Heterogeneous Initial Stress Parameterization for Dynamic Rupture Simulation Considering Style-of-Faulting and Loading Characteristics

By

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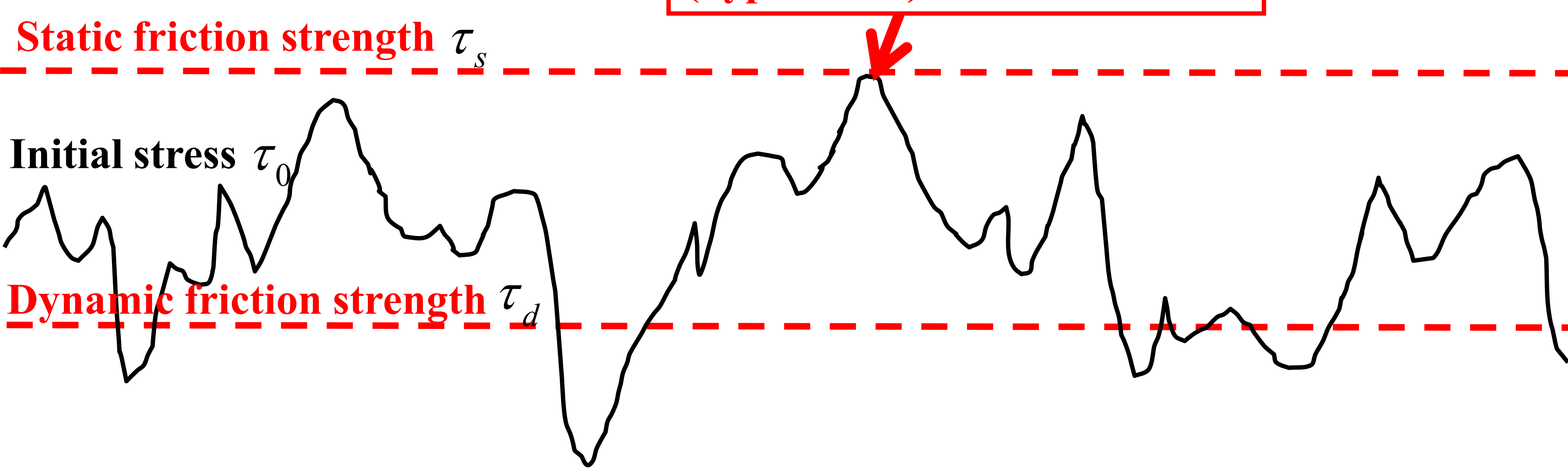
Imaging state of stress prior to earthquake
(Inspired from a though from J. Andrews, 2008)

- Imagine physical properties on a fault surface that are defined before an earthquake and are not dependent on the eventual size of the earthquake.
- In the ideal model, the fault surface is extended over an infinite plane or surface. Then, the extension of the fault rupture and magnitude are part of the solution that is subject to a friction law.
- Dynamic events of all sizes coul

Potential zone of Earthquake rupture initiation (hypocenter)

Stress on the



Problem statement for frictional strength and Initial stress parameterization

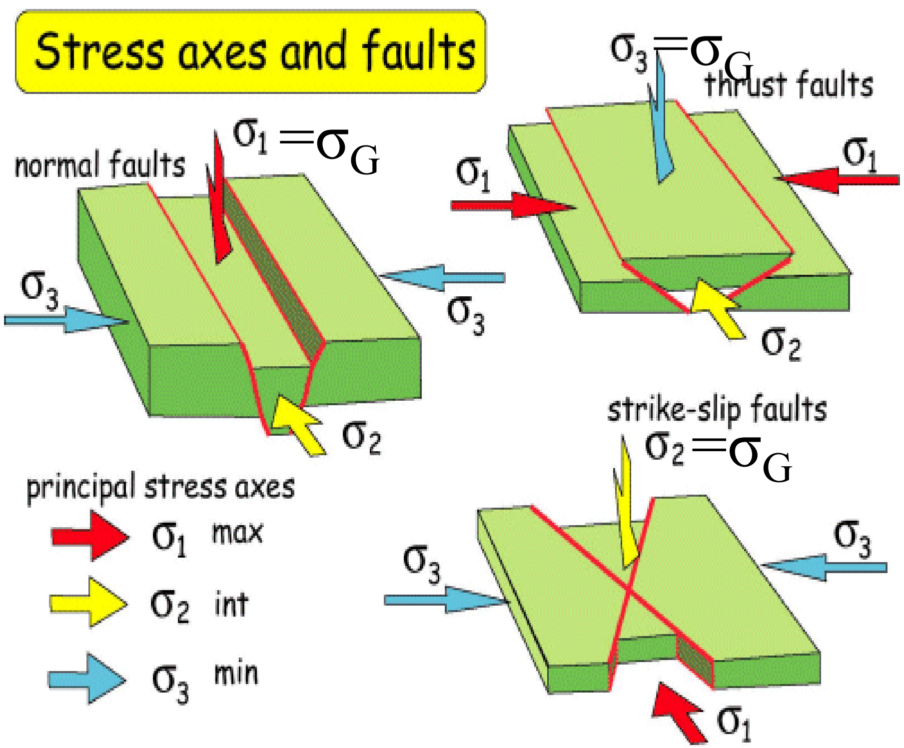
- Friction is usually assumed to be governed by the Coulomb friction criterion

$$\tau_c = c + \mu \sigma_{effect}$$

- Frictional coefficients (more or less well constrained from lab. experiments)
- Normal stress is usually arbitrarily assigned
- Initial stress prior to earthquake rupture is also usually arbitrarily assigned
- The assumption of normal stress and initial stress are fundamental for realistic simulation of earthquakes in nature
- Normal stress can be constrained from theory of tectonic loading regimes (e.g., Sibson, 1991) and gravitational load (so we have physics to constrain it)
- Initial stress prior to earthquake we do not know!!, so can be stochastic with spectral defined features

Physical constraints:

Tectonic loading regime and gravitational load



$$\sigma_G = \rho g h = \text{Gravitational load}$$

(modified from: http://earth.leeds.ac.uk/learnstructure/index.htm)

Compressional regime (Thrust fault)

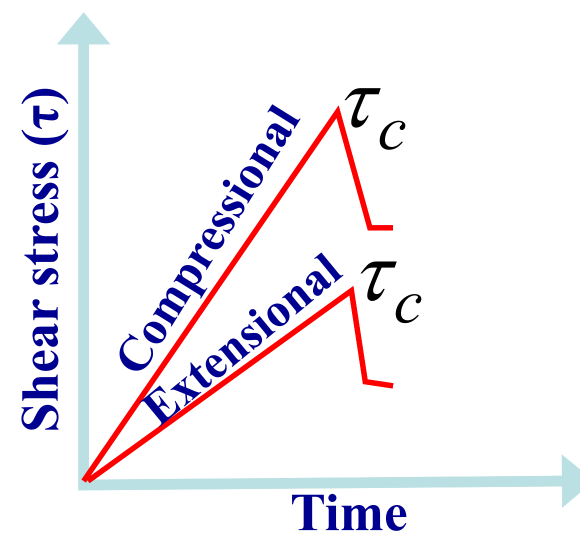
$\boldsymbol{\sigma_1}$ increase

$\boldsymbol{\sigma_n}$ and $\boldsymbol{\tau_c}$ increase as $\boldsymbol{\tau}$ accumulate

Extensional regime (Normal fault)

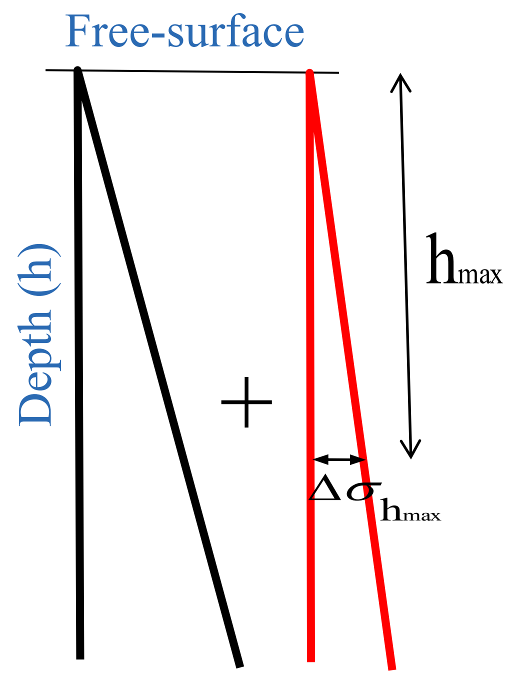
$\boldsymbol{\sigma_3}$ decrease

$\boldsymbol{\sigma_n}$ and $\boldsymbol{\tau_c}$ decrease as $\boldsymbol{\tau}$ accumulate

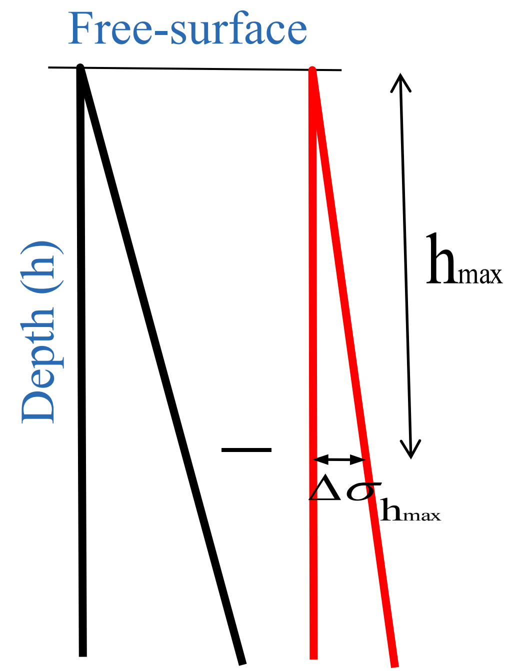


Loading methodology

- **Step 1**: Assume that far-field stress is initially equal to the confining pressure which is equivalent to the gravitational load $\sigma_1 = \sigma_2 = \sigma_3 = \rho g h$
- **Step 2**: Load σ_1 for thrust and strike-slip fault. Unload σ_3 for normal fault



$$\sigma_1 = \rho g h + \Delta\sigma_{load}$$
(loading)



$$\sigma_3 = \rho g h - \Delta\sigma_{load}$$
(unloading)

Loading methodology

- **Step 3**: Estimate the normal stress on fault plane

  θ is the fault plane angle measured with the σ_3 axes

$$\sigma_n = \frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3)\cos(\theta)$$

- **Step 4**: Estimate the frictional strength (Coulomb friction)

$$\tau_c = c + \mu(\sigma_n - p)$$

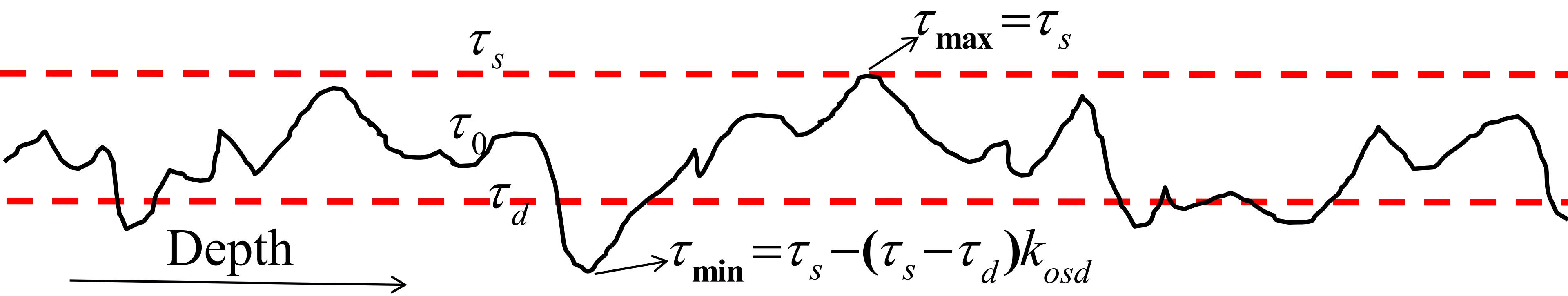
c is cohesion stress, p the pore pressure and μ the friction coefficient function (here slip weakening model, but can be any function)

$$\mu = \begin{cases} \mu_s - (\mu_s - \mu_d) u / d_0 & u < d_0 \\ \mu_d & u > d_0 \end{cases}$$

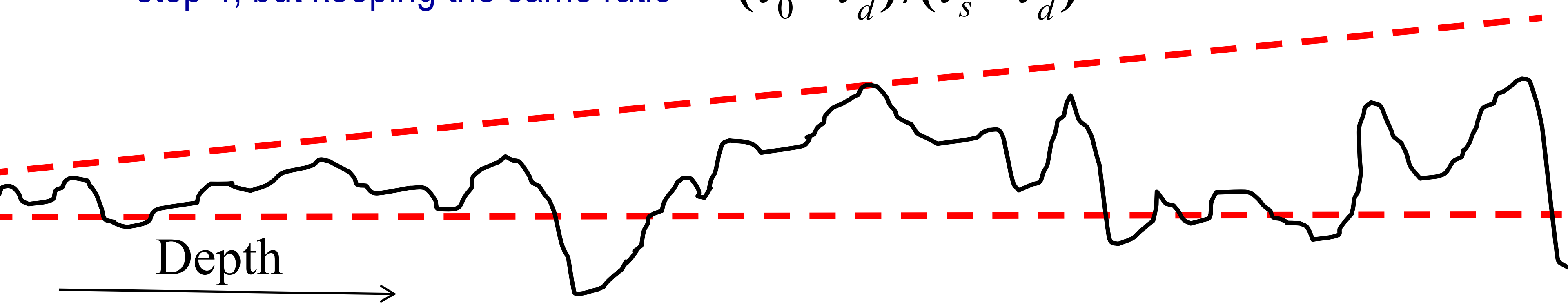
μ_s, μ_d are respectively, static and dynamic friction coefficient, u slip, d_0 critical slip distance

Loading methodology

- **Step 5:** Generate stochastic initial shear stress distribution (Gaussian, Exponential, vonKarman or fractal) in an arbitrary non-depth dependent frictional strength profile, such that its maximum is close to the failure and its minimum is the final stress. The later is characterized by the dynamic overshoot ($k_{osd}>1$) or undershoot ($k_{osd}<1$) coefficient.



Then the initial stress is adjusts to the depth dependent frictional strength profile defined in step 4, but keeping the same ratio $(\tau_0-\tau_d)/(\tau_s-\tau_d)$



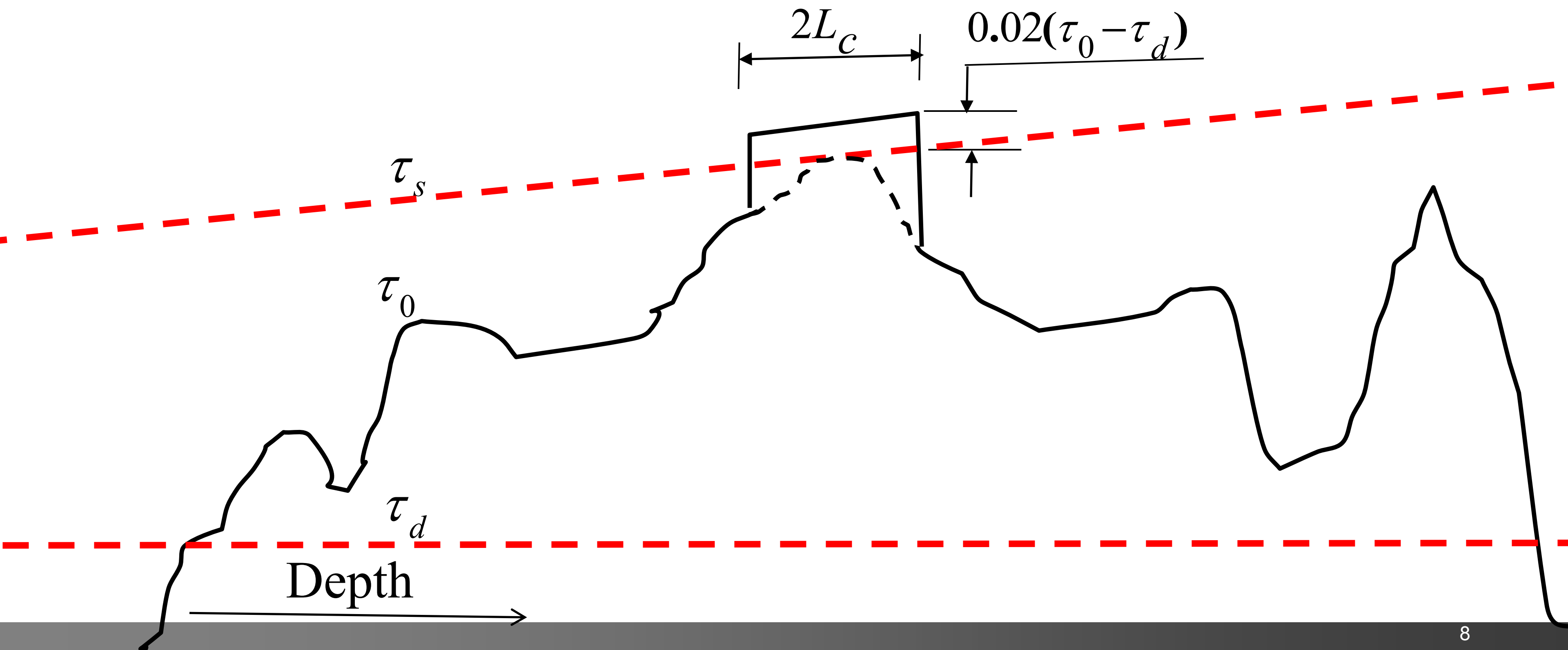
Loading methodology

- **Step 6:** Nucleation, $2L_c$

$$L_c = \frac{\mu d_0(\tau_{bav})}{\pi(\Delta\tau_{av})^2} \leq L_{max}$$

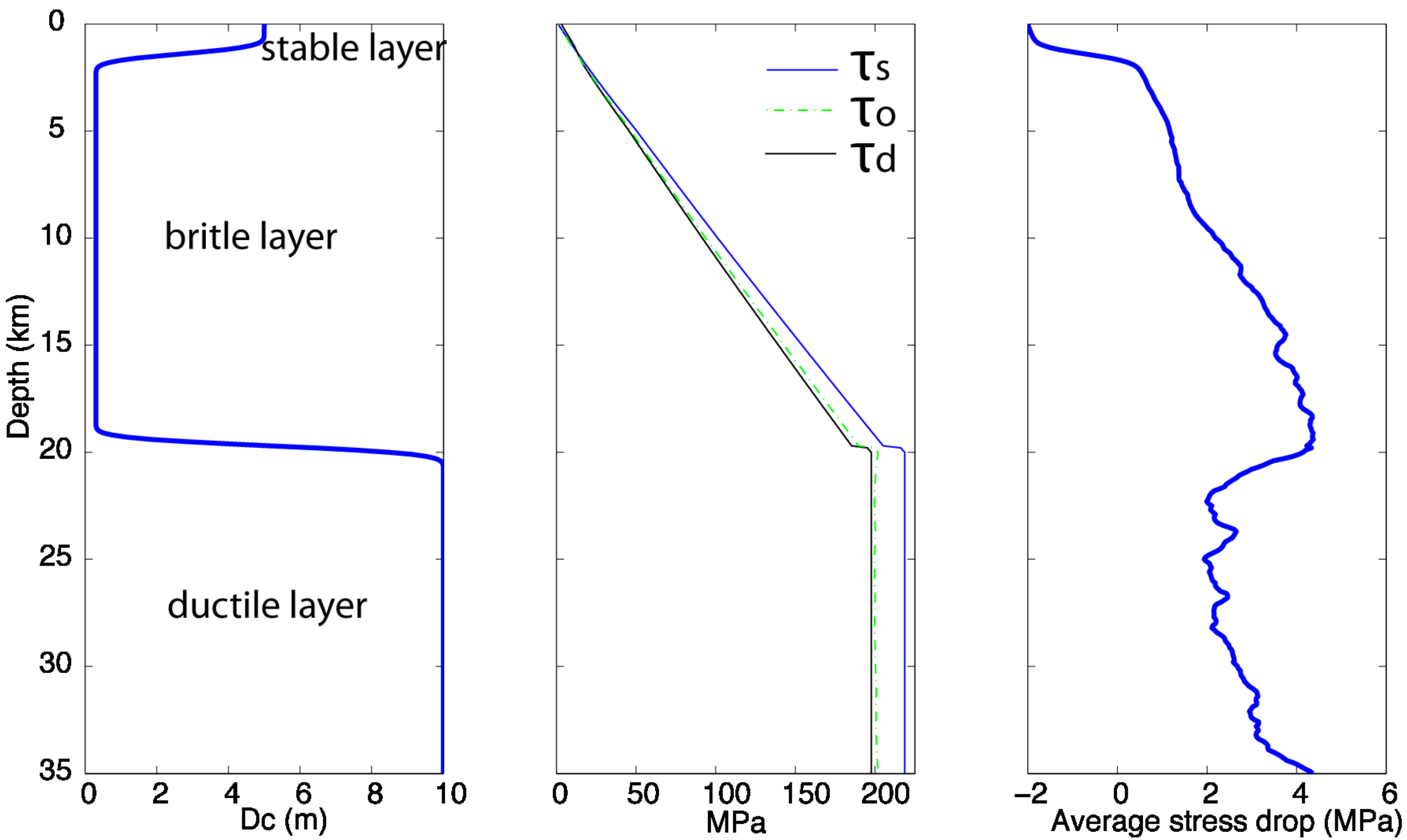
Where μ is the shear modulus, τ_{bav} and τ_{av} are respectively the average breakdown strength drop and average stress drop.

L_{max} Is the maximum half of nucleation size (here 2.0km)



Loading methodology

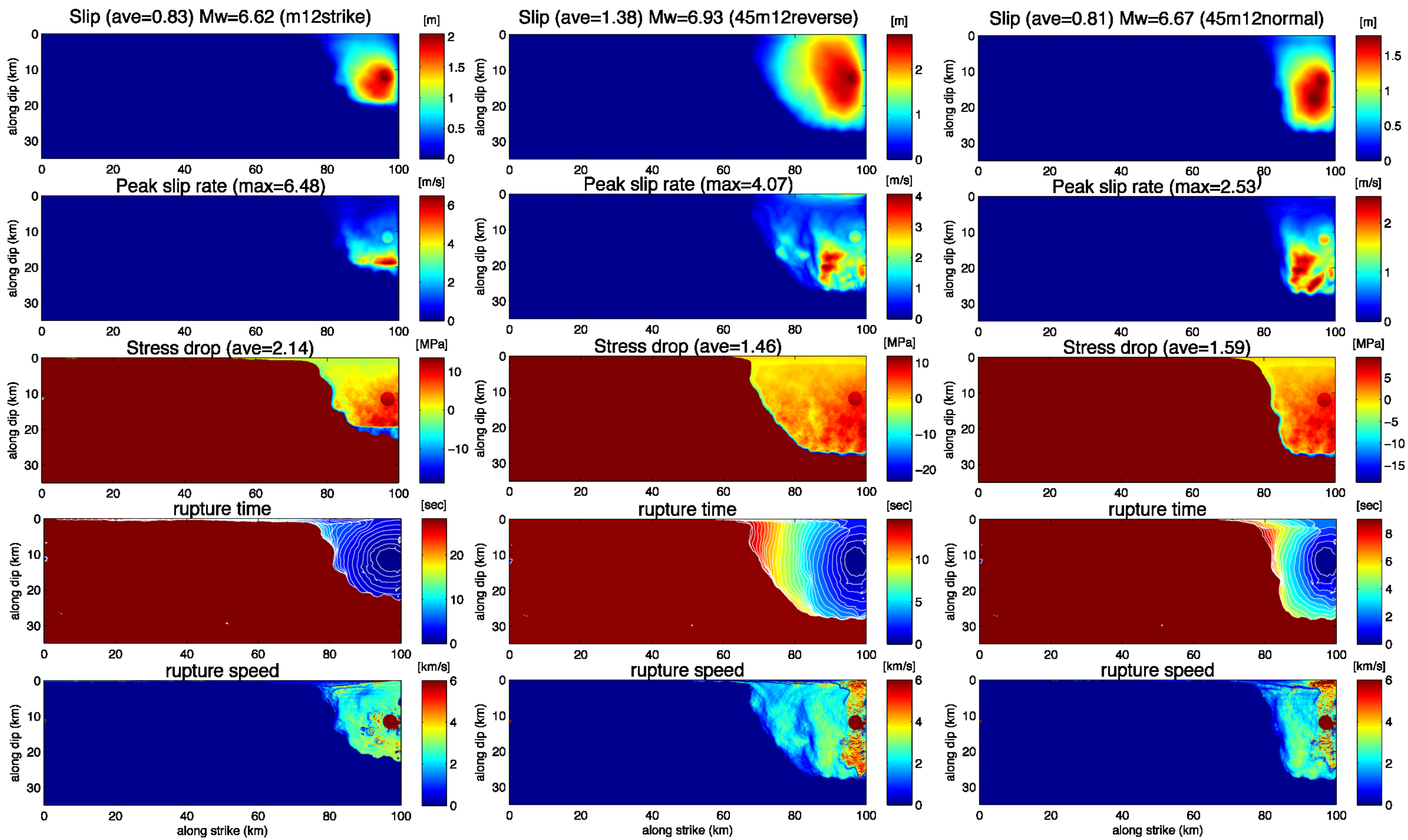
- **Step 7:** Shallow, brittle crust and ductile zone



Some dynamic rupture models

(Same initial random stress)

Strike | Thrust | Normal



Some rupture models

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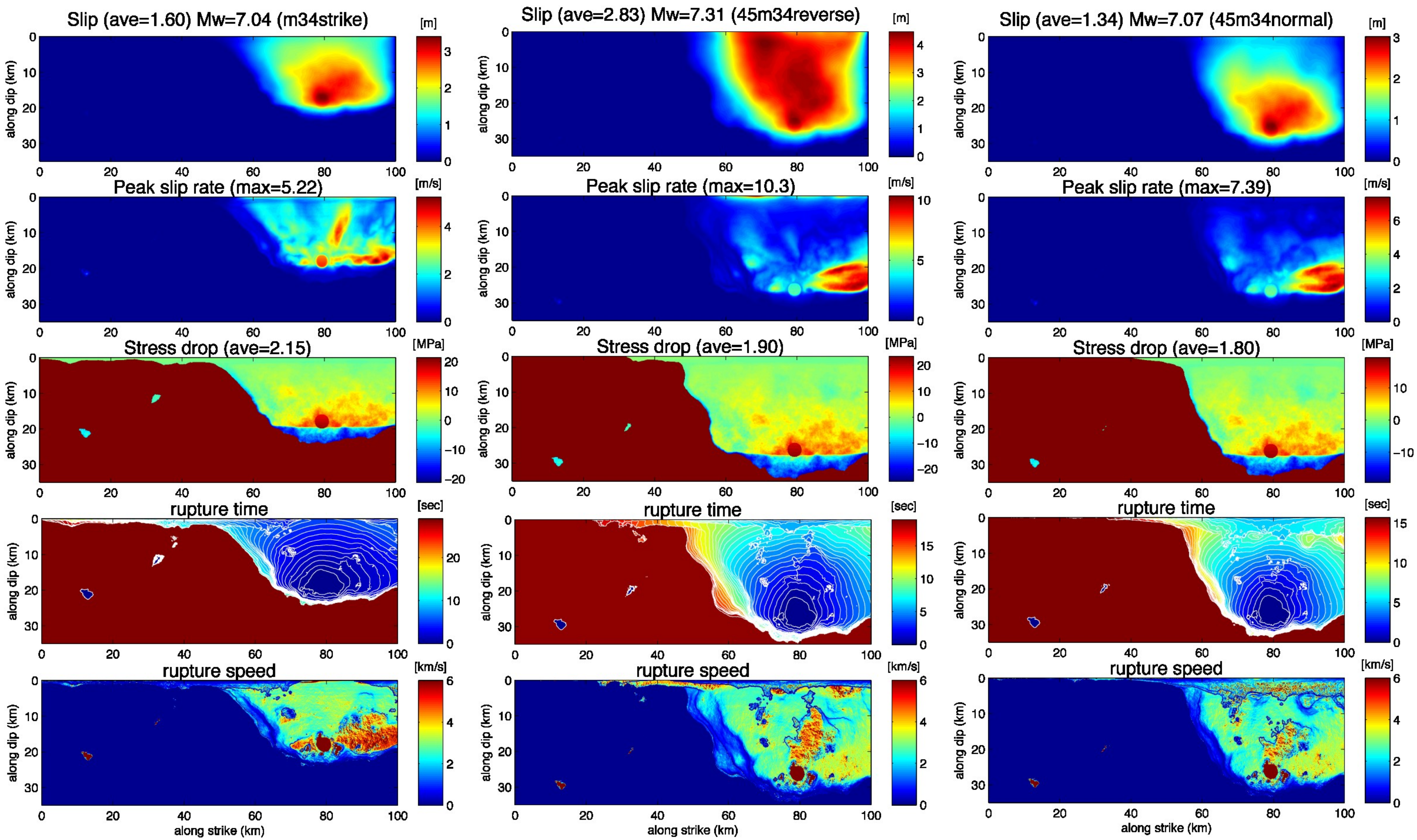
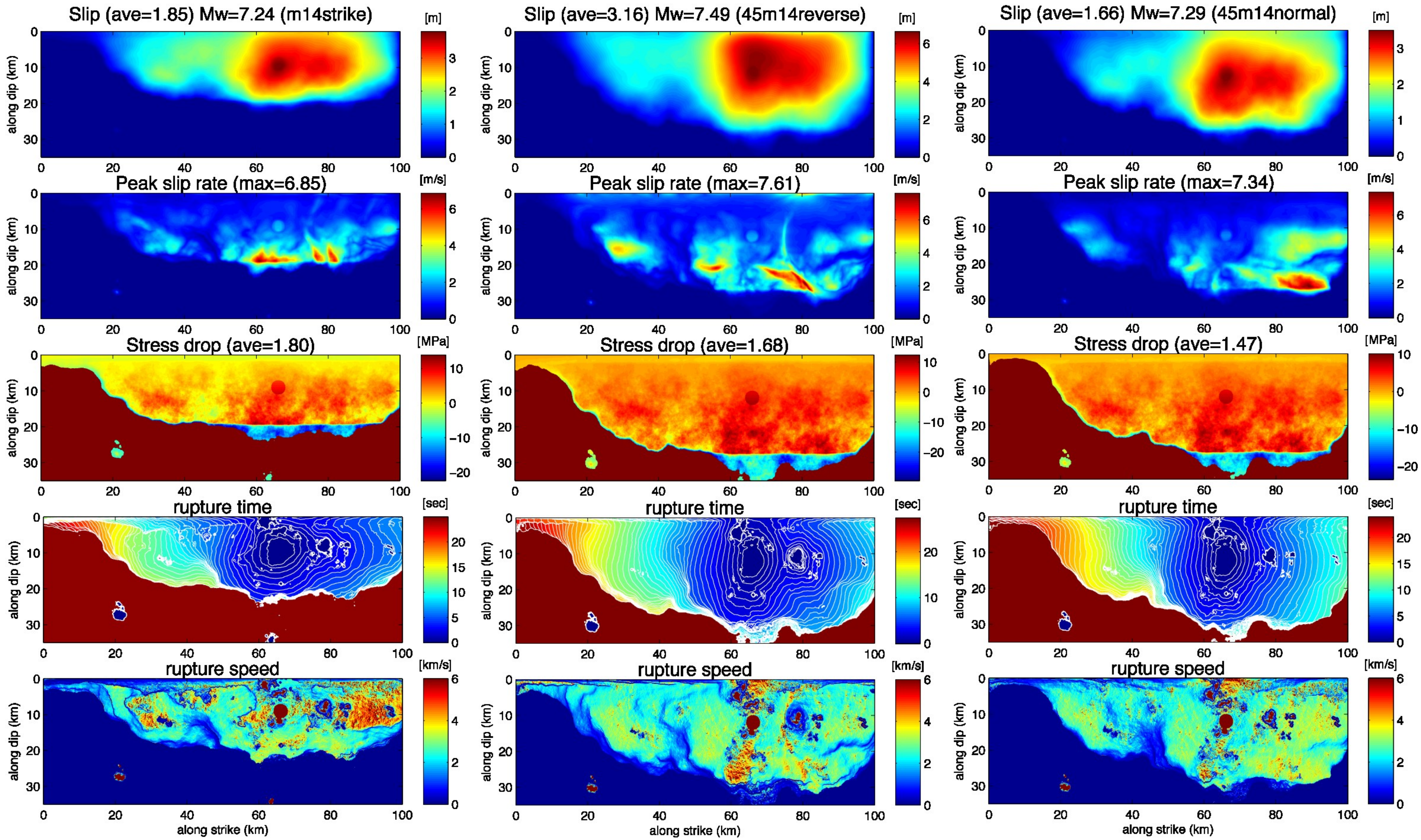


Some rupture models

(Same initial random stress)

Strike | Thrust | Normal

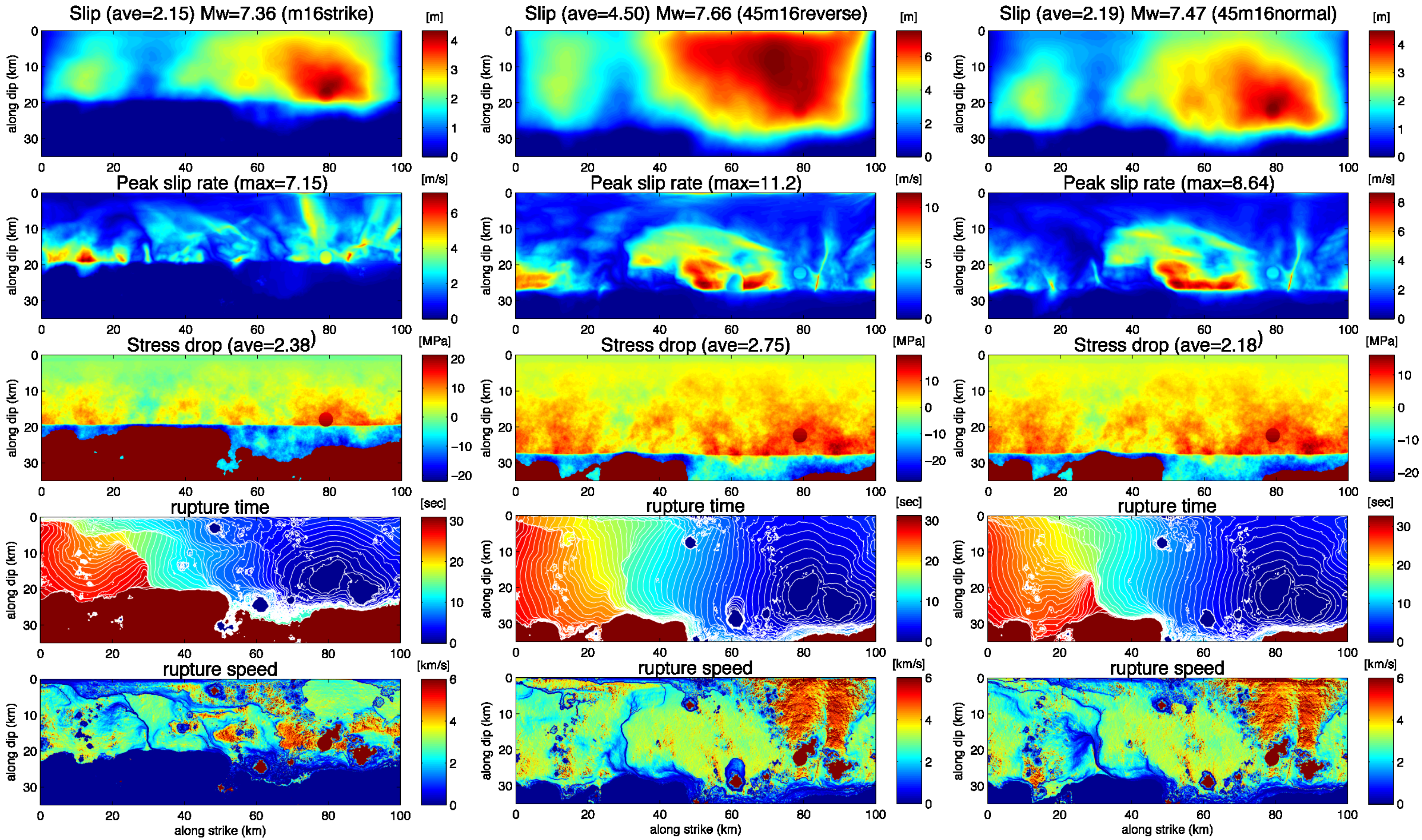


Some rupture models

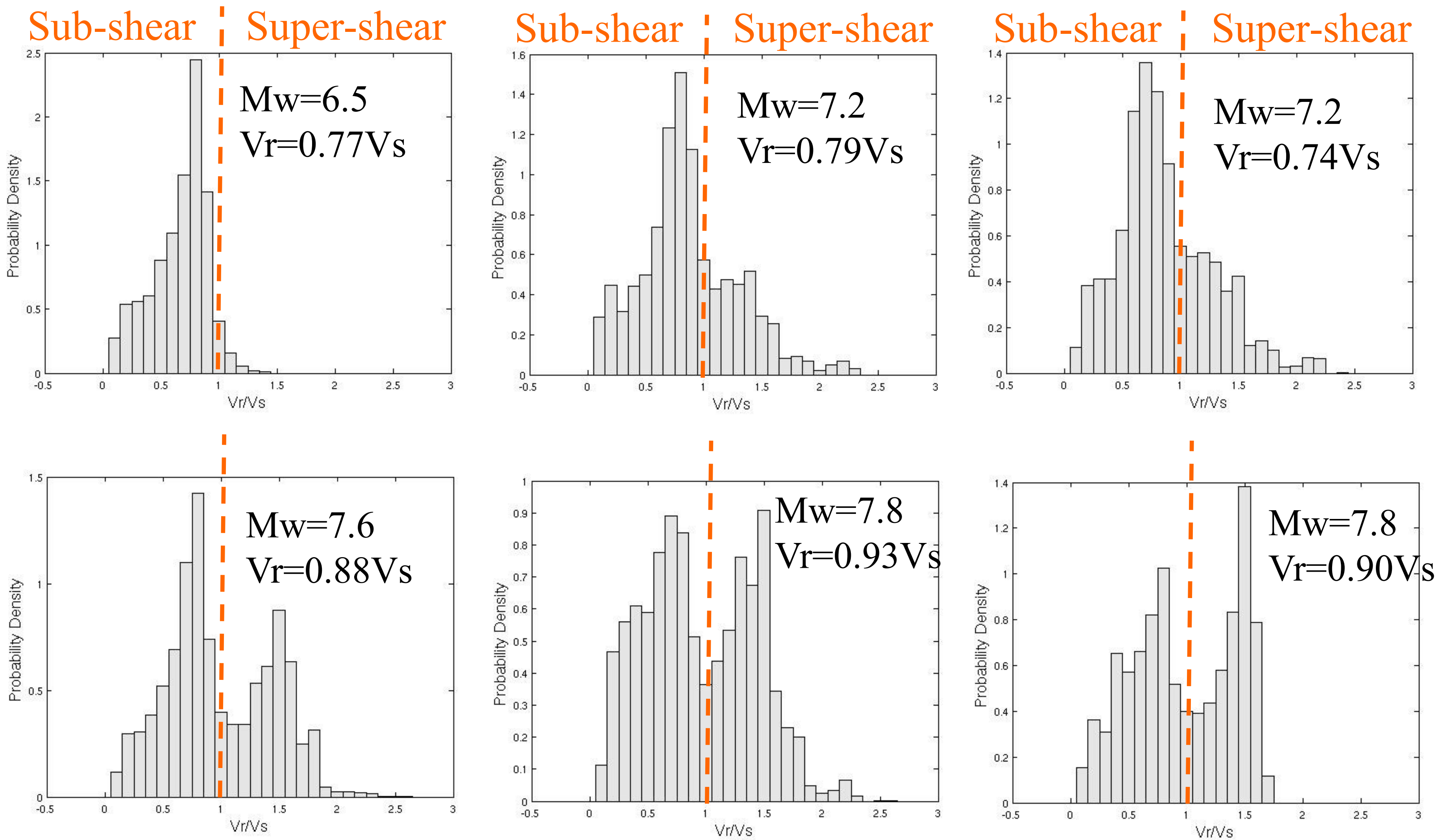
Numerical code: SORD (Support Operator Rupture Dynamics) from Ely (2008)

(Same initial random stress)

Strike | **Thrust** | **Normal**

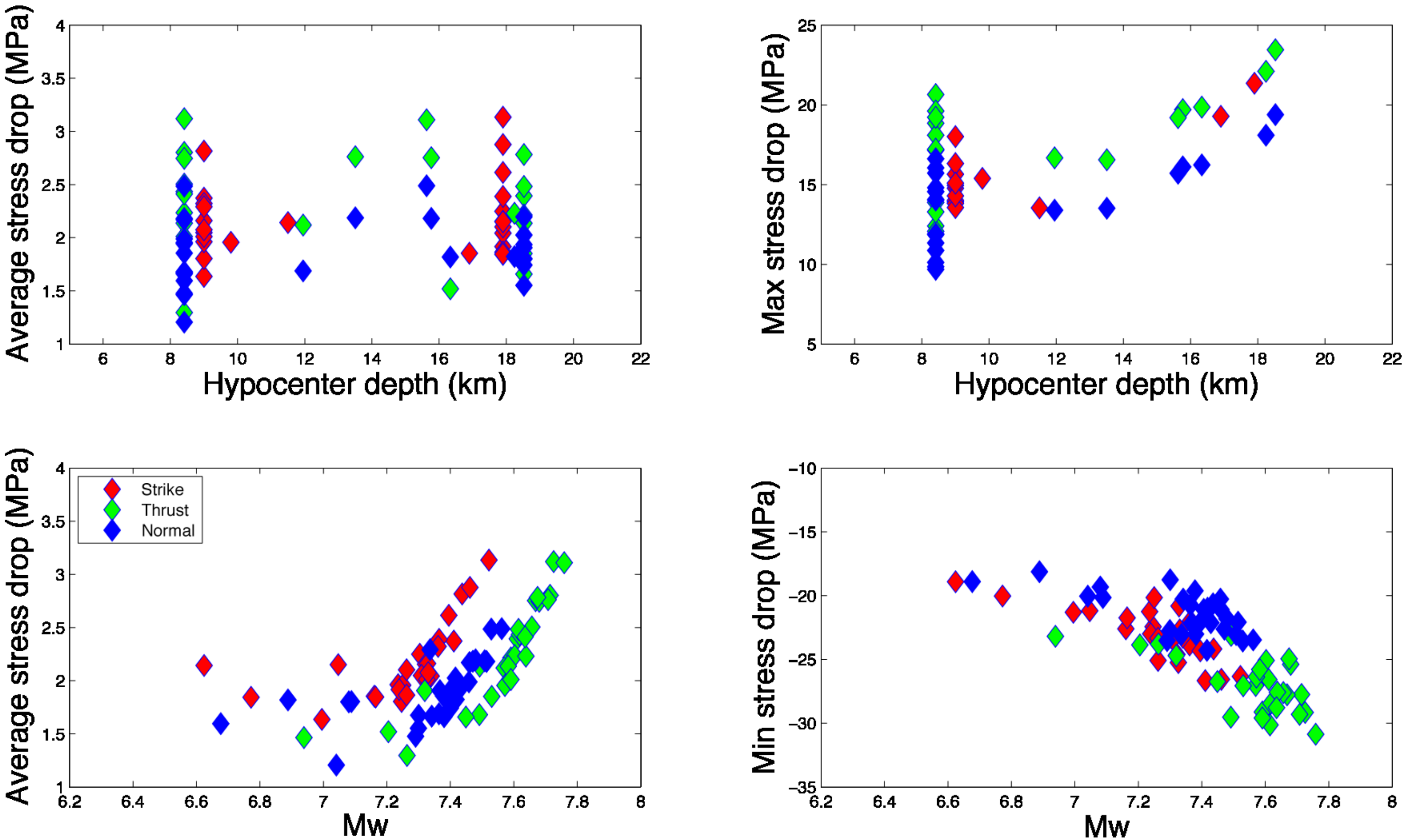


Local supershear rupture in strike slip faults

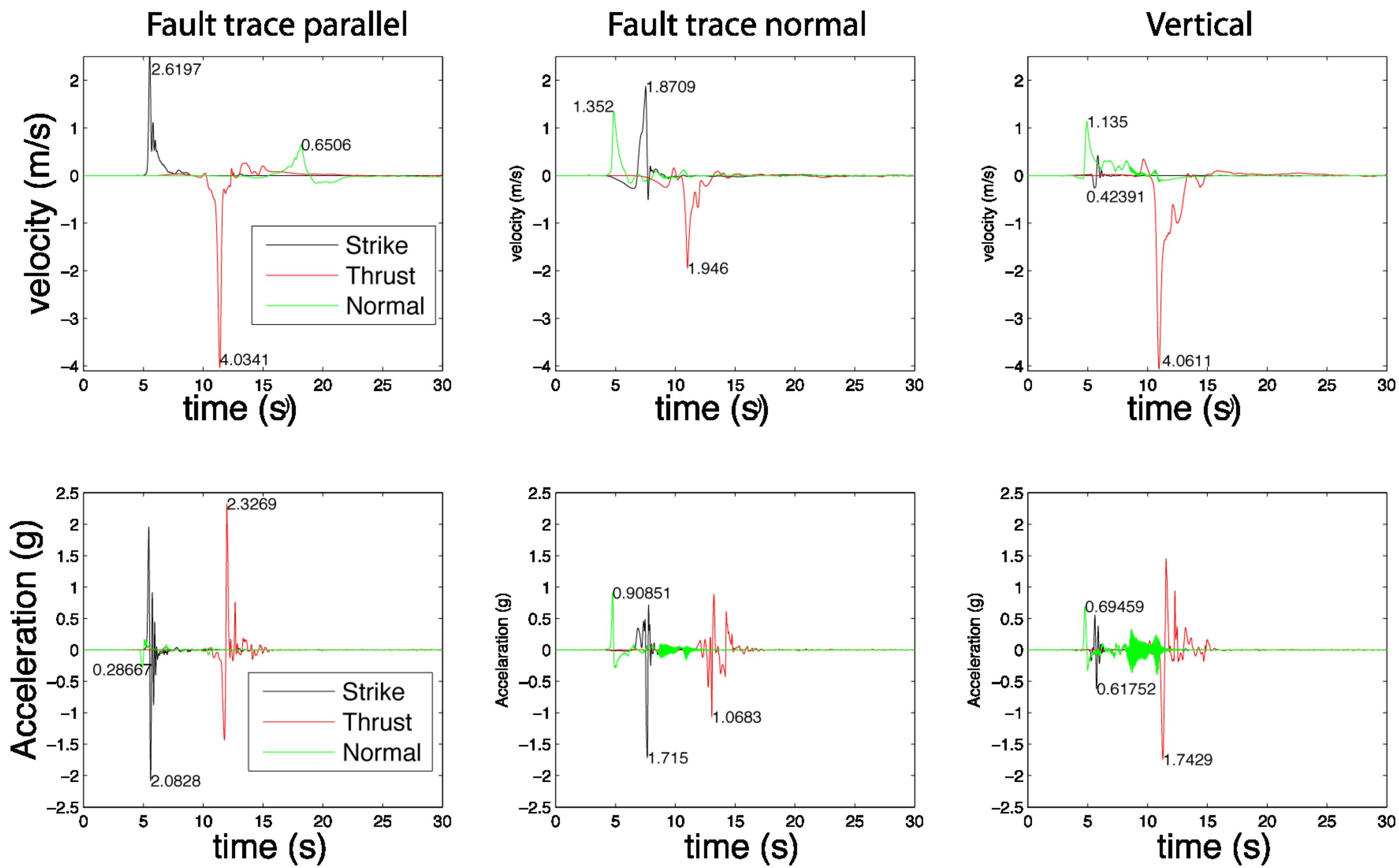


(Courtesy from Banu Mena)

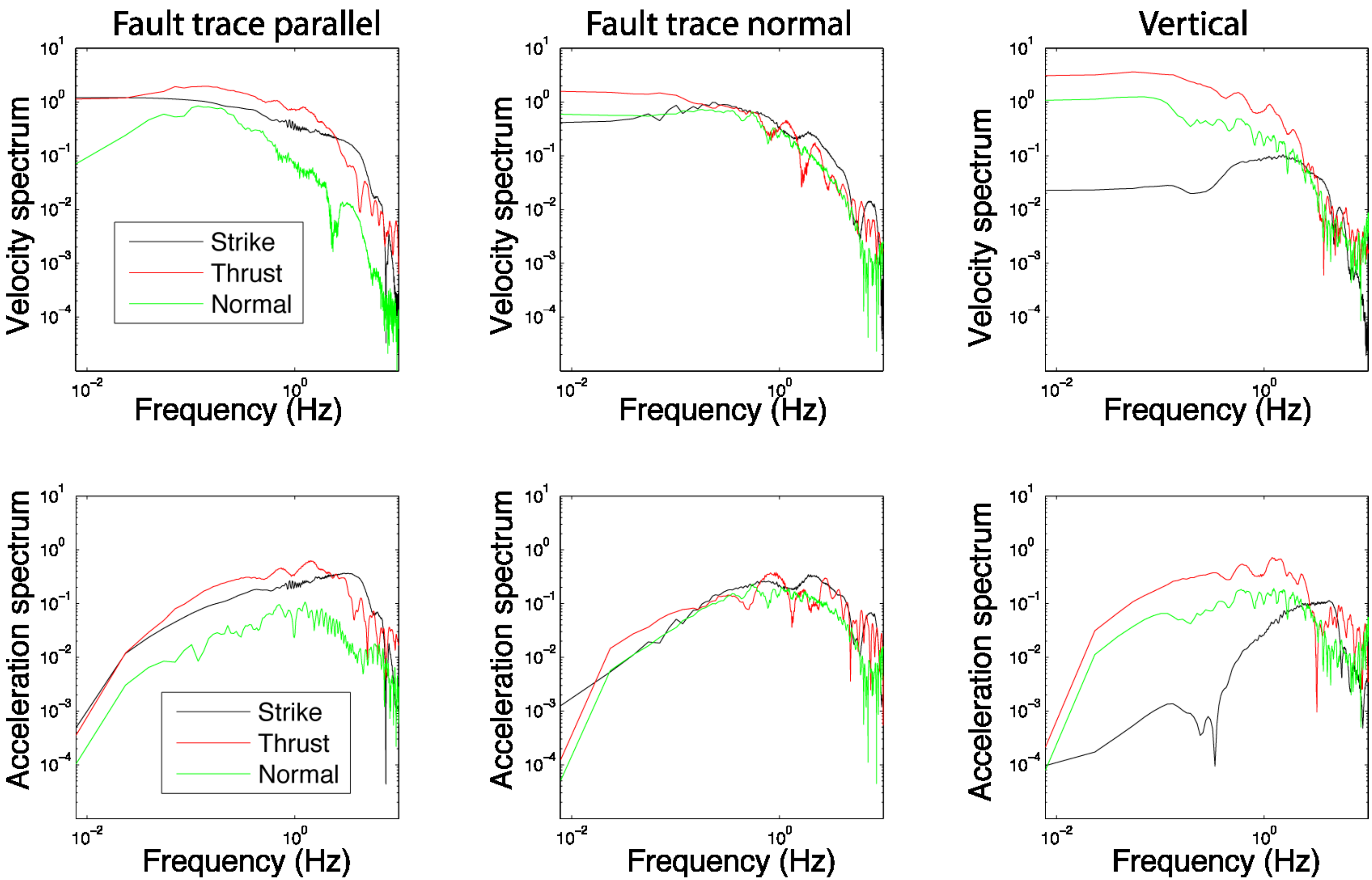
Stress drop Vs Hypocenter depth and Mw



Max velocity and Acceleration ground motion (model m16)



Max velocity and Acceleration ground motion (model m16)



Preliminary Conclusions

- Physical constraints of normal stress depth dependent combined with loading tectonic regimes mark the differences between strike, thrust and normal faults (this constraints are not arbitrary), relevant for seismic hazard assessment
- Rupture area and stress drop are part of the solution, that depend on the stochastic nature of the initial stress
- Local super-shear rupture speed is present at all earthquake size and type of faulting. In Strike slip faults, local supershear rupture area increases with earthquake size.
- Average stress drop is not depth dependent, but it increase with earthquake size
- Negative stress drop increase with earthquake size
- Thrust fault earthquake generate the strongest ground motion, and normal faulting the weakest.

Concerns

- Lets stop to use constant normal stress or with some arbitrary variations. it is not physical!!. But up to what depth is reasonable to use normal stress depth dependent?
- In the framework of slip weakening distance, what values of critical slip distance is realistic?, or it just have to be guided by the grid resolution?
- Cohesion stress. I think it can be constrained with lab experiments, so lets work on it. (cohesion stress may also change during failure, not only the friction coefficient)
- What nucleation procedure is more appropriate?

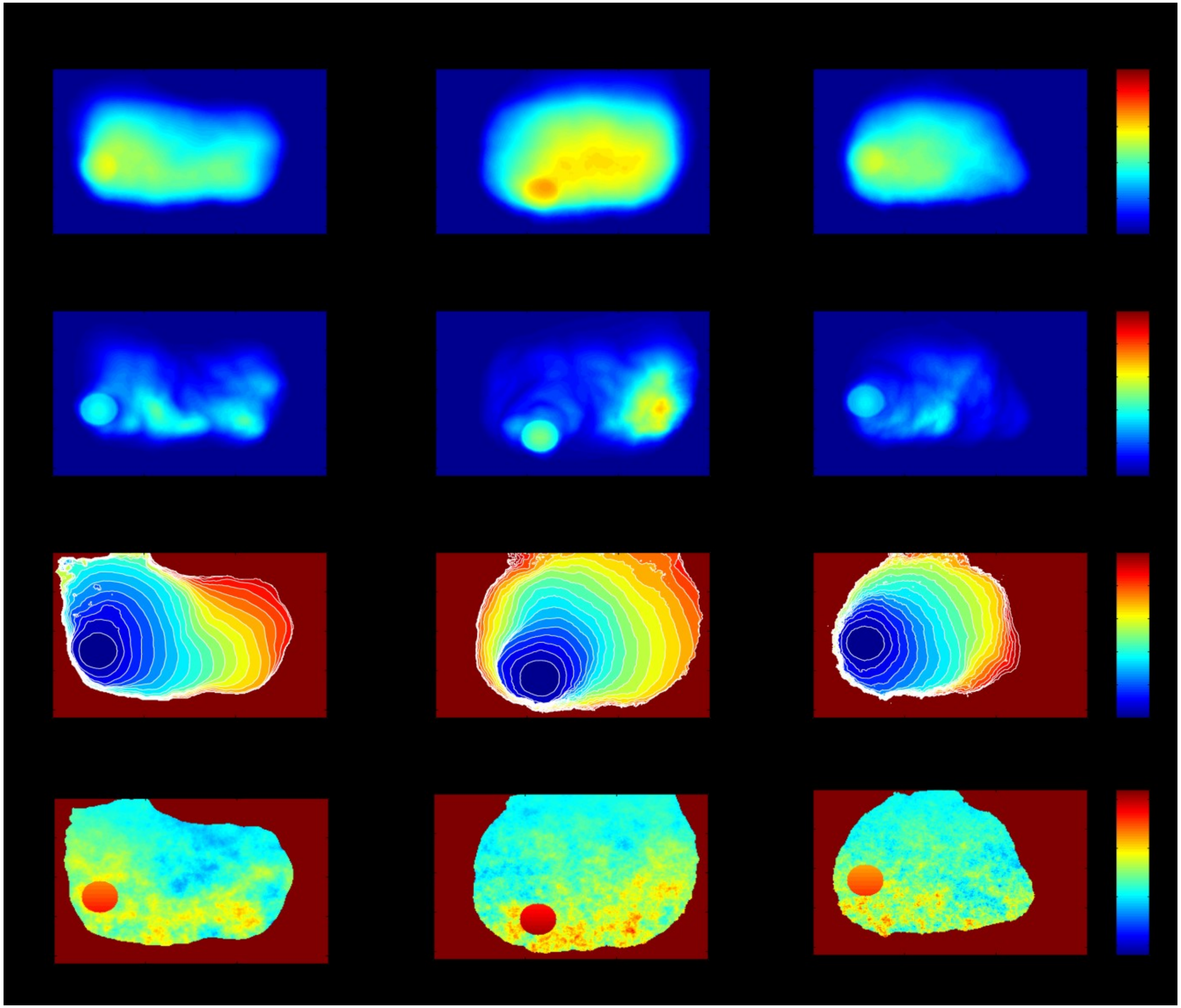
How to model a predefined Mw (6.5) in the proposed methodology?

- Predefine source dimensions following empirical source-scaling relations (Mai & Beroza, 2000; Wells & Coppersmith, 1994)
- Initial predefined average stress drop about 2.5MPa

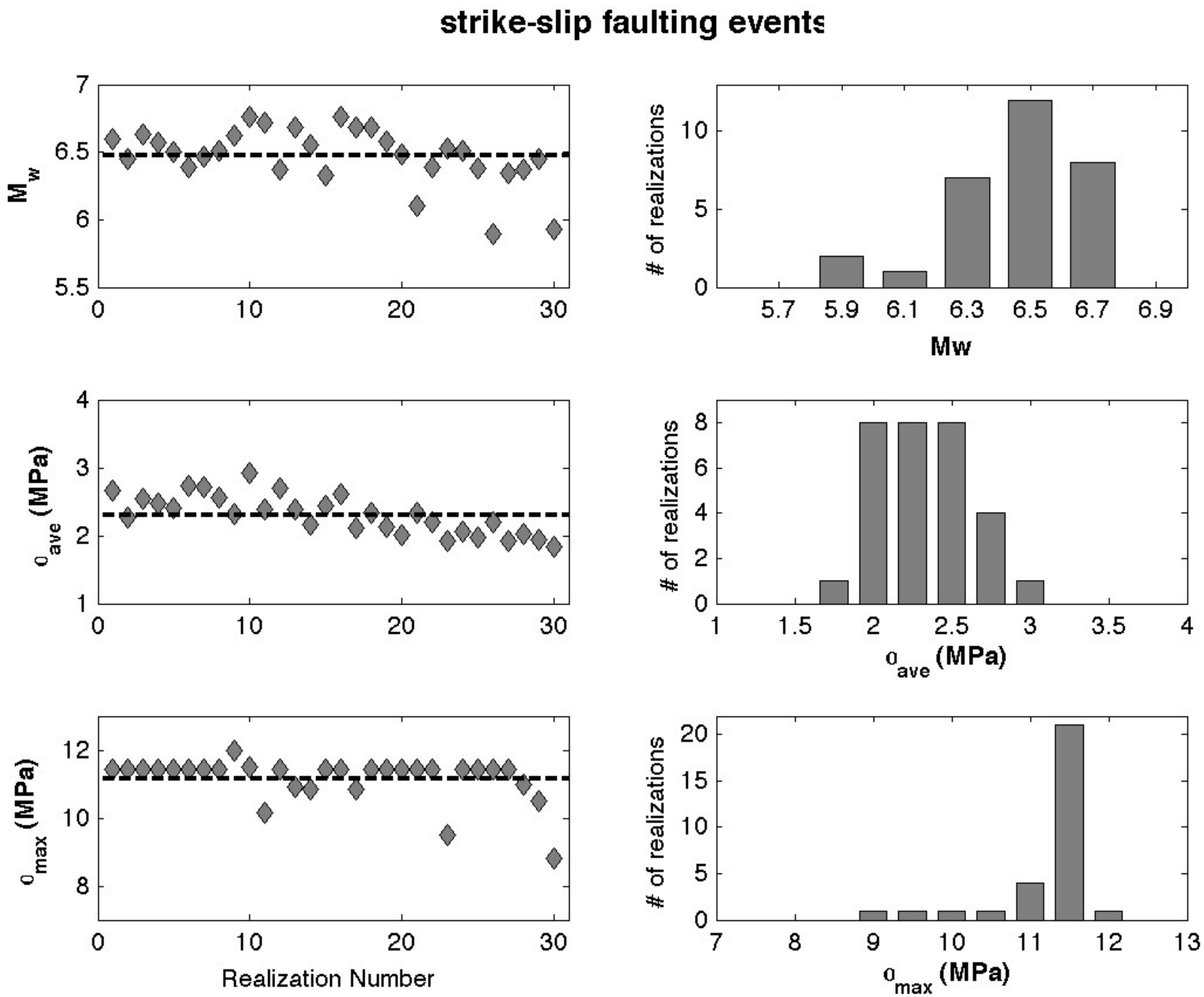
Parameters for Mw~6.5 (buried fault, 5km depth)

- Strike-slip faulting: dip=90° ; fault length = 30km; fault width=12km
- Thrust faulting: dip=45° ; fault length = 24km; fault width=15km
- Normal faulting: dip=60° ; fault length = 24km; fault width=15km
- The faults are buried at 5km depth, so no surface faulting.
- Static friction coefficient = 0.6 Dynamic friction coefficient = 0.56
- Critical slip-weakening distance = 0.3 m Dynamic overshoot coefficient = 1.5
- In our calculations, we use a 1D velocity-density structure, derived from tomographic velocity models of Switzerland
- Initial stress τ_0: stochastic field realization based on a *von Karman* distribution with correlation lengths 8.0 km, and variable Hurst number H=0, 0.25 and 0.5 (Mai and Beroza, 2002)

Some Example Results: Normal-Faulting Case



Statistics of Resulting Source Parameters



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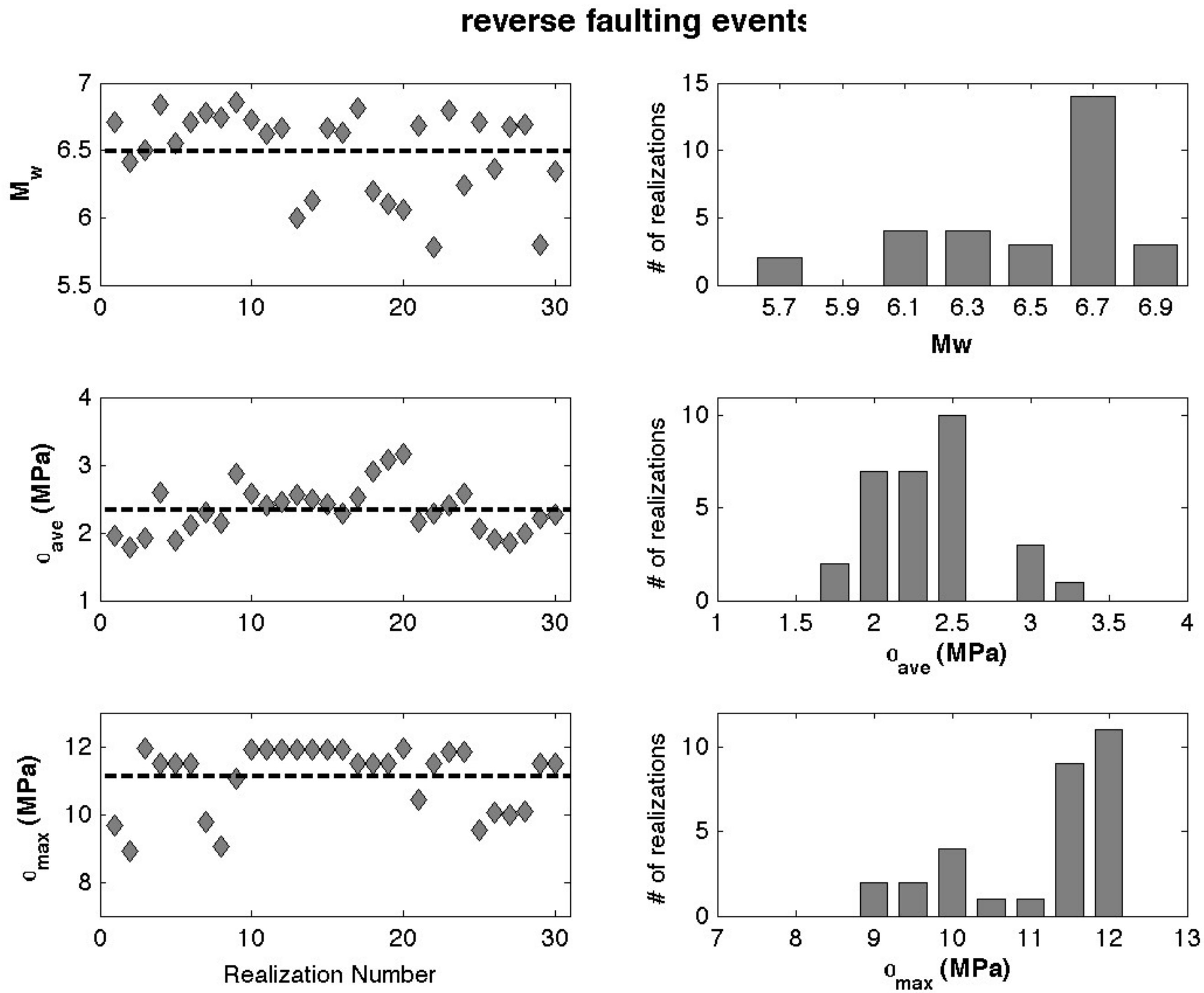

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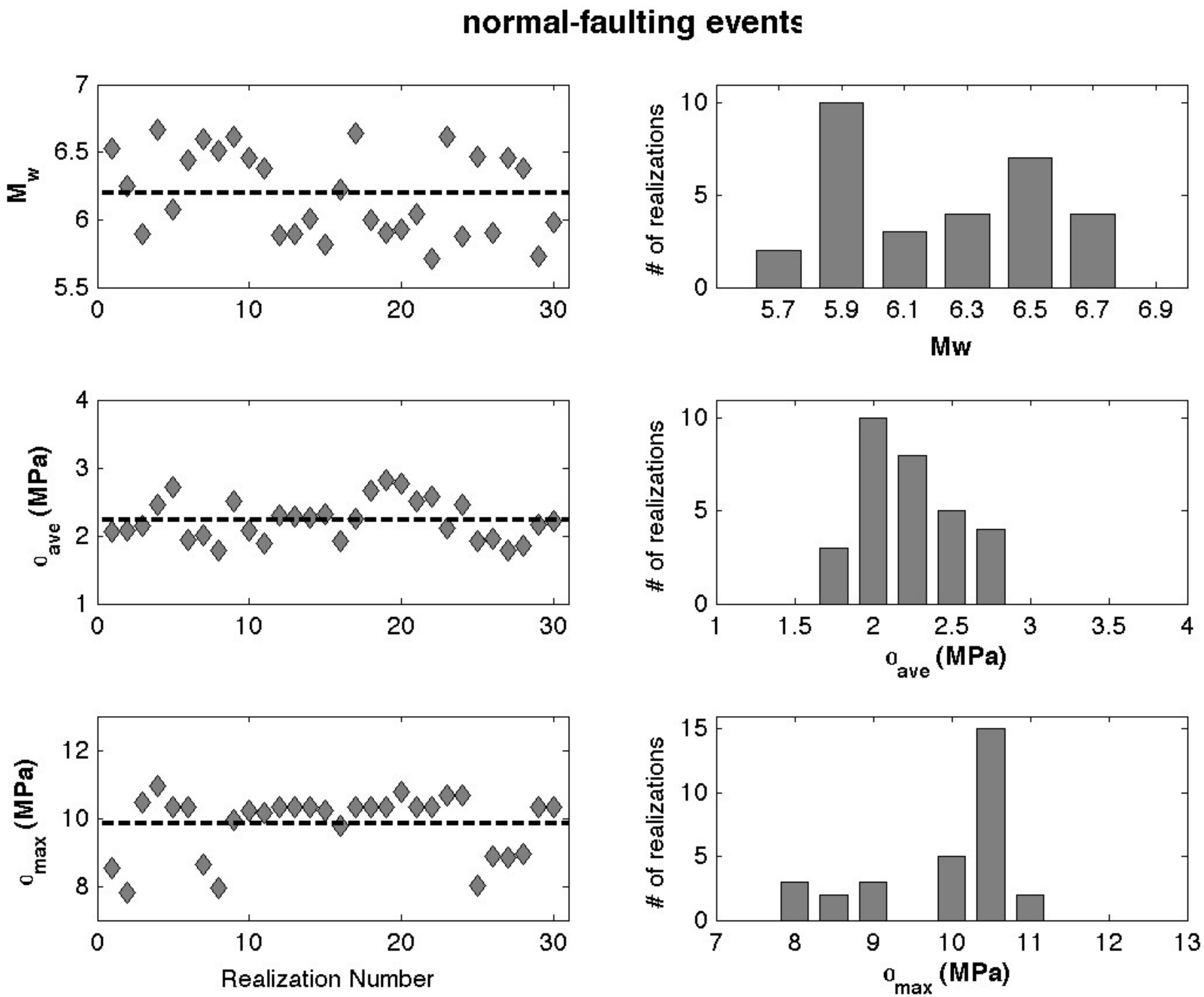
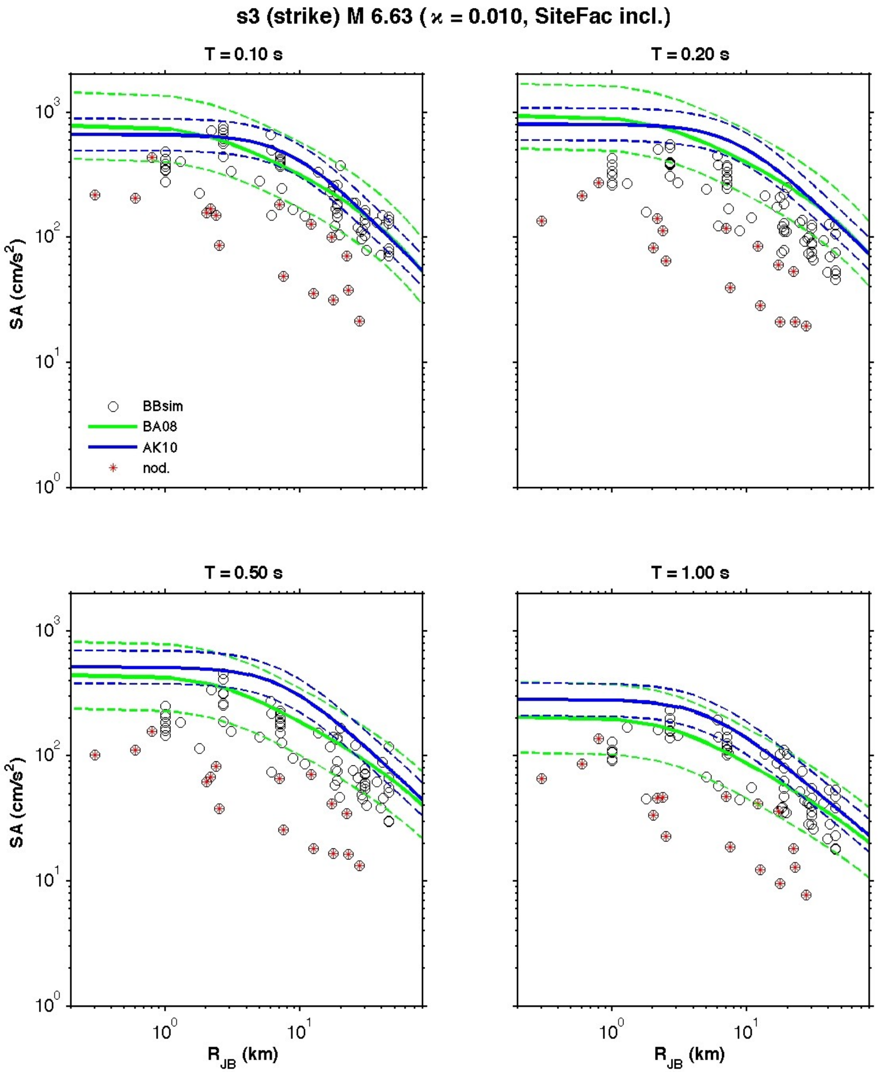
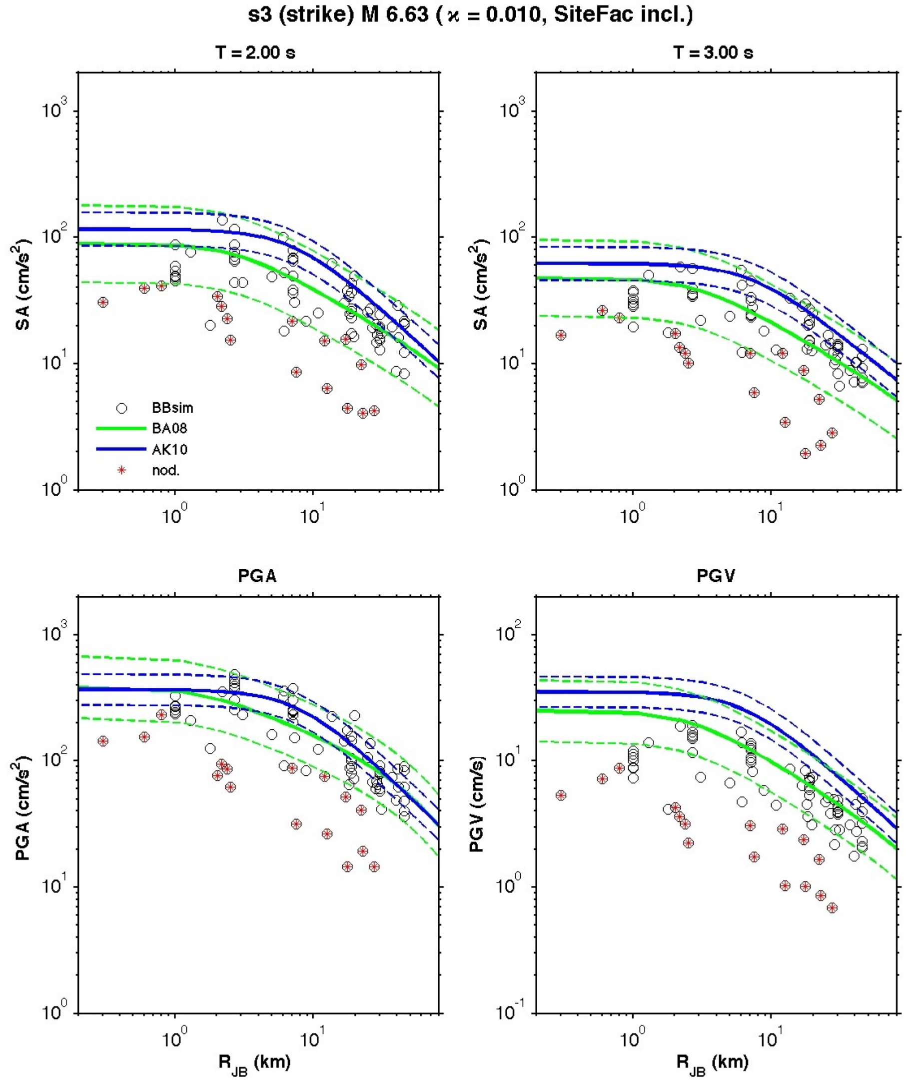
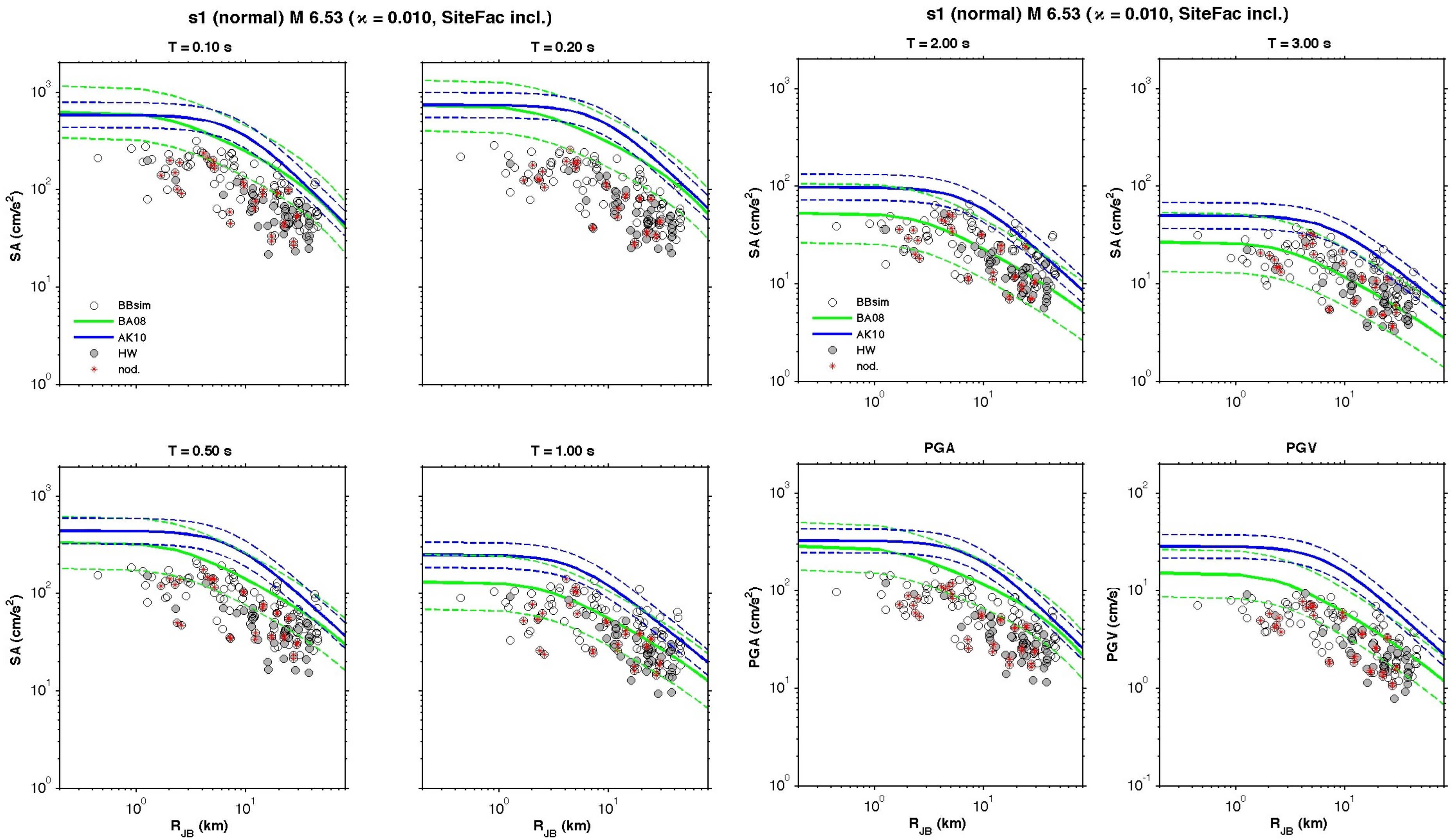


Broadband ground motion
Comparison with GMPE’s: Single event, SA(T), Strike-slip

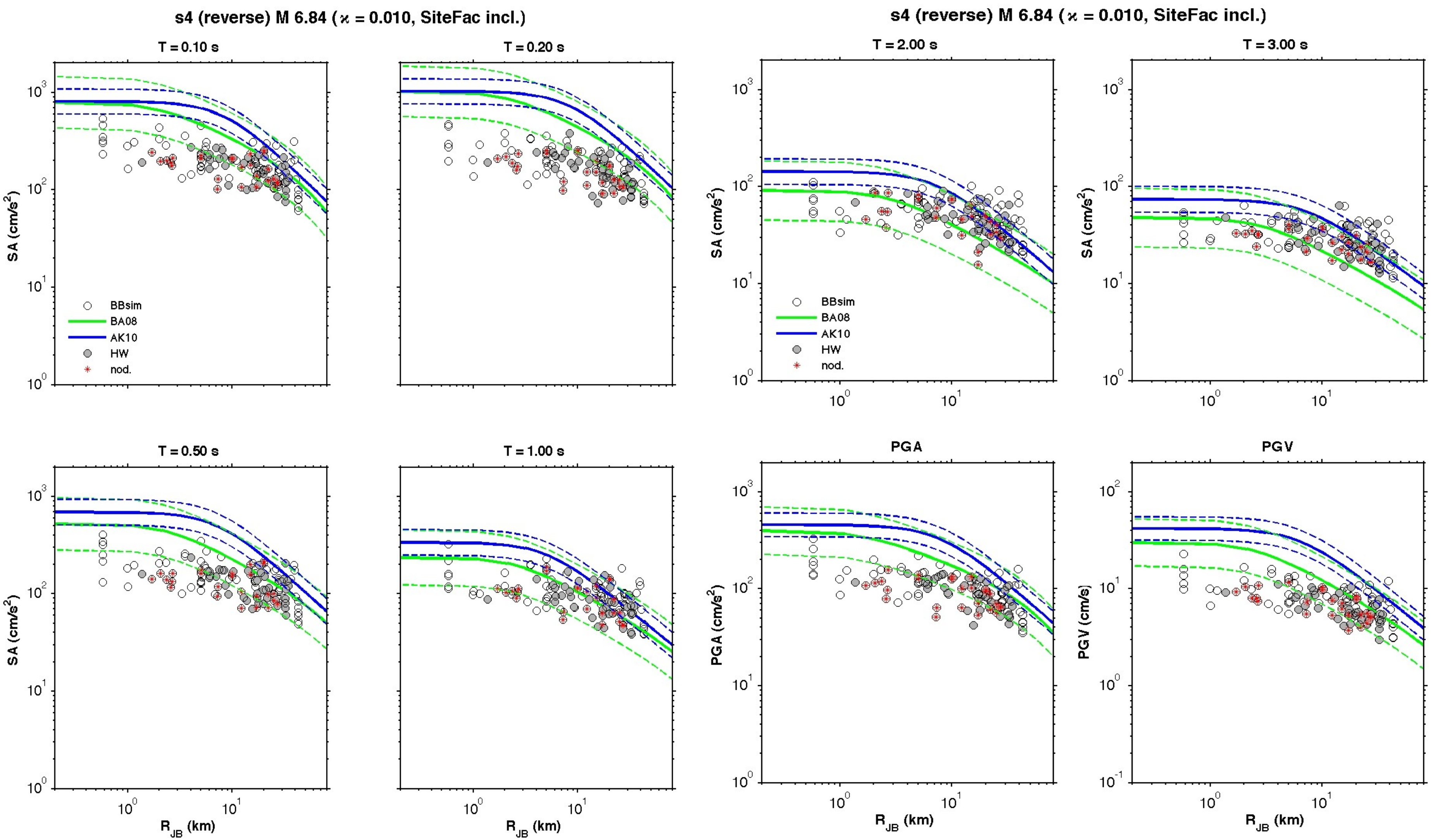




Broadband ground motion
Comparison with GMPE's: Single event, SA(T), Normal



Broadband ground motion
Comparison with GMPE’s: Single event, SA(T), Reverse



Conclusions on Ground Motion compared with GMPE

- For the single events, we note a reasonable consistency for the strike-slip case (except for the nodal stations)
- For the reverse and normal faulting event, the short-period spectral accelerations appear to be underpredicted
- Note that the GMPE's are parameterized (usually) for V_{s30} = 760 m/s, but we have only V_{s30} = 1500 m/s (after site-amplification correction)

Answer to questions stated by Michael Barall

I. Is the write-up of the proposed method clear, precise, and complete?

The write-up is complemented by the ppt presentation and a matlab script "dyna_param.m". This script create output for input to dynamic codes.

II. Our '100 runs' project aims to generate many realizations of an earthquake source, each of which is an M6.5 earthquake. Does the write-up explain how to produce earthquakes of this magnitude?

yes

III. Does the proposed method generate a significant number of realizations that are "bad" in some way? (e.g., physically unrealistic, difficult to nucleate, produces the wrong-magnitude earthquake, etc.).

Difficult to answer. We did not develop a method that discard realizations.

IV. The '100 runs' project requires initial conditions for a 60-degree dipping normal fault. Does the proposal describe a method for this fault geometry?

describe for normal, reverse and strike slip fault.

Answer to questions stated by Michael Barall

V. Is the proposed method repeatable? E.g., if the method is re-run on a different computer that may have different floating-point properties, or by multiple codes (that have been tested with our code-validation benchmarks) will the method produce the same result?

Since the input is only one, it can be re-run in different computers and also adapted to the input format to other codes. I expect the results be the same

VI. What experience exists for the proposed method?

The matlab script “dyna_param” has been used to create input for SORD and SGSN code. But it can easily adapted for any dynamic code.

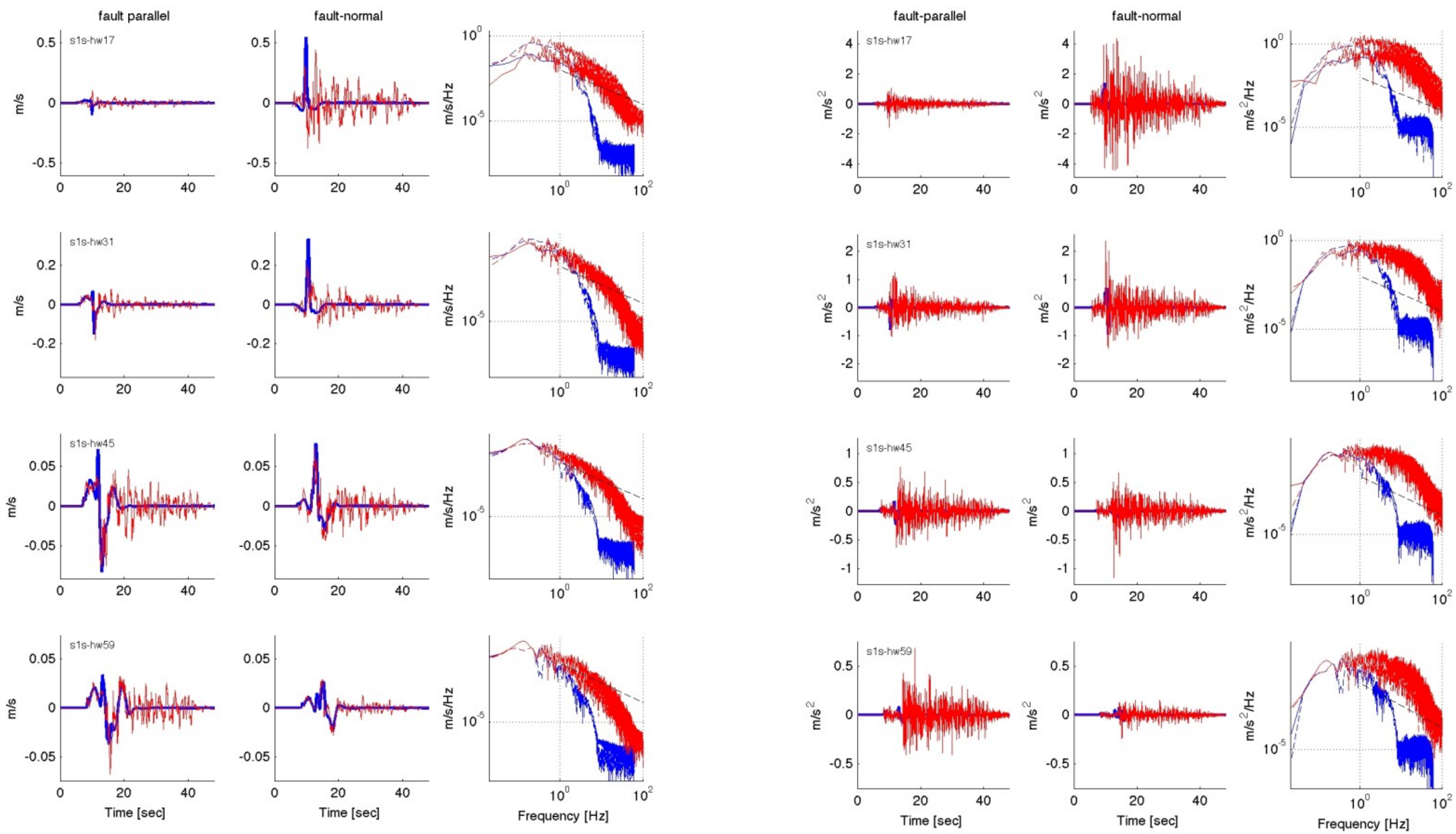
Some preliminary results was published in AGU2008, 2009

Broadband ground motion simulation procedure

low-frequency seismograms, directly computed/saved from the dynamic runs, are combined with high-frequency scattering seismograms, according to Mai & Olsen (2009).

LF-dynamic waveforms

BB-hybrid waveforms

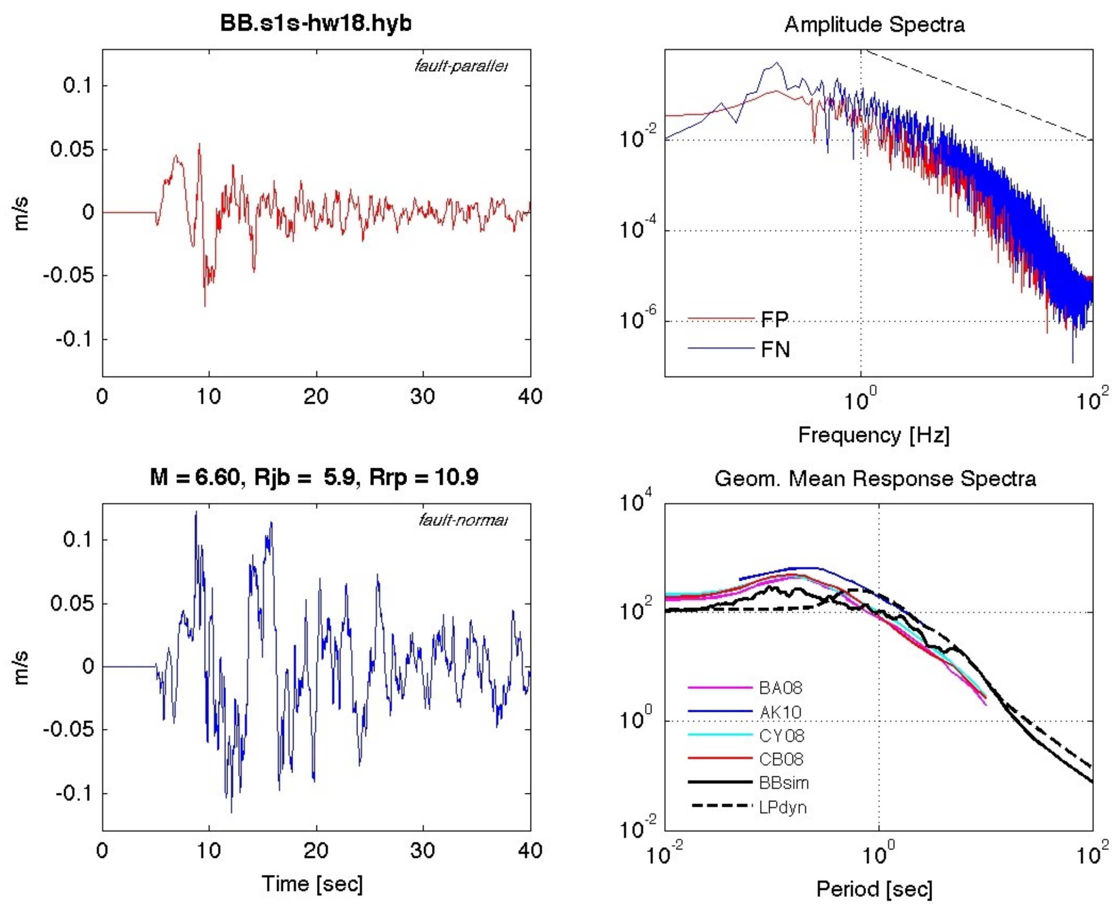


Broadband ground motion simulation

The engineering perspective: very near-field, R ~ 2km

fault-parallel

fault normal

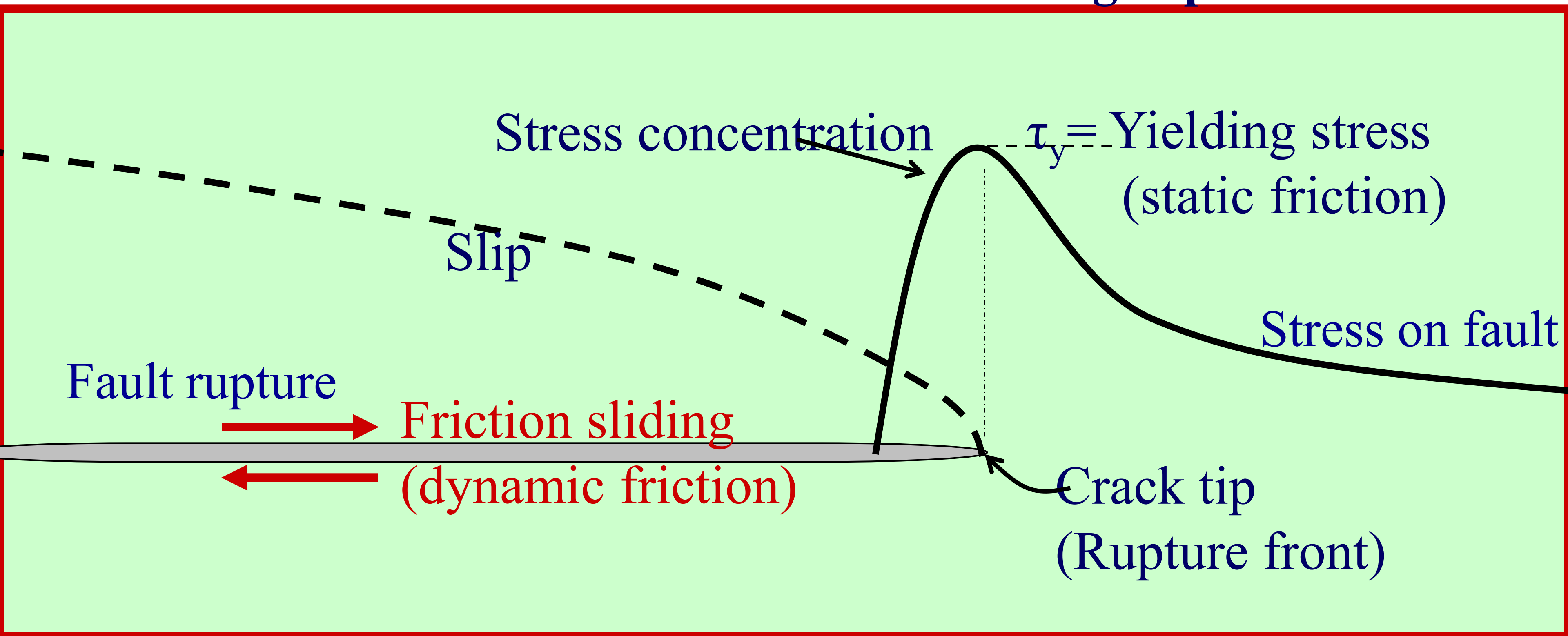


comparison with GMPE's (using geometric mean)

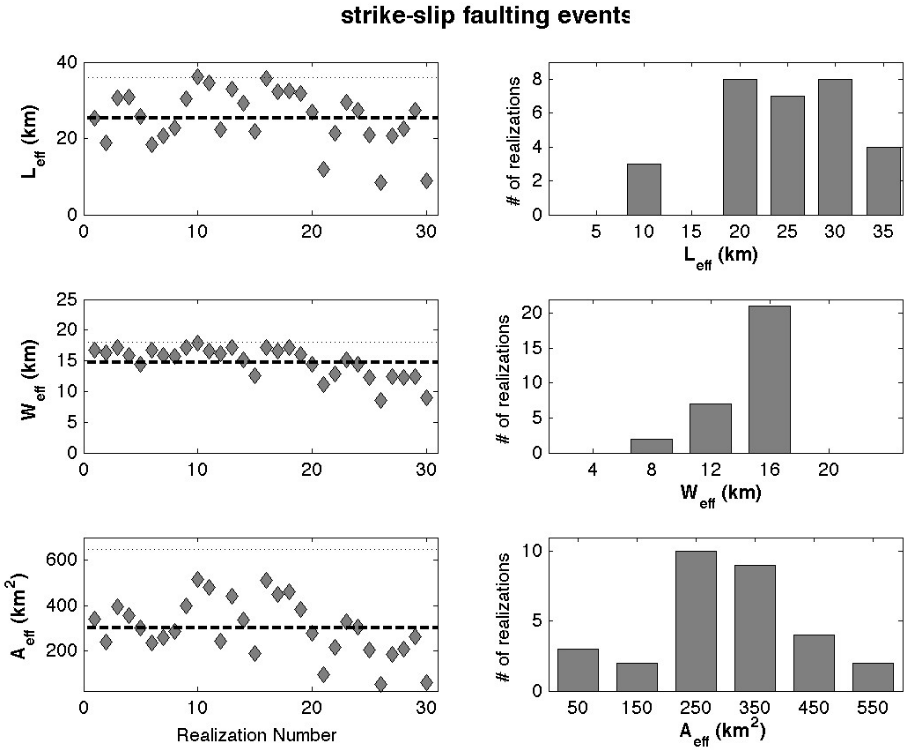
Introduction

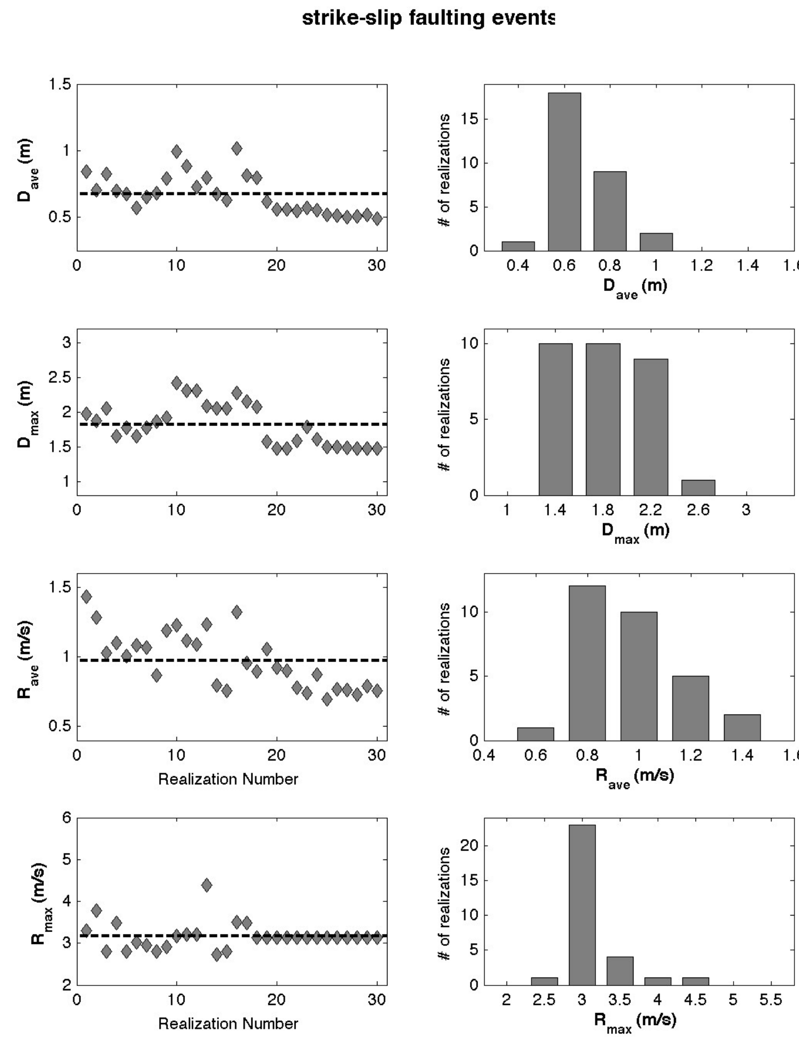
- Dynamic modeling allows us to deal more closely with the physical processes that determine an earthquake.

Stress and friction on the fault during rupture

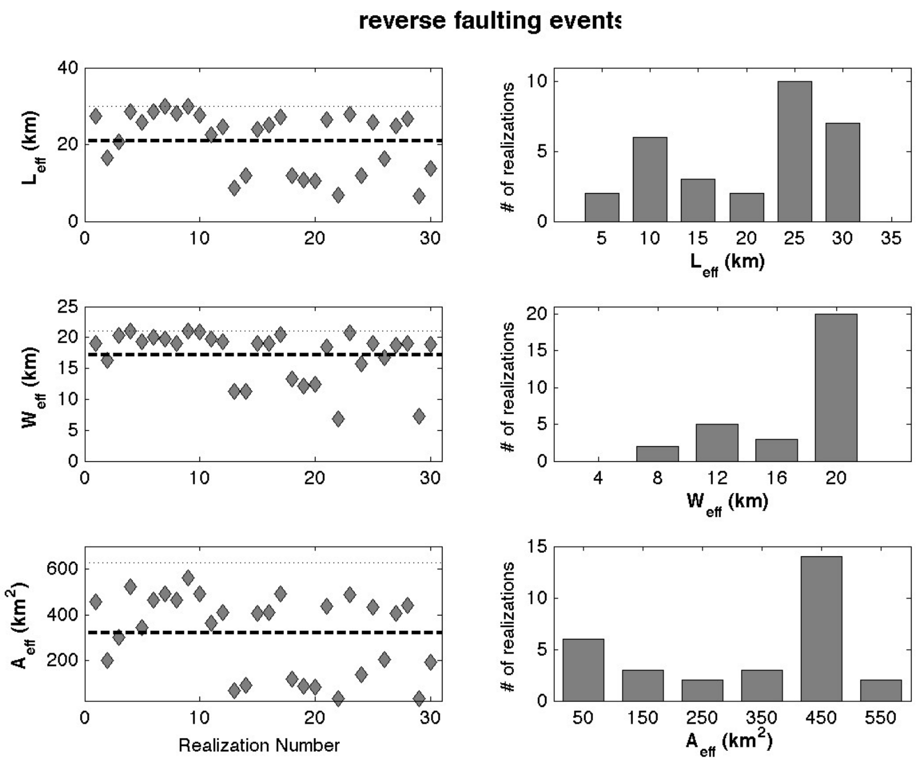


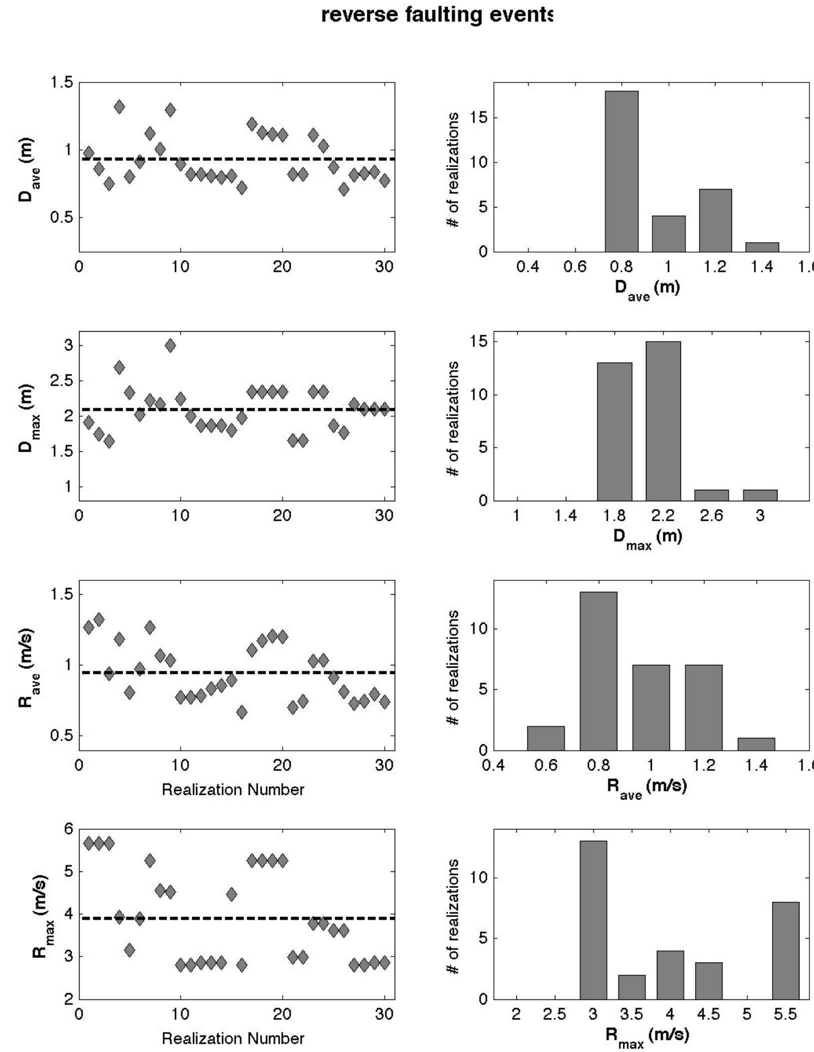
Source parameter statistics: Strike-slip





Source parameter statistics: Reverse faulting





Source parameter statistics: Normal faulting