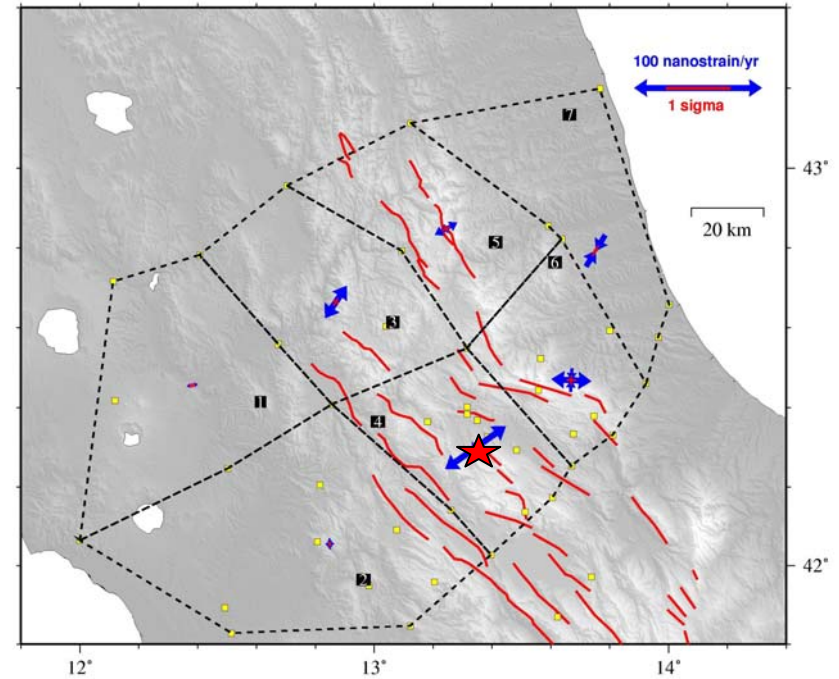


Interseismic strain inferred from GPS

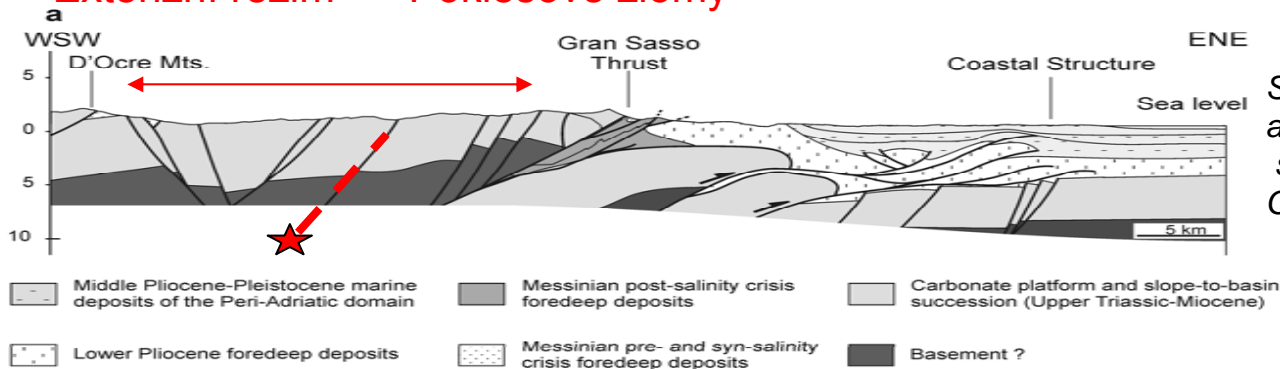
Velocity field



Strain Rate



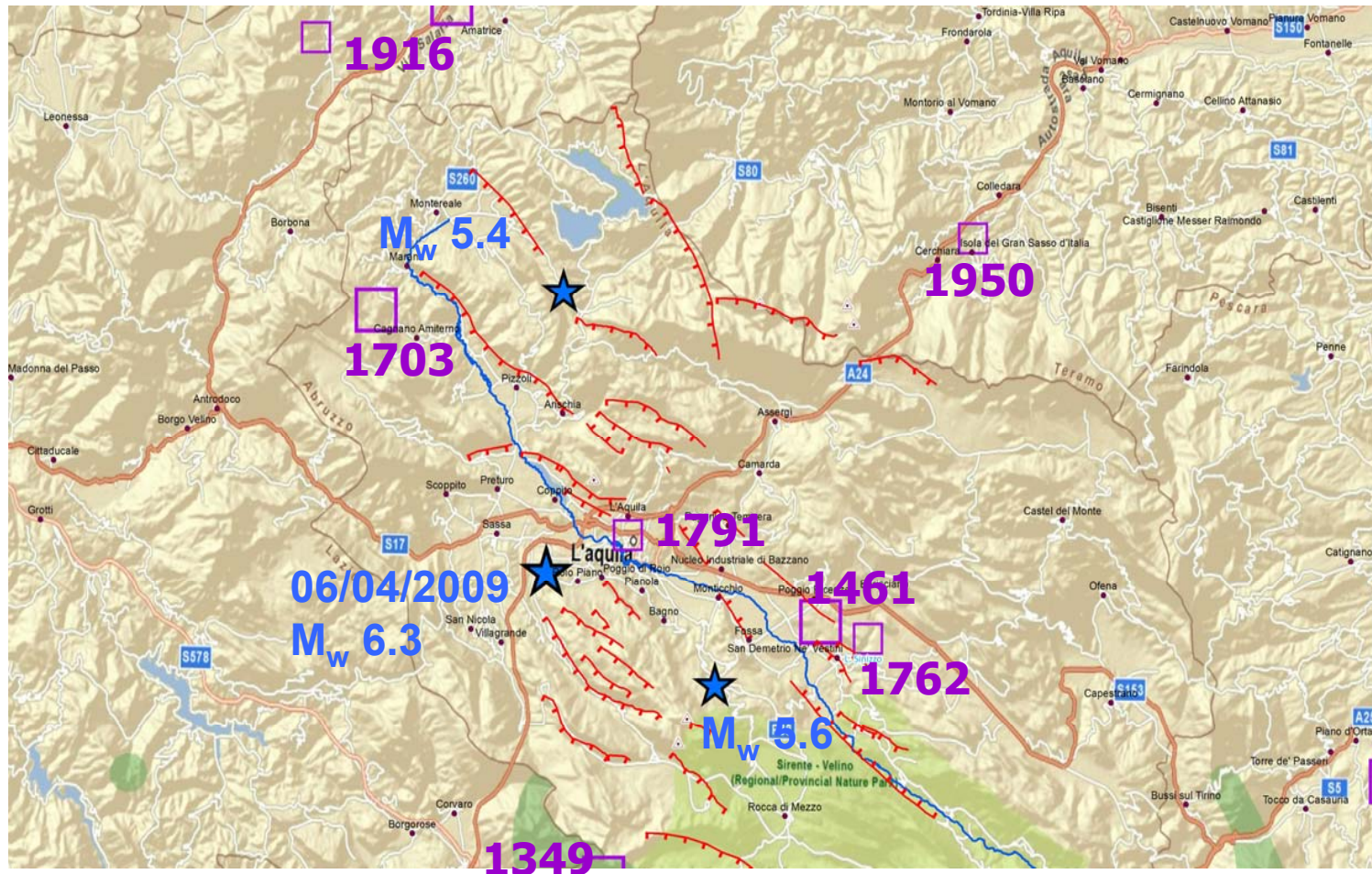
Extenzní režim => Poklesové zlomy

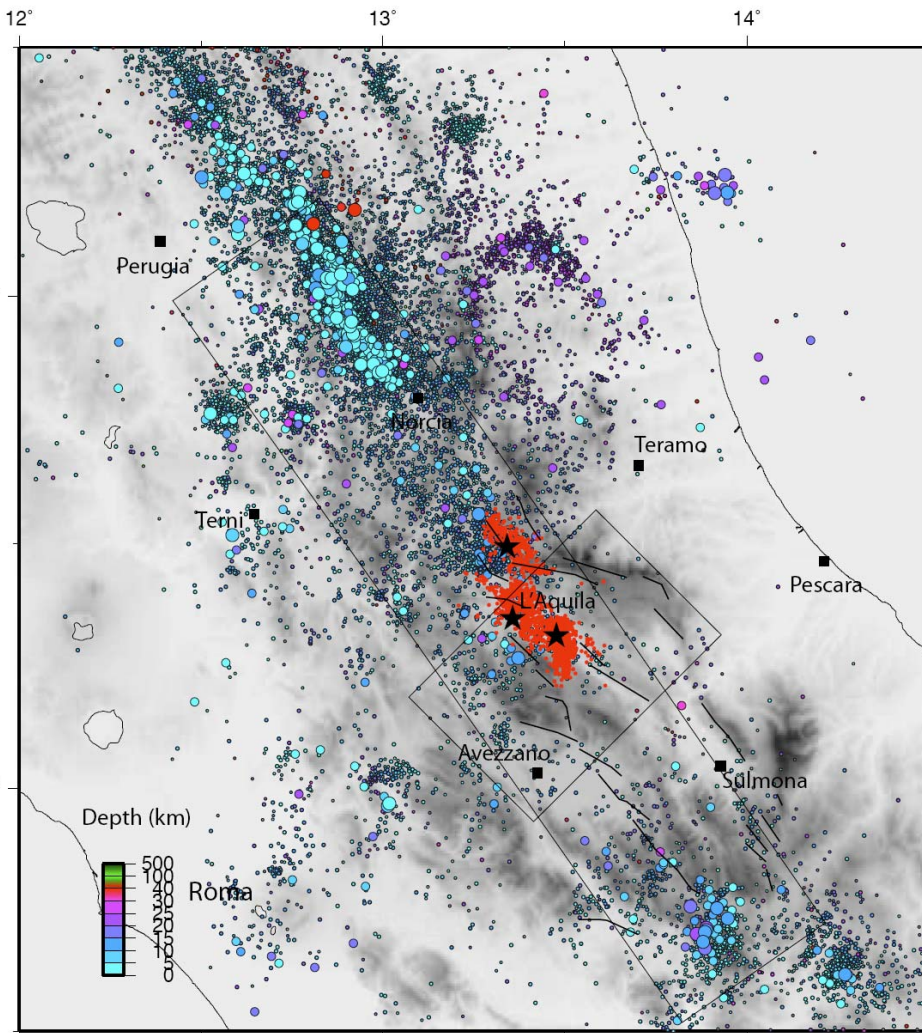


Schematic geological section across the M. D'Ocre – Gran Sasso structures (after Satolli and Calamita 2008)

Historical seismicity and faults

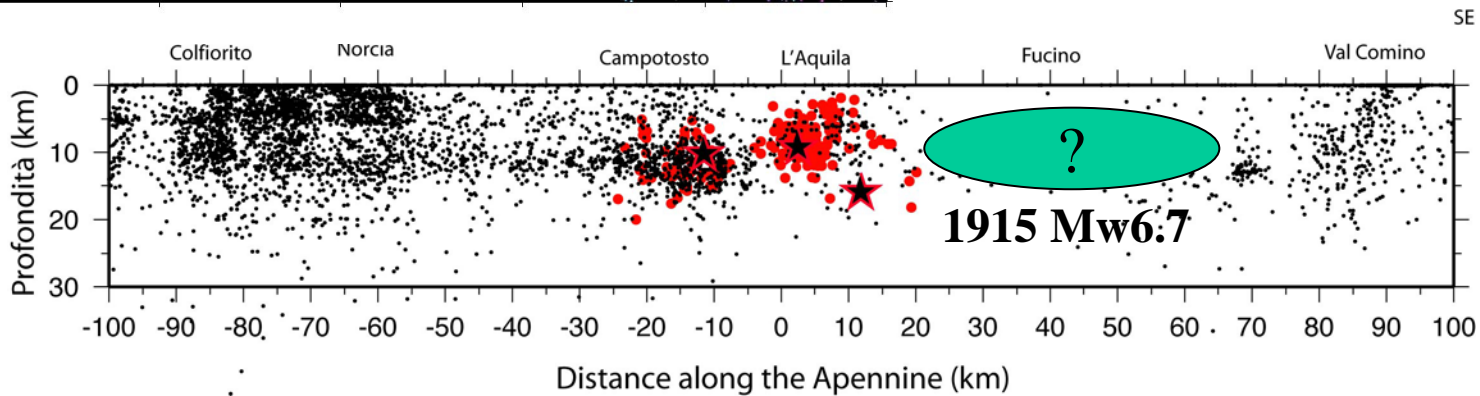
CPTI04 Catalogue

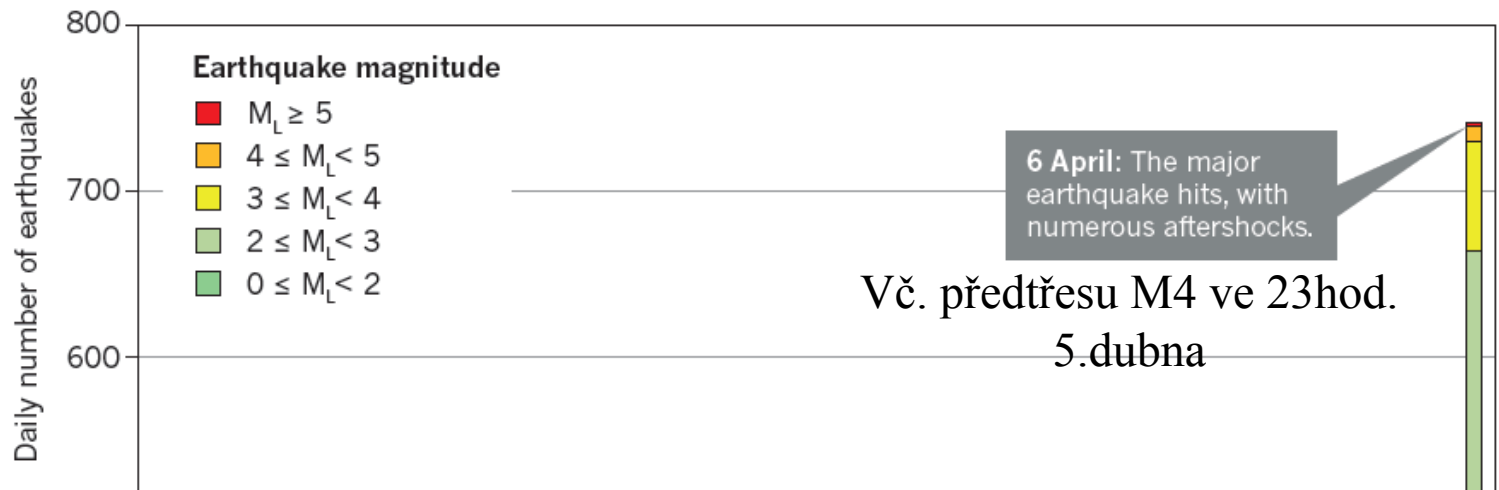




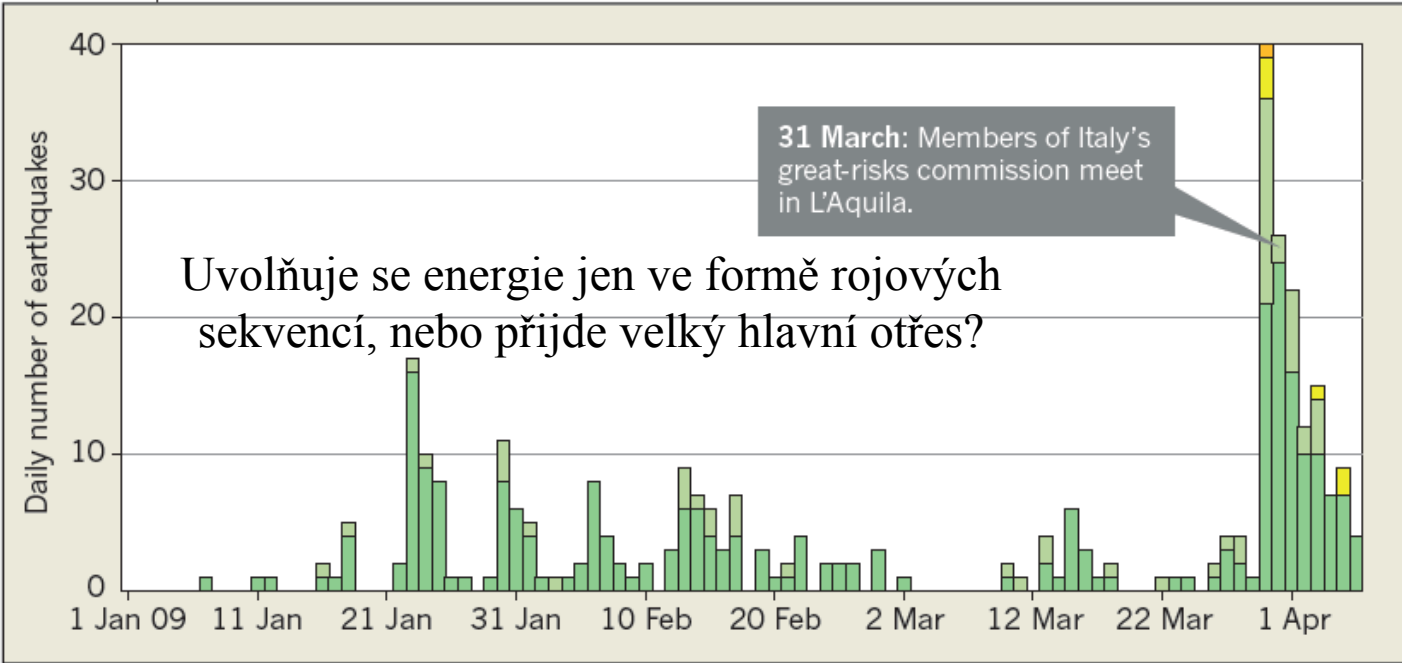
Seismicity in central Apennines CSI catalog 1980-2008 April 2009 seismic sequence

The seismic sequence is located at the border between a relatively high seismicity rate area to the North and a almost quiescent area to the South.

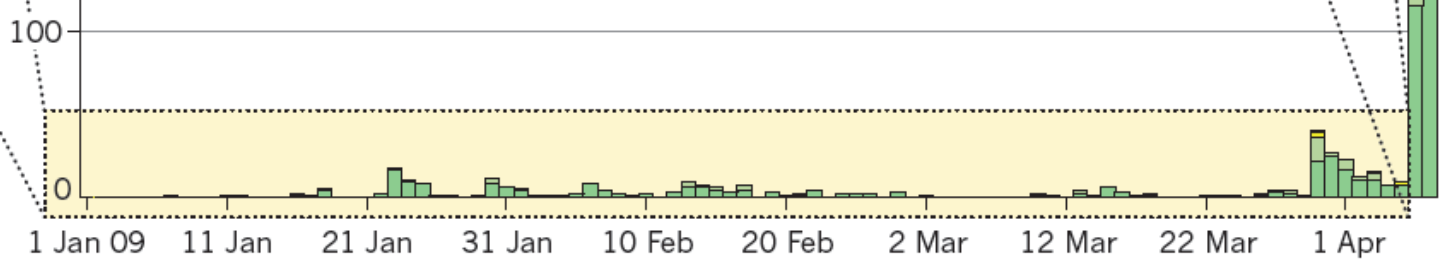




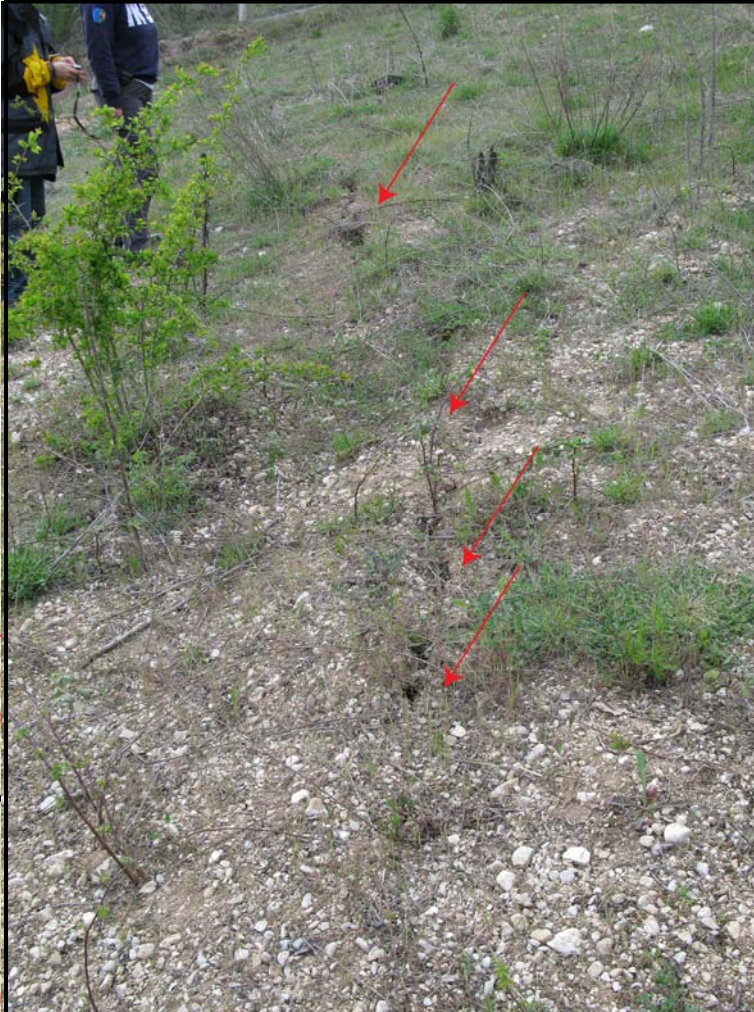
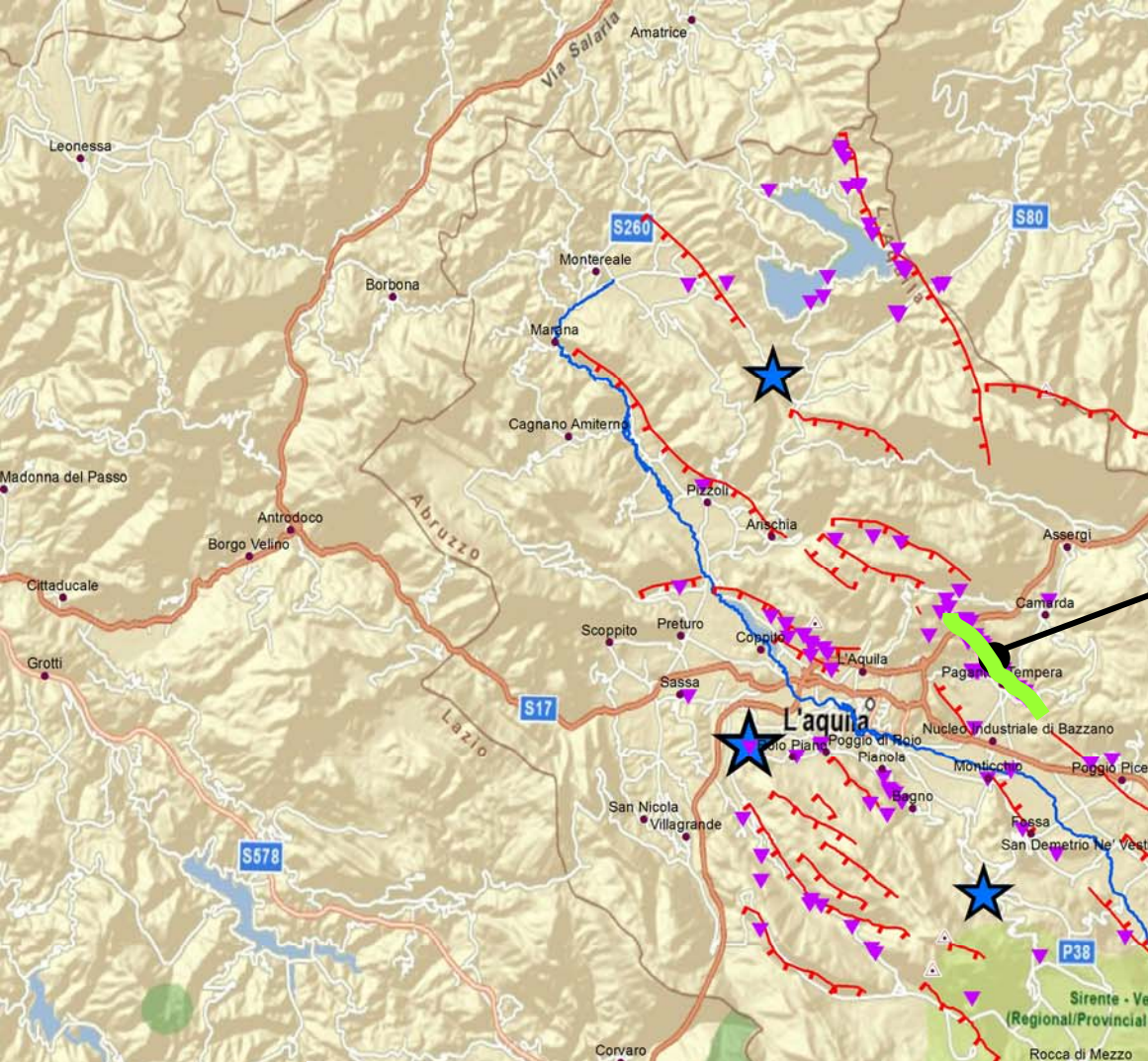
Vč. předtřesu M4 ve 23hod.
5.dubna



Uvolňuje se energie jen ve formě rojových sekvencí, nebo přijde velký hlavní otřes?



Coseismic effects observation points (pink triangles).
More than 200 sites were surveyed.



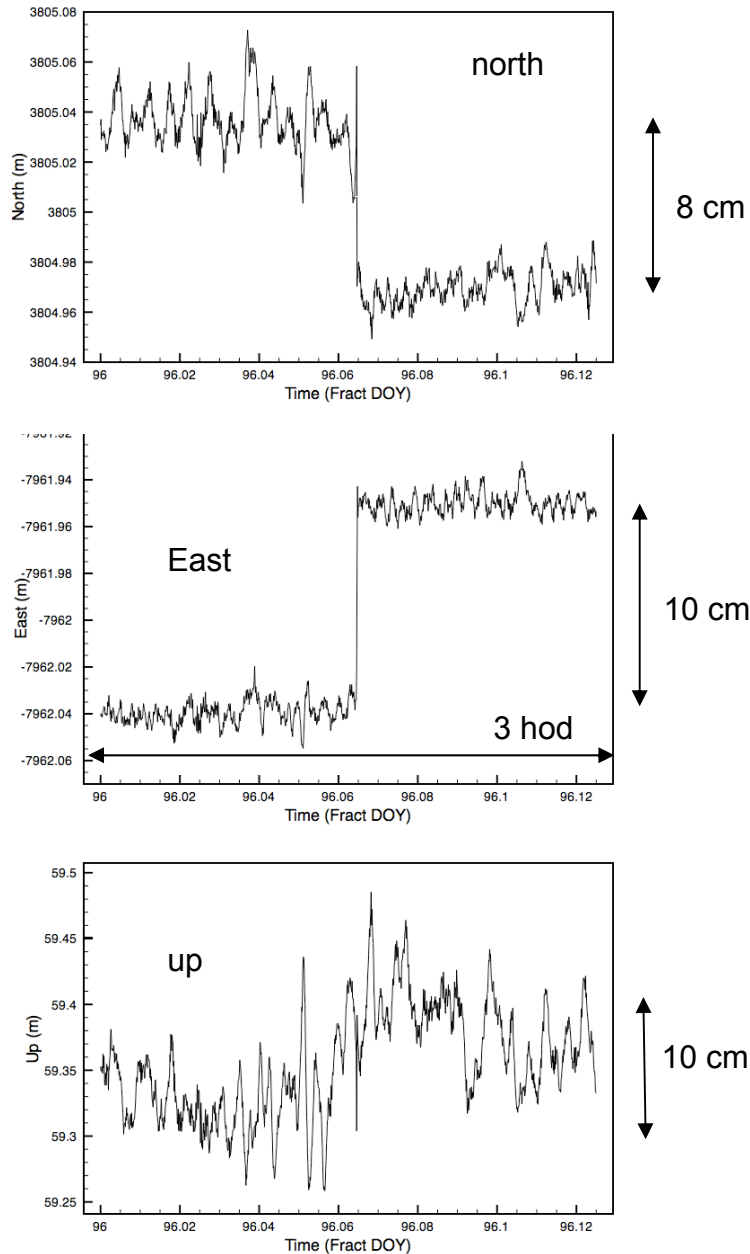
The ruptures cut across open fields, slopes, roads and manufacts and can be traced for about 5 km in a NW-SE direction; throw is to the SW.

The green line is the trace of the fault surface expression

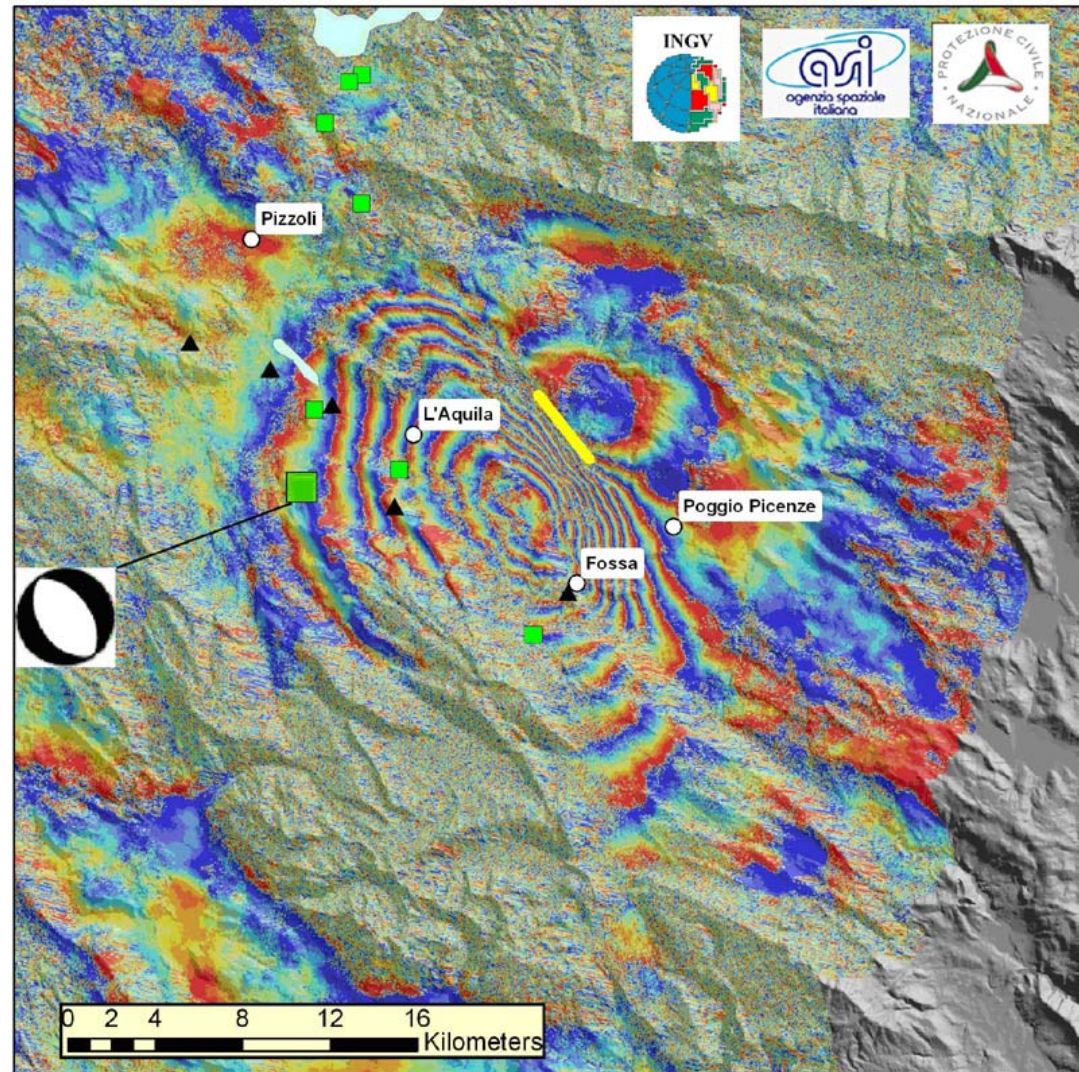


Continuous GPS

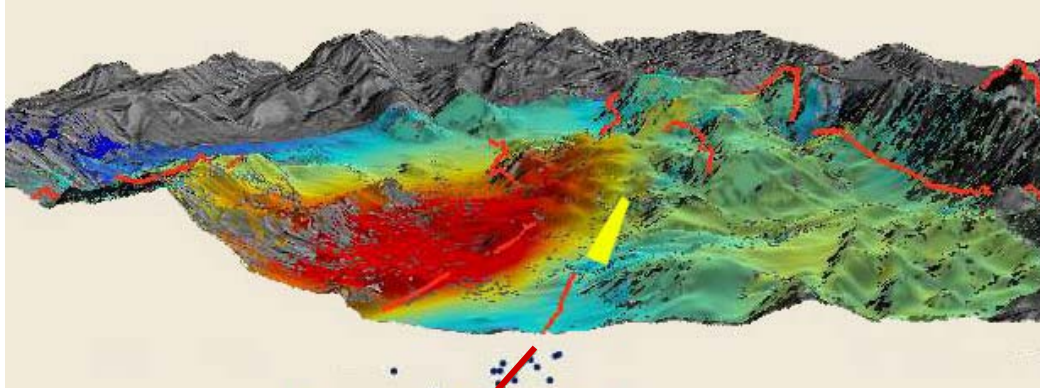
1Hz data Preturo site (L'Aquila)



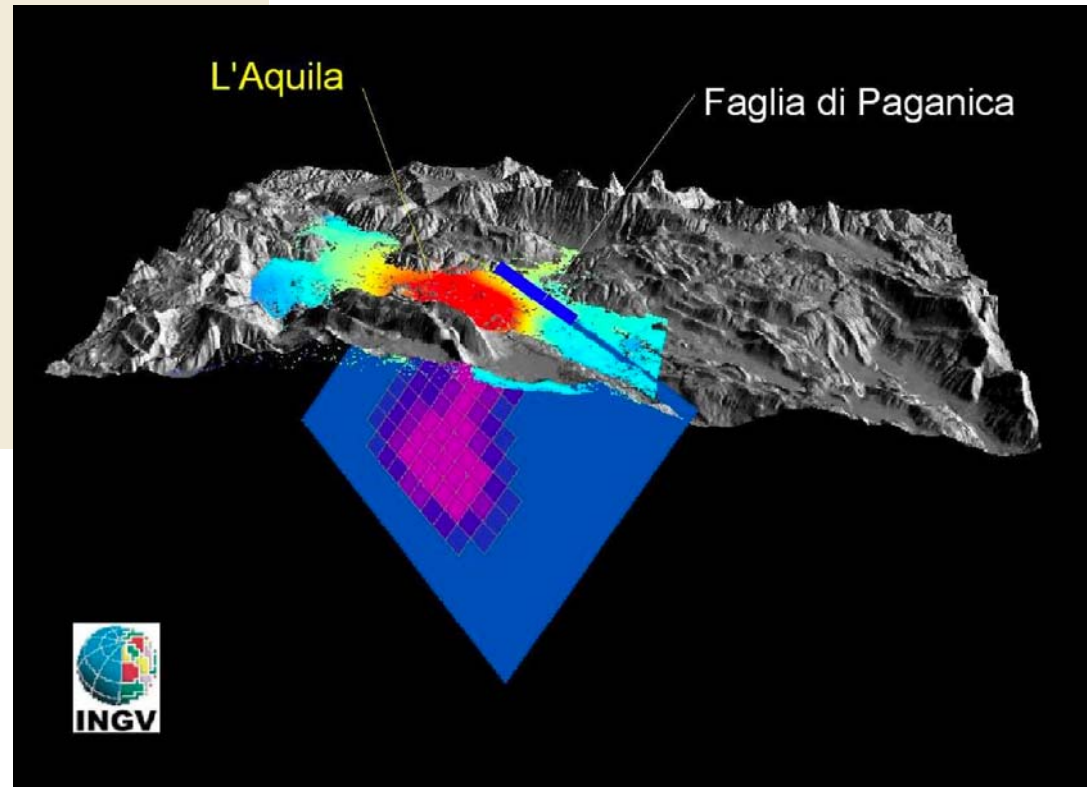
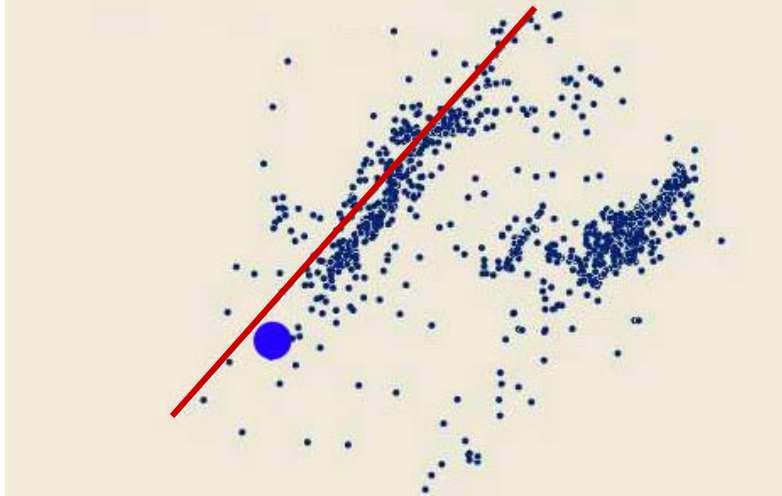
Družicová interferometrie (InSAR)



Relocated aftershocks



Validation:
Aftershock seismicity
confirms the model
fault geometry

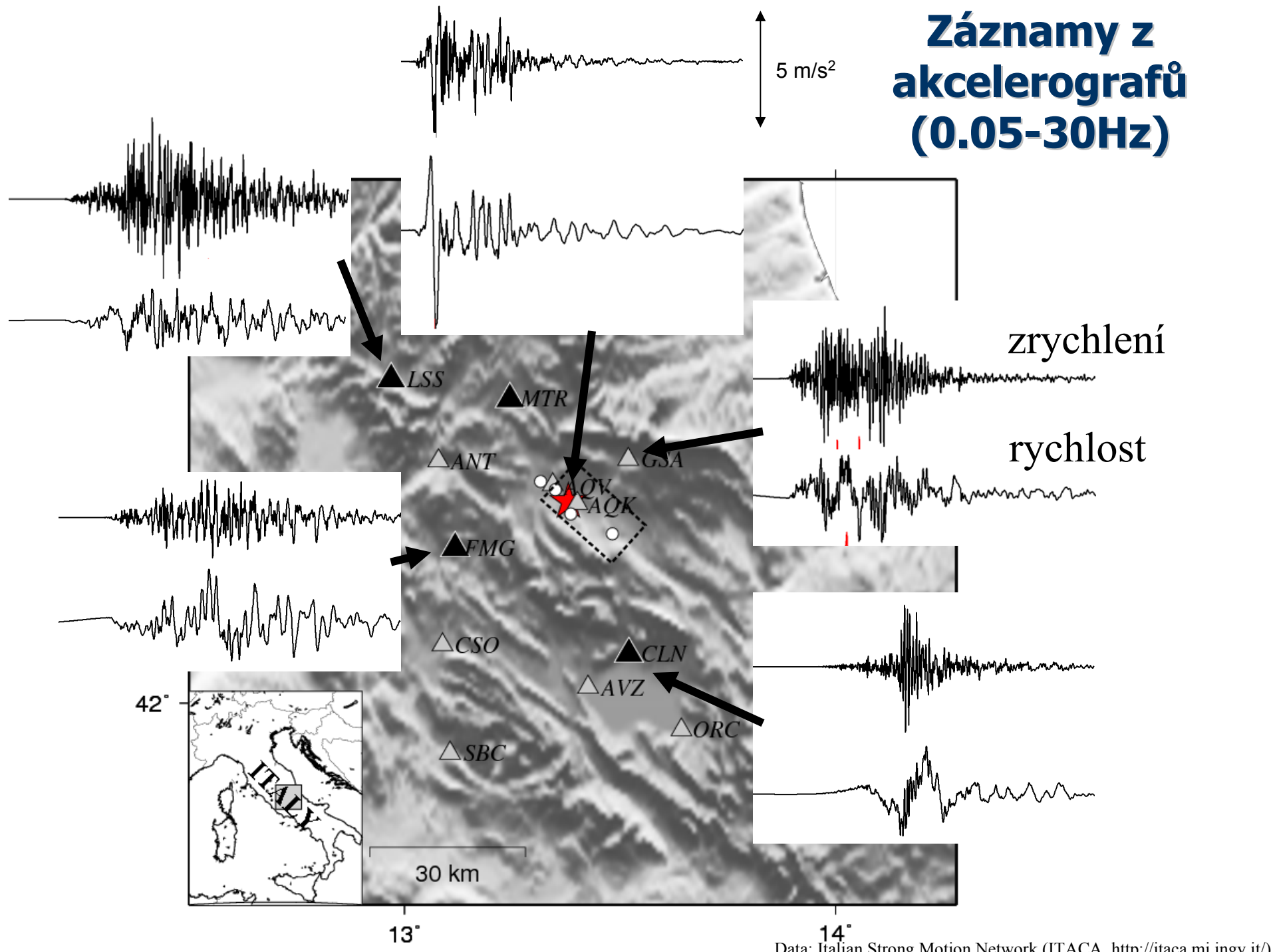


Naše výsledky

(ve spolupráci s INGV v Miláně)

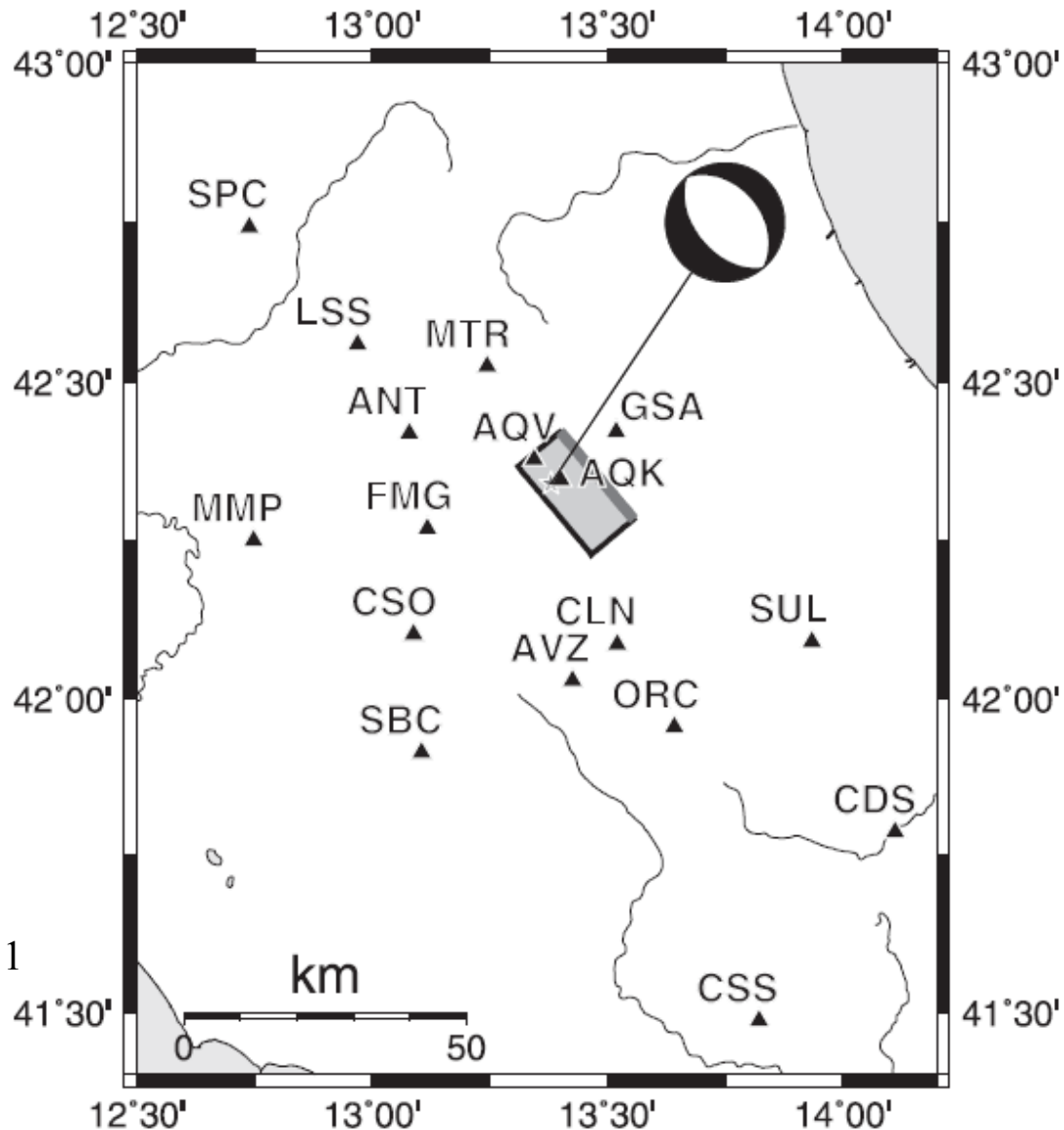
Záznamy z akcelerografů (0.05-30Hz)

5 m/s²



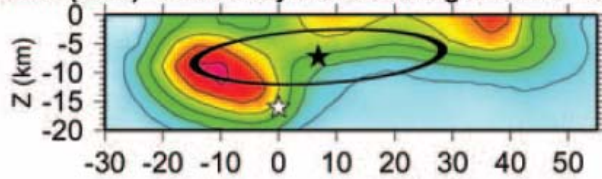
Skluzová inverze

- K poklesu na zlomu nedošlo všude ve stejný čas
- Čelo trhliny se šíří z hypocentra a postupně porušuje celý zlom
- Jak konkrétně šíření trhliny vypadalo v tomto případě?
- Důležité pro další porozumění dynamice seismického zdroje

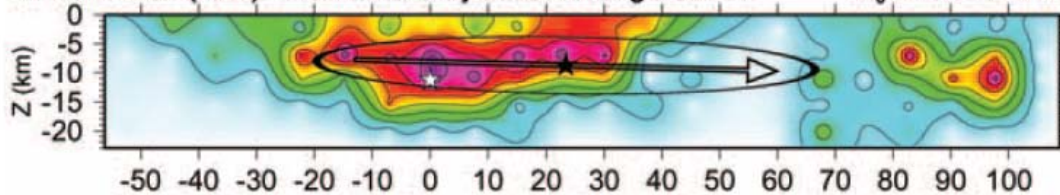


Problém: nejednoznačnost inverzí

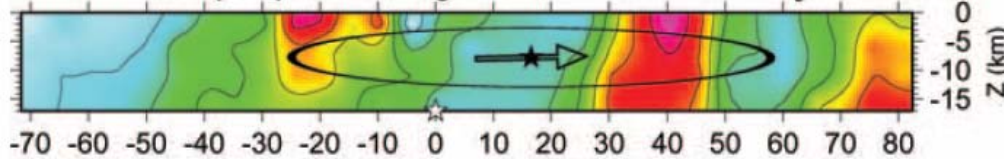
Yagi and Kikuchi (2000) - From body waves+strong motions $M_0 = 1.17 \cdot 10^{20}$ N.m



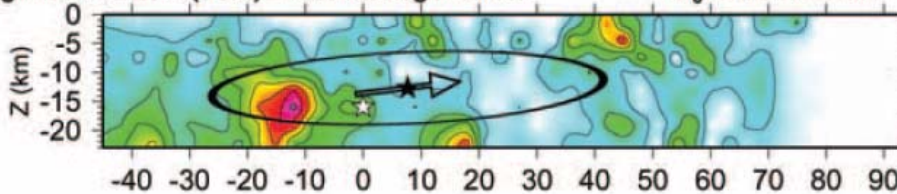
Delouis et al. (2000) - From SAR+body waves+strong motions $M_0 = 2.58 \cdot 10^{20}$ N.m



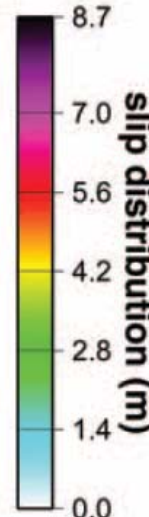
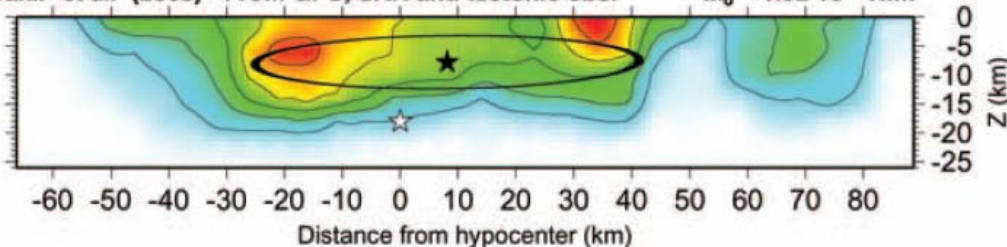
Bouchon et al. (2002) - From strong motions $M_0 = 2.62 \cdot 10^{20}$ N.m



Sekiguchi and Iwata (2002) - From strong motions $M_0 = 1.51 \cdot 10^{20}$ N.m



Cakir et al. (2003) - From GPS, SAR and tectonic obs. $M_0 = 1.92 \cdot 10^{20}$ N.m



Porovnání výsledků různých autorů pro stejně zemětřesení

Clévédé et al. (2004)
M7.4 1999 Izmit, Turecko

Jak výsledkům inverzí věřit?
Standardní praxe je neudávat rozlišení – nutno změnit!

Formulation of the slip inversion

- Representation theorem

$$u_j^s(t) = \iint \Delta \dot{u}(x, \tau) H_j^s(x, t - \tau) dx d\tau, \quad \longrightarrow \quad d = \mathbf{G}m,$$

- Vector d contains displacement waveforms
- Vector m contains discretized slip velocity functions on the fault; each of the samples represent a space-time point source
- Each column of G contains elementary seismograms due to the space-time point sources

- Solution by Truncated Singular Value Decomposition (TSVD)

Truncated Singular Value Decomposition (TSVD)

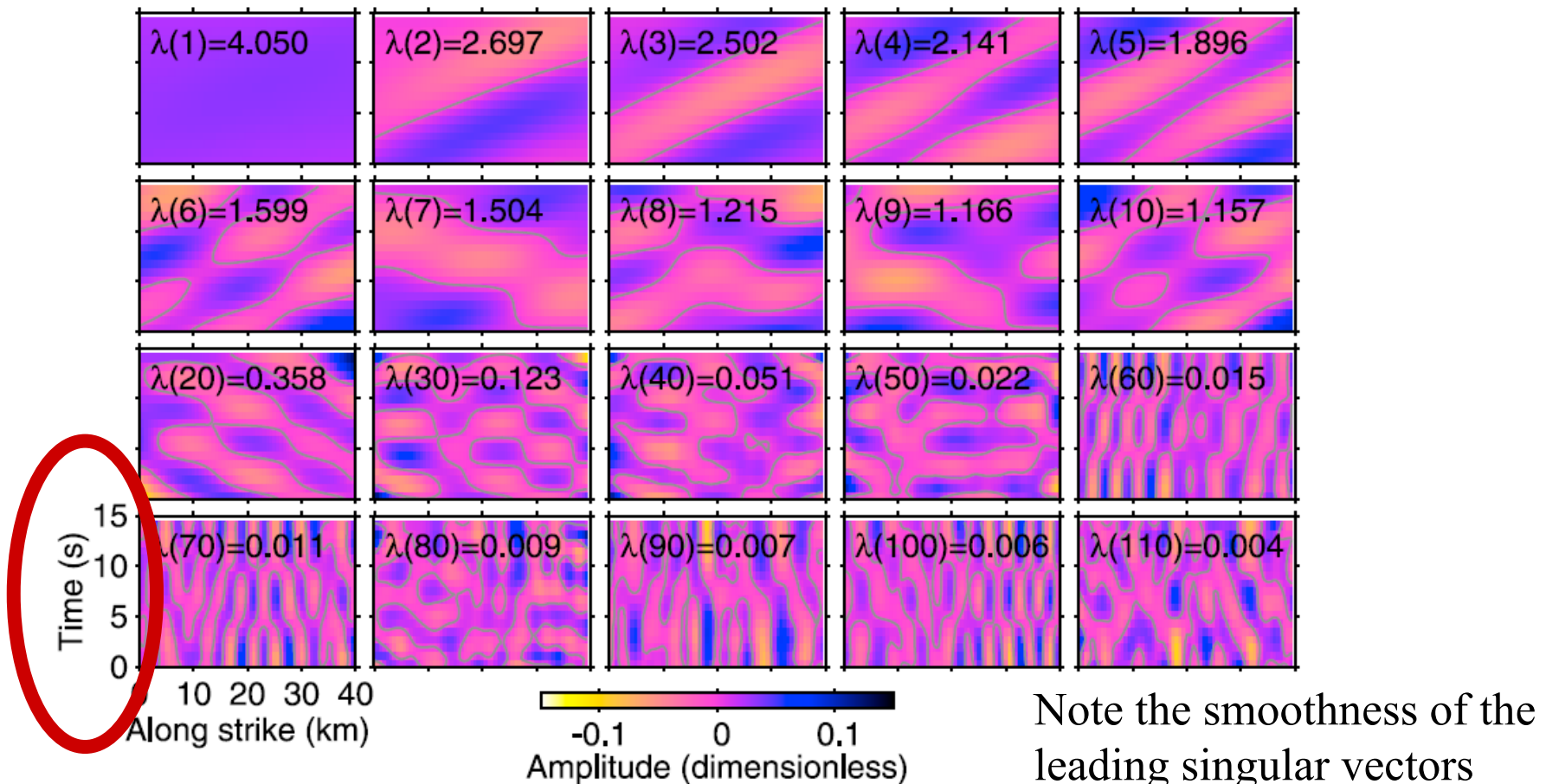
- Generalized inverse matrix

$$\tilde{\mathbf{G}} = \mathbf{V}\mathbf{\Lambda}^{-1}\mathbf{U}^T \longrightarrow \tilde{\mathbf{m}} = \sum_{i=1}^M \frac{\mathbf{U}^{(i)} \cdot \mathbf{d}}{\lambda_i} \mathbf{V}^{(i)}$$

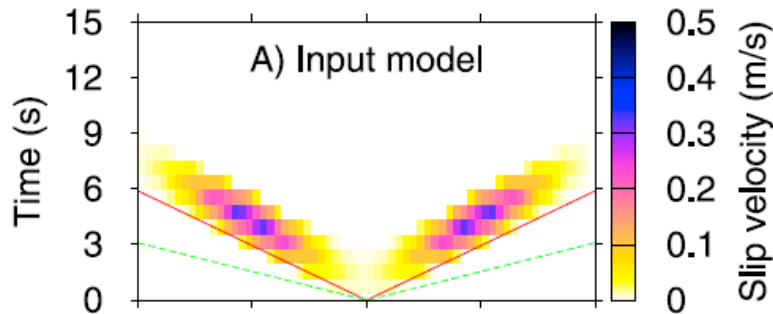
- The inverse solution $\tilde{\mathbf{m}}$ is composed of singular vectors \mathbf{V} that are combination of model parameters, i.e. “slip patterns”
- Vector \mathbf{U} are normalized seismograms for the corresponding slip pattern \mathbf{V}
- λ 's are singular values
- Truncation necessary not only because of the data error, but also due to incorrect Green's functions (imprecise knowledge of propagation medium)
- Truncation causes not only loss of resolution, but can also lead to incorrect interpretations!

Synthetic tests for a LINE fault

- Example of singular vectors for three stations around a fault (near regional data)

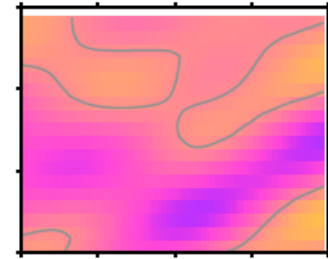


Synthetic tests for a LINE fault

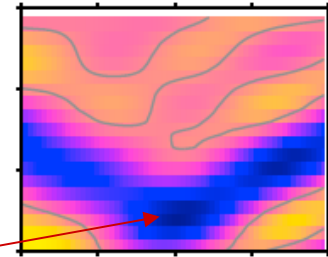


- Various truncation levels for the bilateral rupture
- The truncation in real application dictated by the imperfect Green's functions
- ...in double precision the result is perfect

$$\lambda_{\min} = \lambda_{\max}/5$$



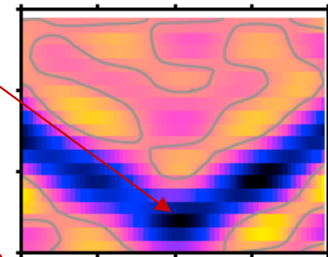
$$\lambda_{\min} = \lambda_{\max}/10$$



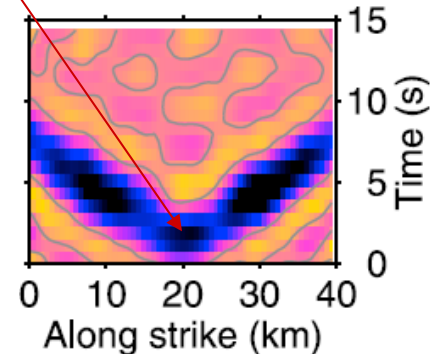
Typical value in real data analysis

Spurious asperity!

$$\lambda_{\min} = \lambda_{\max}/100$$



$$\lambda_{\min} = \lambda_{\max}/1000$$

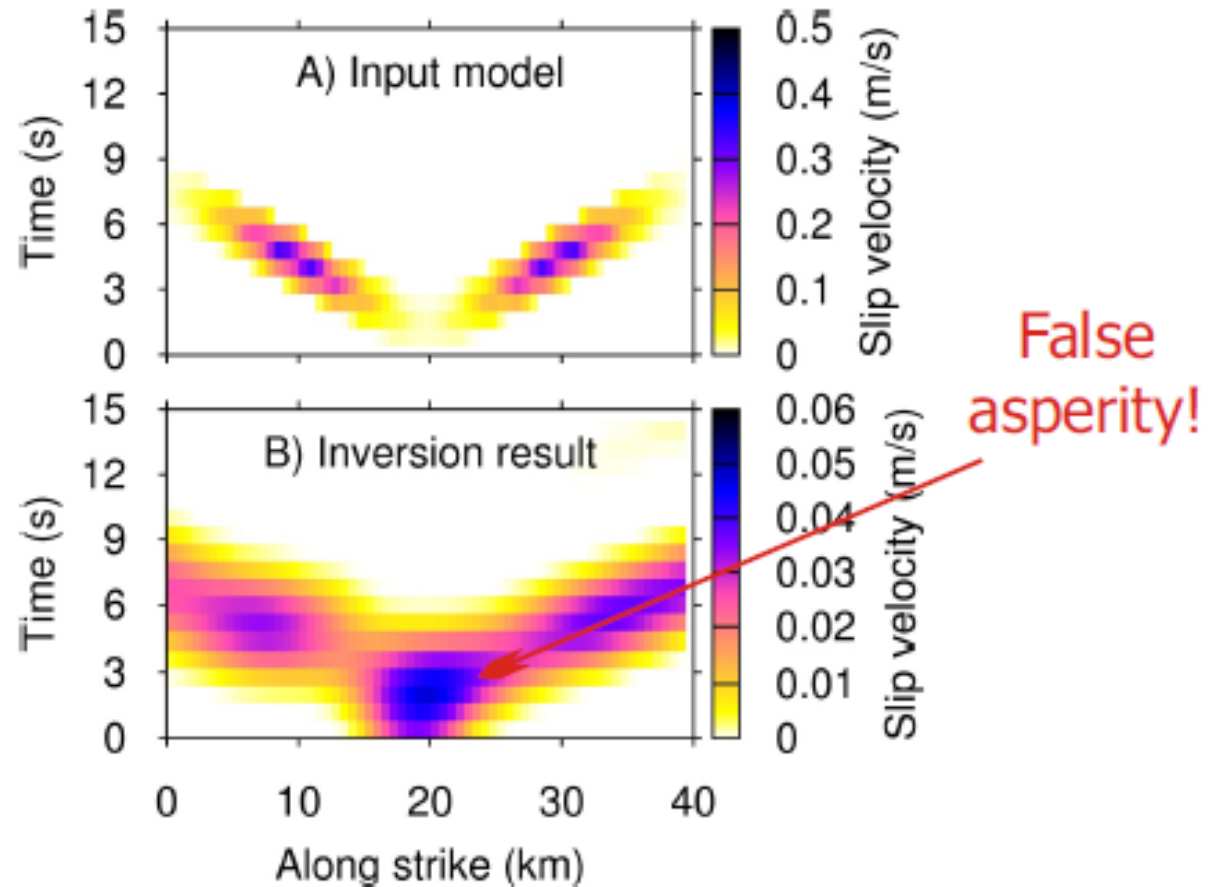


Time (s)

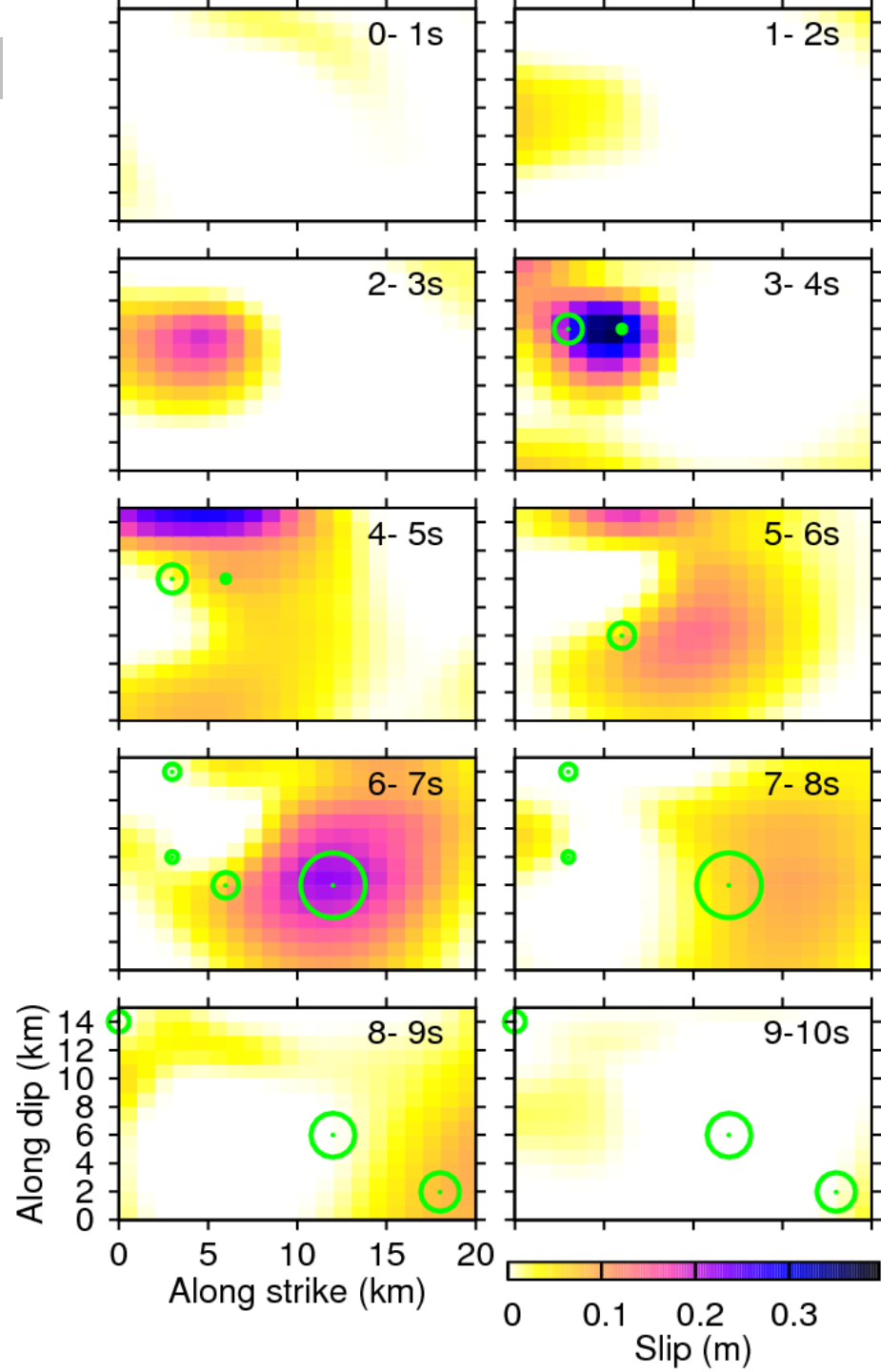
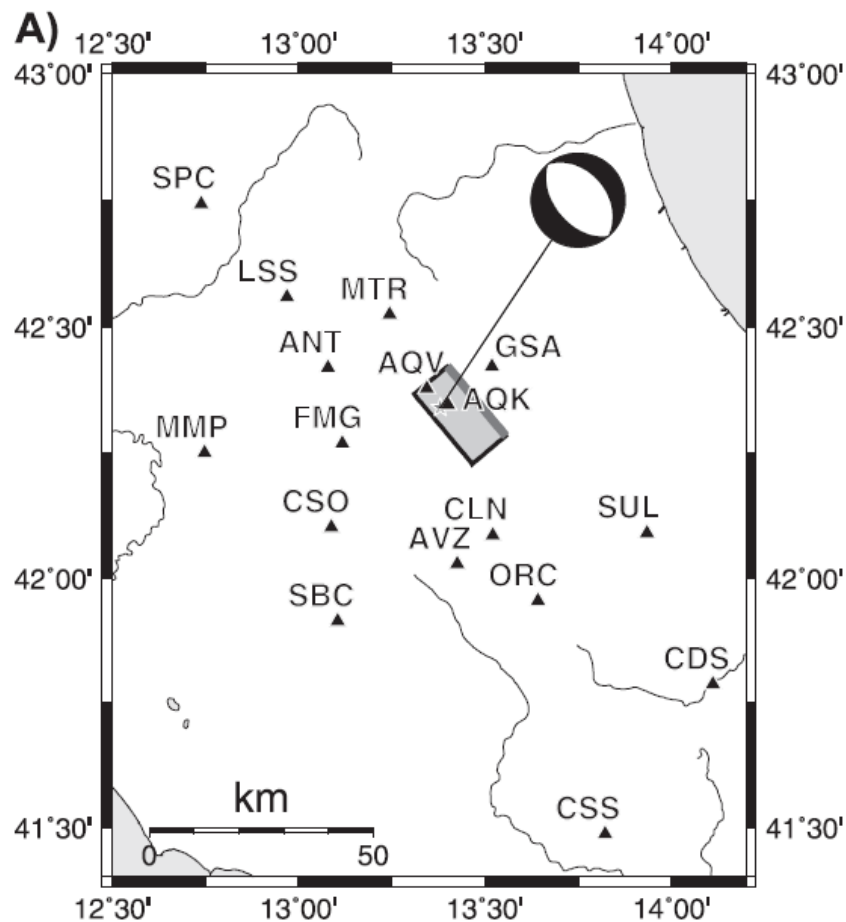
Along strike (km)

Synthetic tests for a LINE fault

- Note that since the singular vectors are smooth, inversion employing smoothing as stabilization (instead of truncation) does not help...



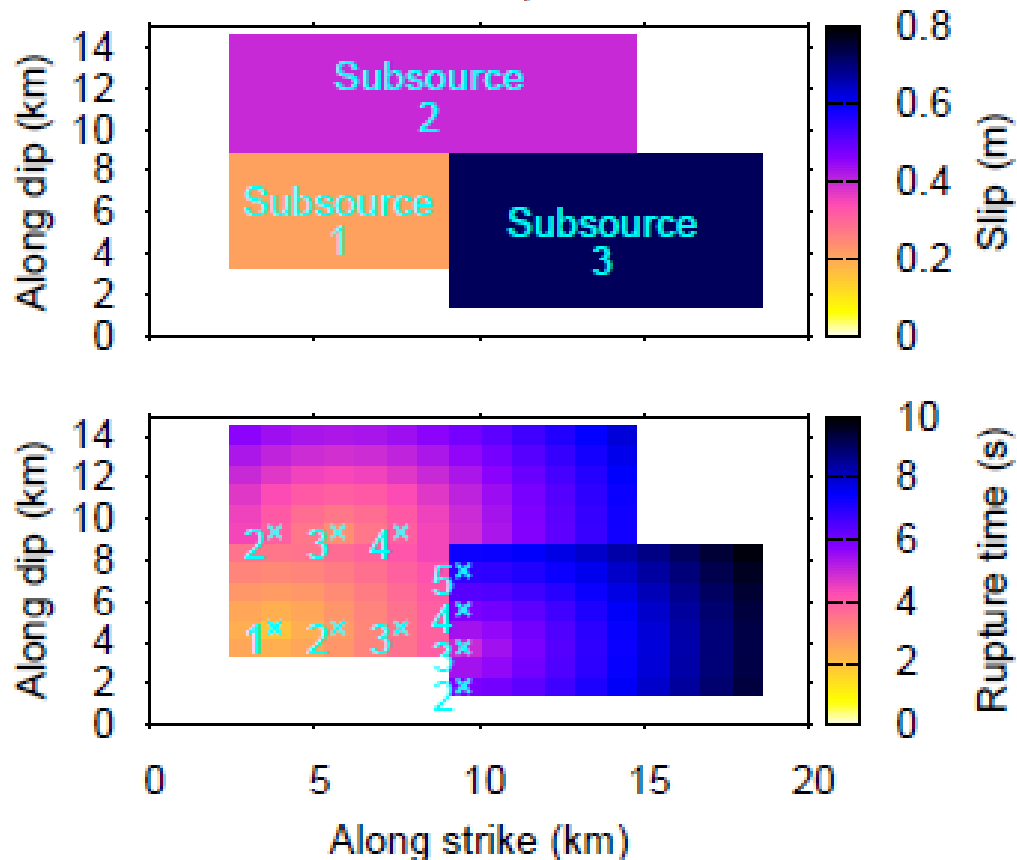
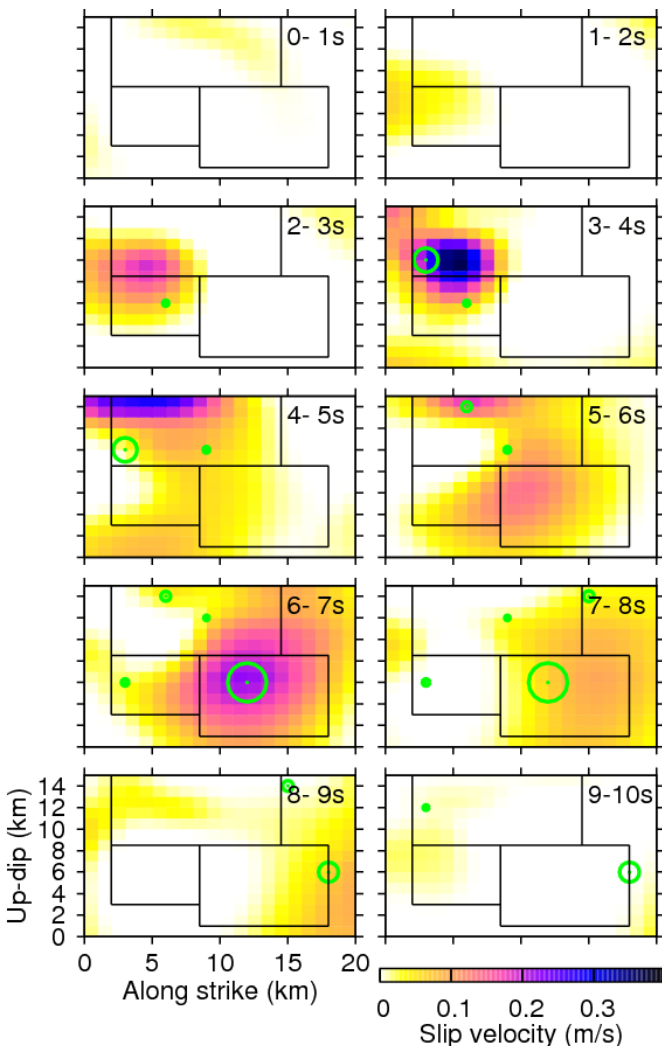
TSVD inversion of **real** **data** of the 2009 L'Aquila Mw 6.2 (**rectangular fault**)

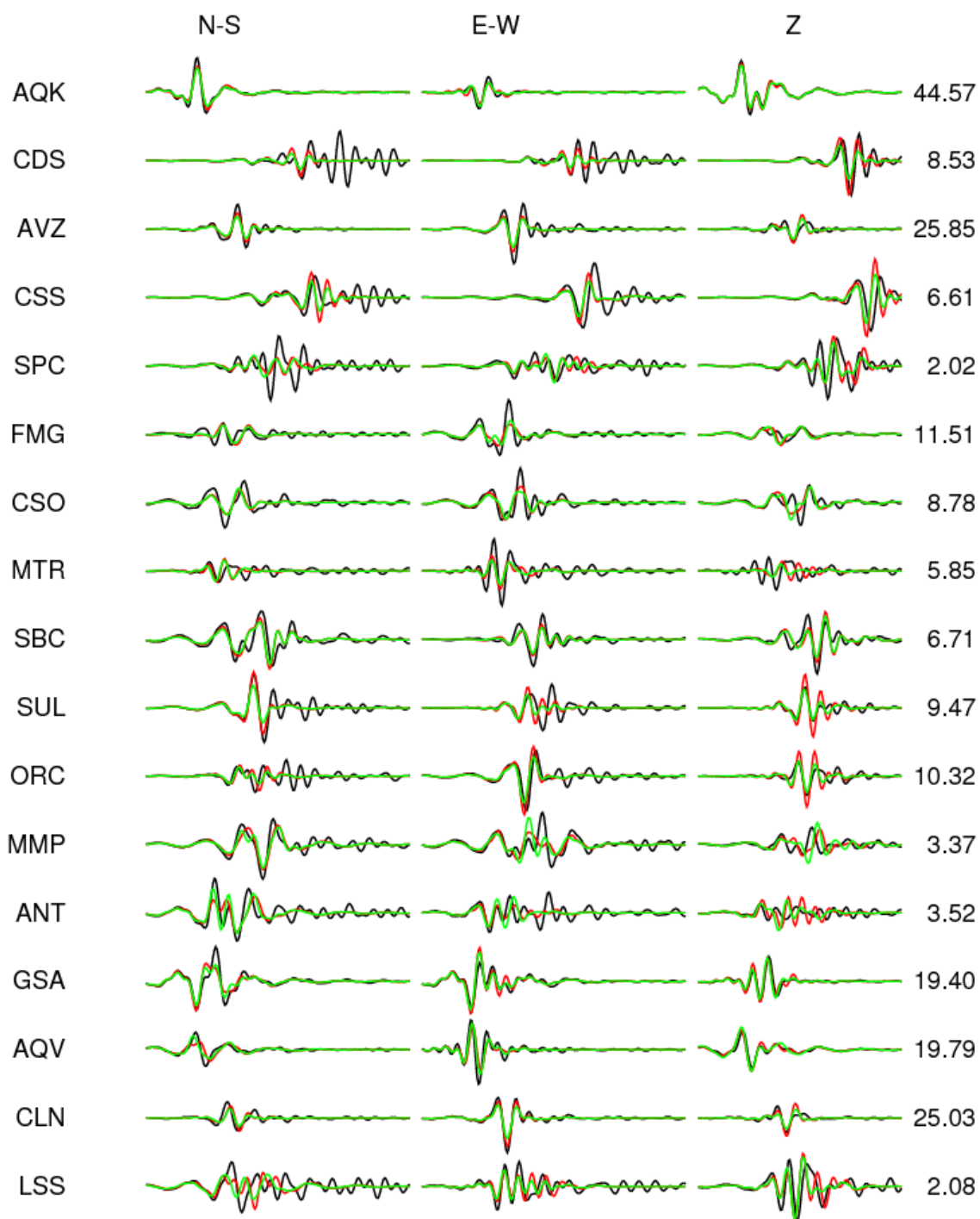


Alternative solution: Multiple Finite-Extent (MuFEx) source model

- Simplification of the model based on the TSVD result

Důvod: „šikovně“ snížit počet fyzikálních parametrů a odhadnout jejich neurčitost

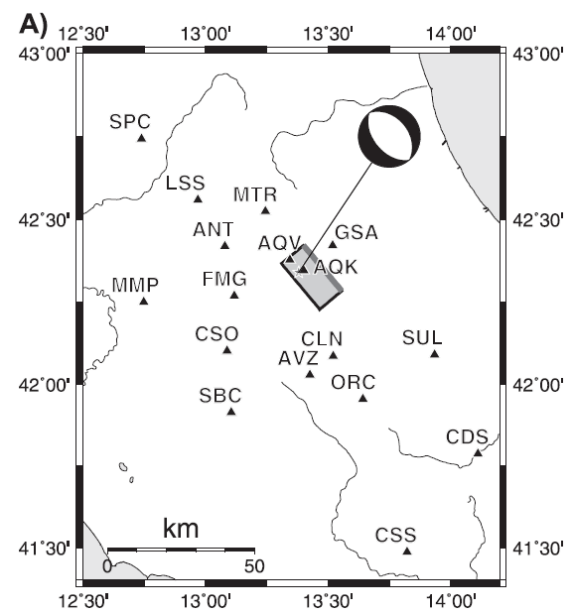




Displacement waveforms
 100s windows
 Filter 0.05-0.30 Hz
 Amplitudes in mm

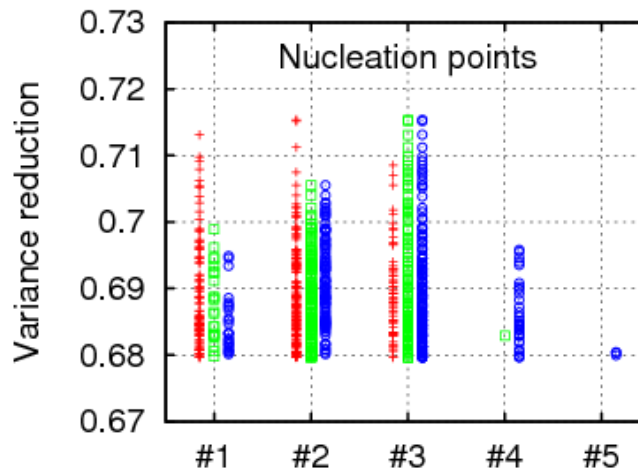
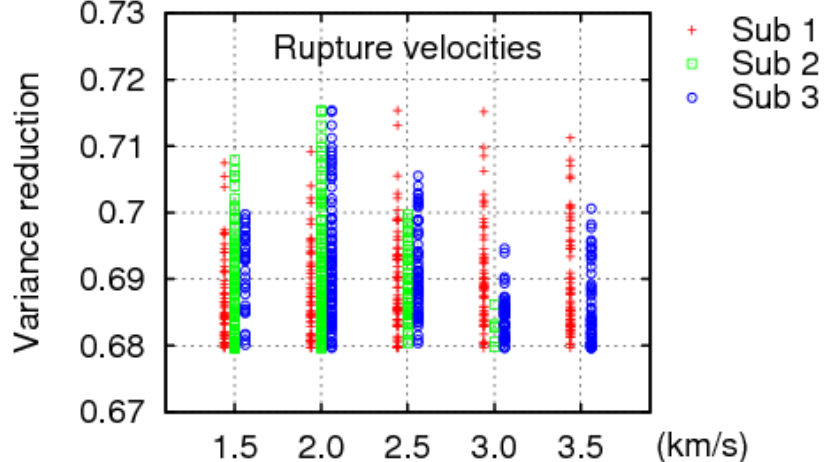
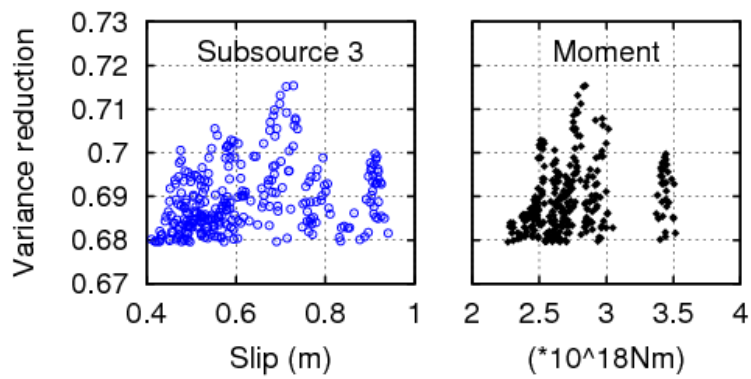
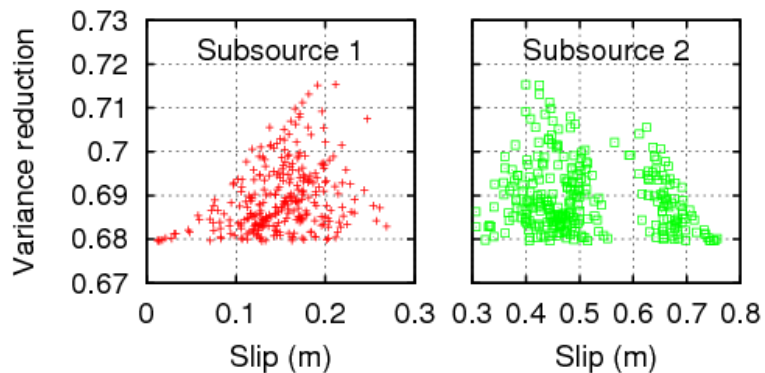
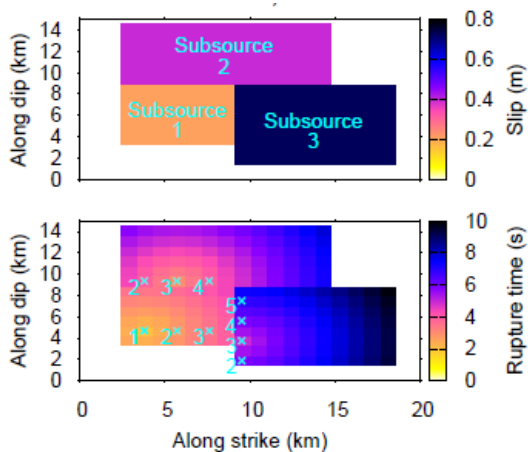
Observed
 MuFEx model
 TSVD

Téměř stejně dobré
 vystižení dat (VR=0.7)...

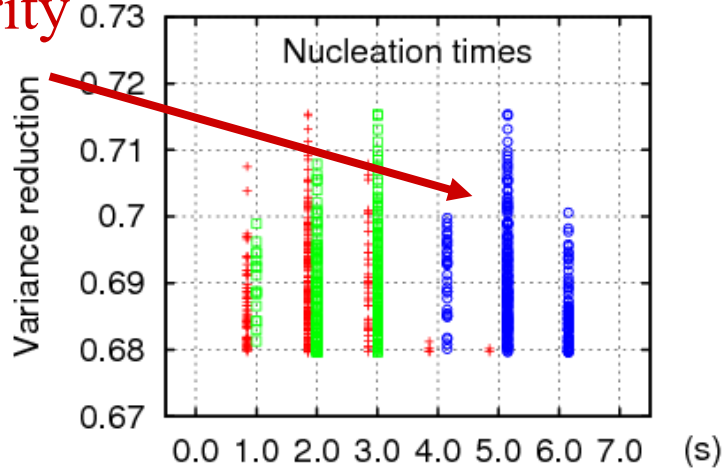


Přidaná hodnota: analýza neurčitosti řešení

Best fitting model

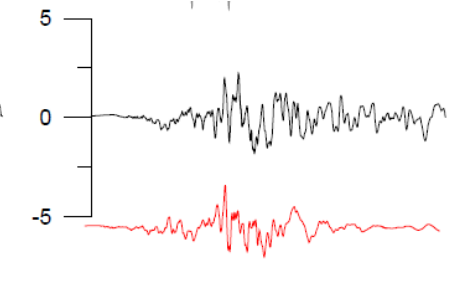
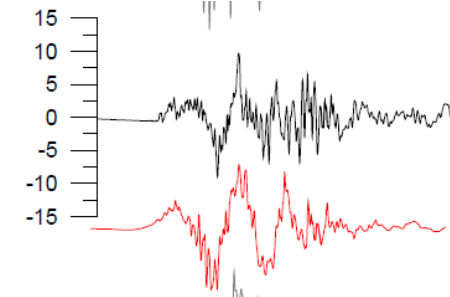
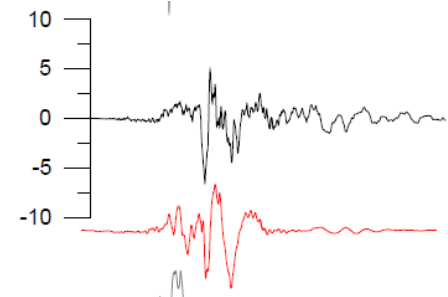
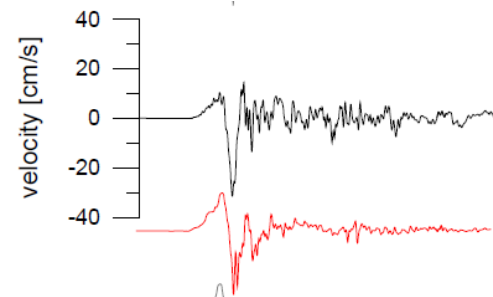
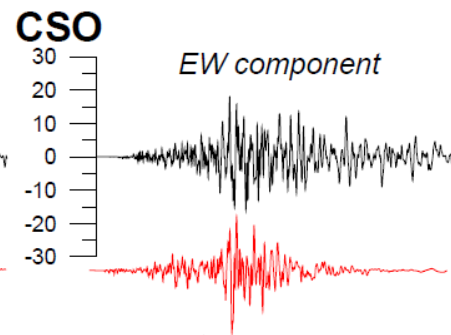
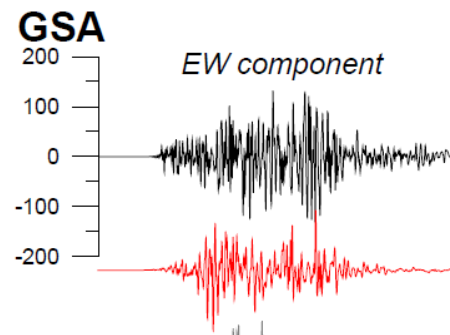
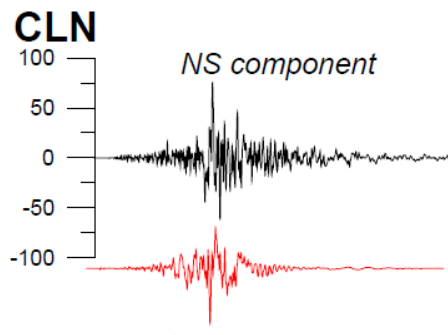
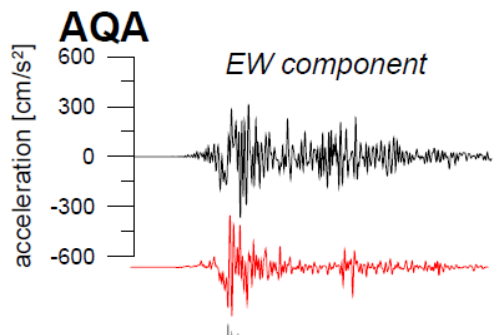


Asperity delay



Rozšíření modelování do oblasti 10 Hz (silné pohyby)

- Zjištěný model skluzu je doplněn o stochastickou vysokofrekvenční část



Reálná data
Syntetická data

Shrnutí

- Zemětřesení L` Aquila patří k nejlépe zaznamenaným jevům v Evropě
- V první etapě INGV aplikoval veškeré rutinní postupy na analýzu geodetických, geologických a seismických dat
- V druhé etapě tato kvalitní data iniciovala vznik nových metod (např. TSVD, MuFEx, a jiné v jiných zemích)
- Efektivní spolupráce s italskými kolegy: Praha – teorie, Itálie – data (=> 2 články v J. Geophys. Res.)
- Nové poznatky o zemětřeseních (střípky do mozaiky):
 - Složitost zlomového procesu (zpoždění trhliny)
 - Interpretace procesu porušení reologickými vlastnostmi zlomu a jeho okolí (Di Stefano, 2011)
 - Výzkum nukleačního procesu (Ellsworth a Chiaraluce, 2009)
 - Postseismická relaxace (Cheloni et al., 2010)
- Co bude dál: hledání nových zlomů, paloseismologie (Falcucci a kol., 2011), dynamický model zdroje
- Společenská odpovědnost seismologů (?); sociologie