Uncertainty Quantification in Earthquake Source Studies:

The SIV-Initiative and its Implications for Source Parameter Estimation

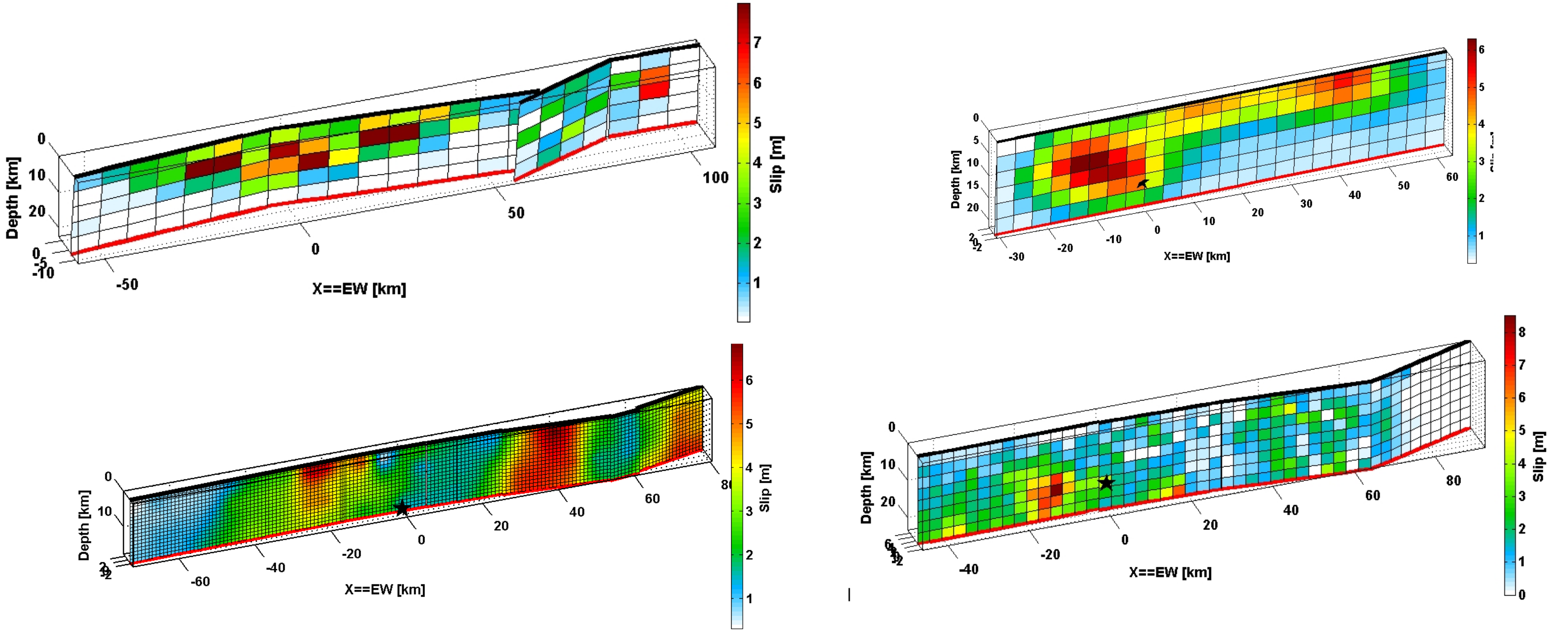
SIV = Source Inversion Validation

Overview

- The Source Inversion Validation (SIV) project
- Source parameters from finite-fault rupture models

- Finite-source inversion are done routinely today, using a variety of inversion / modeling approaches, different data sets and processing steps
- We use the slip models to infer rupture dynamics, for source-characterization for ground-motion simulations, to perform Coulomb stress modeling, etc. pp
- If multiple slip-inversion solutions exist for a single earthquake we often find striking differences in the slip maps!

A suite of models for the 1999 Izmit (M 7.5) earthquake



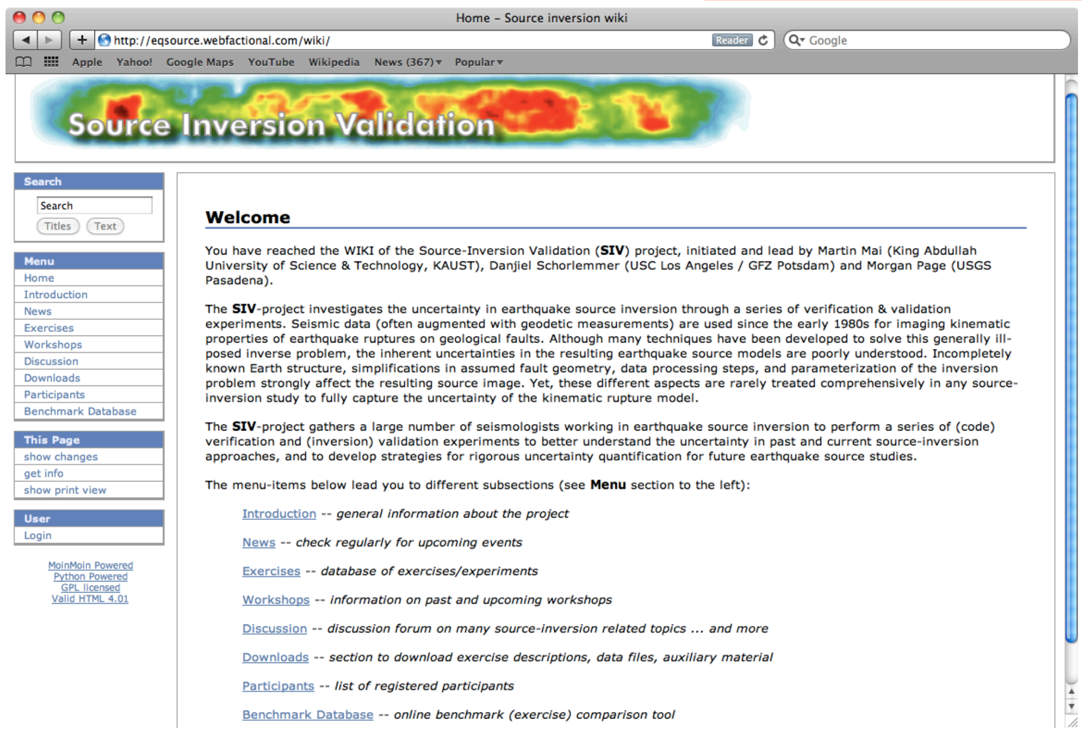
Source Inversion Validation

The Source Inversion Validation (SIV) project

- Cooperative initiative for (code) verification and (inversion) validation
- Goal: rigorous uncertainty quantification in earthquake rupture modeling
- several workshops since 2008, following the 2006/2007 SPICE "blindtest" for earthquake source inversion

eqsource.webfactional.com/wiki

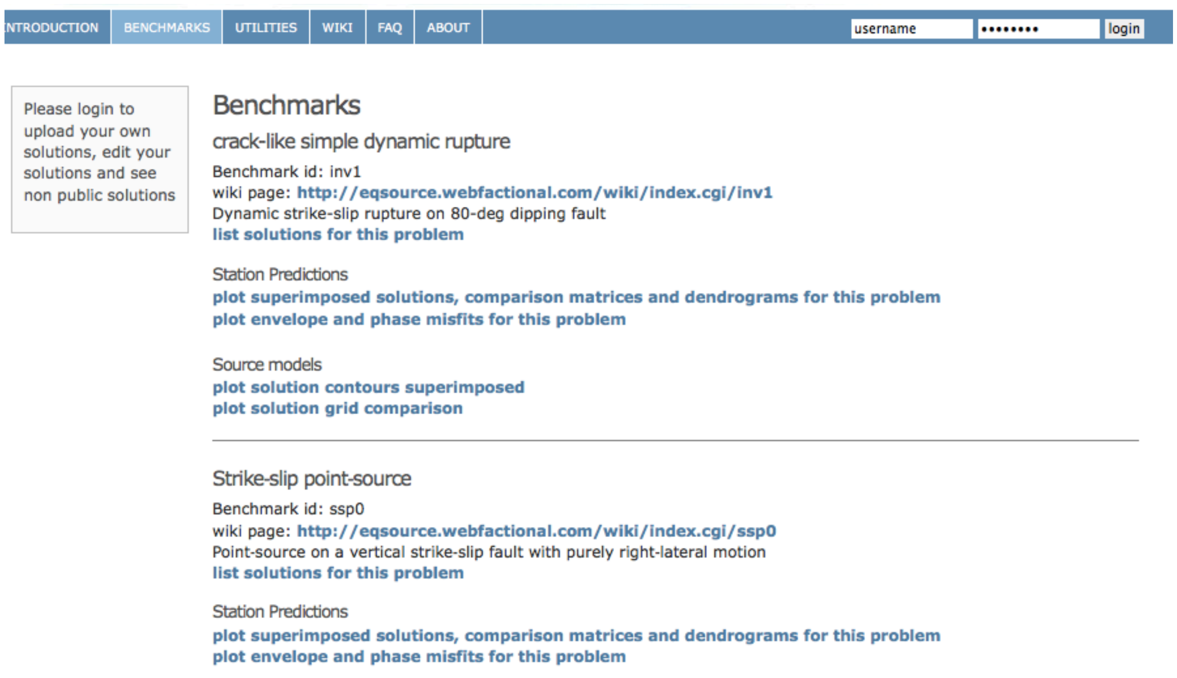
NEW: http://equake-rc.info



Strategy

- **Develop a series of benchmarks with varying degree of complexity, with and without "noise" in the data (and perhaps in some of the input parameters)**
  - **4 forward-modeling tests and 2 inversion problems are available (3rd to be released Oct 2012)**
- **All benchmarks remain accessible for all interested users; only for the most recent test the solution (input model) is not released**

Online list of all benchmarks



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Please login to upload your own solutions, edit your solutions and see non public solutions

Benchmarks

crack-like simple dynamic rupture

Benchmark id: inv1
wiki page: http://eqsource.webfactional.com/wiki/index.cgi/inv1
Dynamic strike-slip rupture on 80-deg dipping fault
list solutions for this problem

Station Predictions
plot superimposed solutions, comparison matrices and dendrograms for this problem
plot envelope and phase misfits for this problem

Source models
plot solution contours superimposed
plot solution grid comparison

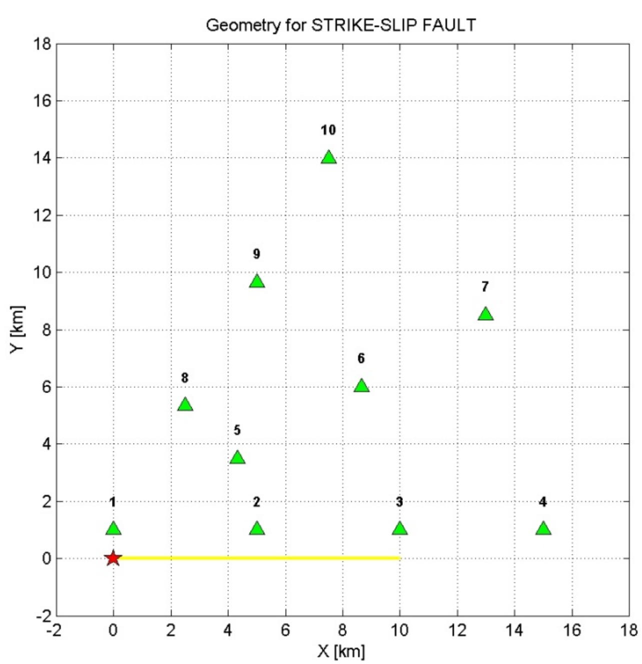
Strike-slip point-source

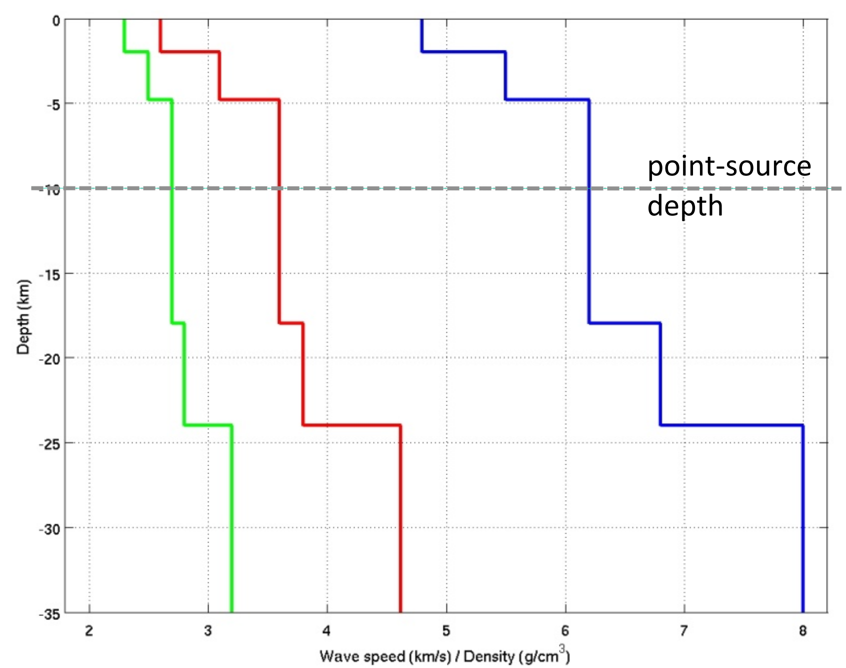
Benchmark id: ssp0
wiki page: http://eqsource.webfactional.com/wiki/index.cgi/ssp0
Point-source on a vertical strike-slip fault with purely right-lateral motion
list solutions for this problem

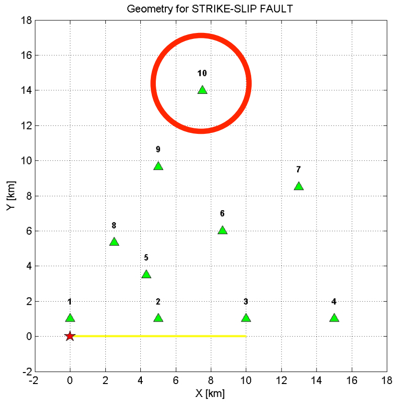
Station Predictions
plot superimposed solutions, comparison matrices and dendrograms for this problem
plot envelope and phase misfits for this problem

Step 0: Green's Function Validation

- **Forward problem: are we able to compute the Green's function correctly?**
- **The SIV-project started with a zero-order test to verify GF-computations:**
  - point-source at 10 km depth, parameterized as a 1 x 1 km^2 slip patch with homogeneous slip and boxcar slip-function of duration $\tau_r = 0.2$ sec
  - The shear-modulus at the given depth result in: M_w 4.992, $M_0 = 3.4992 \times 10^{16}$
  - Two cases: left-lateral strike-slip on vertical fault; thrust-faulting on 40° dipping fault

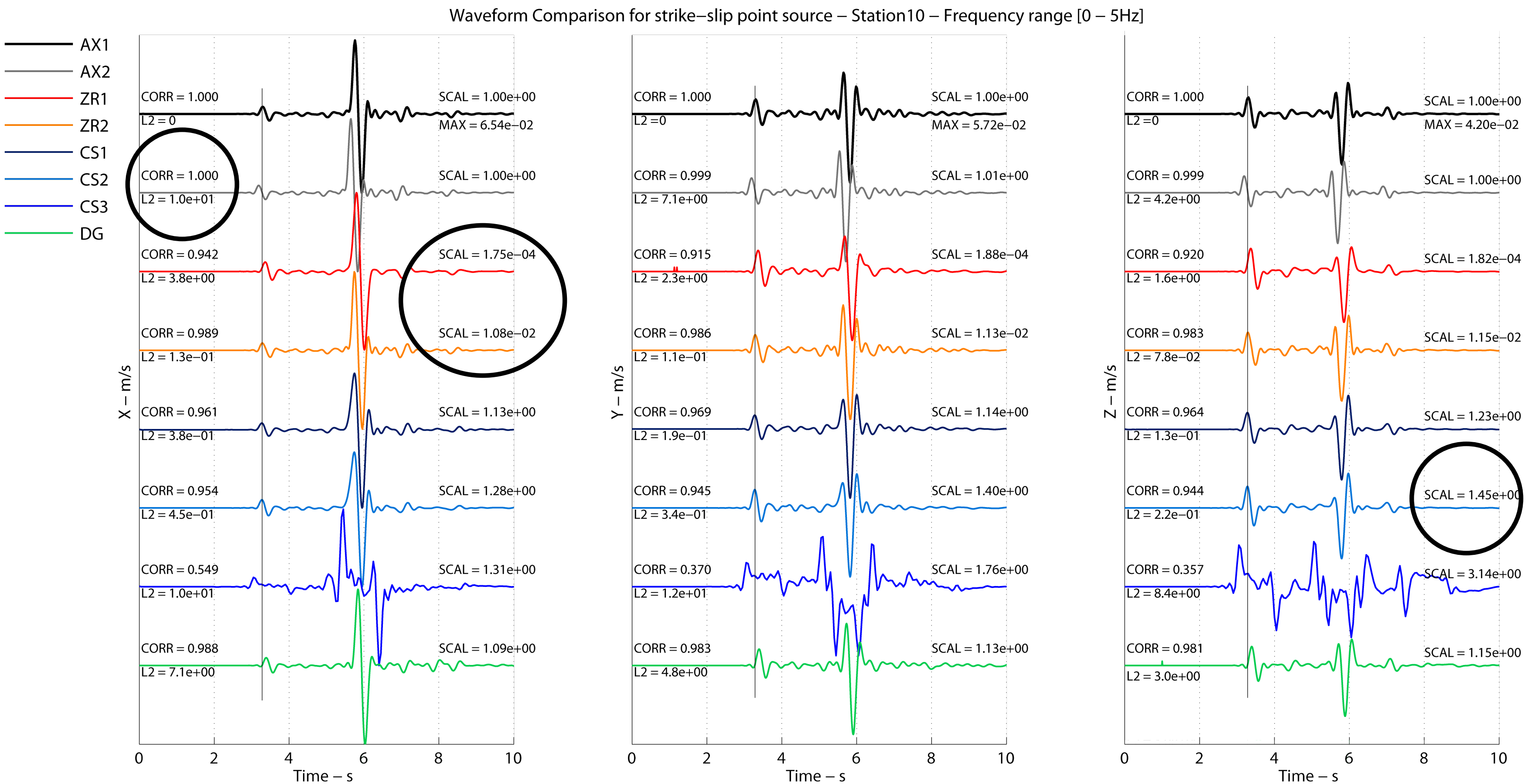




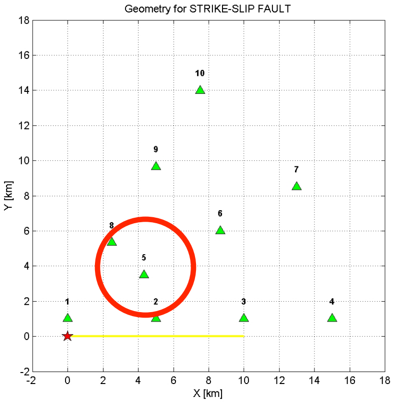


Source Inversion Validation

Strike-slip points-source, single site



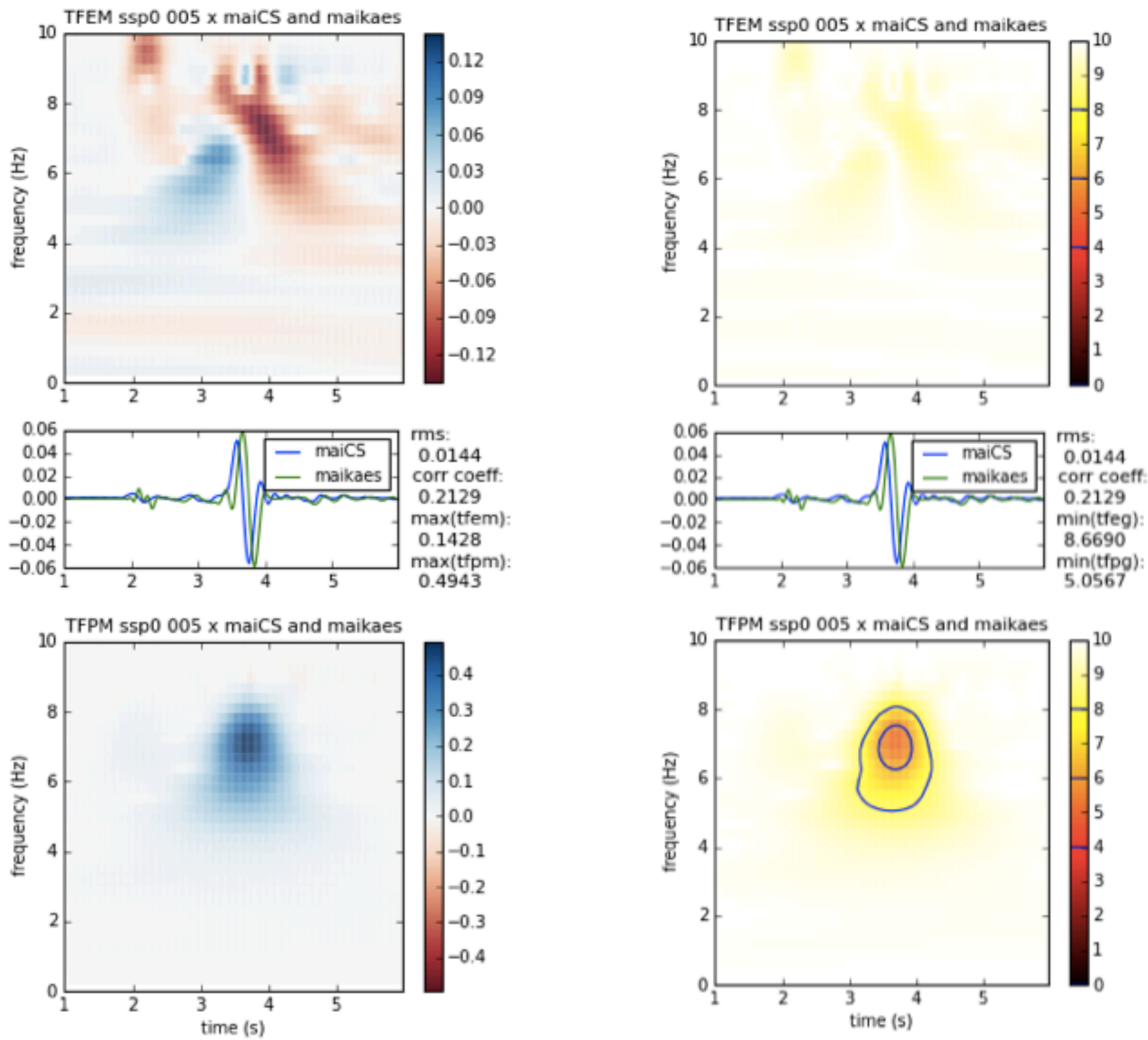
Source Inversion Validation



Strike-slip points-source, single site, two methods

Time-frequency envelope

Time-frequency phase mist

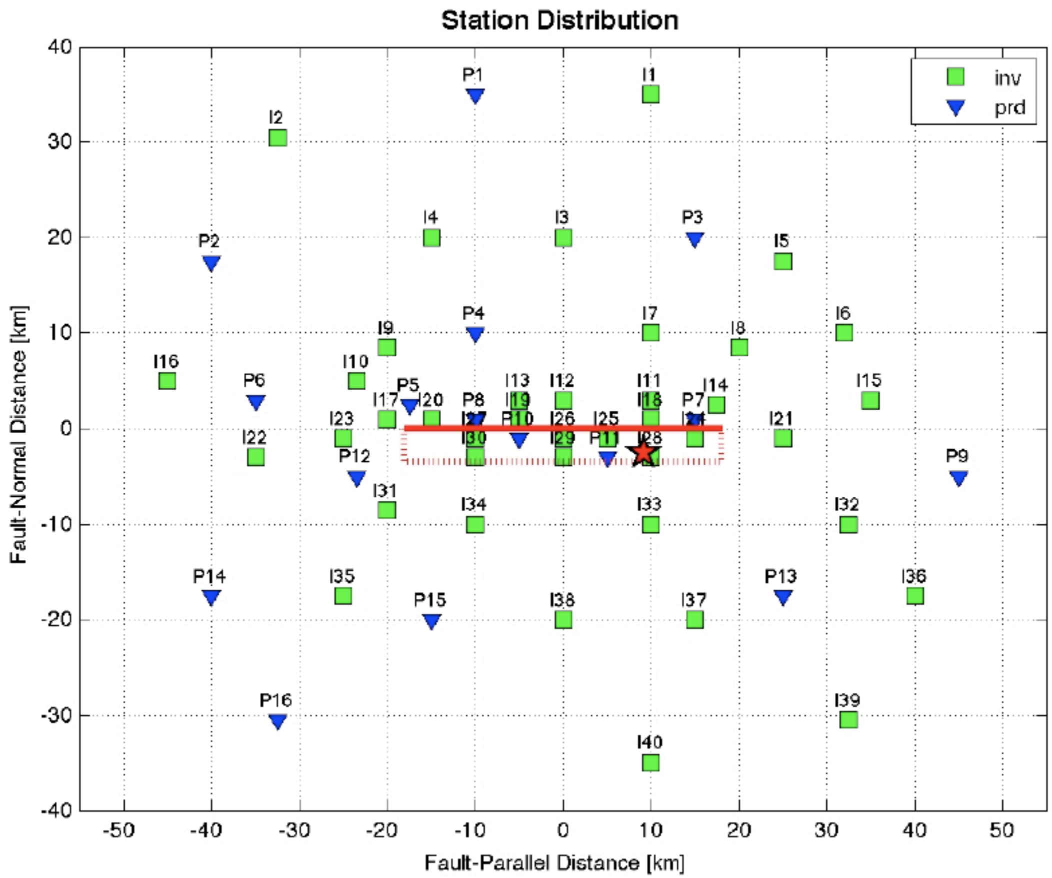


Goodness of fit in envelope

Goodness of fit in phase

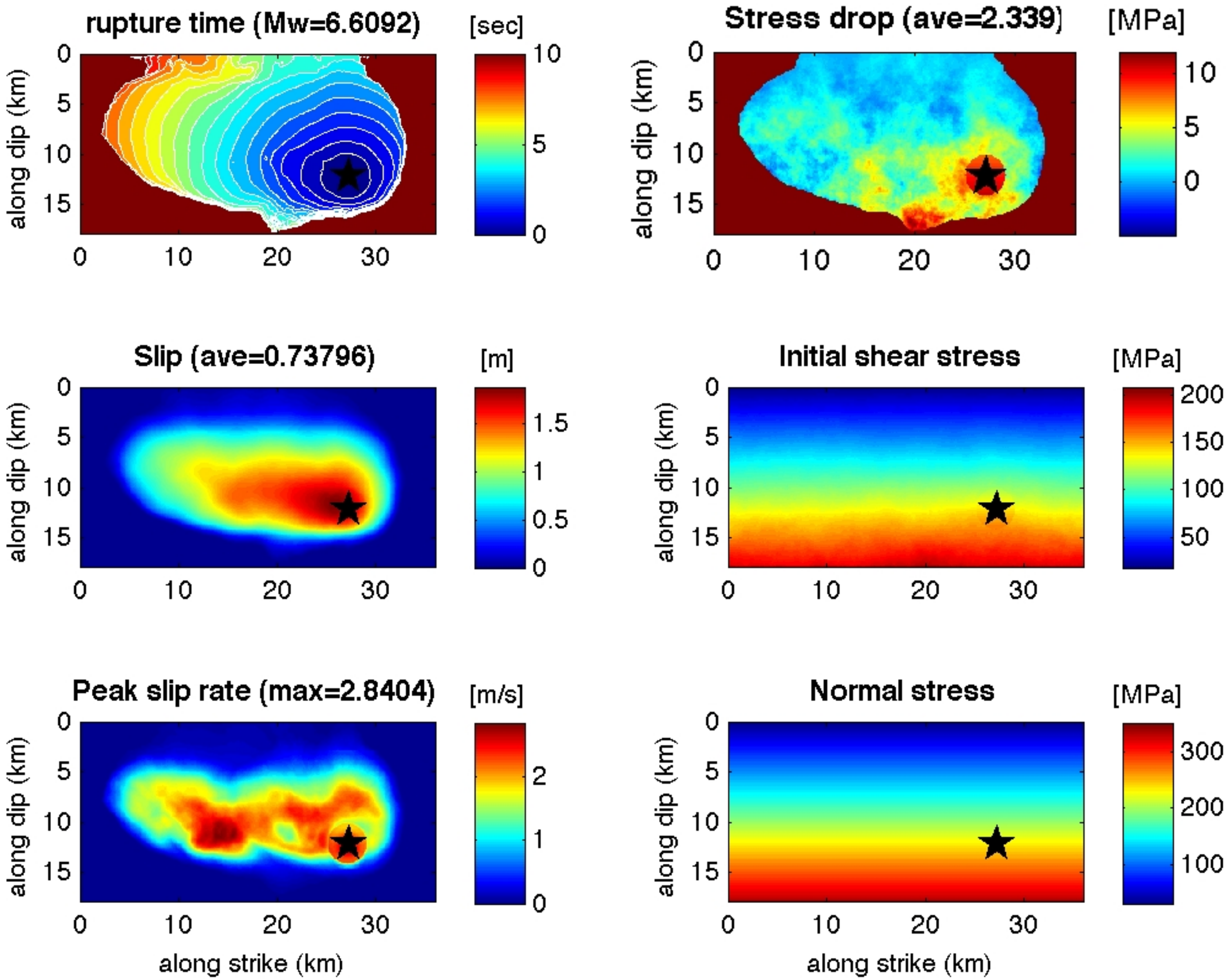
Example: a “simple” dynamic rupture

- M ~ 6.5 strike-slip earthquake on 80° dipping fault
- 40 sites for which waveforms are provided; at 16 additional sites “blind” predictions are required
- Earth model: 1D layered structure (same as in the Green’s function test)



Example: a "simple" dynamic rupture

- **The dynamic rupture model: random initial stress, depth-dependent normal stress, slip-weakening with Dc = 0.4** (increasing to the edges for smooth termination)



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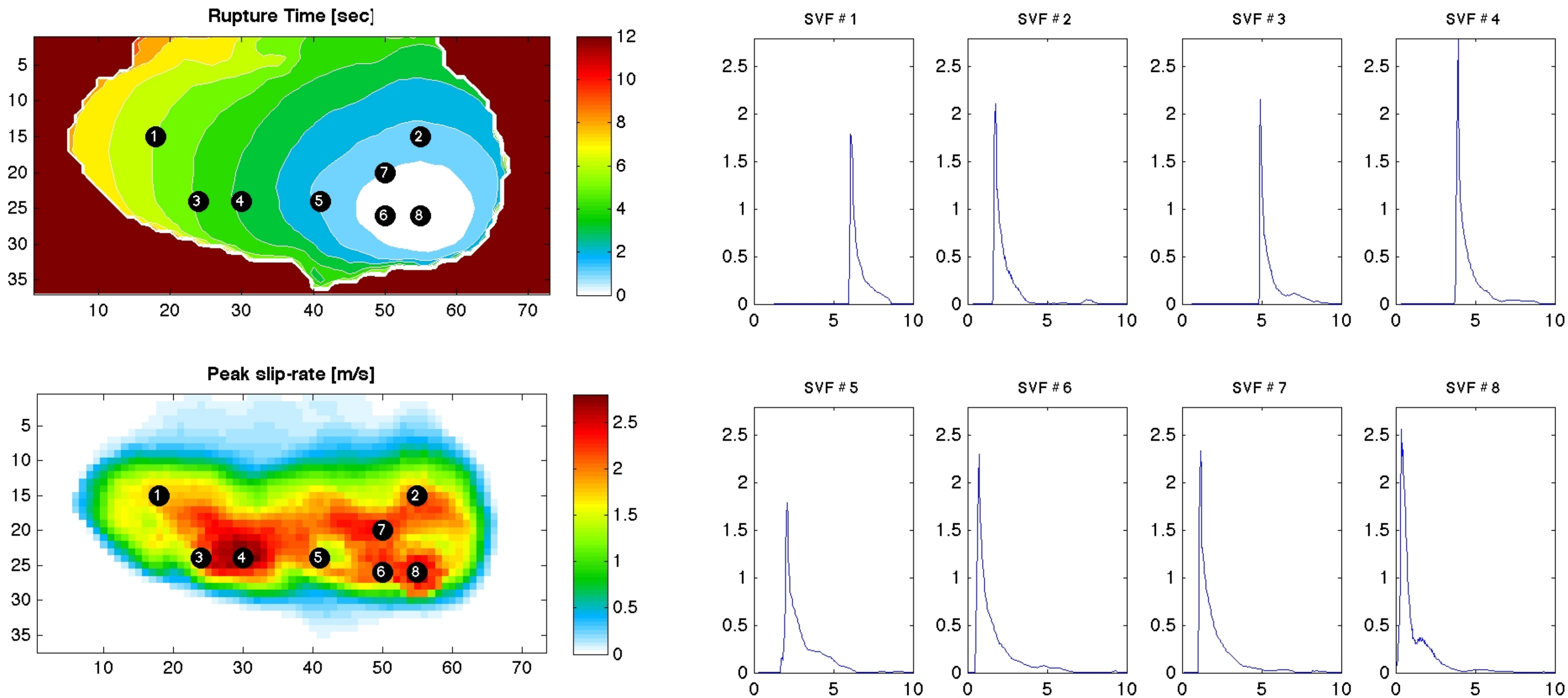
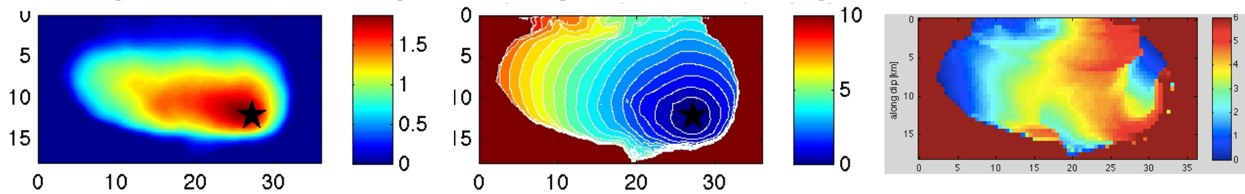


Source Inversion Validation

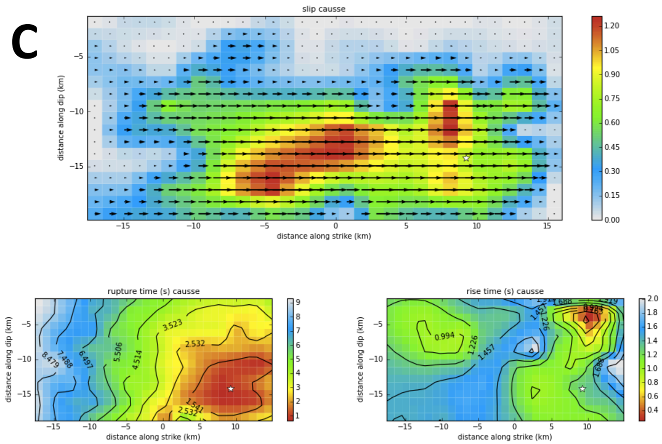
Example: a "simple" dynamic rupture

- **Source models**



dynamic slip & rupture time & rise time

C



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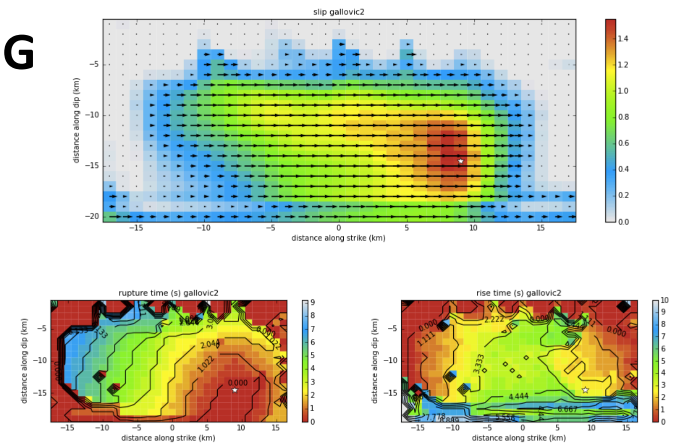
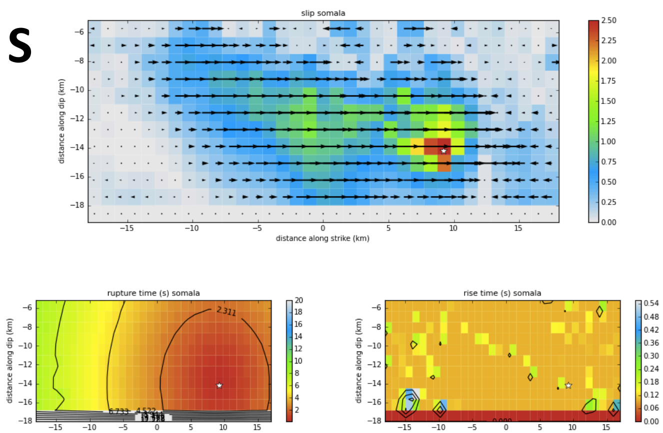


S



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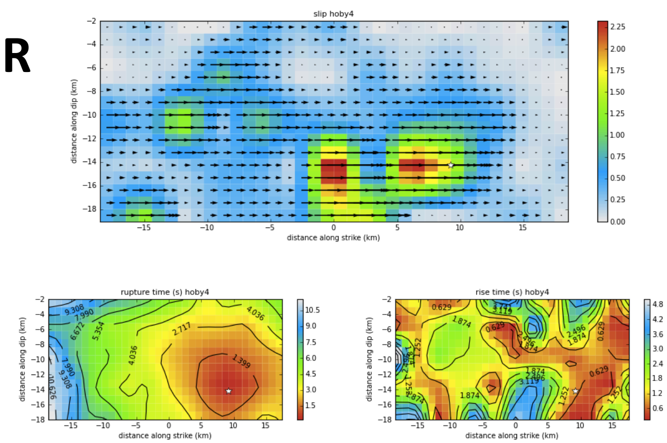


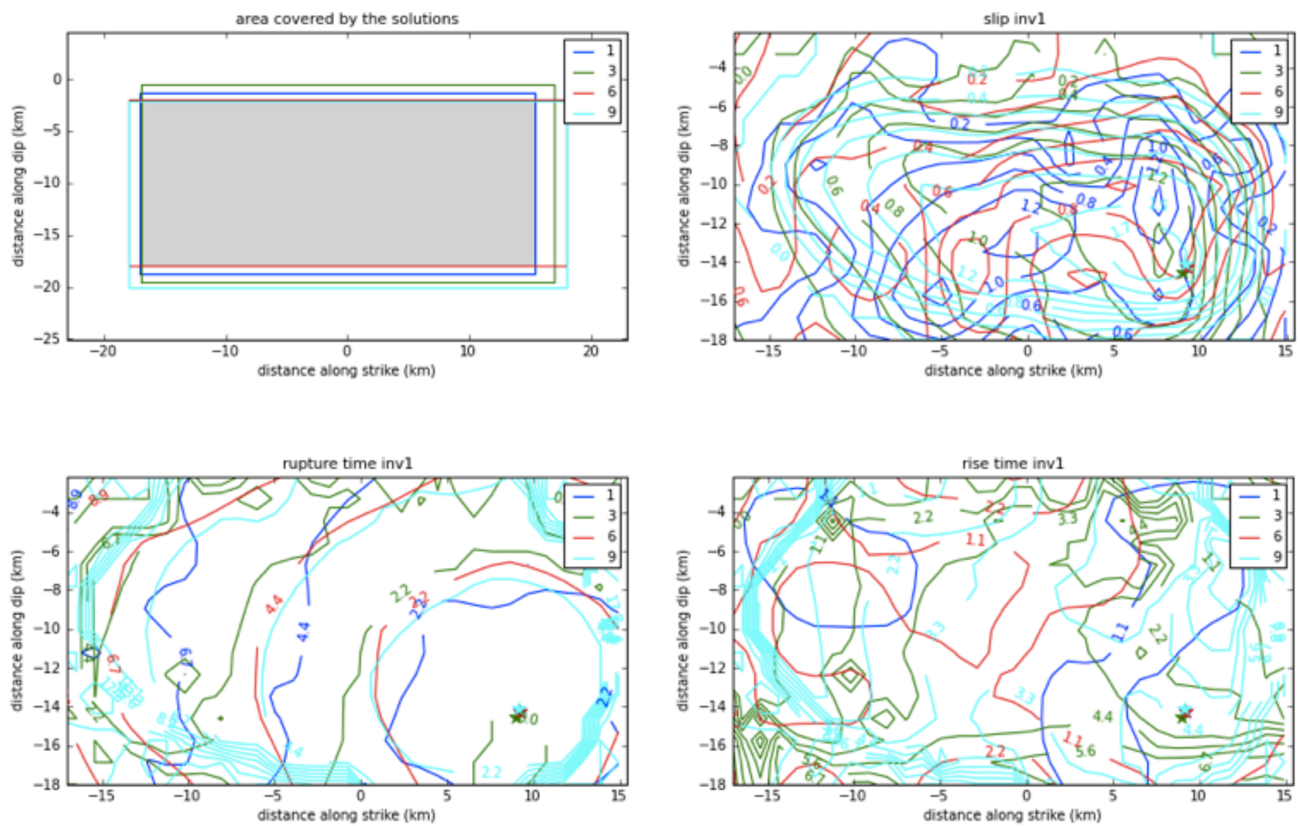
Example: a “simple” dynamic rupture

- **Source model comparison**

Dynamic strike-slip rupture on 80-deg dipping fault

Select Solutions to be plotted:
causse (1): ☑ gallovic (2): ☐ gallovic2 (3): ☑ gallovic3 (4): ☐ hoby (5): ☐ hoby1 (6): ☑ hoby2 (7): ☐ hoby4 (8): ☐ mai (9): ☑ somala (10): ☐ somala1 (11): ☐ re

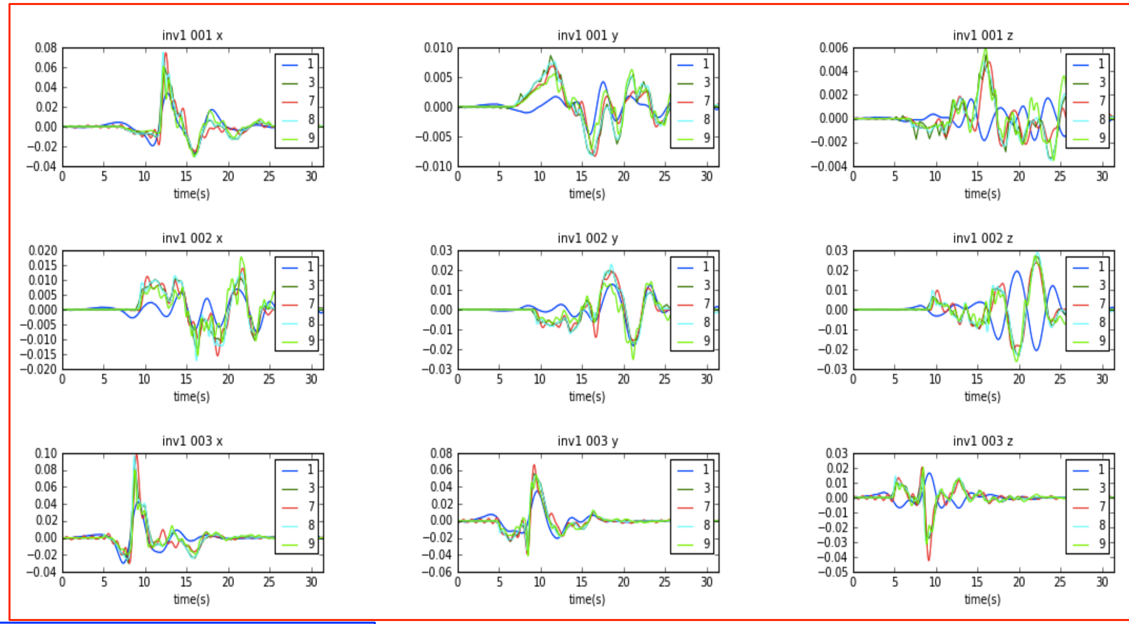
Interpolation parameters (leave blank for default):
spacing along strike: 1 spacing along dip: 1 reload



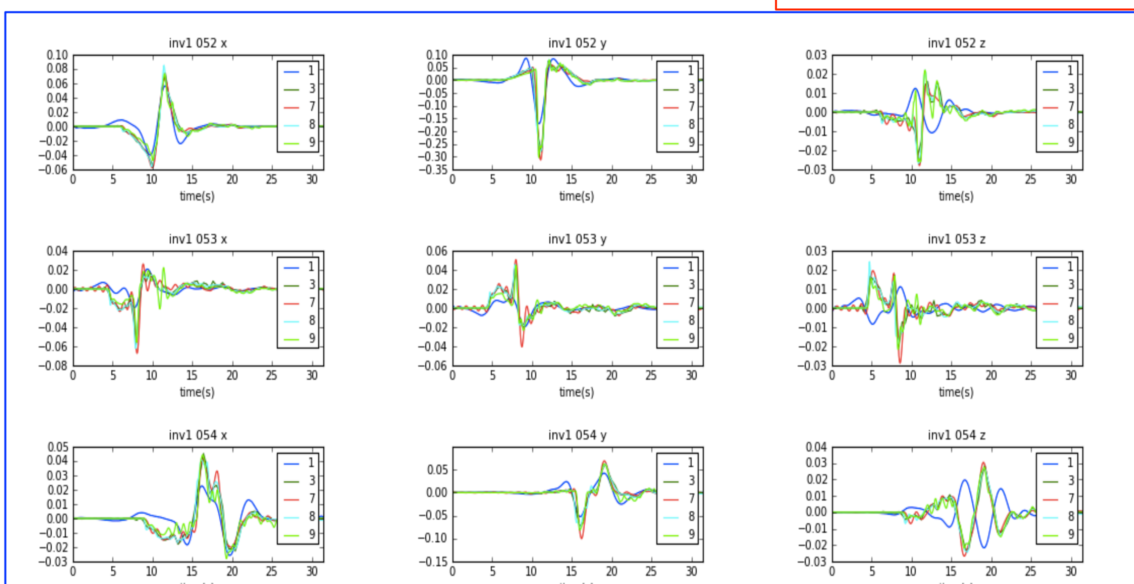
Example: a "simple" dynamic rupture

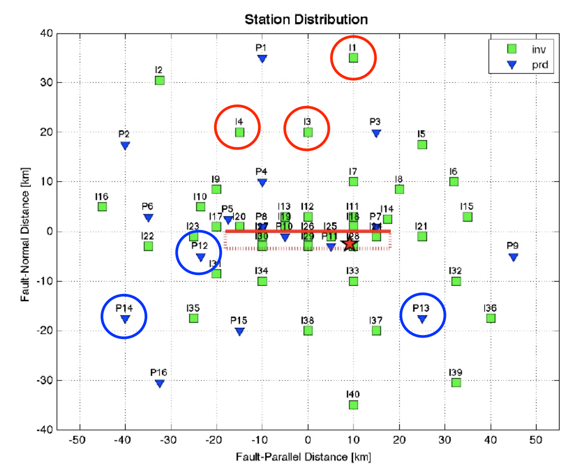
- **Graphical waveform comparison (at 1 Hz):**

stations used for inversion



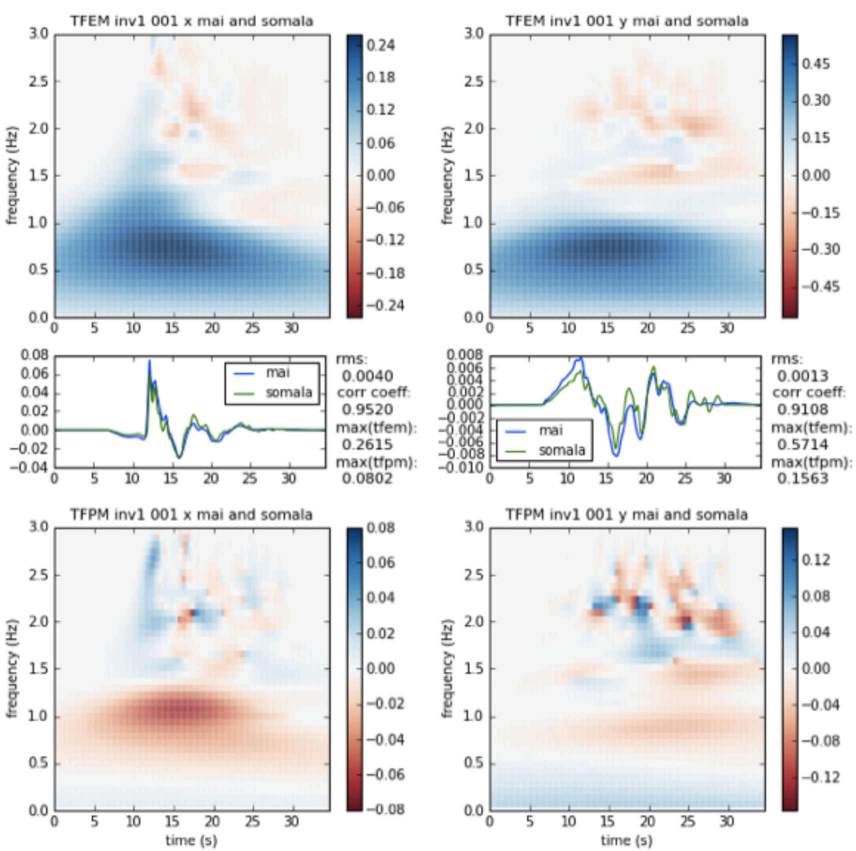
forward-predicted sites

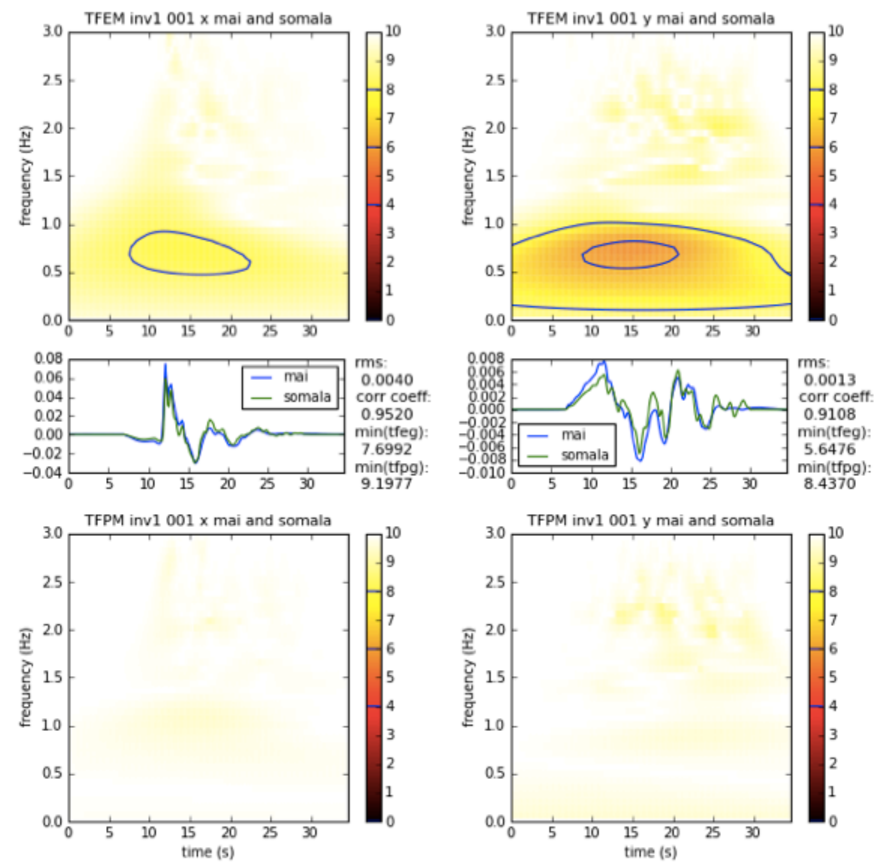




Example: a "simple" dynamic rupture

- Time-frequency envelope and time-frequency phase misfit (left) and goodness-of-fit (right) for two solutions, at one site for horizontal components





Example: “simple” dynamic rupture

- Differences in inferred slip; similar rupture timing; rise times poorly determined
- Overall good waveform fits at ~1 Hz
- What is needed to improve these solutions?
  - Static displacements as additional constrains? Any other data?
  - Revisit the impact of the assumed slip-rate function?
  - Is the dynamic model too complicated? Too unrealistic?

- Need additional analysis to fully comprehend what causes the differences
  - Map various goodness-of-fit measures to check how misfits vary spatially
  - Examine the actual local slip-rate functions (from the modelers and the dynamics)

SIV: The next steps

- Develop & disseminate additional benchmarks
  - add noise to synthetics; withhold initial information or report slightly incorrect parameters; random variations in the velocity model
- Create larger data sets (GPS, InSAR, teleseismic)
- Expand online submission & comparison tools
  - Error reporting; some flexibility in formatting
  - Quantitative assessment of waveform & model performance

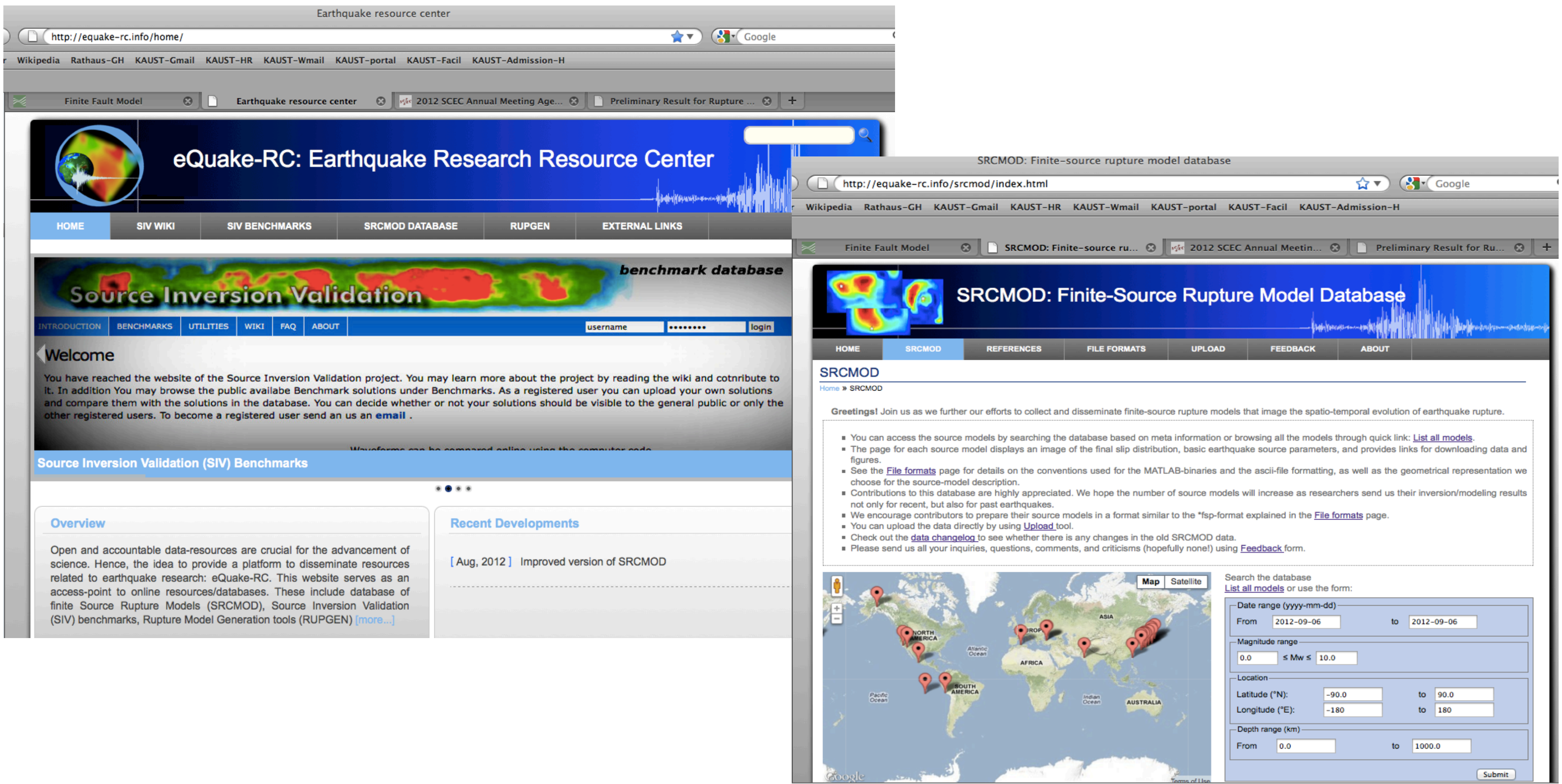
- **Motivate more source-modeling teams to participate & contribute**
  - email: martin.mai@kaust.edu.sa

    account@eqsource.webfaction.com

Improved online accessibility

- **The SIV benchmarks and the upgraded SRCMOD database have moved to a common web-site for improved accessibility**

equake-rc.info / equake-rc.org / equake-rc.net

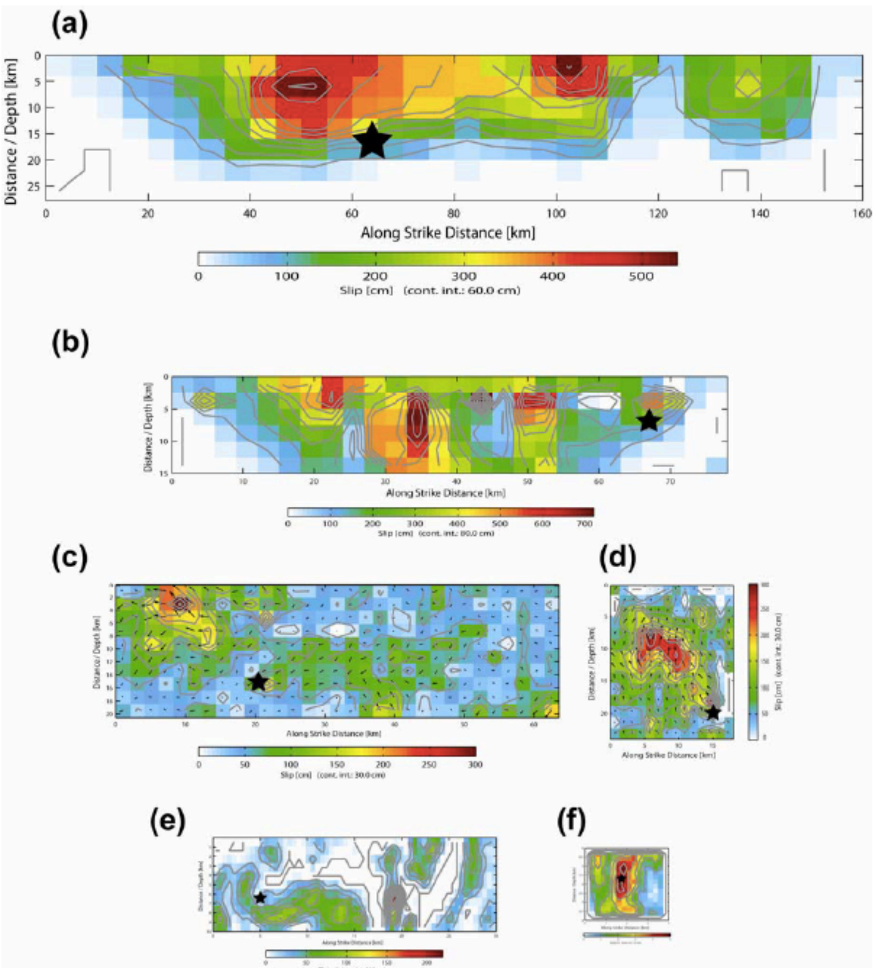


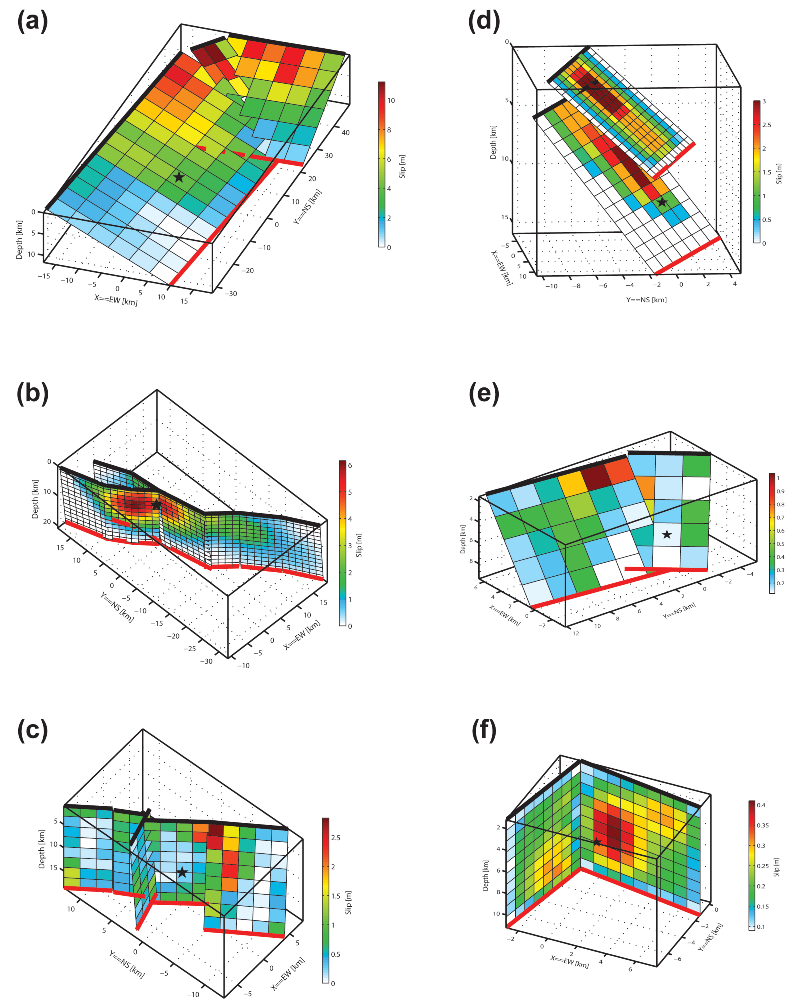
Overview

- The Source Inversion Validation (SIV) efforts
- Source parameters from finite-fault rupture models

Source Parameters from finite-fault models

- **Exploit database of rupture models**





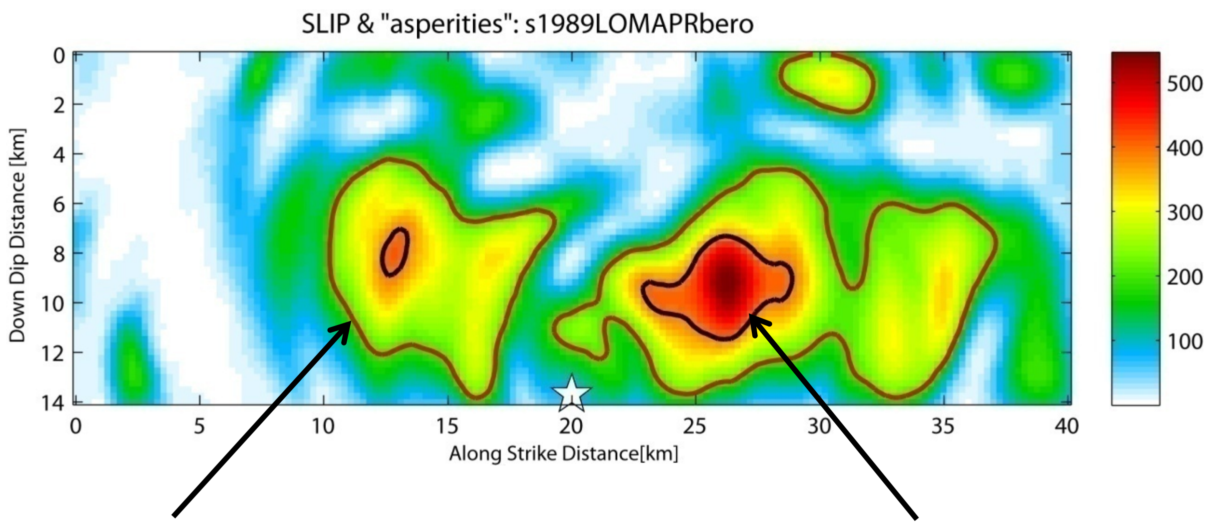
Source Parameters from finite-fault models

Slip patches ("asperities") and stress-change on the fault

How to quantify / define an asperity in such slip models?

- **Somerville et al (1999): regions in which** $D \geq 2 \cdot D_{ave}$
- **Mai et al (2005): large-slip** $1/3 \cdot D_{max} \leq D < 2/3 \cdot D_{max}$

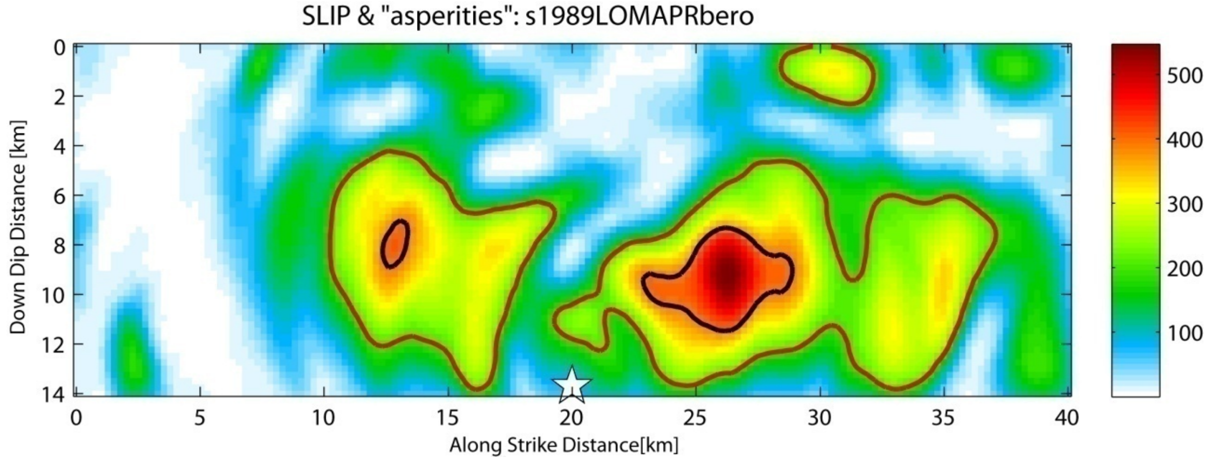
  very-large slip $D \geq 2/3 \cdot D_{max}$

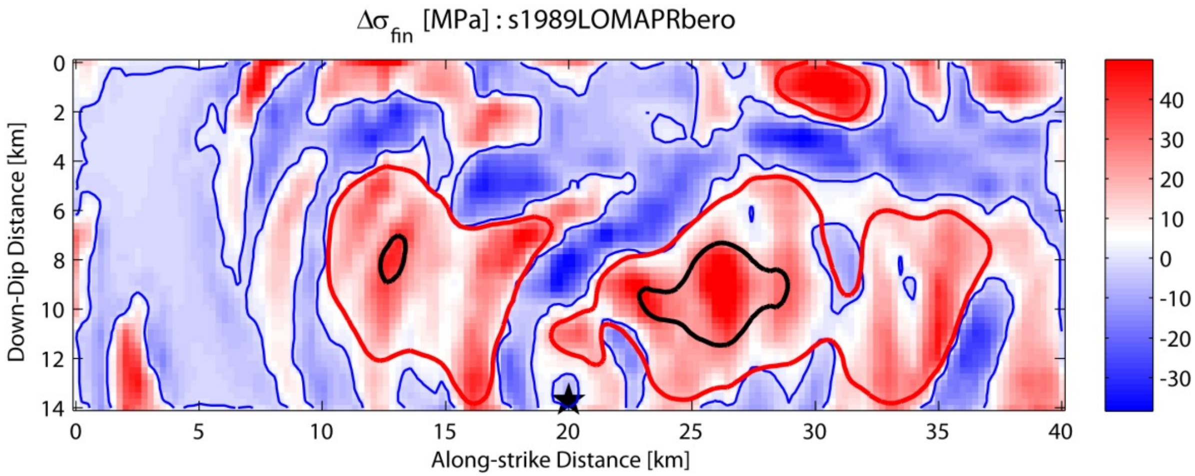


$1/3 \cdot D_{max} \leq D < 2/3 \cdot D_{max}$ $D \geq 2/3 \cdot D_{max}$

Source Parameters from finite-fault models

- **Slip patches ("asperities") and stress-change on the fault**

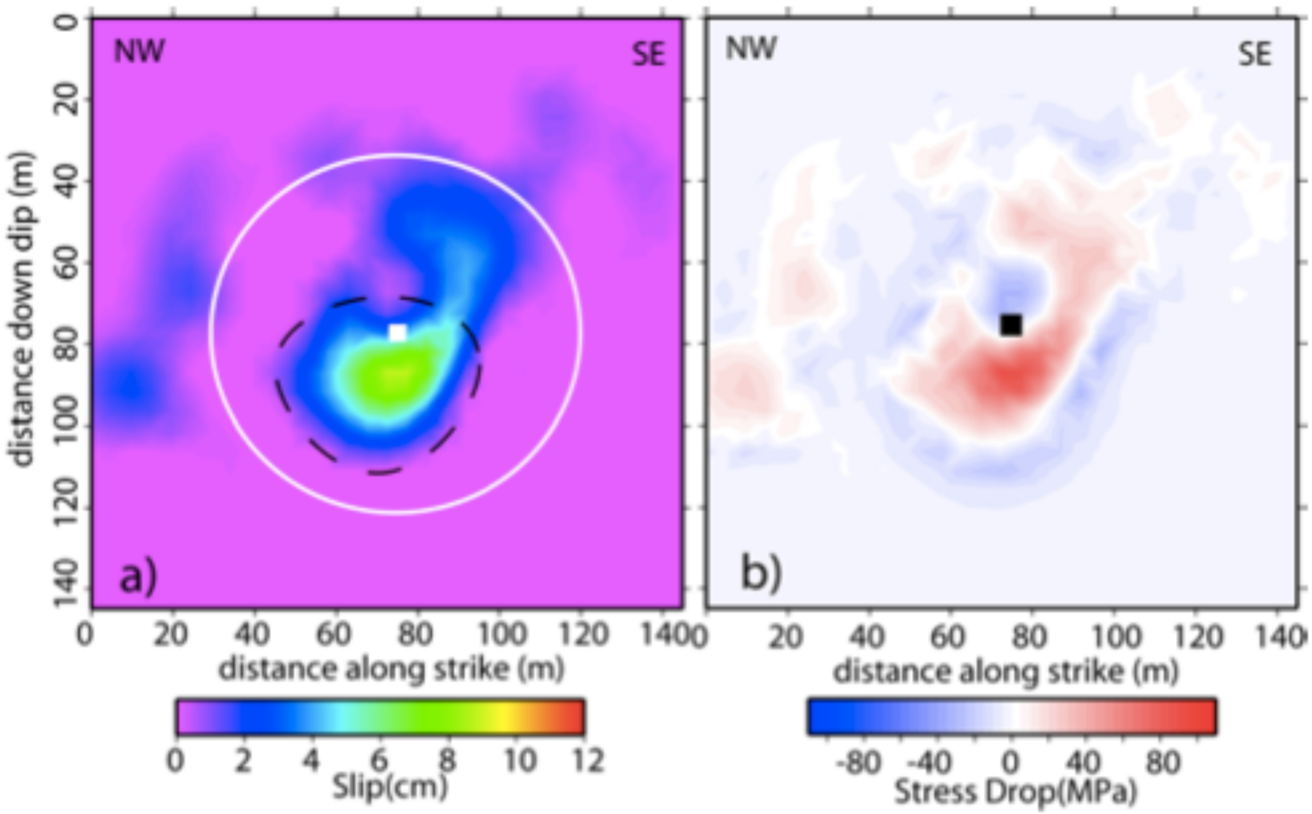




Stress change after Ripperger & Mai (2004)

Source Parameters from finite-fault models

- **Slip patches ("asperities") and stress-change on the fault**

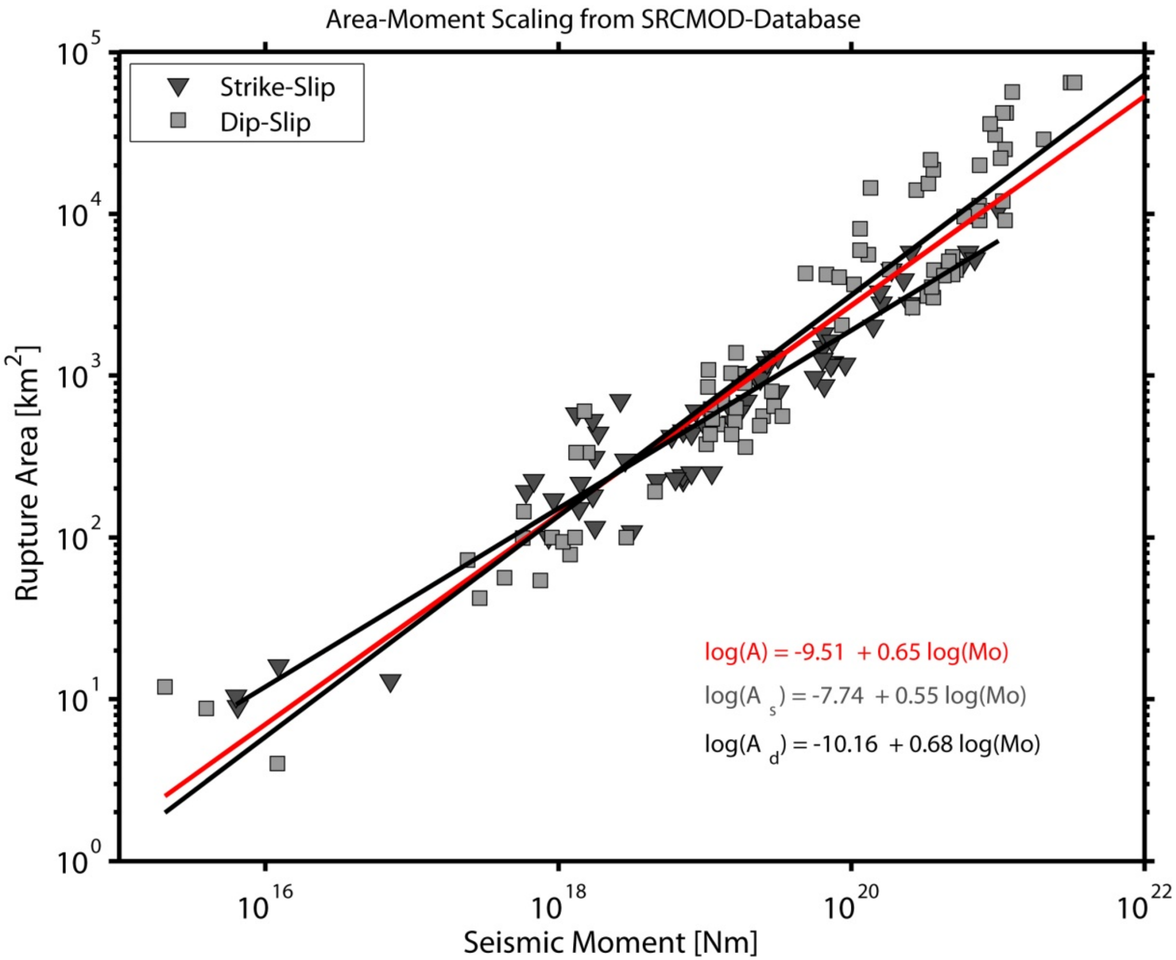


- Parkfield repeater (Mw 2.1): stress drop averaged over fault ~11MPa where stress drop > 0 roughly consistent with spectral estimate by Imanishi et al (2004)

Dreger et al, 2007

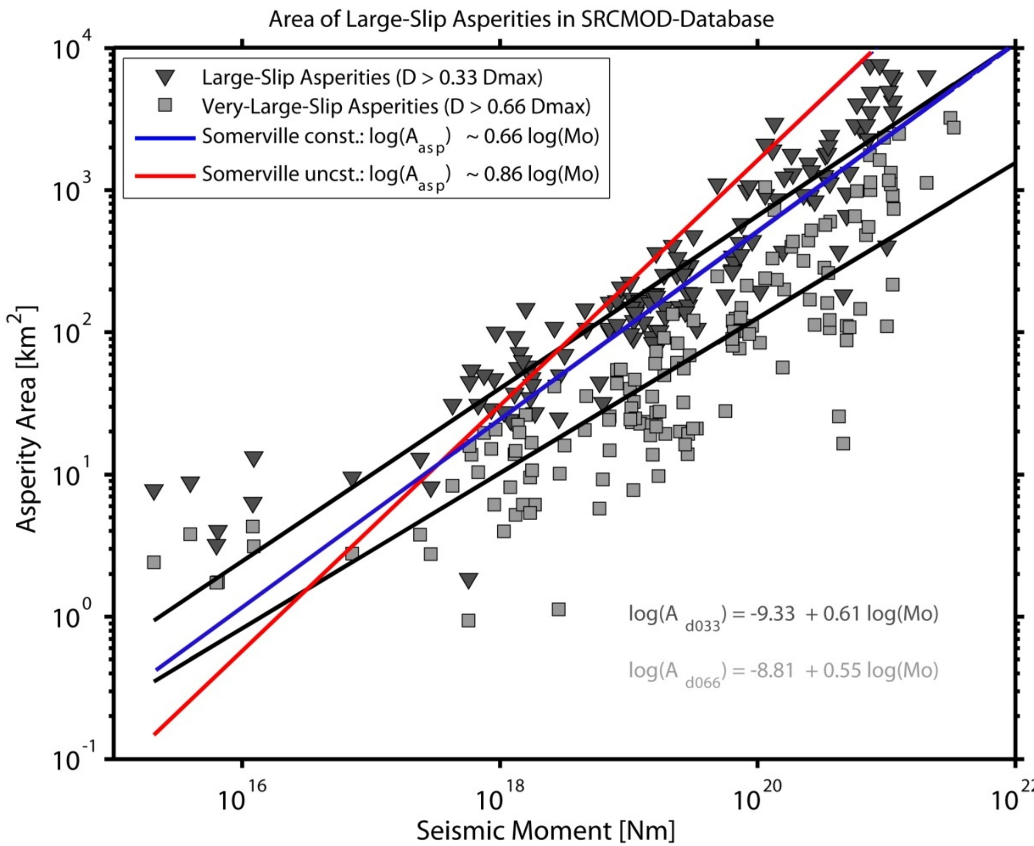
Source Parameters from finite-fault models

- **Area-moment scaling in finite-fault models: scale invariant ($M_0 \propto 2/3 \cdot A$)**



Source Parameters from finite-fault models

- **Area-moment scaling of asperity regions is NOT scale invariant**
  - large-slip asperities occupy ~25% of fault plane, releasing ~40% of the total moment
  - very-large-slip asperities occupy ~10% of the fault, releasing ~25% of the total moment



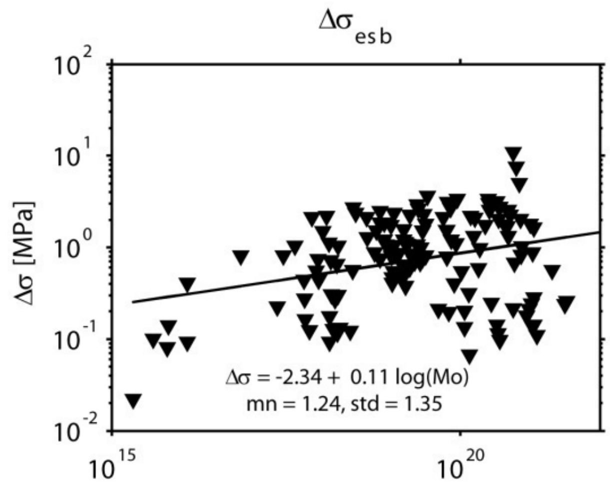
Source Parameters from finite-fault models

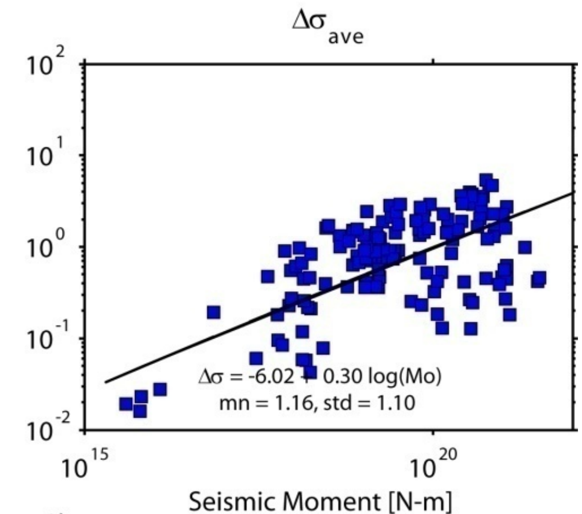
- **Stress-drop estimates over the fault**

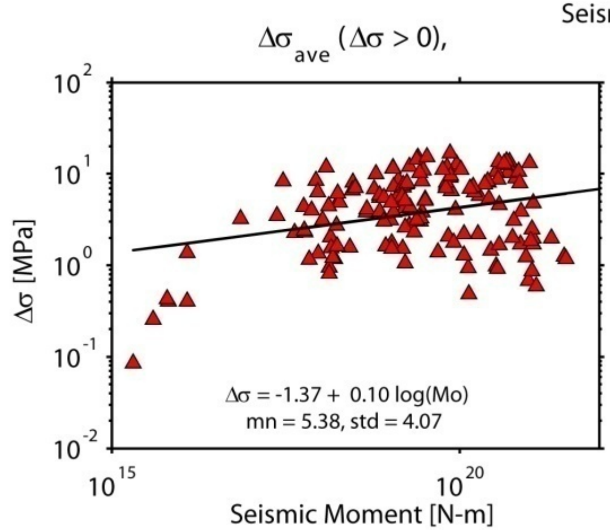
$$\Delta\sigma_{esb} = c \cdot \frac{D_{ave}}{L_c}$$

$$\Delta\sigma_{ave}$$

$$\Delta\sigma_{ave}(\Delta\sigma > 0)$$







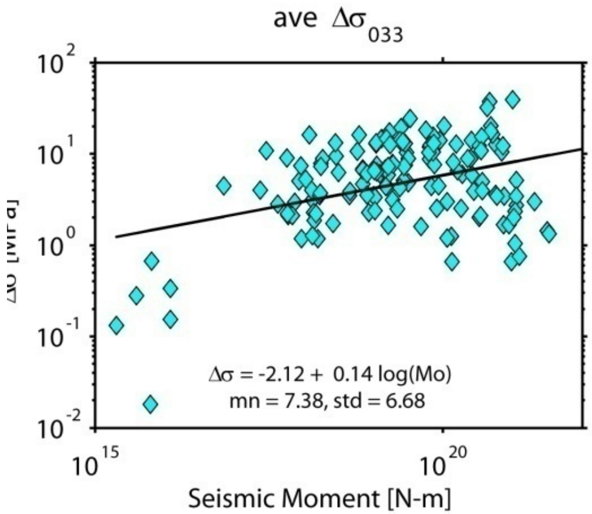
Source Parameters from finite-fault models

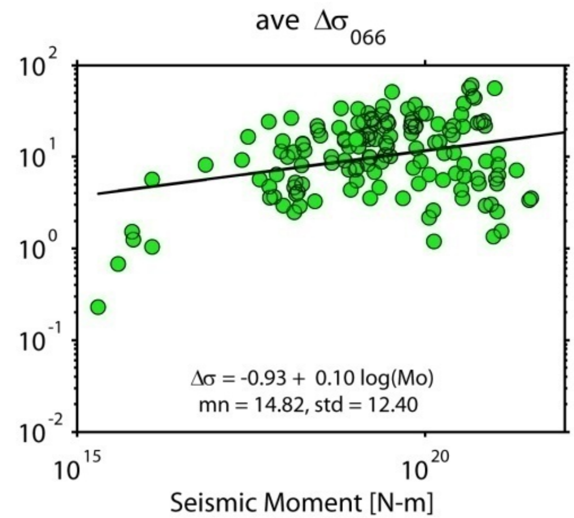
- **Stress-drop estimates using on the regions of large and very-large slip**

$$\Delta\sigma_{esb} = c \cdot \frac{D_{ave}}{L_c}$$

$$\Delta\sigma_{ave}$$

$$\Delta\sigma_{ave}(\Delta\sigma > 0)$$





- **Considering the entire fault plane, the average stress-drops are on the order of 1 MPa ($\Delta\sigma_{esb}$, $\Delta\sigma_{ave}$), and about 5MPa over the regions of pos. stress-drop**
- **Considering the asperity regions, stress drops are 7MPa – 15 Mpa**

Summary

- **In the light of the scaling debate, which aspects of the kinematic (dynamic) rupture model are captured by spectral estimates of stress drop?**

- **Improved finite-fault inversions, including proper uncertainty quantification, are needed to better understand rupture dynamics and to link the various measures of earthquake source properties**