

Uncertainty Quantification in Earthquake Source Studies:

The SIV-Initiative and its
Implications for Source Parameter
Estimation

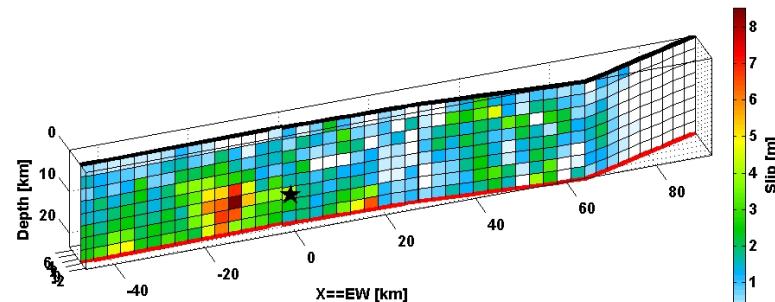
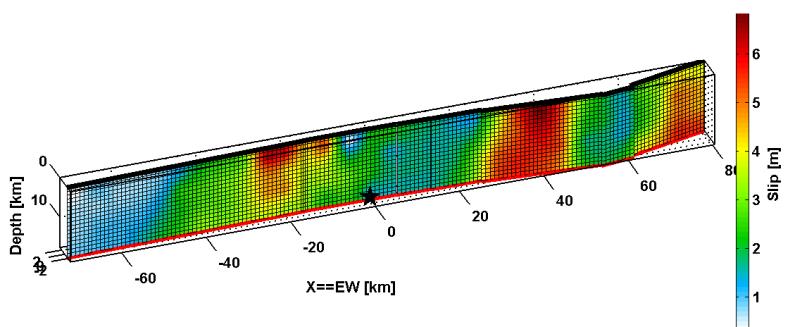
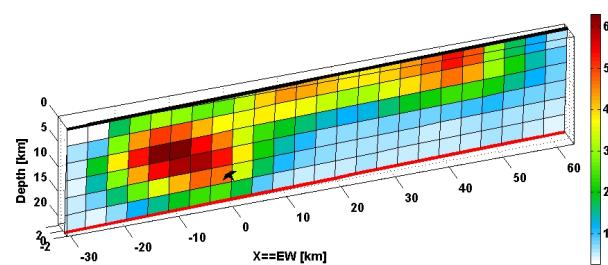
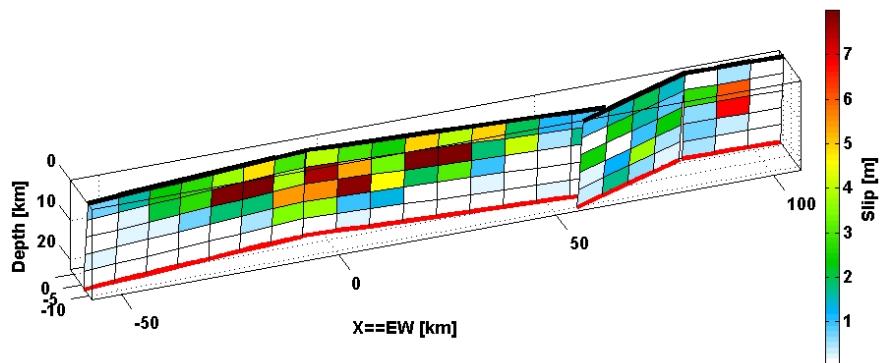
SIV = Source Inversion Validation

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

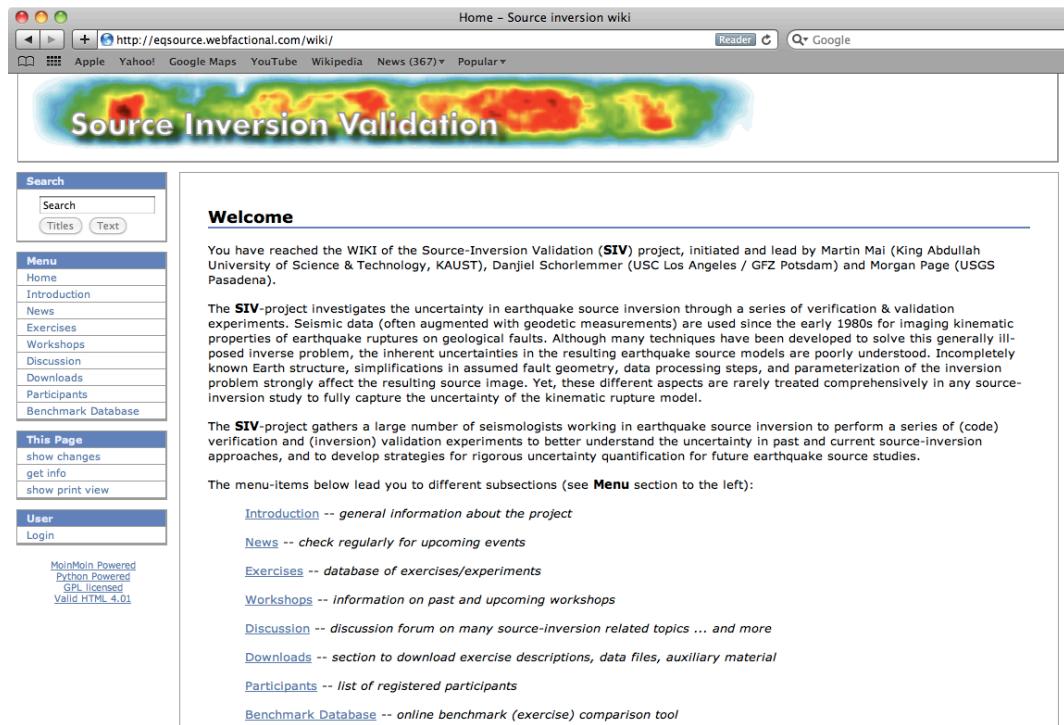


The Source Inversion Validation (SIV) project

- 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>



Home - Source inversion wiki

Reader Google

Source Inversion Validation

Welcome

You have reached the WIKI of the Source-Inversion Validation (**SIV**) project, initiated and lead by Martin Mai (King Abdullah University of Science & Technology, KAUST), Danjel Schorlemmer (USC Los Angeles / GFZ Potsdam) and Morgan Page (USGS Pasadena).

The **SIV**-project investigates the uncertainty in earthquake source inversion through a series of verification & validation experiments. Seismic data (often augmented with geodetic measurements) are used since the early 1980s for imaging kinematic properties of earthquake ruptures on geological faults. Although many techniques have been developed to solve this generally ill-posed inverse problem, the inherent uncertainties in the resulting earthquake source models are poorly understood. Incompletely known Earth structure, simplifications in assumed fault geometry, data processing steps, and parameterization of the inversion problem strongly affect the resulting source image. Yet, these different aspects are rarely treated comprehensively in any source-inversion study to fully capture the uncertainty of the kinematic rupture model.

The **SIV**-project gathers a large number of seismologists working in earthquake source inversion to perform a series of (code) verification and (inversion) validation experiments to better understand the uncertainty in past and current source-inversion approaches, and to develop strategies for rigorous uncertainty quantification for future earthquake source studies.

The menu-items below lead you to different subsections (see **Menu** section to the left):

- [Introduction -- general information about the project](#)
- [News -- check regularly for upcoming events](#)
- [Exercises -- database of exercises/experiments](#)
- [Workshops -- information on past and upcoming workshops](#)
- [Discussion -- discussion forum on many source-inversion related topics ... and more](#)
- [Downloads -- section to download exercise descriptions, data files, auxiliary material](#)
- [Participants -- list of registered participants](#)
- [Benchmark Database -- online benchmark \(exercise\) comparison tool](#)

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Python Powered
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Valid HTML 4.01

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

INTRODUCTION	BENCHMARKS	UTILITIES	WIKI	FAQ	ABOUT	username	login
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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 dendograms 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](#)

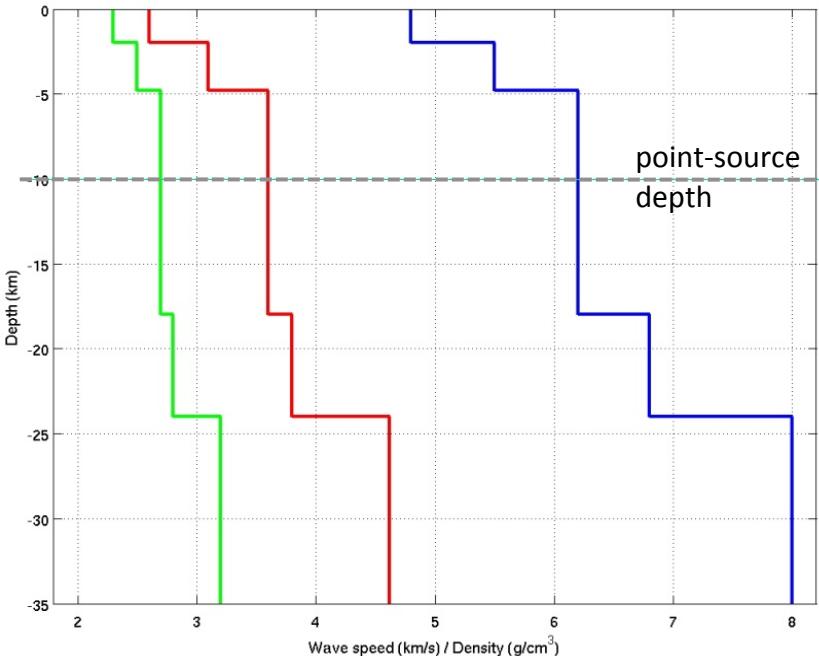
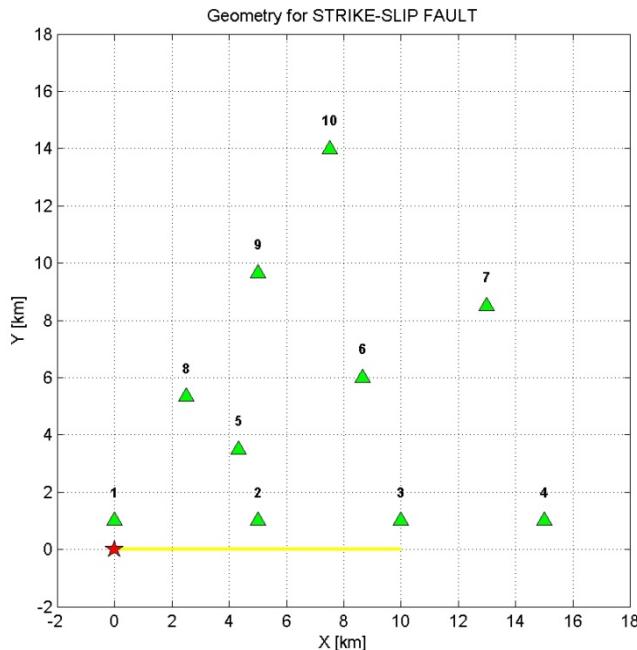
Station Predictions

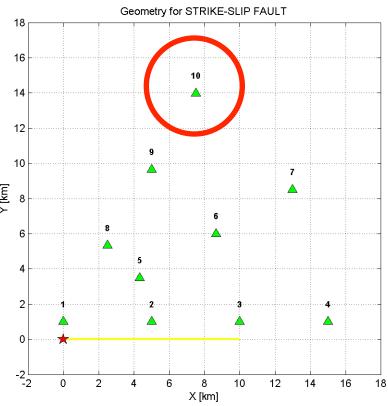
[plot superimposed solutions, comparison matrices and dendograms for this problem](#)

[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 $1 \times 1 \text{ km}^2$ slip patch with homogeneous slip and boxcar slip-function of duration $\tau_r = 0.2 \text{ sec}$
 - 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



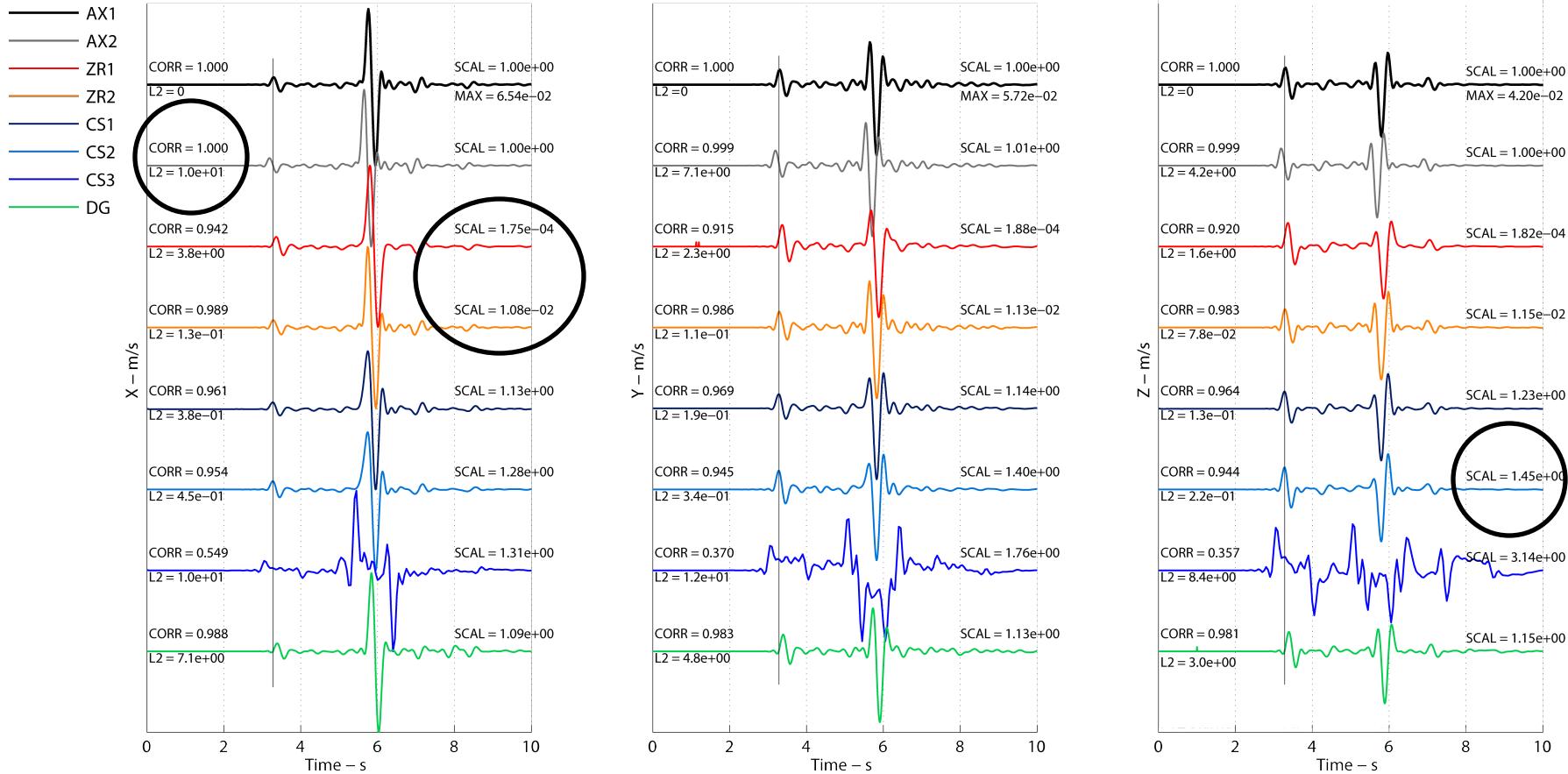


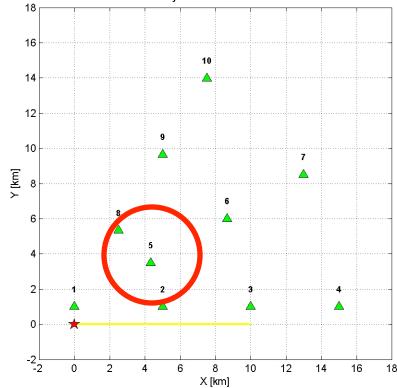
Source Inversion Validation

scec

Strike-slip points-source, single site

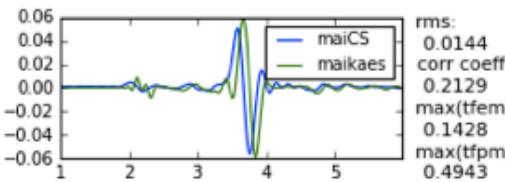
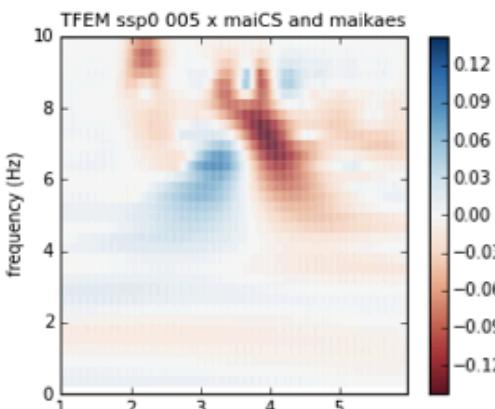
Waveform Comparison for strike-slip point source – Station10 – Frequency range [0 – 5Hz]



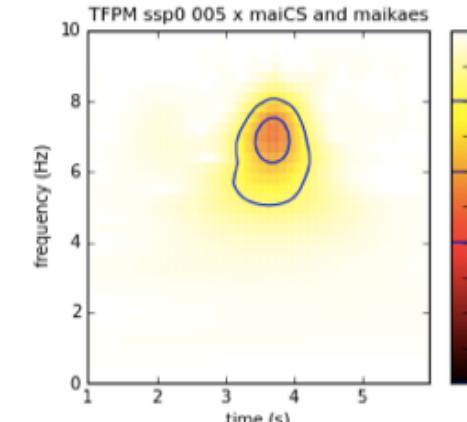
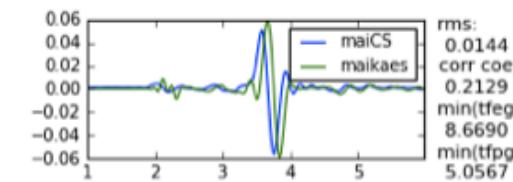
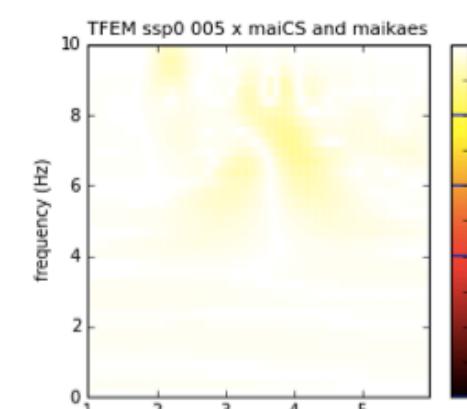
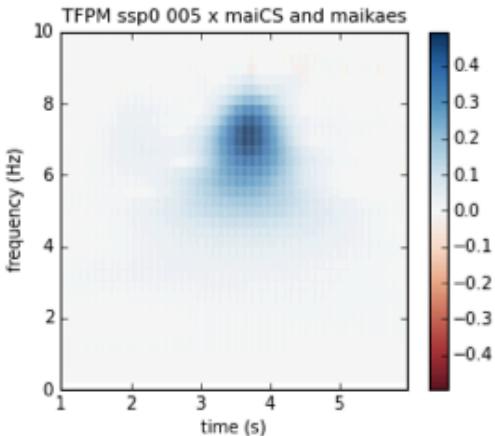
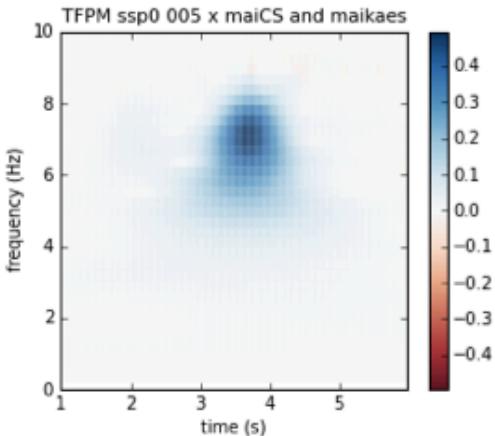


Strike-slip points-source, single site, two methods

Time-frequency
envelope



Time-frequency
phase mist

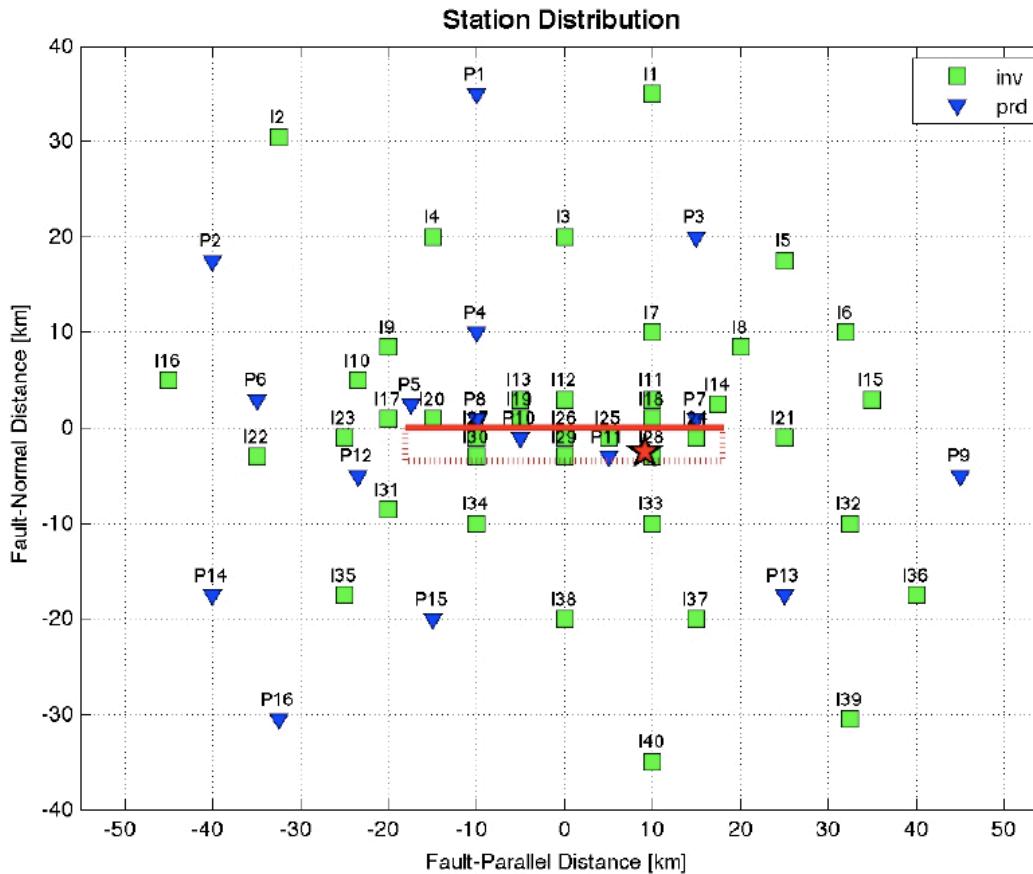


Goodness
of fit in
envelope

Goodness
of fit in
phase

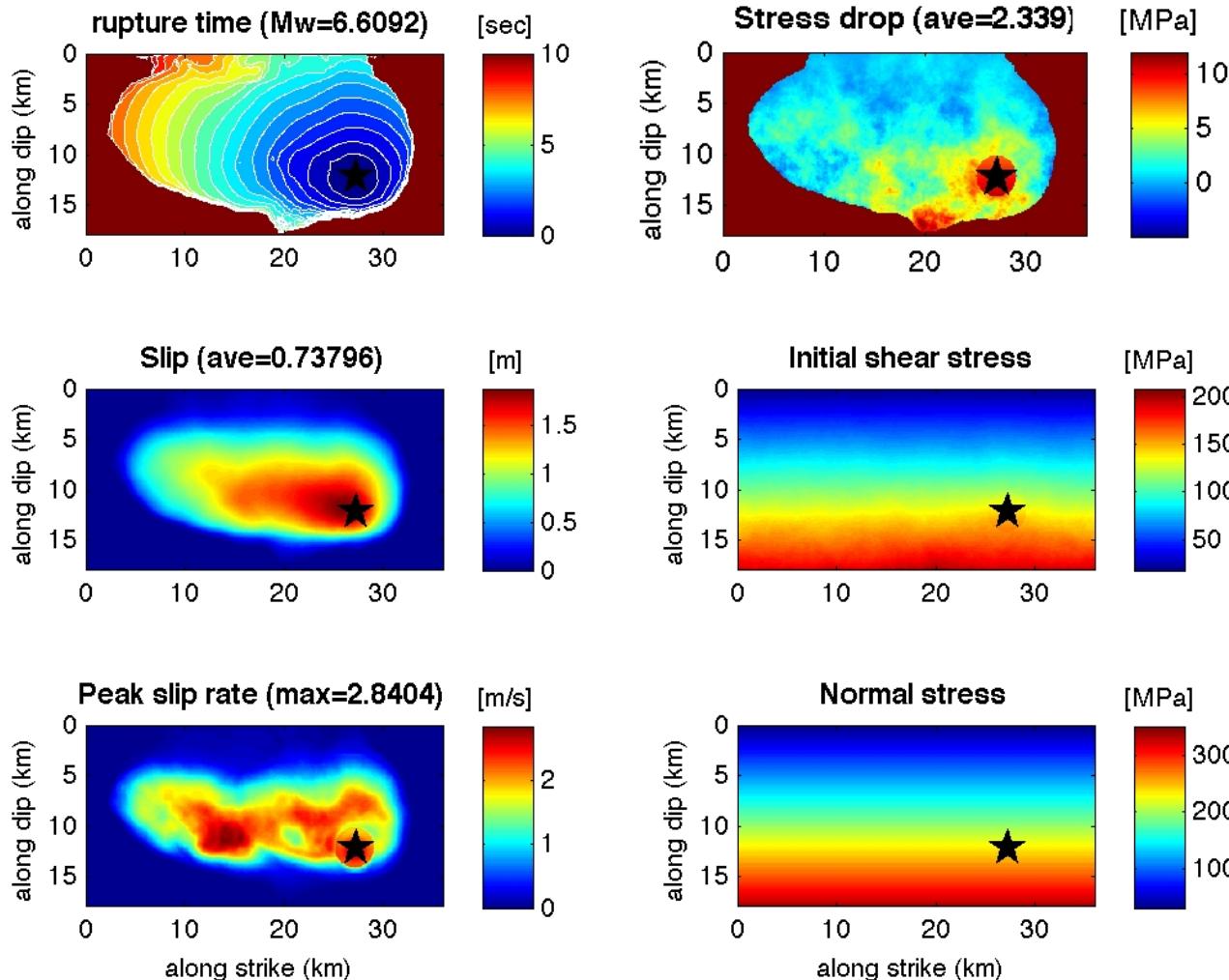
Example: a “simple” dynamic rupture

- **$M \sim 6.5$ 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)**



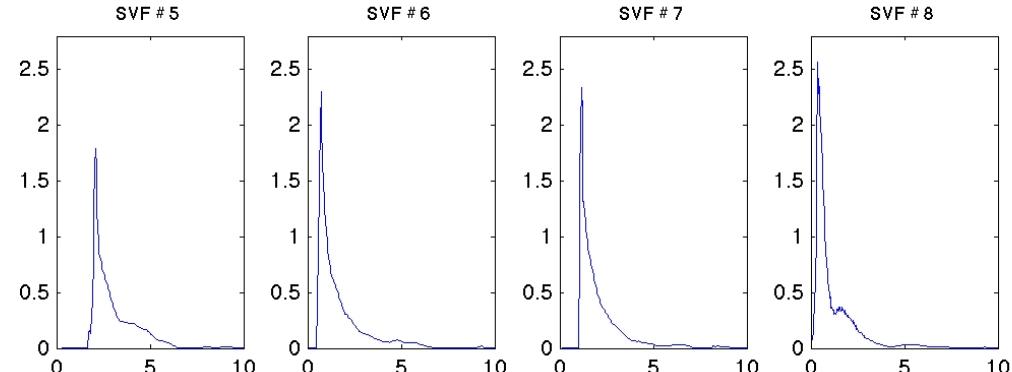
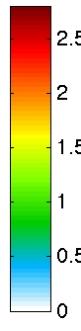
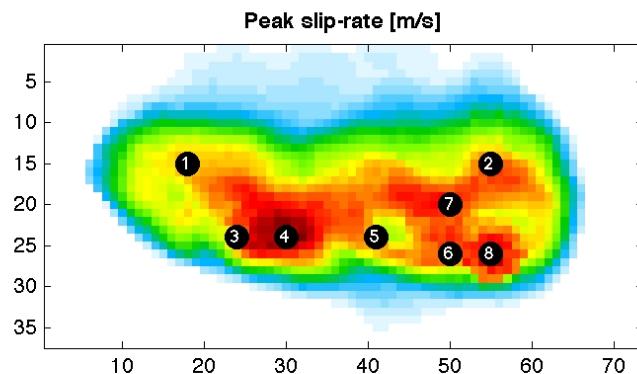
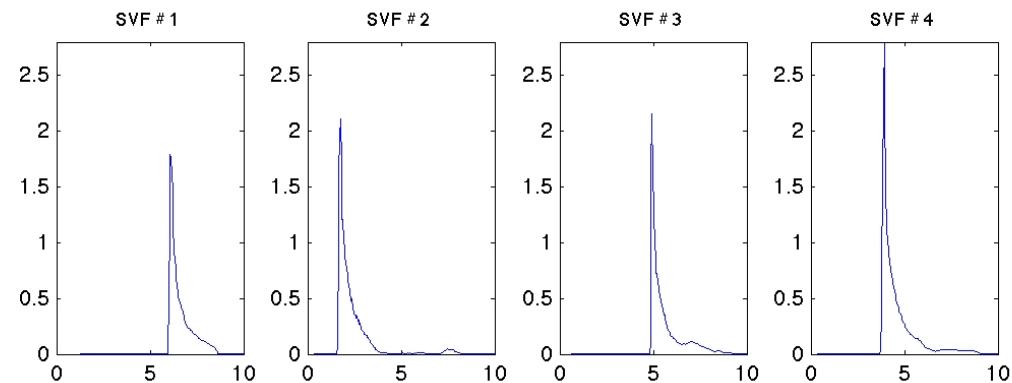
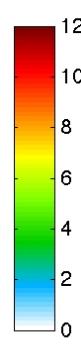
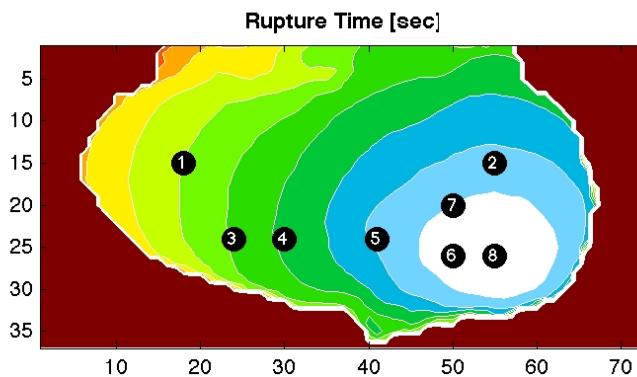
Example: a “simple” dynamic rupture

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



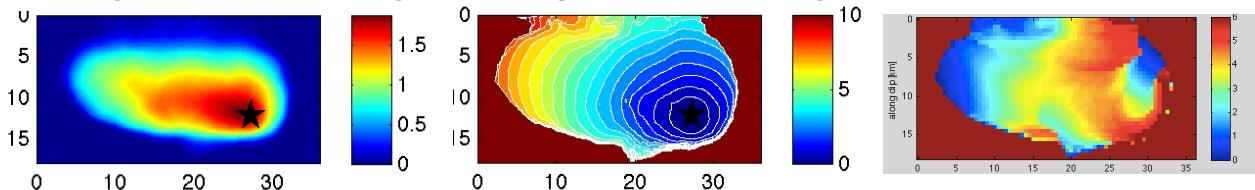
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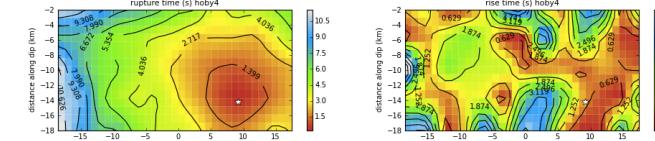
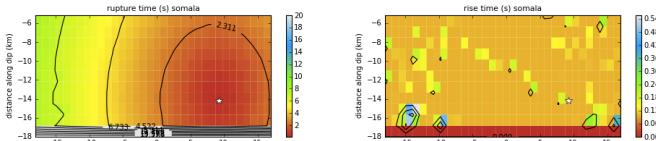
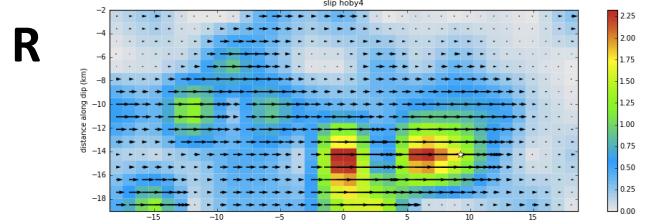
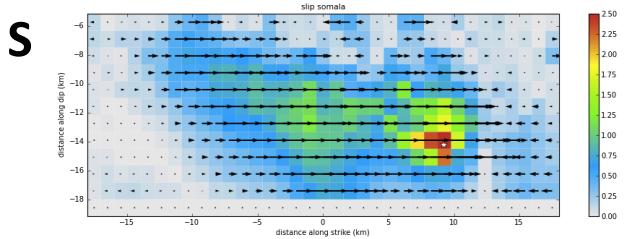
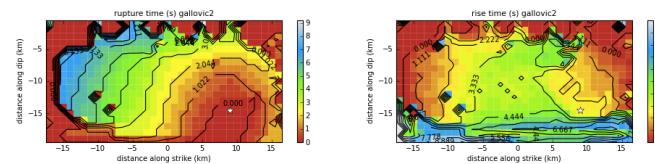
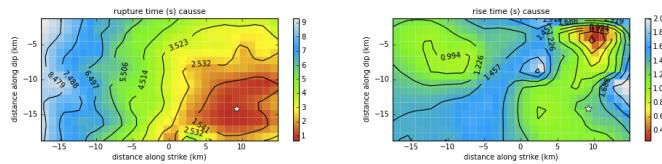
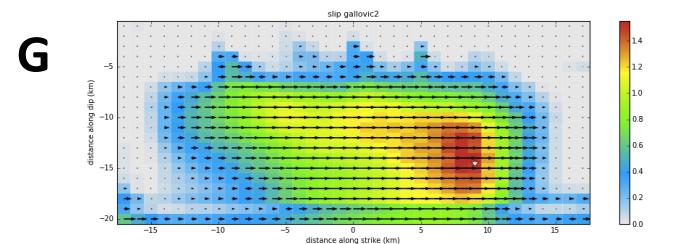
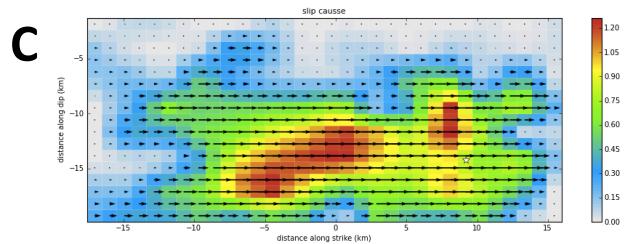


Example: a “simple” dynamic rupture

Source models



dynamic slip & rupture time & rise time



Example: a “simple” dynamic rupture

Source model comparison

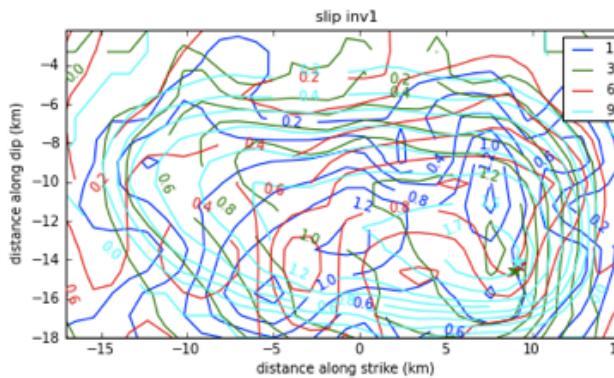
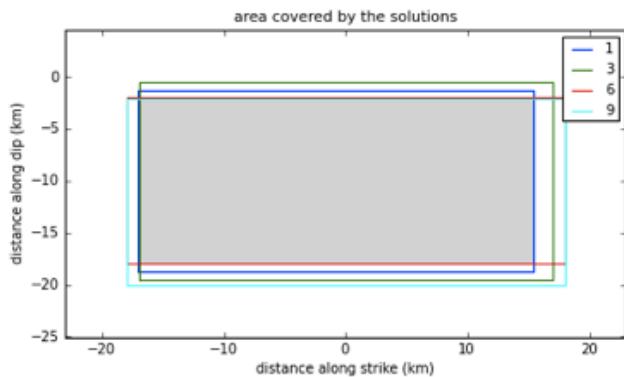
Dynamic strike-slip rupture on 80-deg dipping fault

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

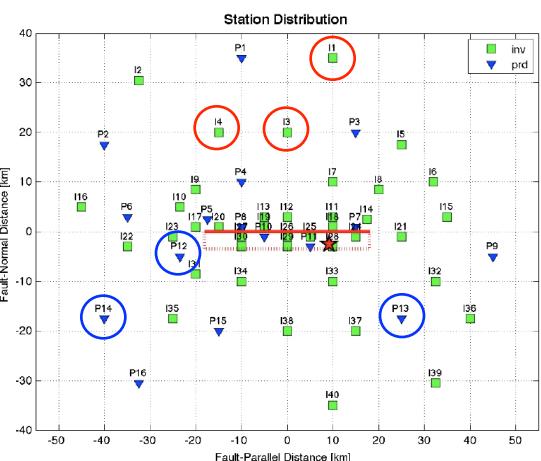
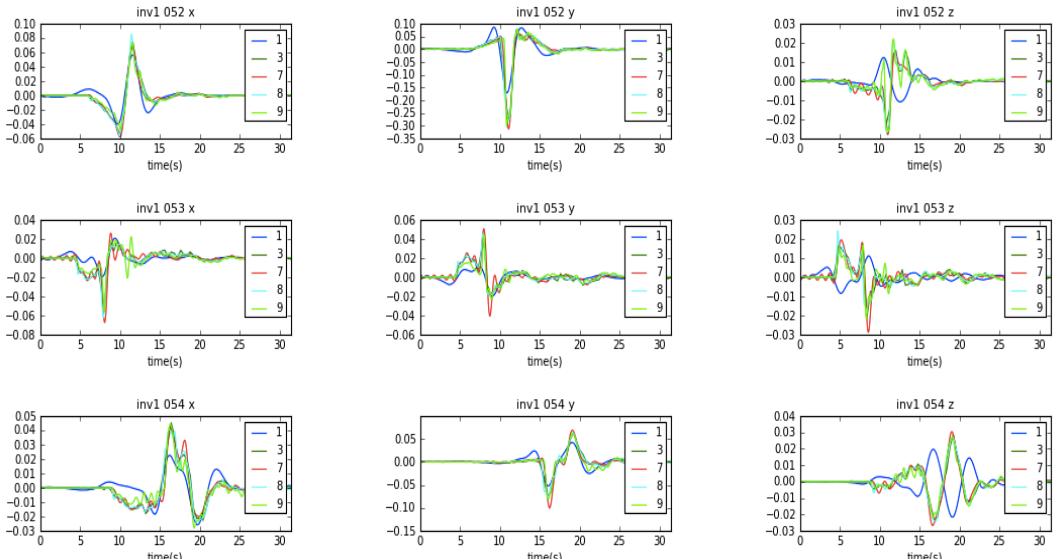
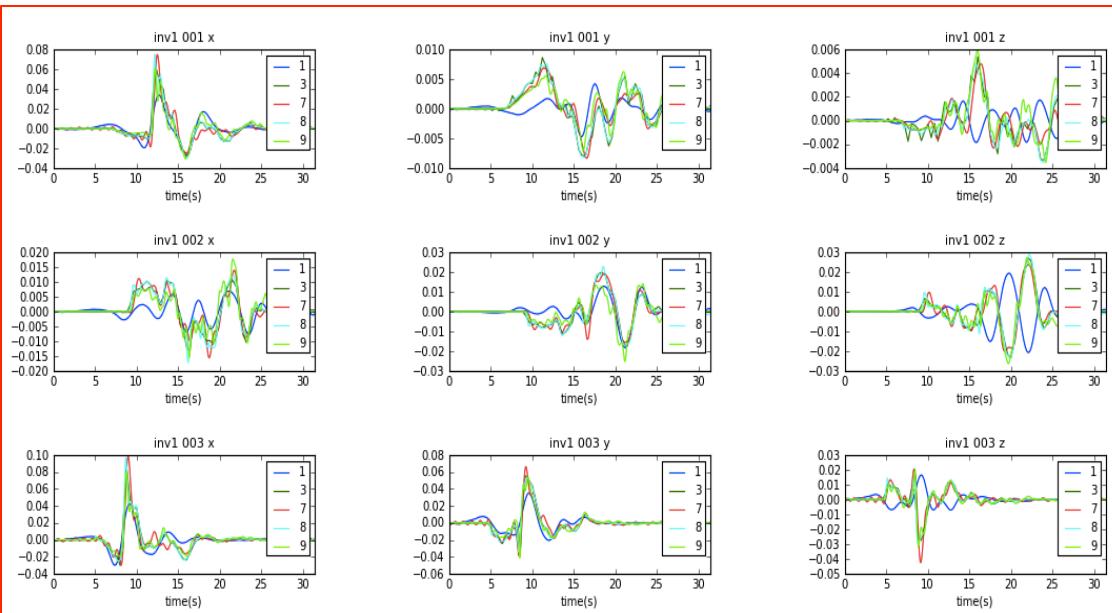


Example: a “simple” dynamic rupture

- Graphical waveform comparison (at 1 Hz):

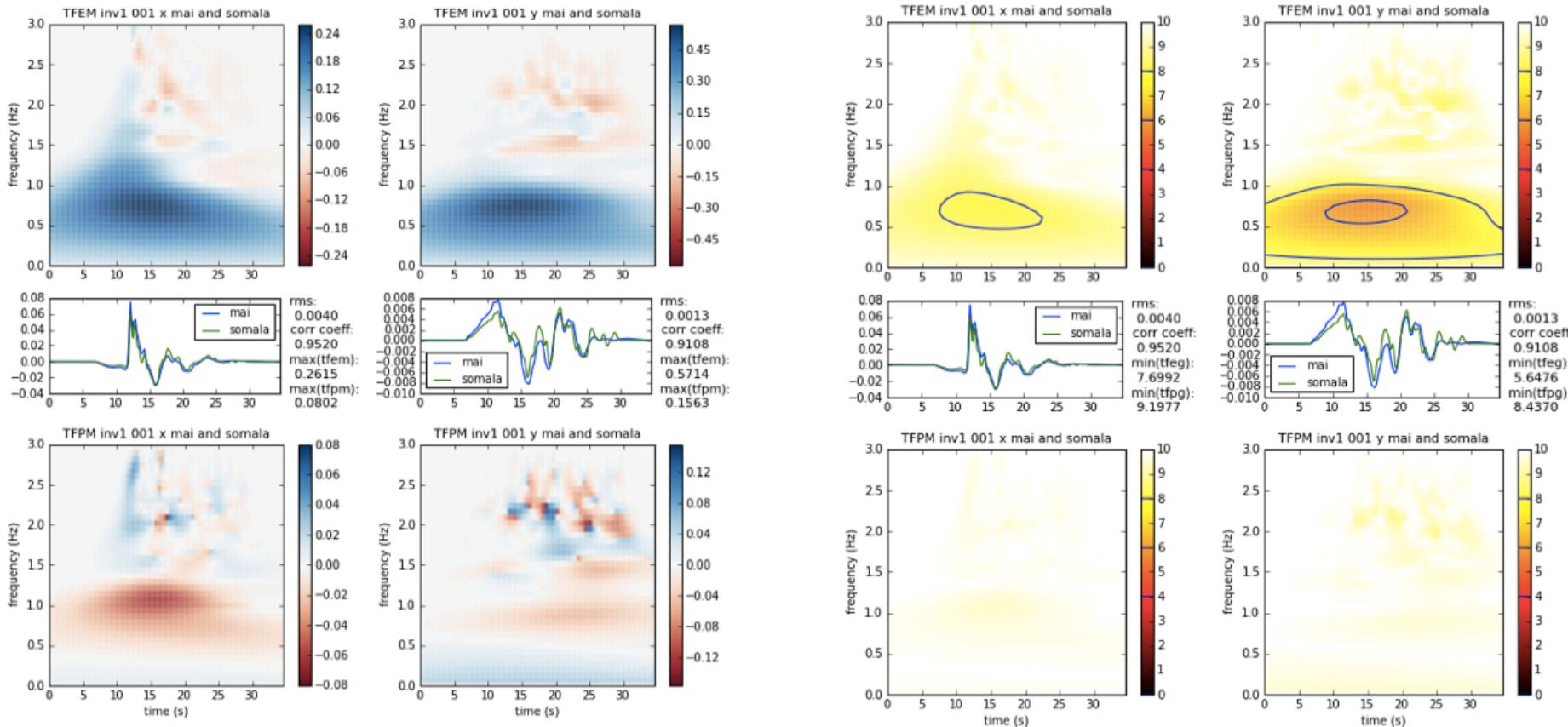
stations used for inversion

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 constraints? 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)

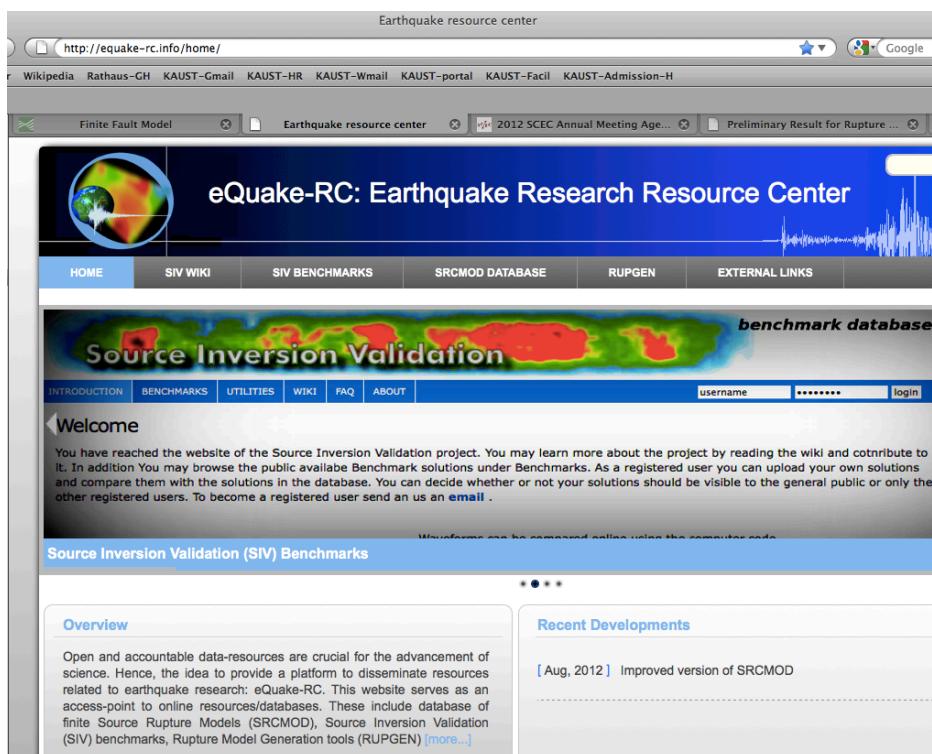
SIV: The next steps

- 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

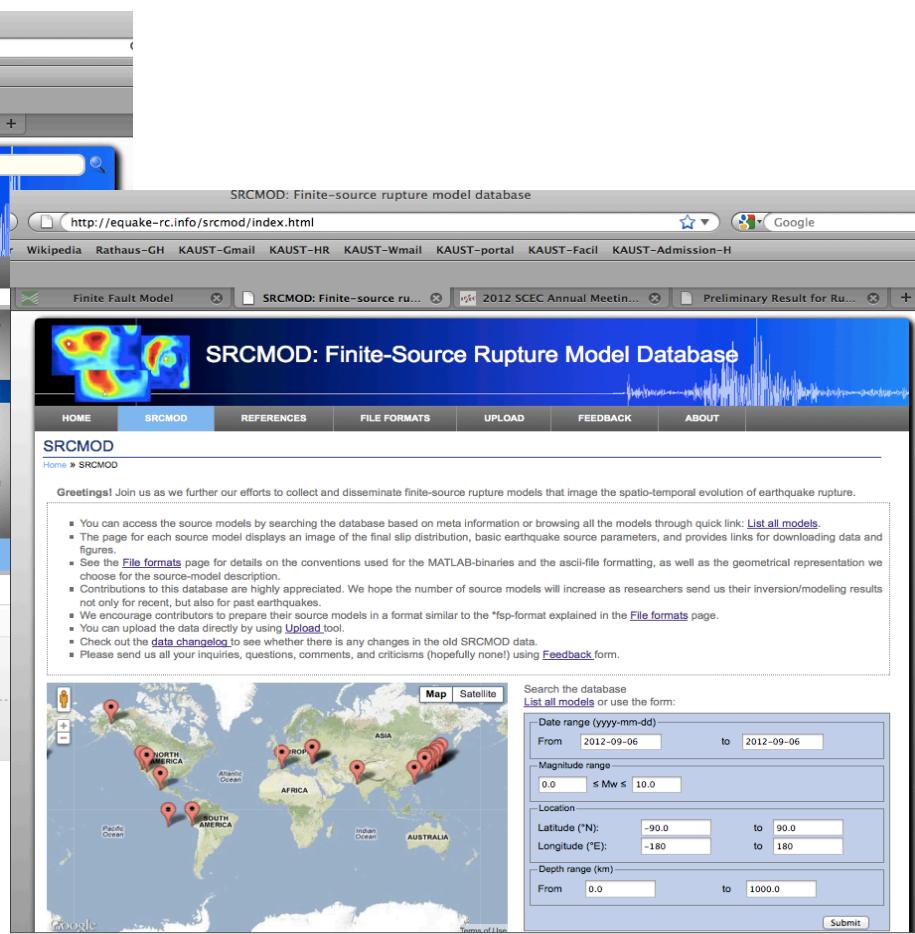
Improved online accessibility

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

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



The screenshot shows the eQuake-RC website's homepage. At the top, there's a navigation bar with links to "HOME", "SIV WIKI", "SIV BENCHMARKS", "SRCMOD DATABASE", "RUPGEN", and "EXTERNAL LINKS". Below the navigation is a banner for "Source Inversion Validation" featuring a heatmap of seismic activity. The main content area has sections for "INTRODUCTION", "BENCHMARKS", "UTILITIES", "WIKI", "FAQ", and "ABOUT". A "Welcome" message is displayed, followed by a paragraph about the project's purpose and how users can contribute. There's also a note about waveform generation.



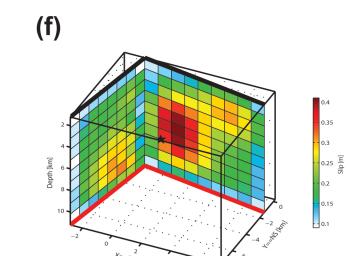
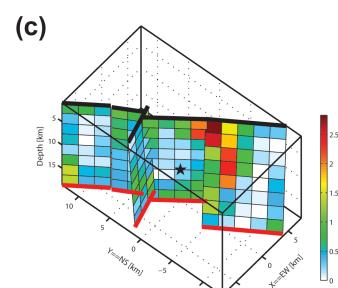
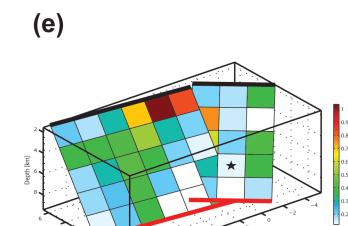
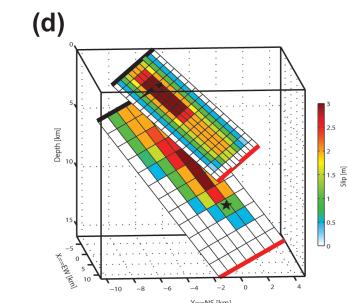
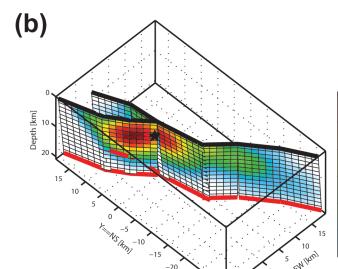
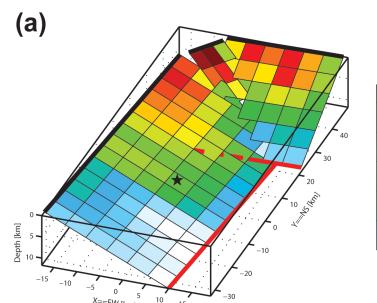
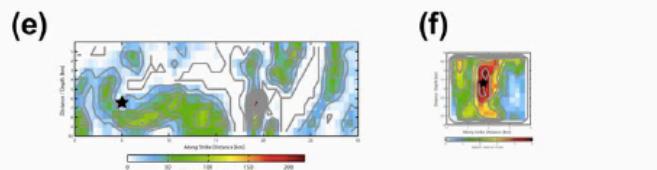
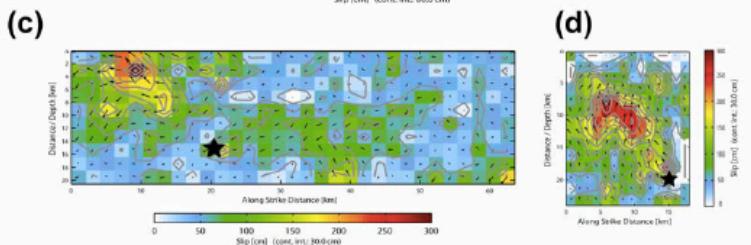
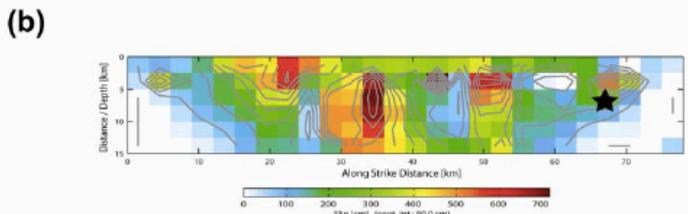
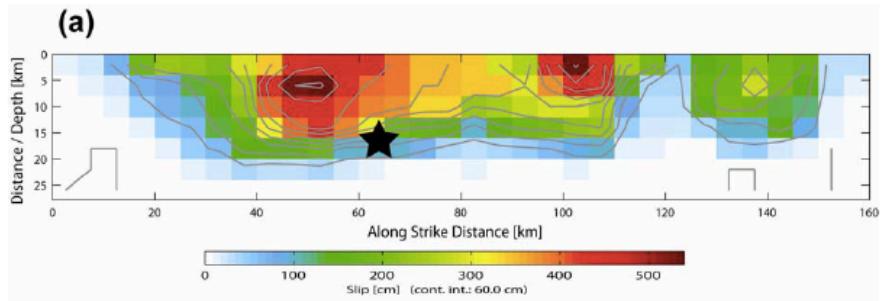
The screenshot shows the SRCMOD database website. The header includes a search bar and links for "HOME", "SRCMOD", "REFERENCES", "FILE FORMATS", "UPLOAD", "FEEDBACK", and "ABOUT". A "Greetings!" message encourages users to contribute models. Below it is a list of instructions for using the database. To the right is a map of the world with red dots indicating model locations, and a search interface for filtering results by date range, magnitude, location, and depth.

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

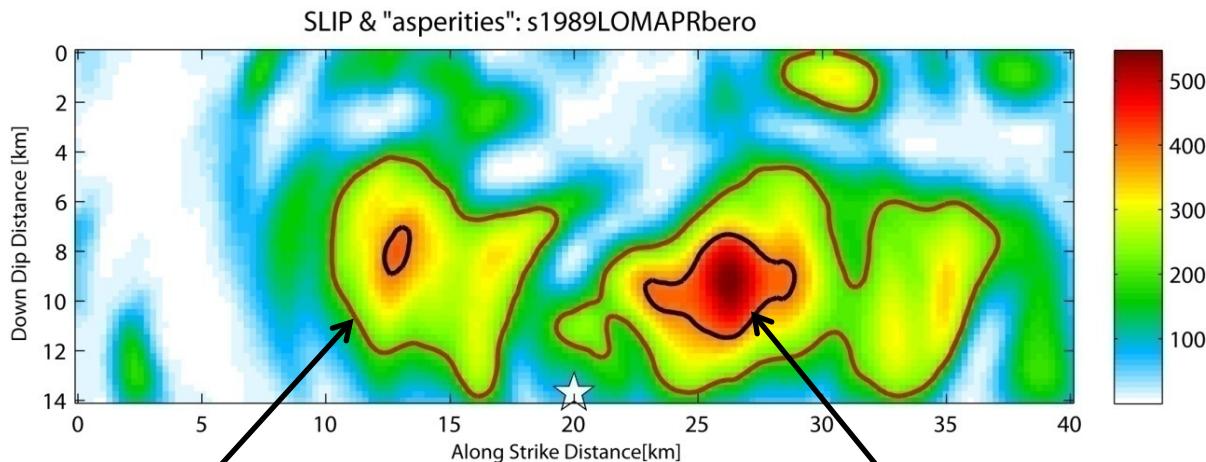
$$D \geq 2 \cdot D_{ave}$$

- Mai et al (2005): large-slip

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

very-large slip

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

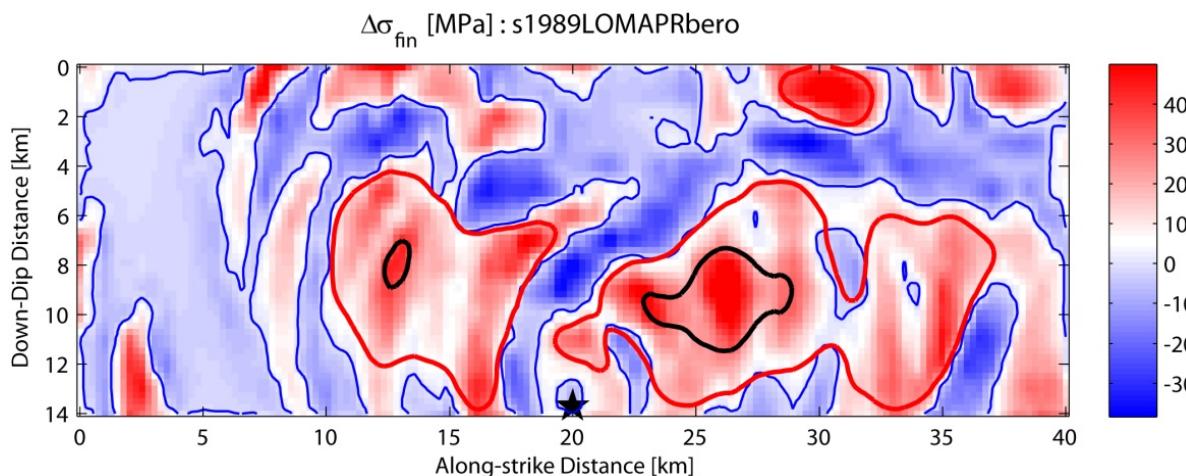
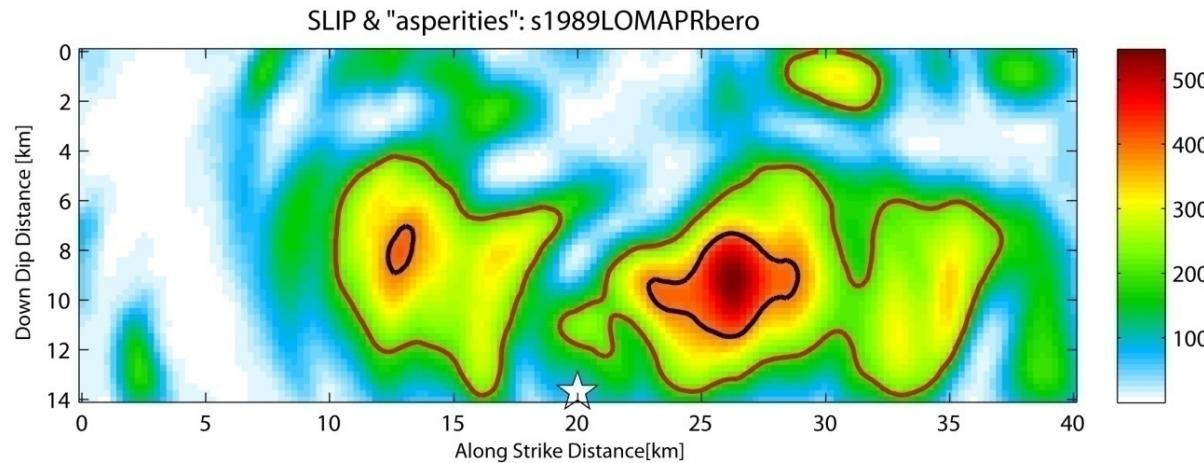


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$$D \geq 2/3 \cdot D_{max}$$

Source Parameters from finite-fault models

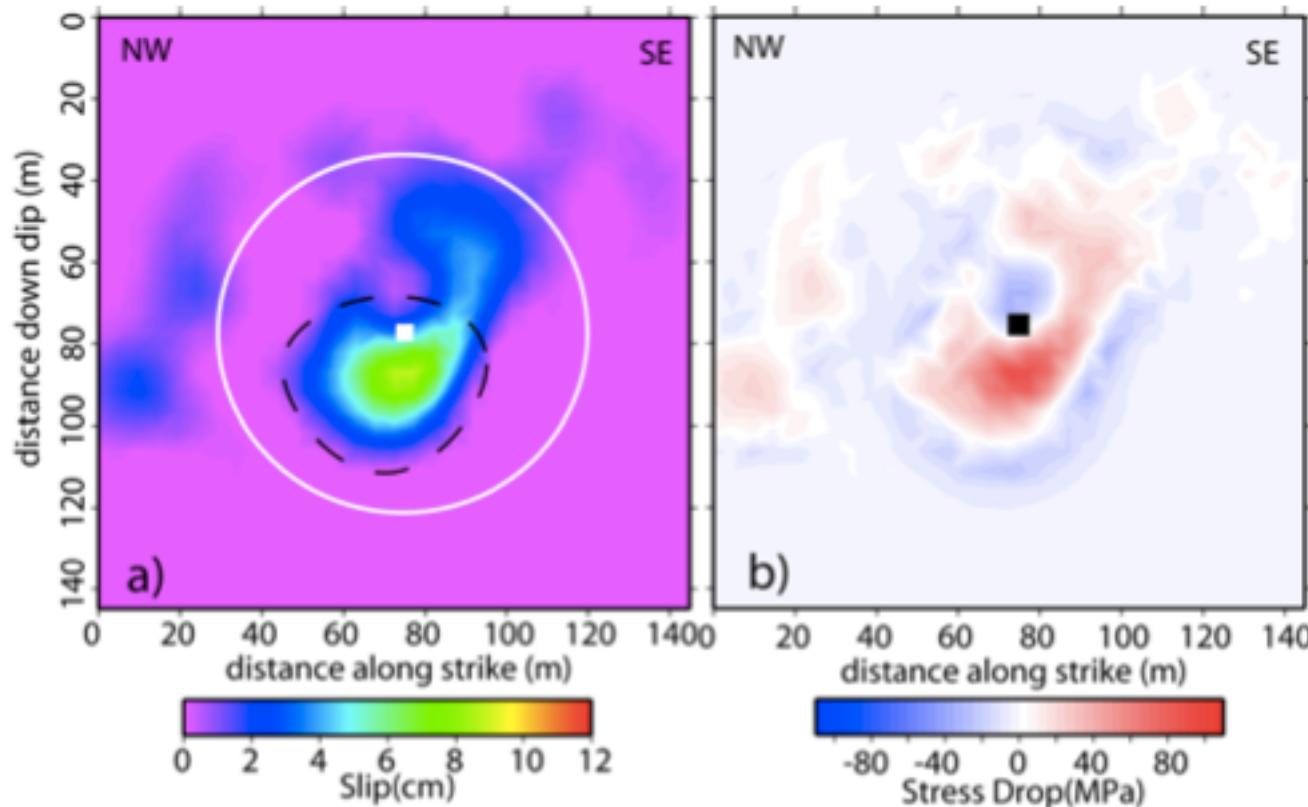
- Slip patches (“asperities”) and stress-change on the fault



Stress change after Ripperger & Mai (2004)

Source Parameters from finite-fault models

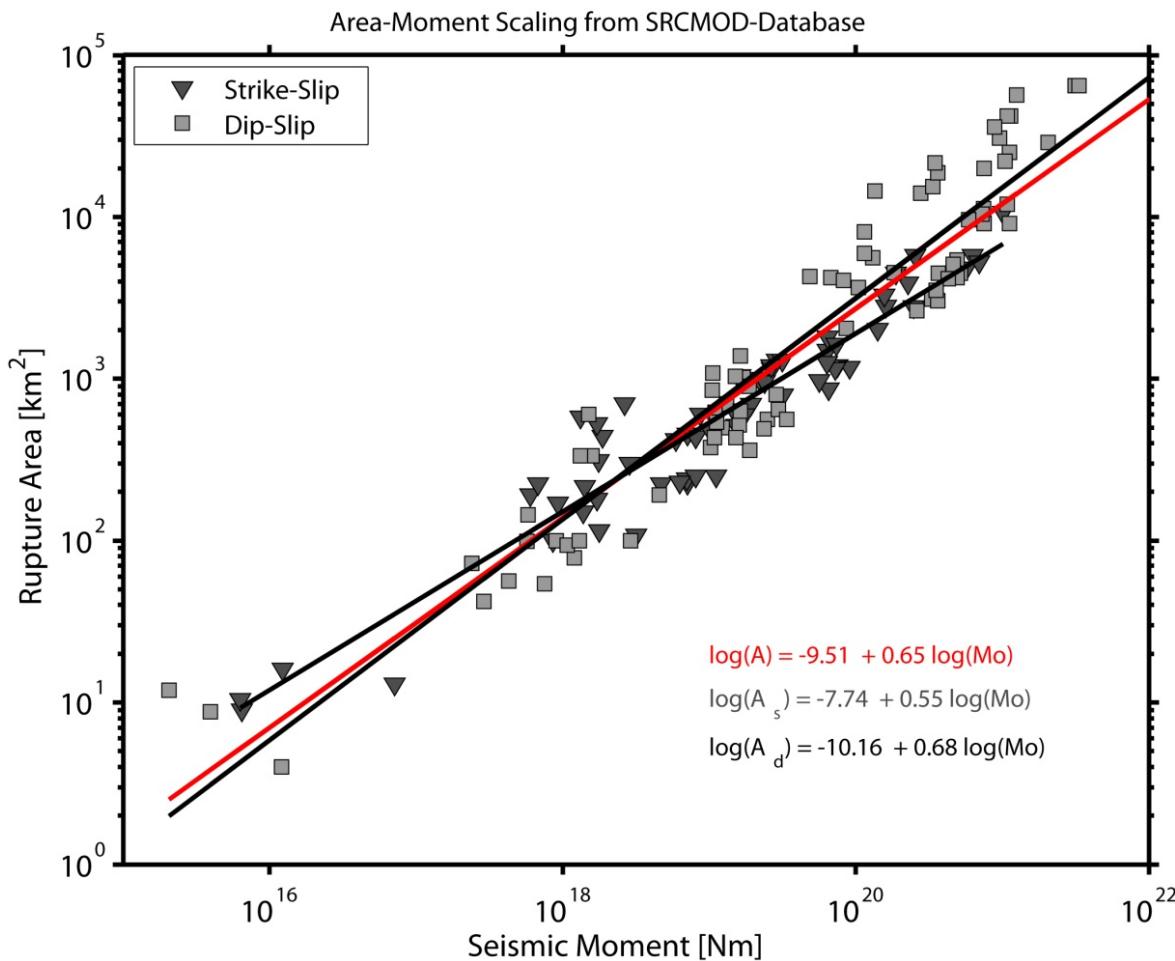
- Slip patches (“asperities”) and stress-change on the fault



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

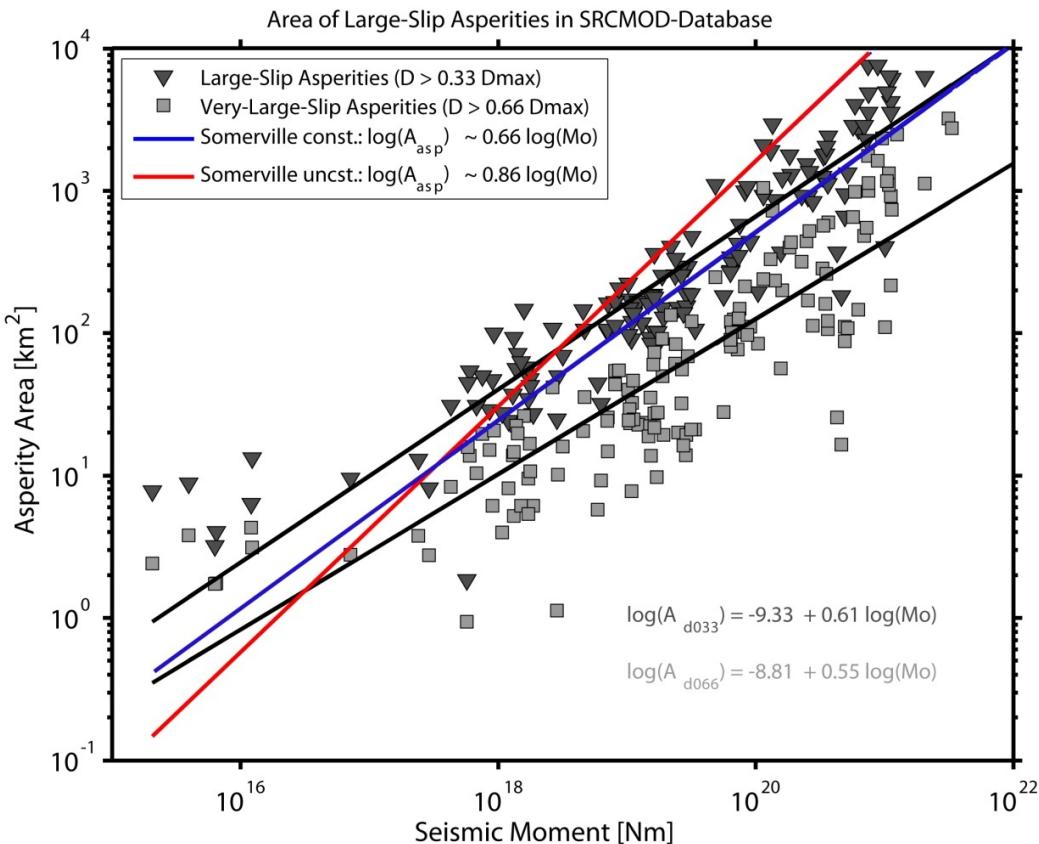
Source Parameters from finite-fault models

- 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



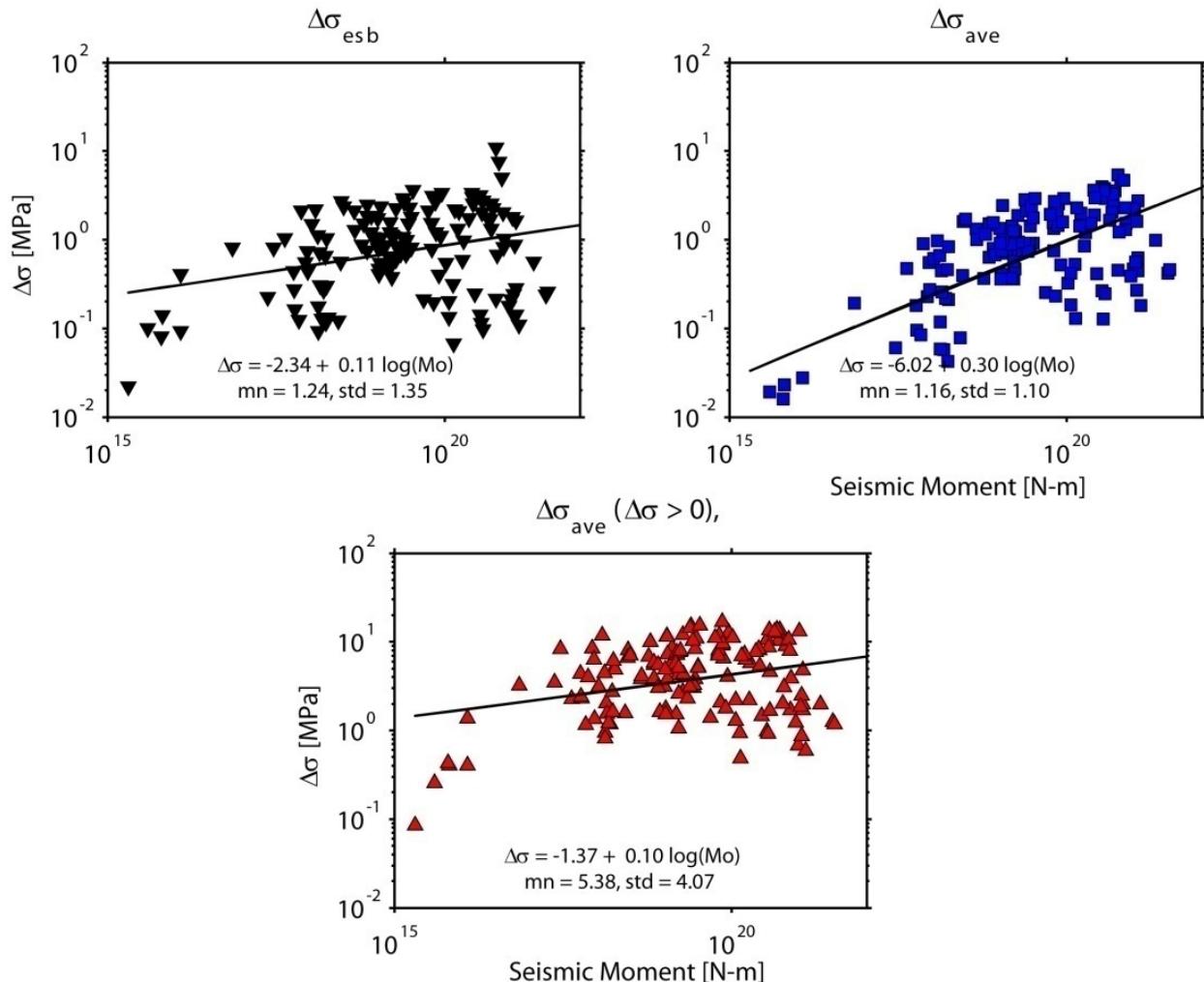
Source Parameters from finite-fault models

- Stress-drop estimates over the fault

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

$$\Delta\sigma_{ave}$$

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



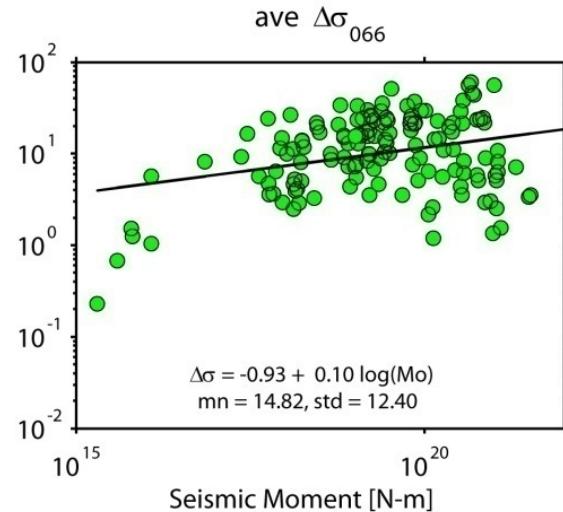
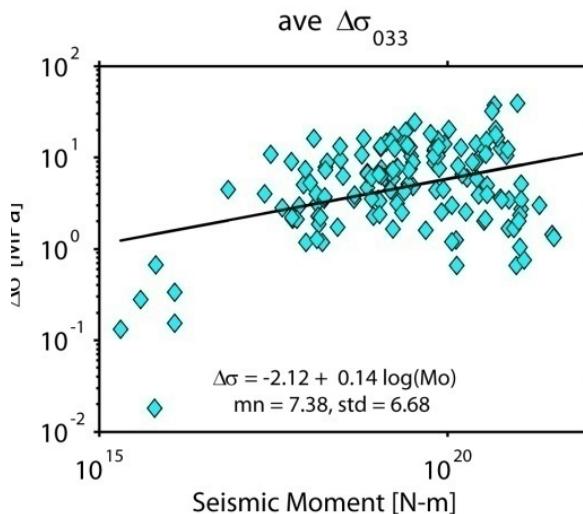
Source Parameters from finite-fault models

- 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 5 MPa over the regions of pos. stress-drop
- Considering the asperity regions, stress drops are 7 MPa – 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