Rupture Dynamics and Seismic Radiation on Rough Faults for Simulation-Based PSHA

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Roadmap for this talk

- Motivation to study dynamics on segmented & rough faults
- Numerical modeling approach
- Rupture & radiation characteristics
- Kinematic approximation for simulation-based PSHA
- Conclusions

Motivation

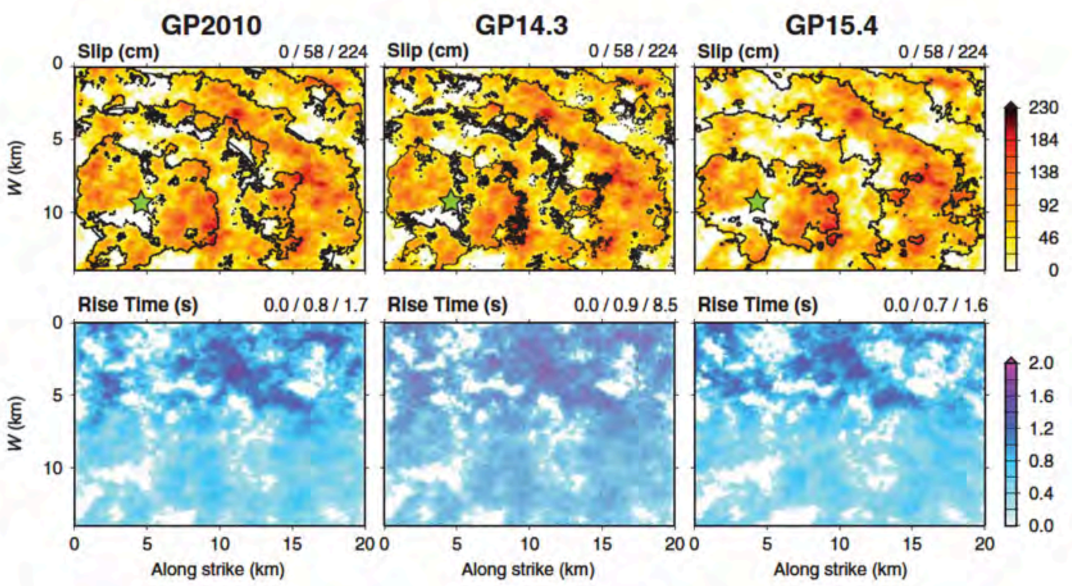
Ground-motion simulation from kinematic ruptures

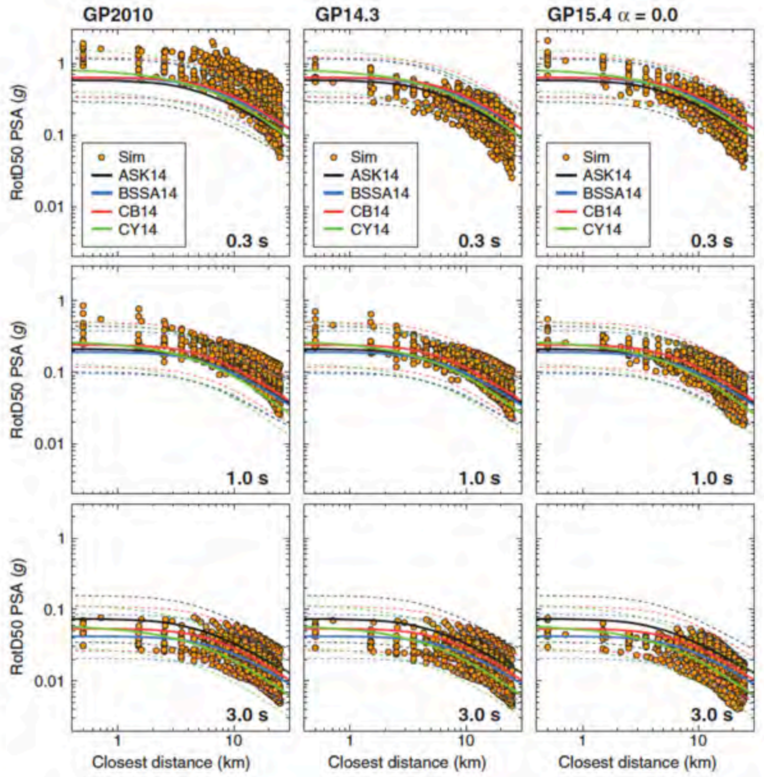
- Numerous studies apply kinematic rupture modeling for simulation-based ground-motion prediction
- The kinematic source is constructed starting from heterogeneous fault slip, using a fractal description or some auto-correlation function (e.g. von Karman) (e.g. Andrews; 1980; Frankel; 1991; Zeng & Anderson, 1993; Herrero & Bernard, 1994; Mai and Beroza, 2002, Gallovic and Brokesova, 2005; …).
- Other kinematic source parameters (rise time, rupture speed, shape of the source time function) are chosen either "ad hoc" (e.g. constant over the fault) or are constrained by source-physics considerations (e.g. Guatteri et al, 2003) or by a statistical approach (e.g. Song et al, 2013)

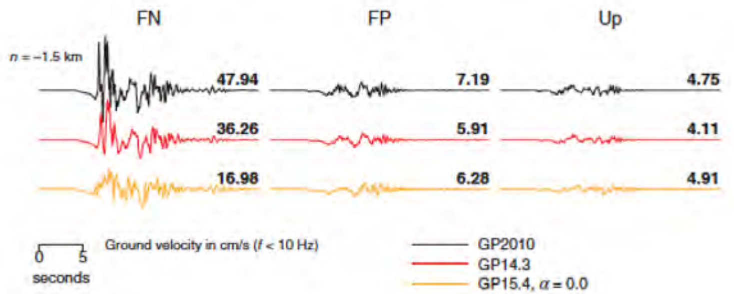
Motivation

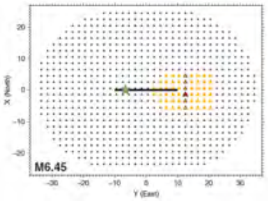
Ground-motion simulation from <u>kinematic ruptures</u>

- An example from Graves & Pitarka (2016)









Motivation

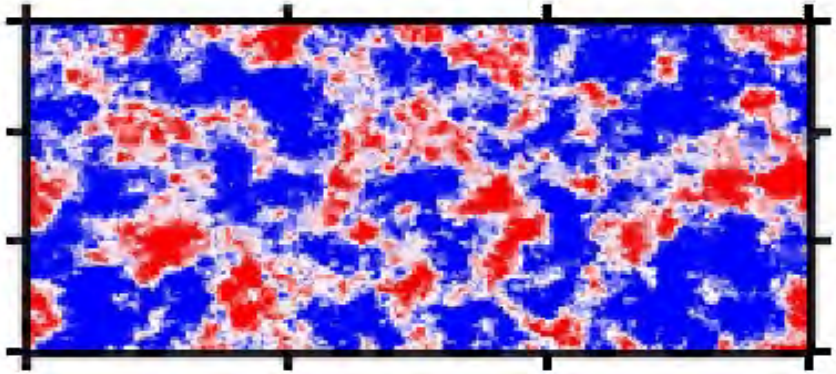
Ground-motion simulation from dynamic ruptures

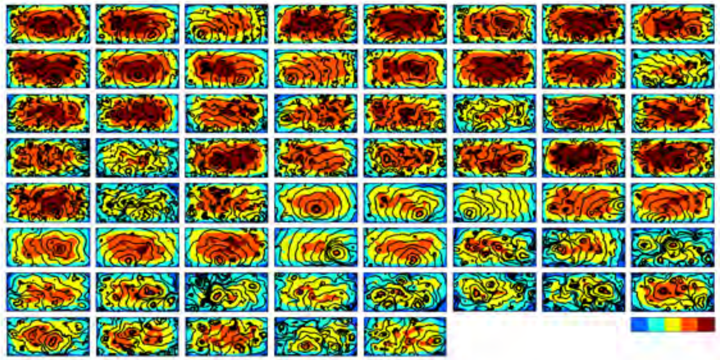
- Previous works on dynamic rupture with heterogeneous initial stress have shown that such simulations provide ground-motions that reproduce median GMPE-estimates, but suggest large inter-event variability (e.g. Ripperger et al., 2008; Dalguer & Mai, 2011, Andrews & Ma, 2015)
- Initial stress is parameterized as a spatial random field using a fractal description or some auto-correlation function
- Other dynamic source parameters (e.g. fracture energy; yield stress) still need to be prescribed, but are difficult to constrain
- **Caveat: the prescribed fault plane is a perfectly planar surface; several planar surfaces may form a multi-segment rupture**

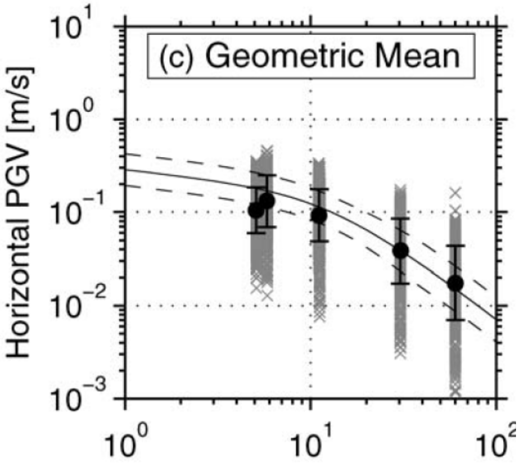
Motivation

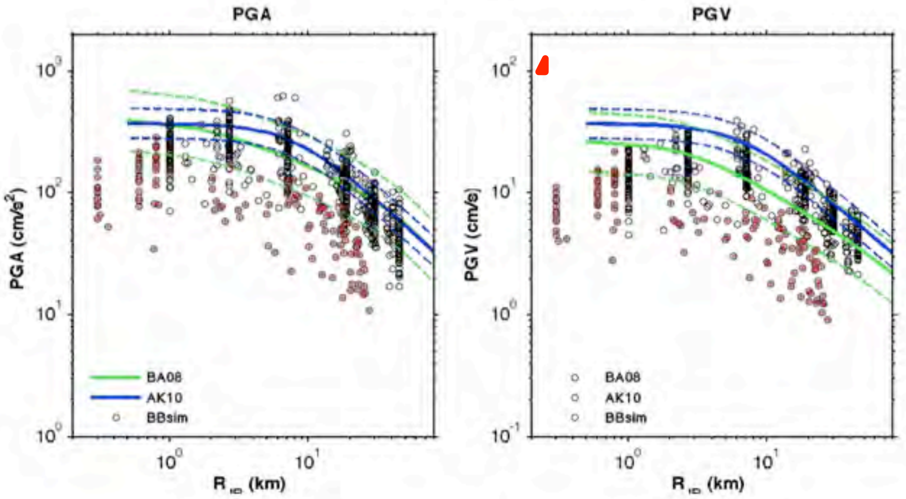
Ground-motion simulation from <u>dynamic ruptures</u>

- Example from Ripperger et al (2008); Dalguer & Mai (2011)









Motivation

Key issues

- **Dynamics** on segmented faults strongly influence how/when **ruptures jump**, and thus **determine total event size** and final ground-motion characteristics (amplitudes, spatial distribution) (e.g. Harris & Day, 1993, 1999; Oglesby, 2005, 2008; Oglesby & Mai, 2012)
- **Where are the high-frequencies radiated?** Can we “produce” them naturally through the rupture process, instead of inserting them stochastically (e.g. artificially in a post-processing step)

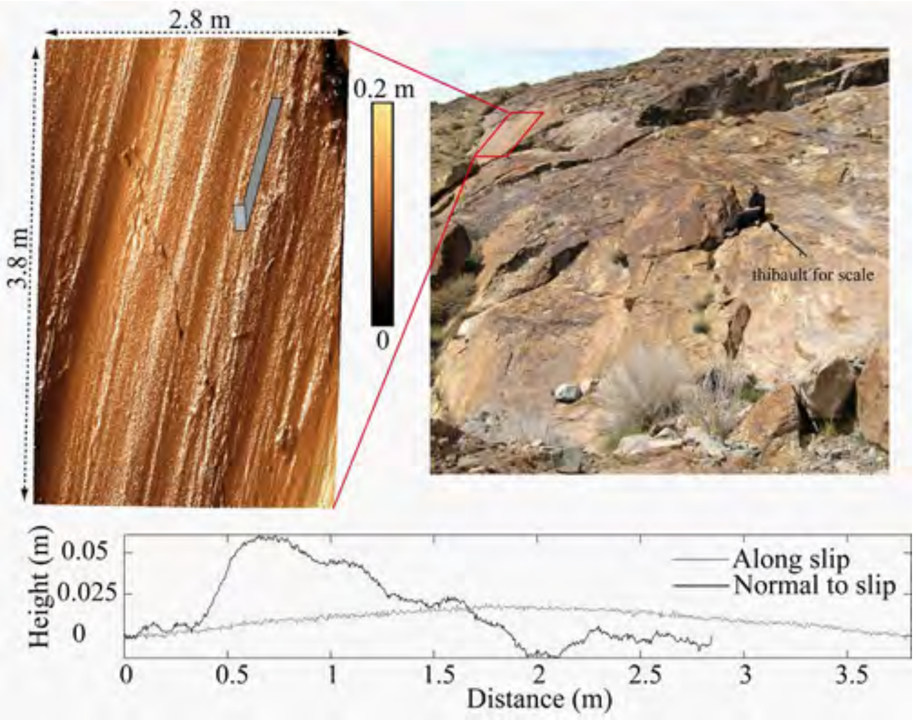
  → **rough-fault rupture dynamics**

- How to include source dynamics into seismic hazard estimation and quantifying the potential shaking – and its variability – in future events? That is, can such simulations satisfy engineering criteria/observations (correlations; building response)?

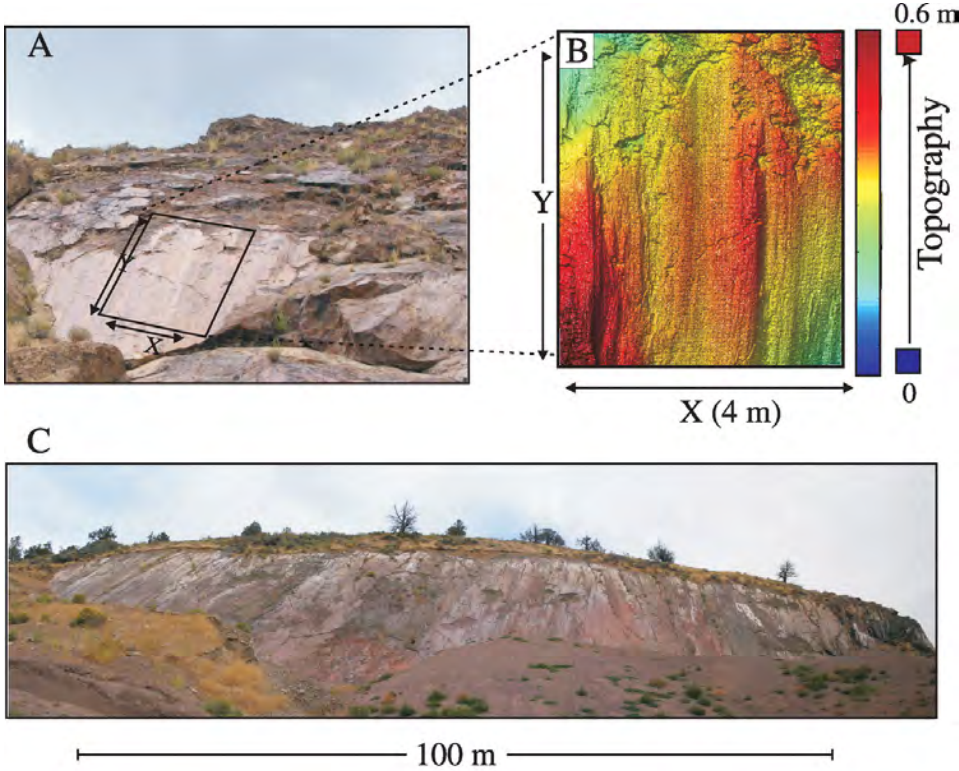
Complex Fault Geometry

Fault Roughness

- Fault surfaces exhibit internal roughness over many size-scales



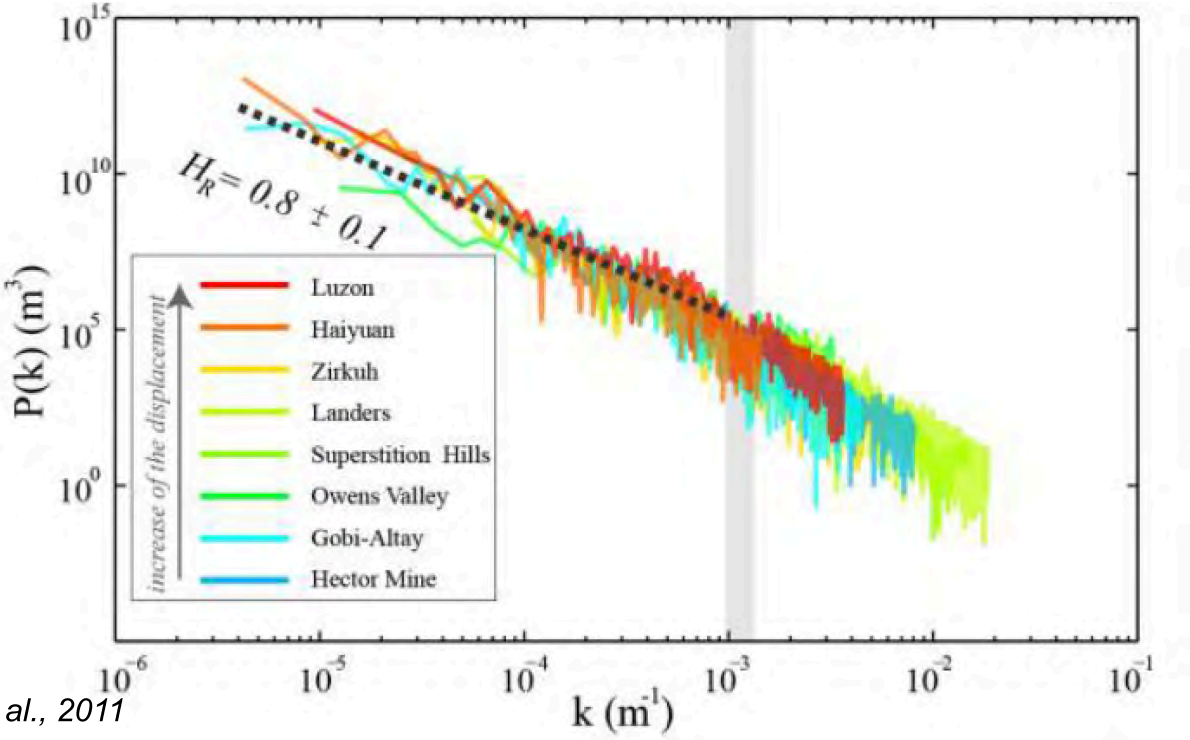
Brodsky et al., 2009



Complex Fault Geometry

Fault Roughness

- Fault surfaces exhibit internal roughness over many size-scales
- Fault roughness shows a power-spectral decay described by a fractal with a Hurst-exponent (H ~0.8) similar to what has been inferred from slip-model inversions (H ~0.7)

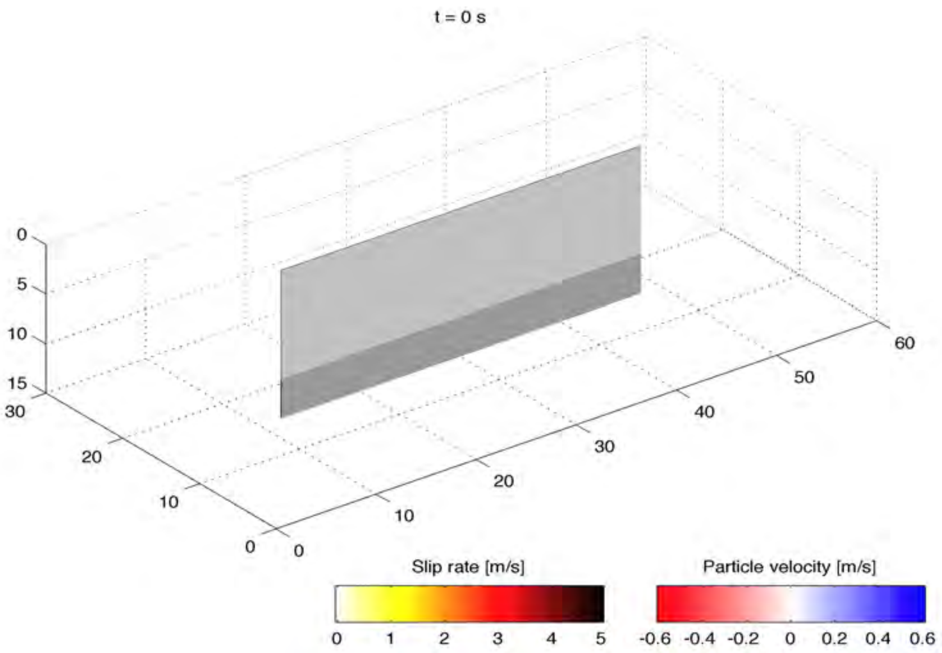


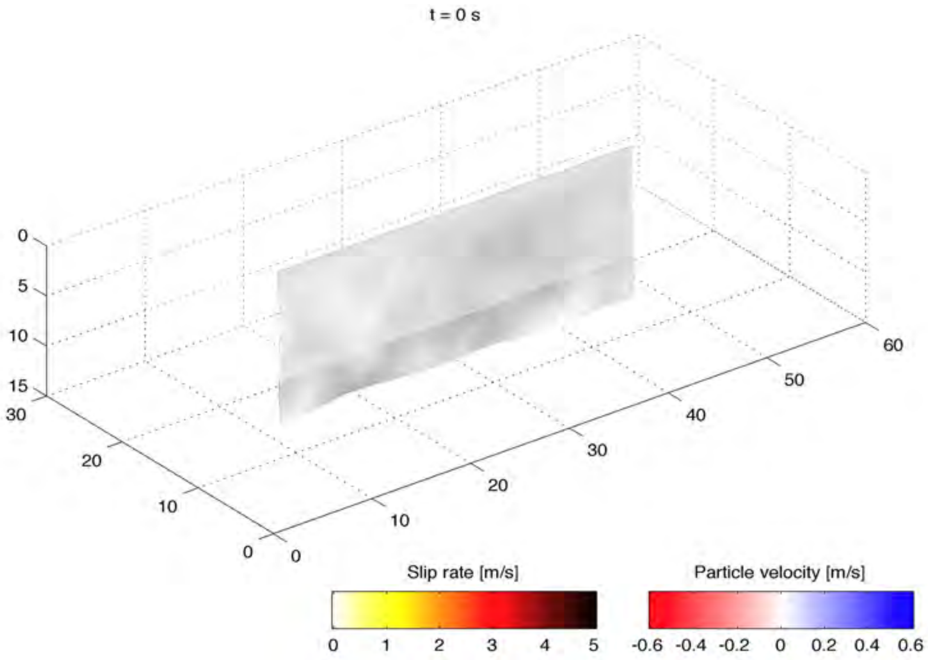
e.g. Candela et al., 2011

Complex Fault Geometry

Fault Roughness

- Fault surfaces exhibit internal roughness over many size-scales
- Fault roughness affects rupture dynamics & seismic radiation





Rough-fault dynamics

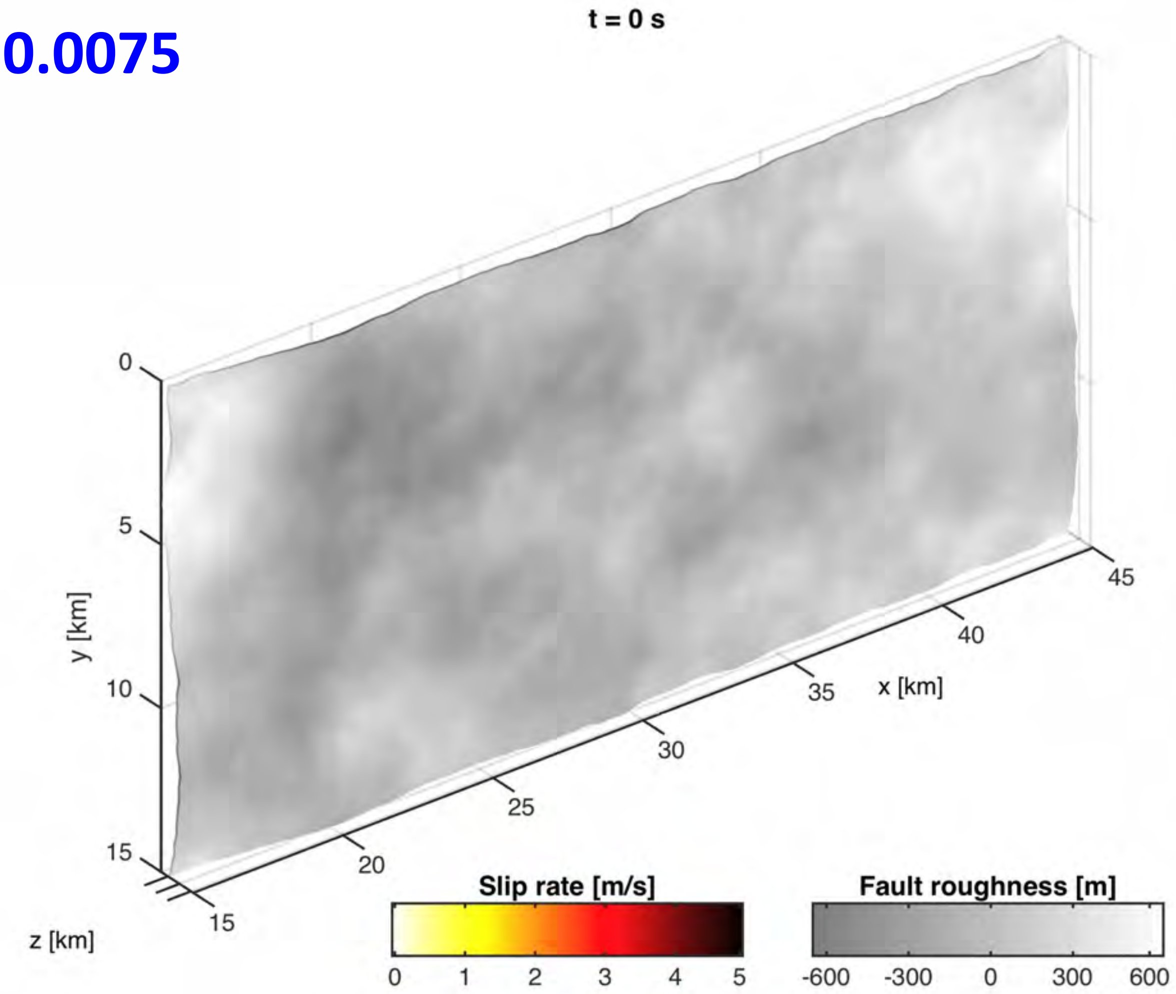
Numerical Modeling Approach

- 3D-generalized FD method (SORD, Ely et al., 2008, 2009)
- Target M ~ 7, with different roughness realizations
- Linear slip-weakening, $\mu_s = 0.677$, $\mu_d = 0.373$, and $d_c = 0.4$ m
- $f_{max} \sim 5.5$ Hz (dx = 50m, $Vs_{min} = 3464$ m/s); domain: 60 km × 30 km × 30 km
- Homogeneous background stress tensor: $\sigma_{xx} = \sigma_{yy} = -60$ MPa, $\sigma_{xy} = 30$ MPa, $\sigma_{zz} = \sigma_{xz} = \sigma_{yz} = 0$ MPa
- Fault roughness: random band-limited self-similar fault surfaces that undulate in-and-out of the nominal (mathematical) rupture plane by
    - ±400m (RMS/ $L_x = 0.005$)
    - ±600m (RMS/ $L_x = 0.0075$)
- **Vary hypocenter position, roughness level, and roughness realizations**

Rough-fault dynamics

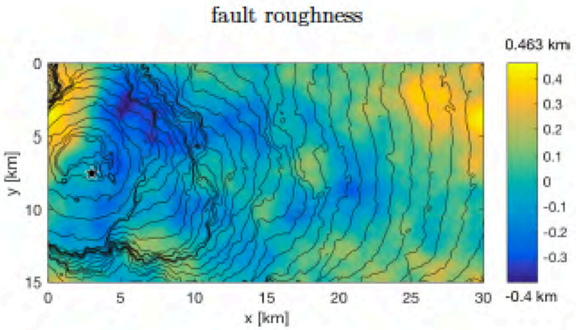
Numerical Modeling Approach

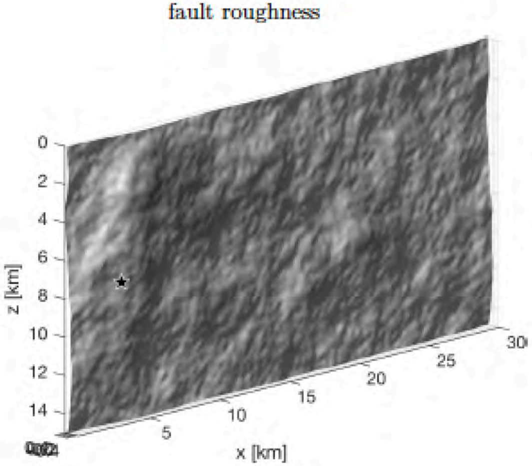
RMS / L_x = 0.0075

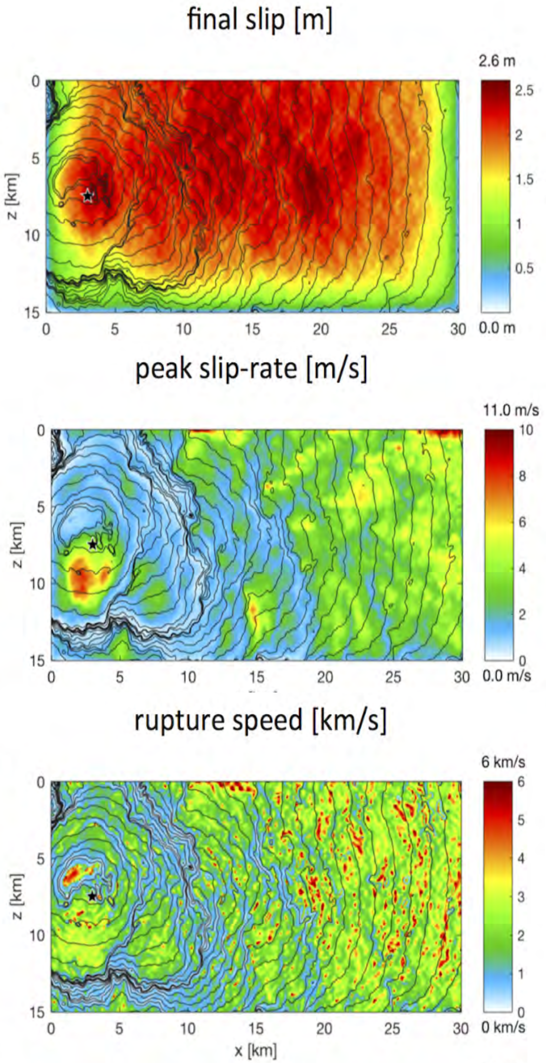


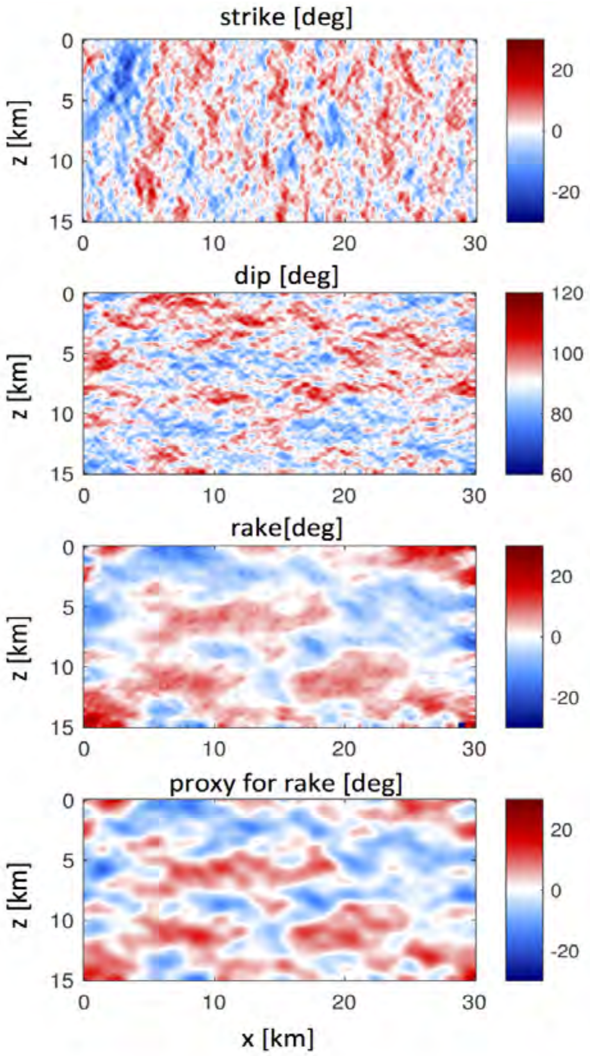
Rough-fault dynamics

Rupture characteristics: overall patterns



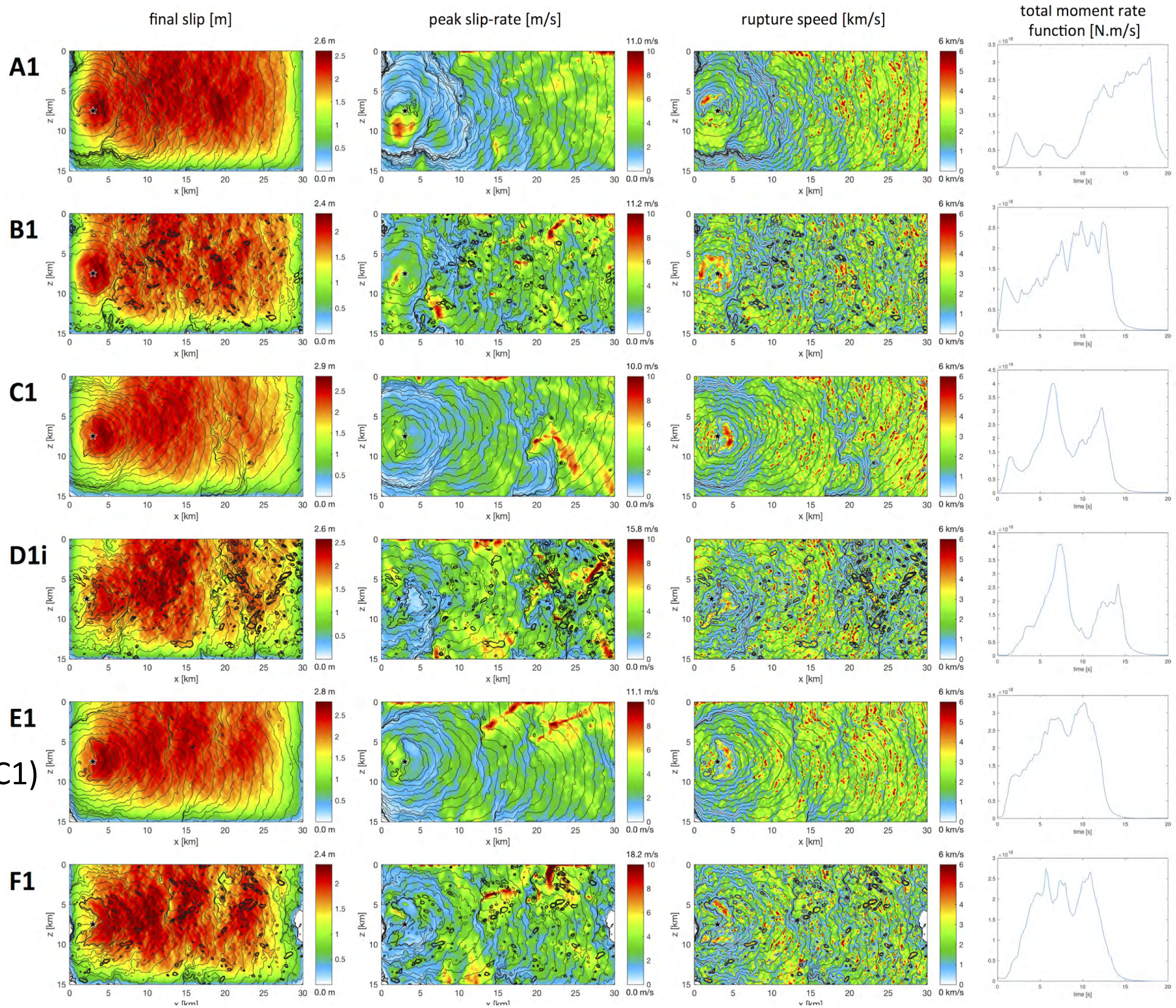






Rough-fault dynamics

Rupture characteristics: overall patterns



RMS / L_x = 0.005

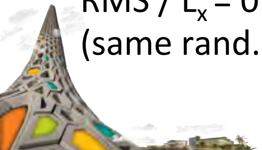
RMS / L_x = 0.0075
(same rand. rel as A1)

RMS / L_x = 0.005
(diff. rand. rel. as A1)

RMS / L_x = 0.0075
(diff. rand. rel. as C1)

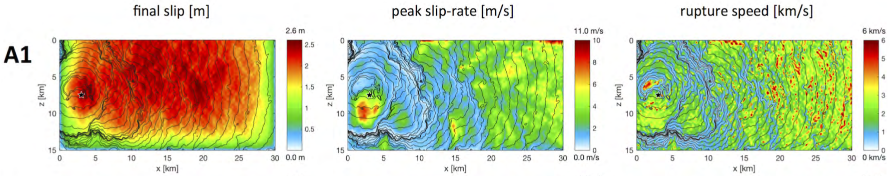
RMS / L_x = 0.005
(diff. rand. rel. as A1, C1)

RMS / L_x = 0.0075
(same rand. rel as E1)



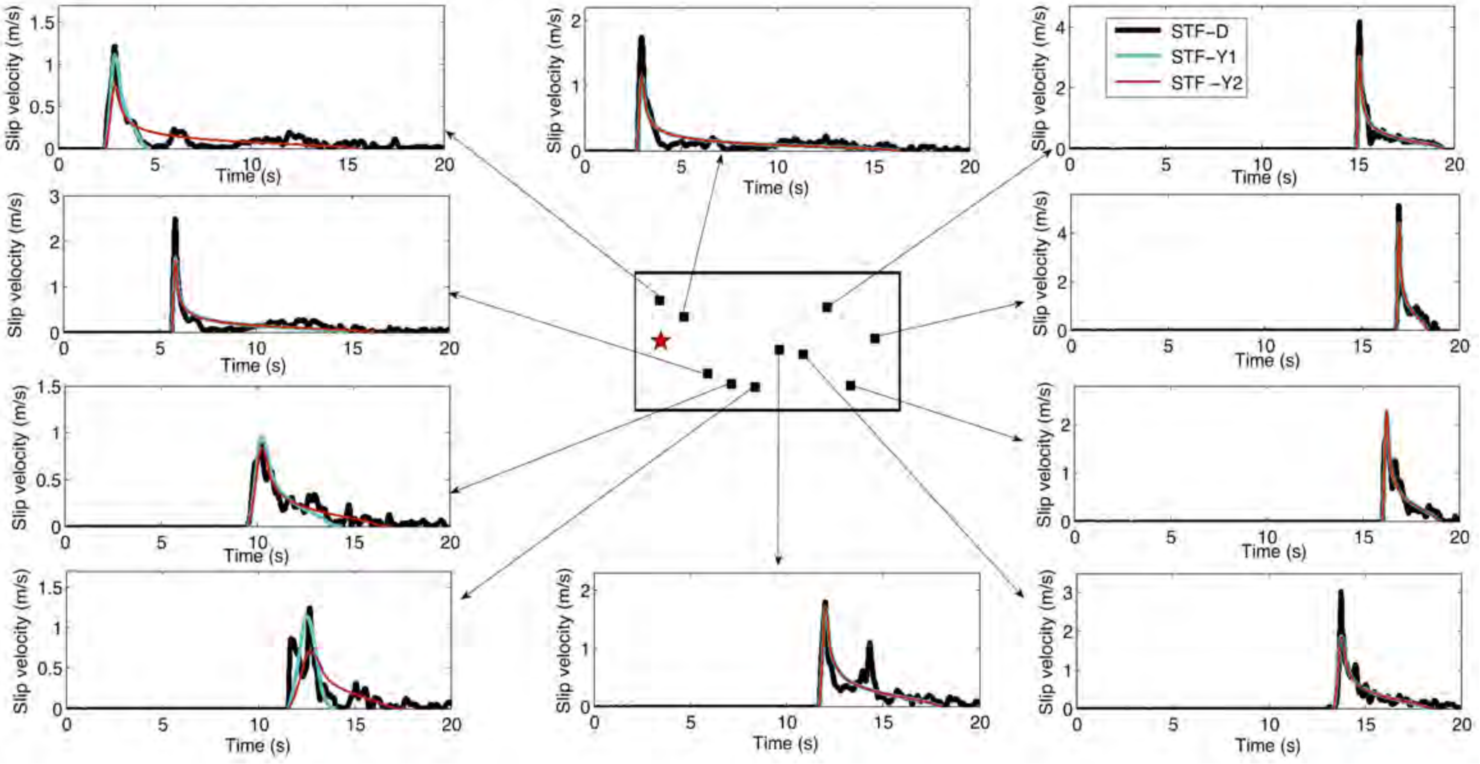
Rough-fault dynamics

Rupture characteristics: local slip-rate function



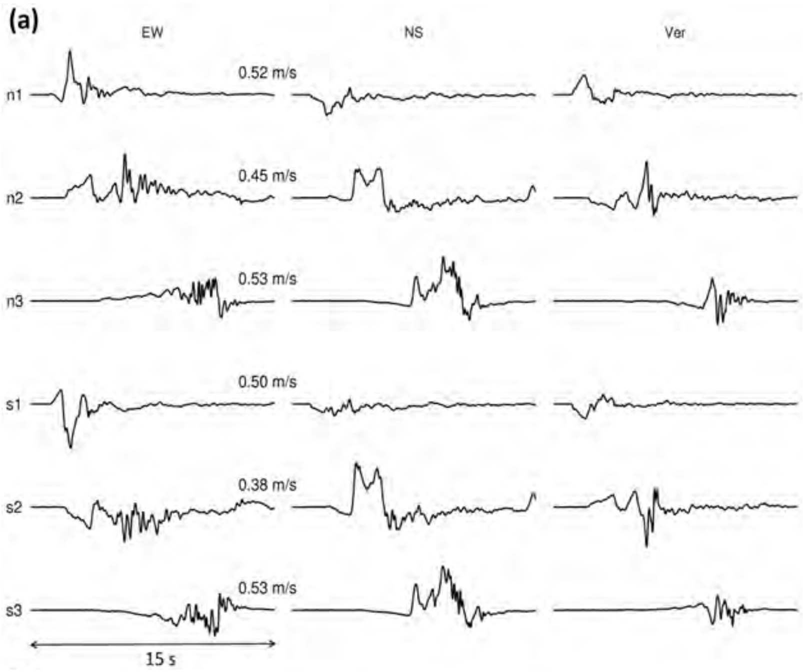
STF's approximated by Yoffe function

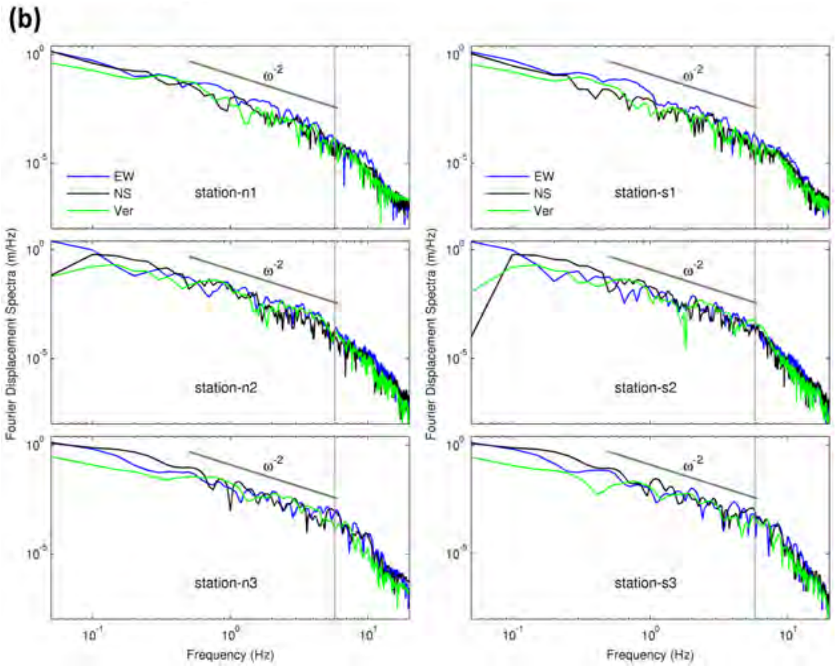
- STF-Y1: slip-rate > 0.001 m/s
- STF-Y2: preserves 95% total dyn. slip

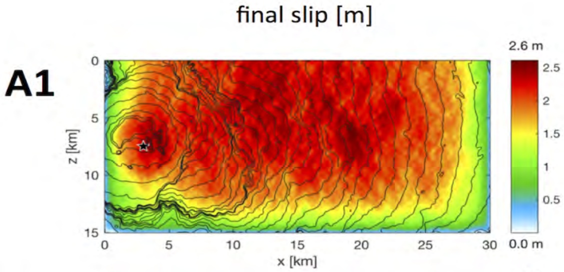


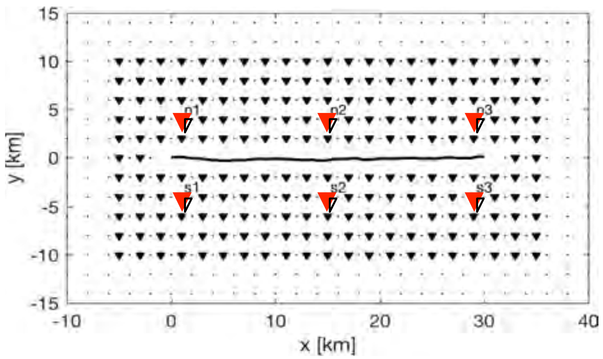
Rough-fault dynamics

Radiation characteristics: waveforms & spectra



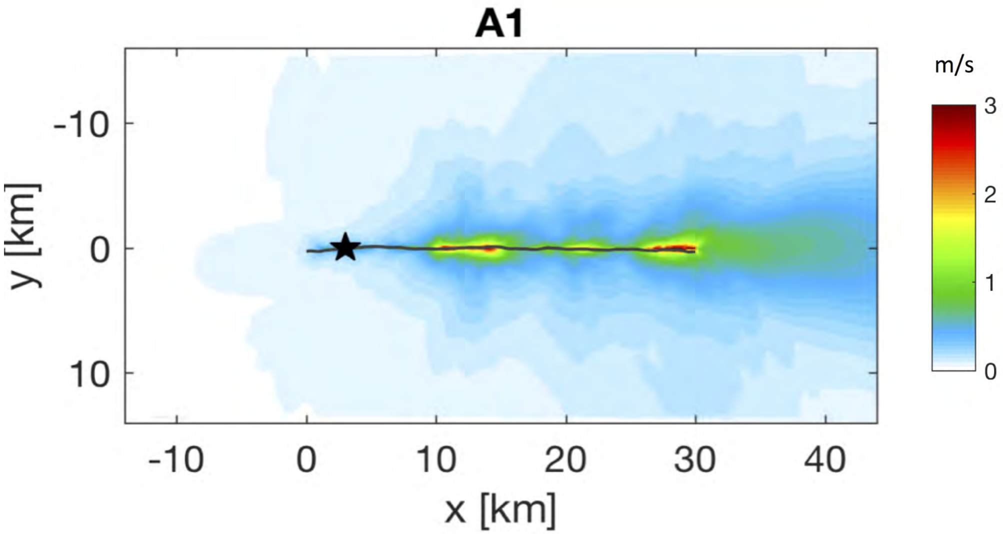


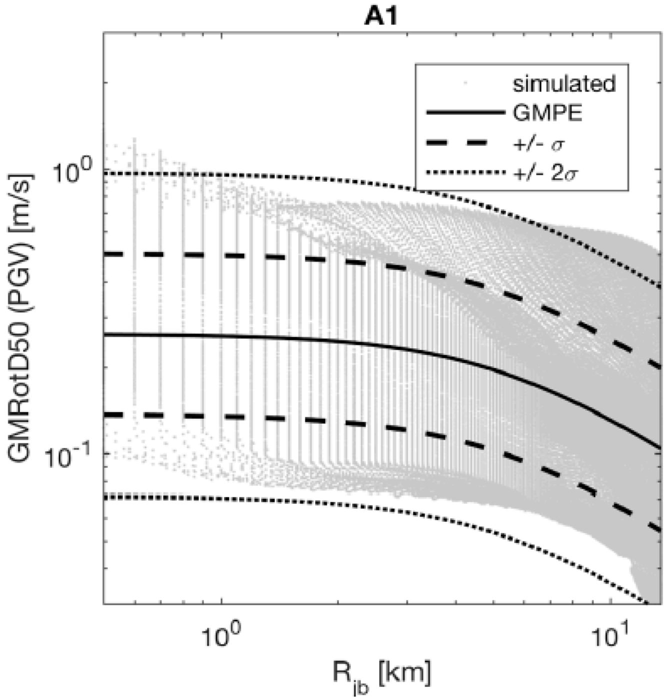


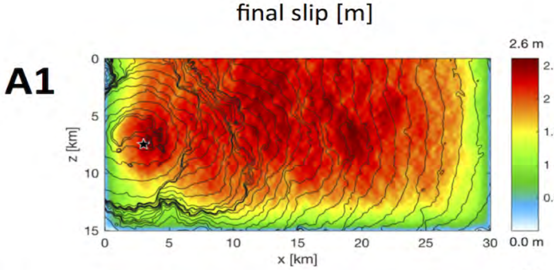


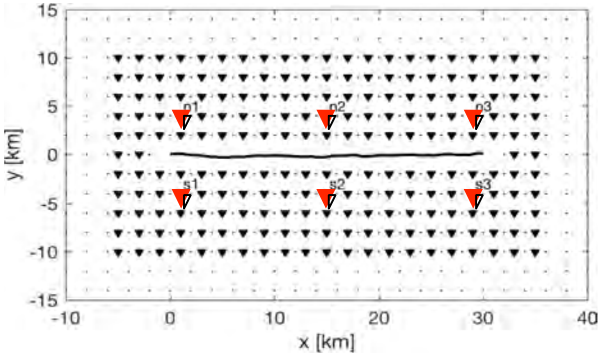
Rough-fault dynamics

Radiation characteristics: shakemap & GMPE-plot





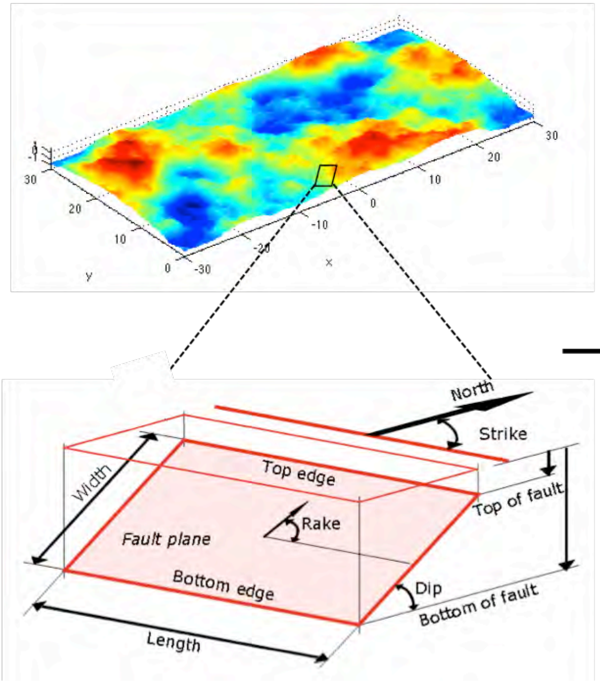


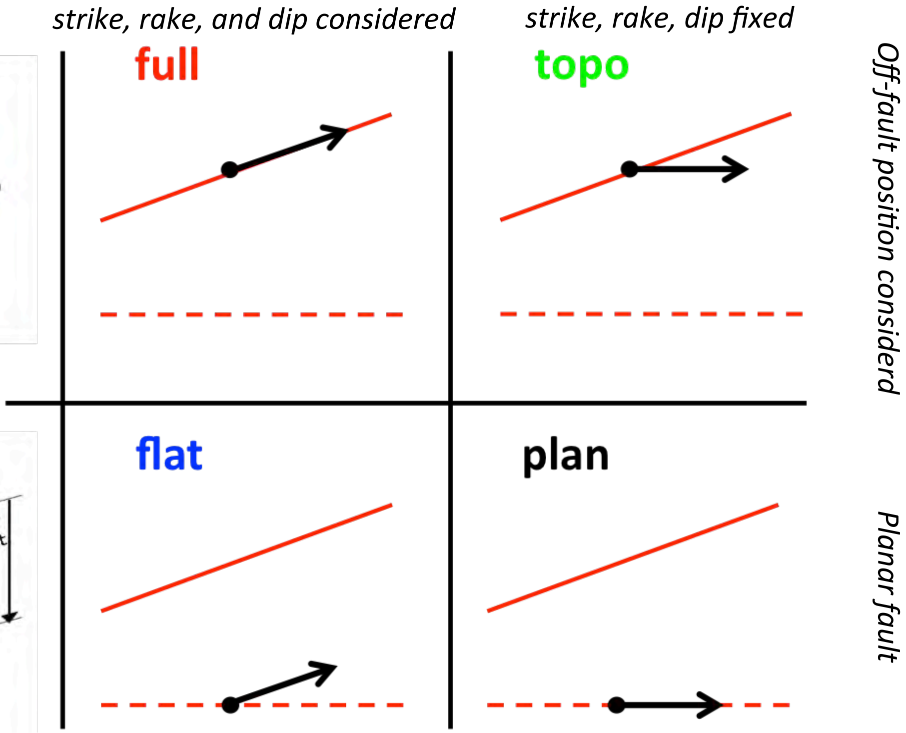


Rough-fault dynamics

Radiation characteristics for approx. kinematic models: simplified geometry

- We capture rough-fault effects kinematically by projecting the moment-tensor on the planar fault, but keeping the variations in strike, dip, rake





strike, rake, and dip considered

strike, rake, dip fixed

full

topo

flat

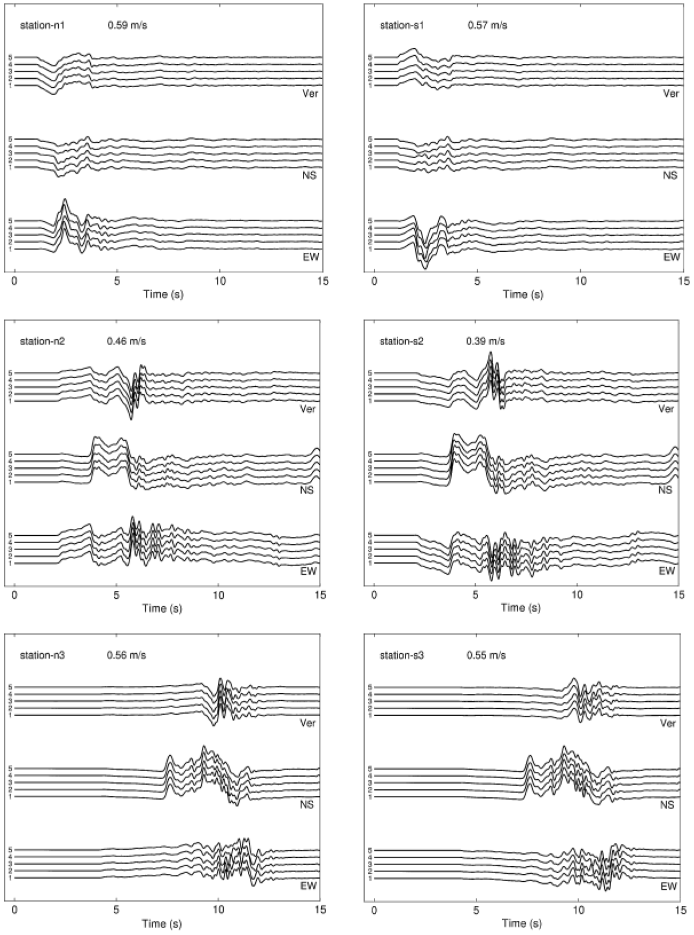
plan

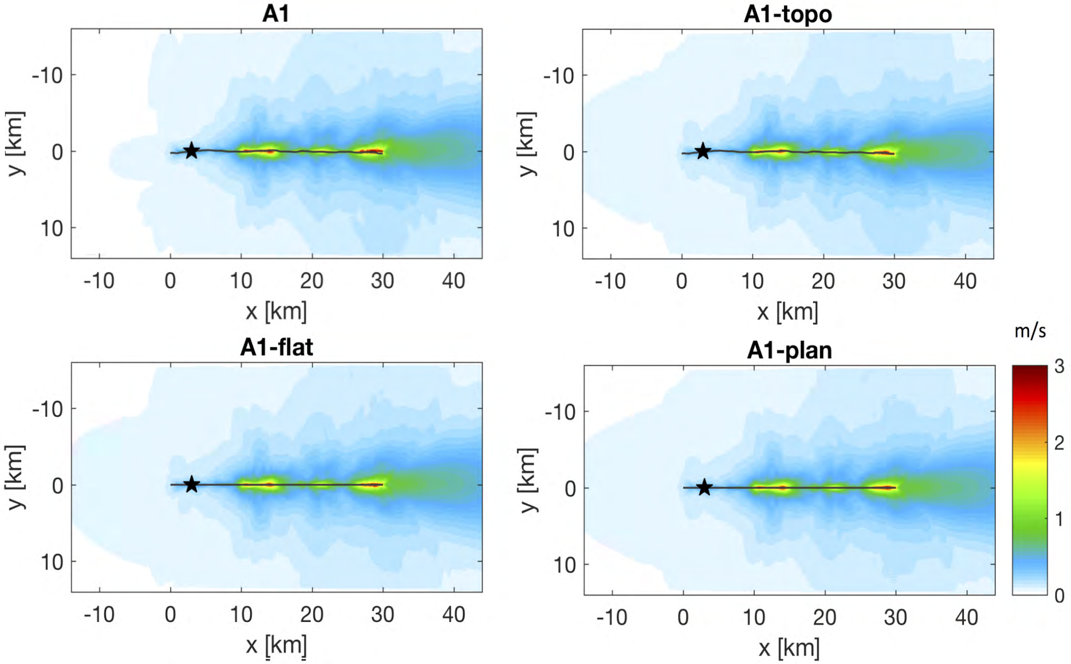
Off-fault position considerd

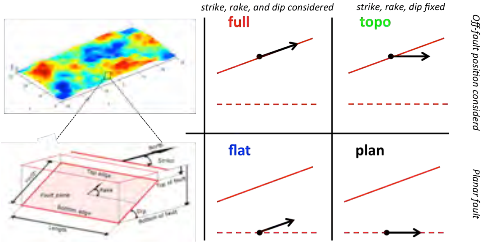
Planar fault

Rough-fault dynamics

Radiation characteristics for approx. kinematic models: simplified geometry using dyn. STFs

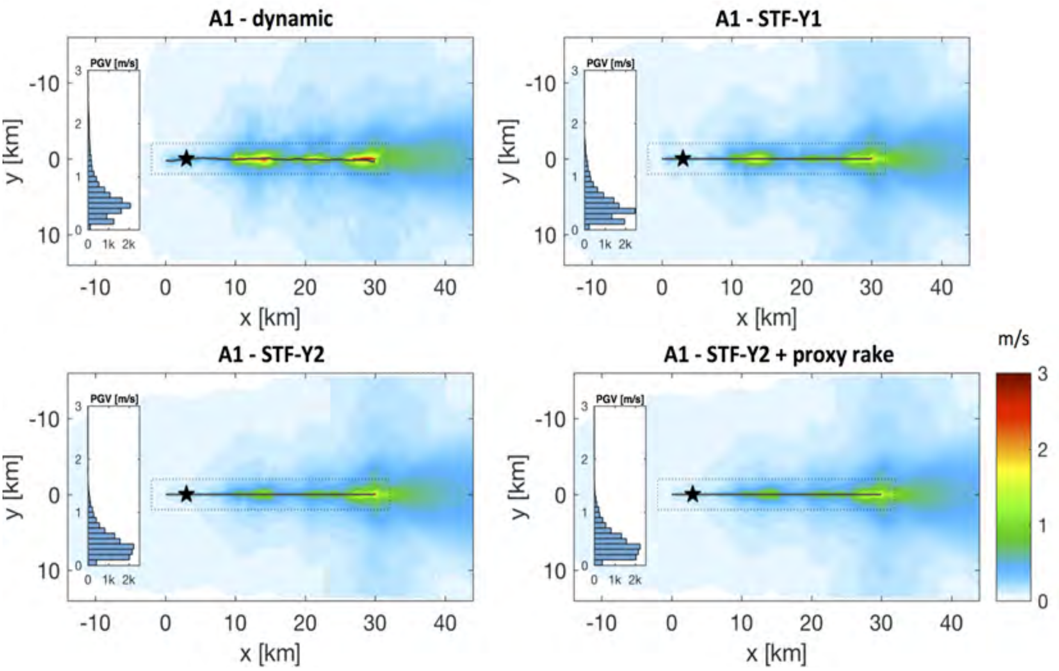


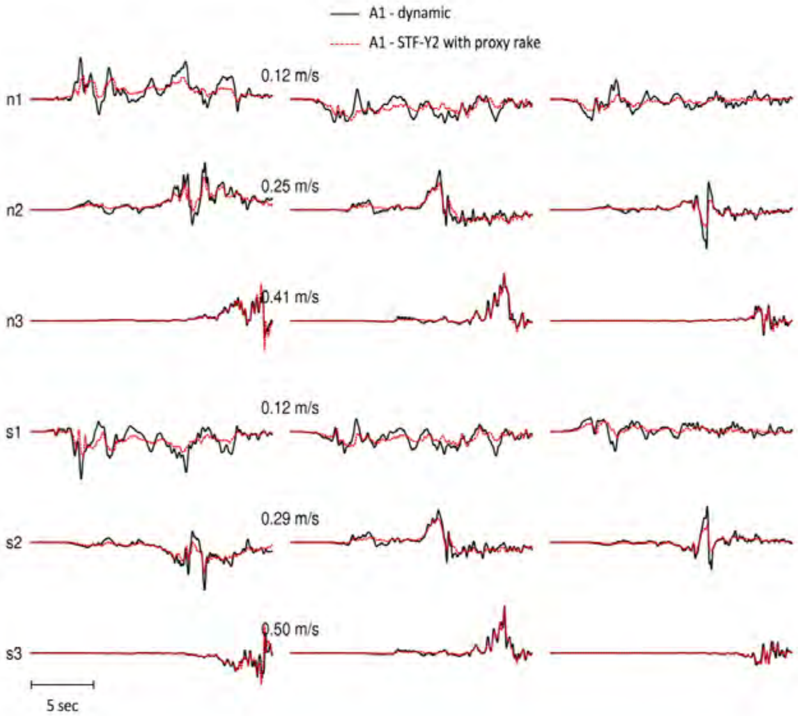




Rough-fault dynamics

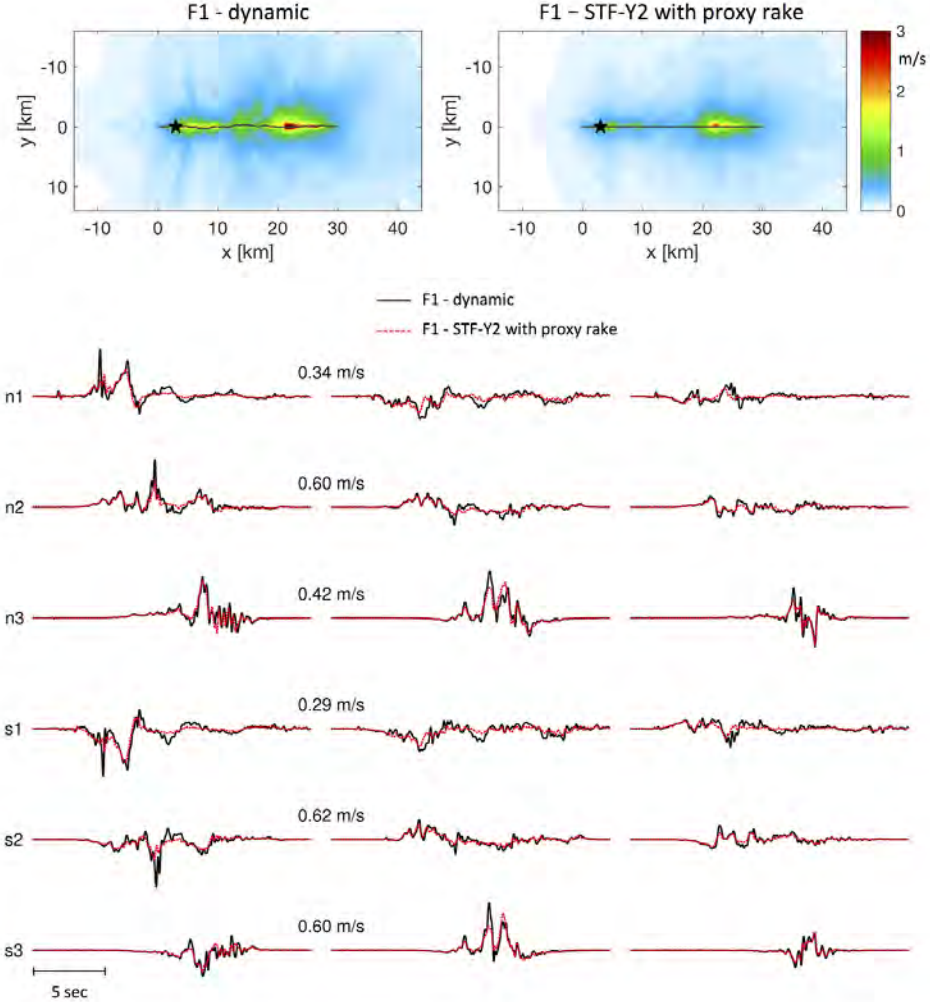
Radiation characteristics for approx. kinematic models: AND simplified STF & proxy rake





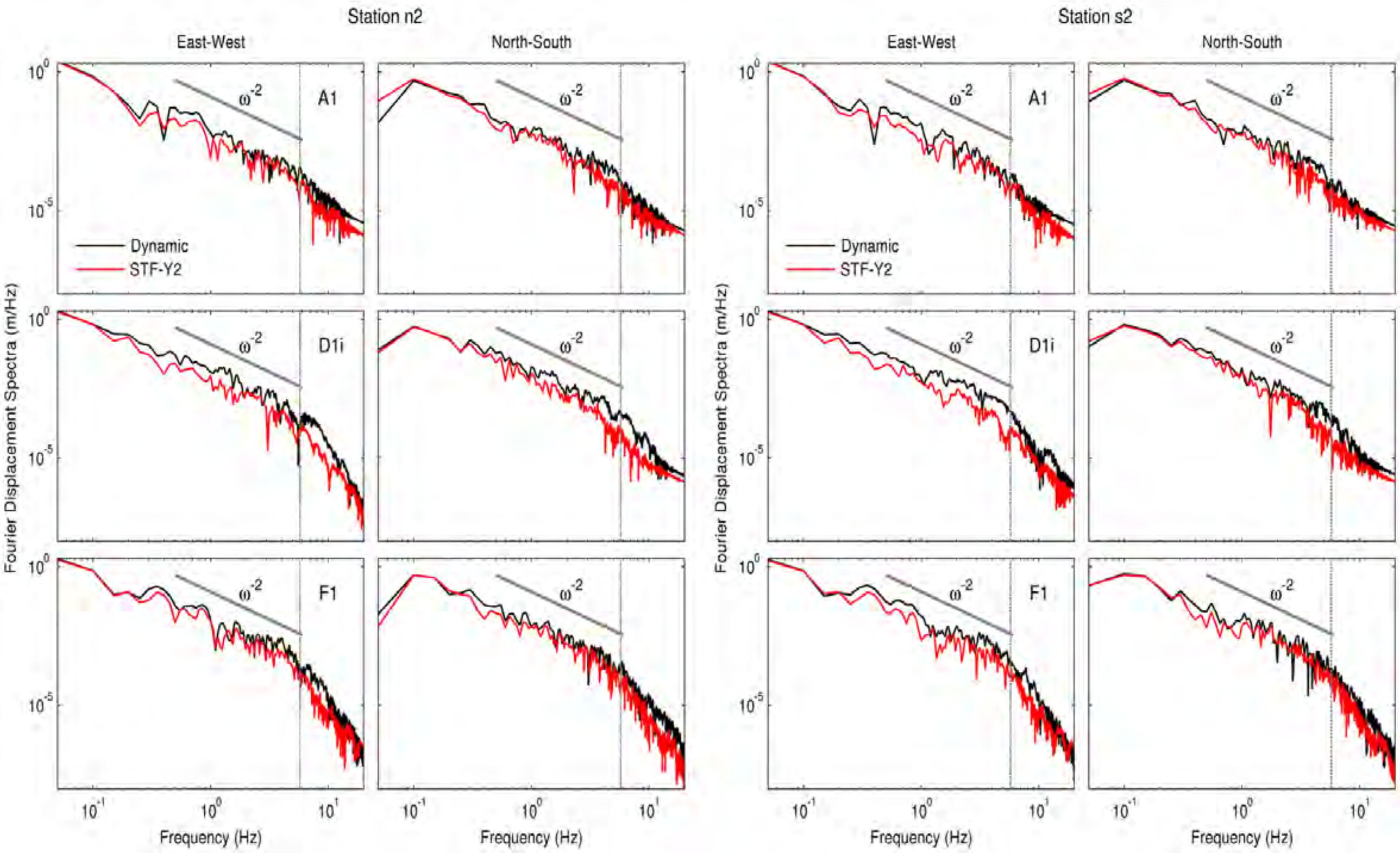
Rough-fault dynamics

Radiation characteristics for approx. kinematic models: AND simplified STF & proxy rake



Rough-fault dynamics

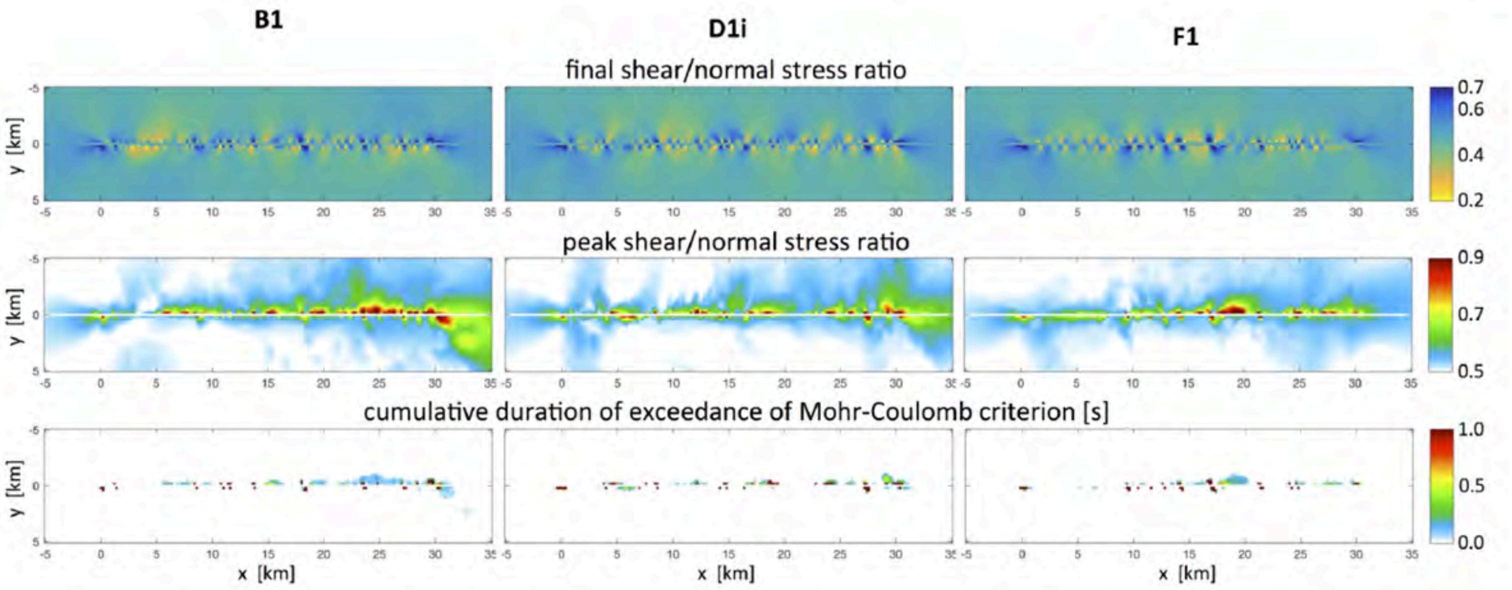
Radiation characteristics for approx. kinematic models – reproduce waveforms & spectra



A few discussion points

Plasticity

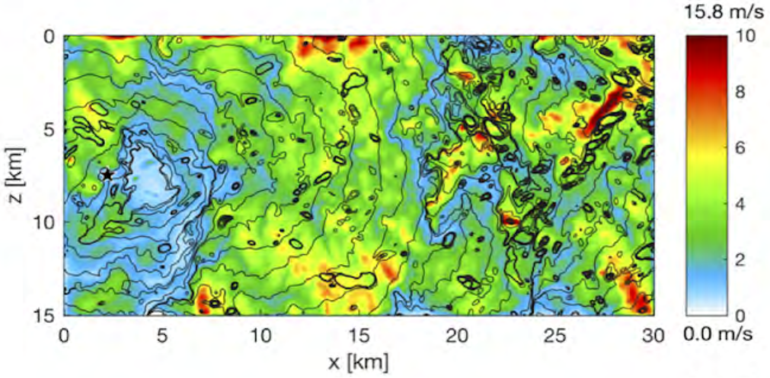
- In principle, plasticity / off-fault deformation needs to be included in rough-fault simulations (Dunham et al., 2011; Shi and Day, 2013; Trugmann & Dunham, 2014)
- Ratios of final shear stress/final normal stress, peak shear stress/peak normal stress, and the cumulative duration of exceeding the Mohr–Coulomb criterion show: plastic yielding would be confined to distances < 1 km away from the fault, and that the yield criterion is only violated for about 0.5 s

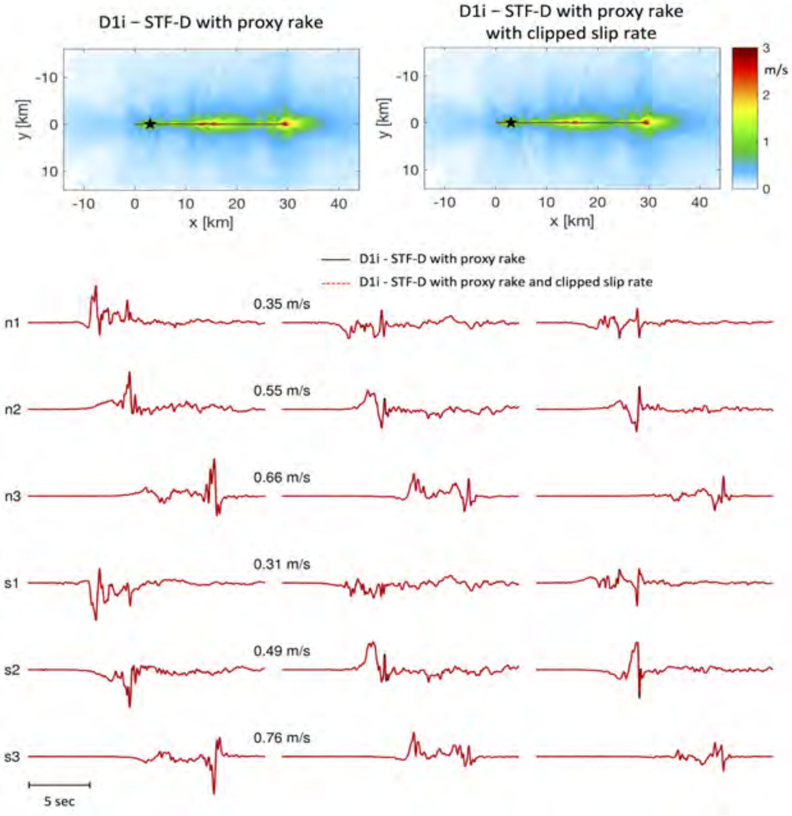


A few discussion points

Very high slip-rates

- Our simulations generate locally, in isolated patches, very high slip rates, exceeding 6 m/s, which is often considered unrealistic (e.g. Andrews, 2005)
- What happens if slip-rates are clipped (e.g., at 6 m/s)? → **NOT MUCH !**

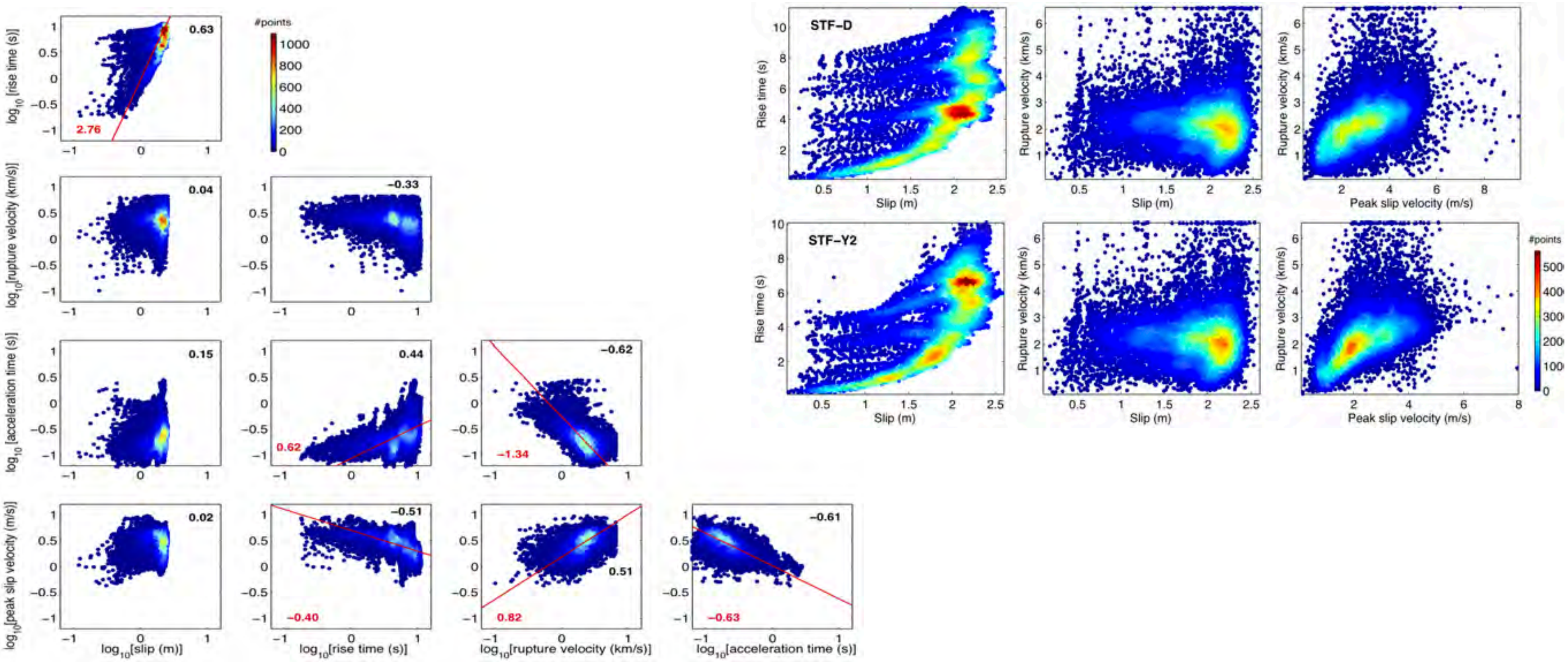




A few discussion points

Correlations in rupture parameters

- We observe correlation between rise-time and slip, and rupture velocity and peak-slip velocity, but not of rupture velocity with slip
- The acceleration time (Tacc) of the STF inverse-correlates with rupture velocity; Tacc also controls the high-frequency radiation



Conclusions

Rupture and Radiation from Rough-Faults

- Rupture histories are complex, with strong spatial variations in rupture speed, peak slip-rate, and Tacc, but relatively smooth slip
- Rough-fault simulations generate ω^{-2} high-frequency radiation
- Rough-fault radiation is maintained when projecting the moment-tensor on a planar fault (keeping the variations in strike, dip, proxy-rake) and using a Yoffe-type STF *(even with clipped peak slip-rate)*
- Correlations between rupture parameters (rise-time with slip; rupture velocity with peak-slip velocity; acceleration time with rupture velocity) enable us to develop a <u>new type of a pseudo-dynamic rupture modeling approach that starts from a fault-roughness realization</u>

To-Do List

Rupture and Radiation from Rough-Faults

- Subject our simulated (dynamic and pseudo-dynamic) ground-motion time histories to engineering scrutiny
- Include (directly in the simulations) plasticity and intrinsic attenuation
- Conduct the rupture-parameter correlation analysis for the available event set (~25 scenarios), and then run more dynamic simulations
- Build and test the new pseudo-dynamic rupture generator

Thank You

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Pure and Applied Geophysics

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Accounting for Fault Roughness in Pseudo-Dynamic Ground-Motion Simulations

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Abstract—Geological faults comprise large-scale segmentation and small-scale roughness. These multi-scale geometrical complexities determine the dynamics of the earthquake rupture process, and therefore affect the radiated seismic wavefield. In this study, we examine how different parameterizations of fault roughness lead to variability in the rupture evolution and the resulting near-fault ground motions. Rupture incoherence naturally induced by fault roughness generates high-frequency radiation that follows an ω^{-2} decay in displacement amplitude spectra. Because dynamic rupture simulations are computationally expensive, we test several kinematic source approximations designed to emulate the observed dynamic behavior. When simplifying the rough-fault geometry, we find that perturbations in local moment tensor orientation are important, while perturbations in local source location are not. Thus, a planar fault can be assumed if the local strike, dip, and rake are maintained. We observe that dynamic rake angle variations are anti-correlated with the local dip angles. Testing two parameterizations of dynamically consistent Yoffe-type source-time function, we show that the seismic wavefield of the approximated kinematic ruptures well reproduces the radiated seismic waves of the complete dynamic source process. This finding opens a new avenue for an improved pseudo-dynamic source characterization that captures the effects of fault roughness on earthquake rupture evolution. By including also the correlations between kinematic source parameters, we outline a new pseudo-dynamic rupture modeling approach for broadband ground-motion simulation.

Key words: Earthquake rupture dynamics, fault-surface roughness, physics-based ground-motion simulations, near-fault shaking, seismic hazard.

1. *Introduction*

Standard ground-motion estimation procedures for seismic hazard assessment utilize empirical methods. The underlying empirical models, known as ground-motion prediction equations (GMPEs), are developed from strong-motion recordings of past earthquakes. They are used to quantify the expected shaking level for an earthquake of given magnitude, at some selected source-to-site distance, potentially involving additional parameters for source and site properties (e.g., Power et al. 2008; Mai 2009; Bozorgnia et al. 2014). The reliability of such empirical models critically depends on the input dataset, that is, the available strong-motion records and related metadata. However, strong-motion databases are limited, in particular for near-field observations of large ($M > 7$) earthquakes. Therefore, developing region-specific GMPEs is still difficult for most of the seismogenic regions across the globe. To overcome this limitation, recordings from several tectonic regimes are combined under the ergodicity assumption that earthquake source properties and seismic wave propagation effects either are identical or can be accounted for (e.g., Anderson and Brune 1999; Delavaud et al. 2012; Stewart et al. 2015). It is then necessary to justify the appropriateness of the GMPE for region-specific applications based on pre-specified selection criteria (e.g., Bommer et al. 2010), or to apply corrections before using them for different seismotectonic conditions (e.g., Campbell 2003; Bora et al. 2014).

Due to the increase in strong-motion instrumentation, and consequently increasing numbers of reliably recorded data and metadata, current GMPEs can be considered well constrained in the distance range 20–30 km for moderate (M 6–6.5) earthquakes (Chiou et al. 2008; Akkar et al. 2014; Ancheta et al.

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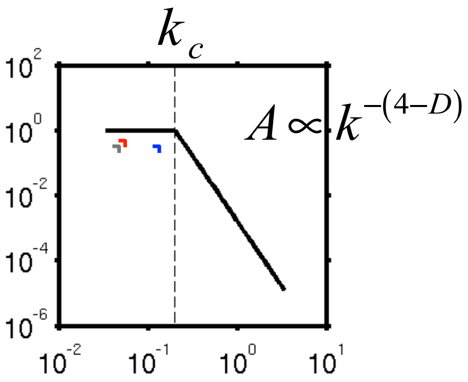
Birkhäuser

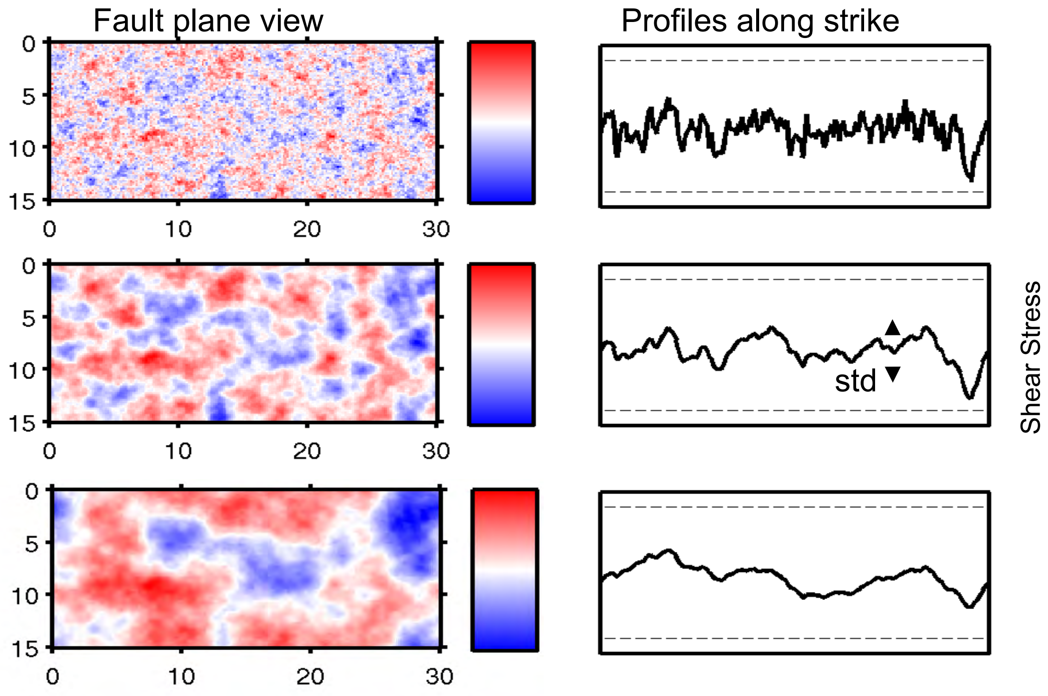
Additional Material

Motivation

Heterogeneous initial stress in dynamic ruptures

What happens if we make certain assumptions on the initial stress on the fault, and then simulate the dynamic rupture process?



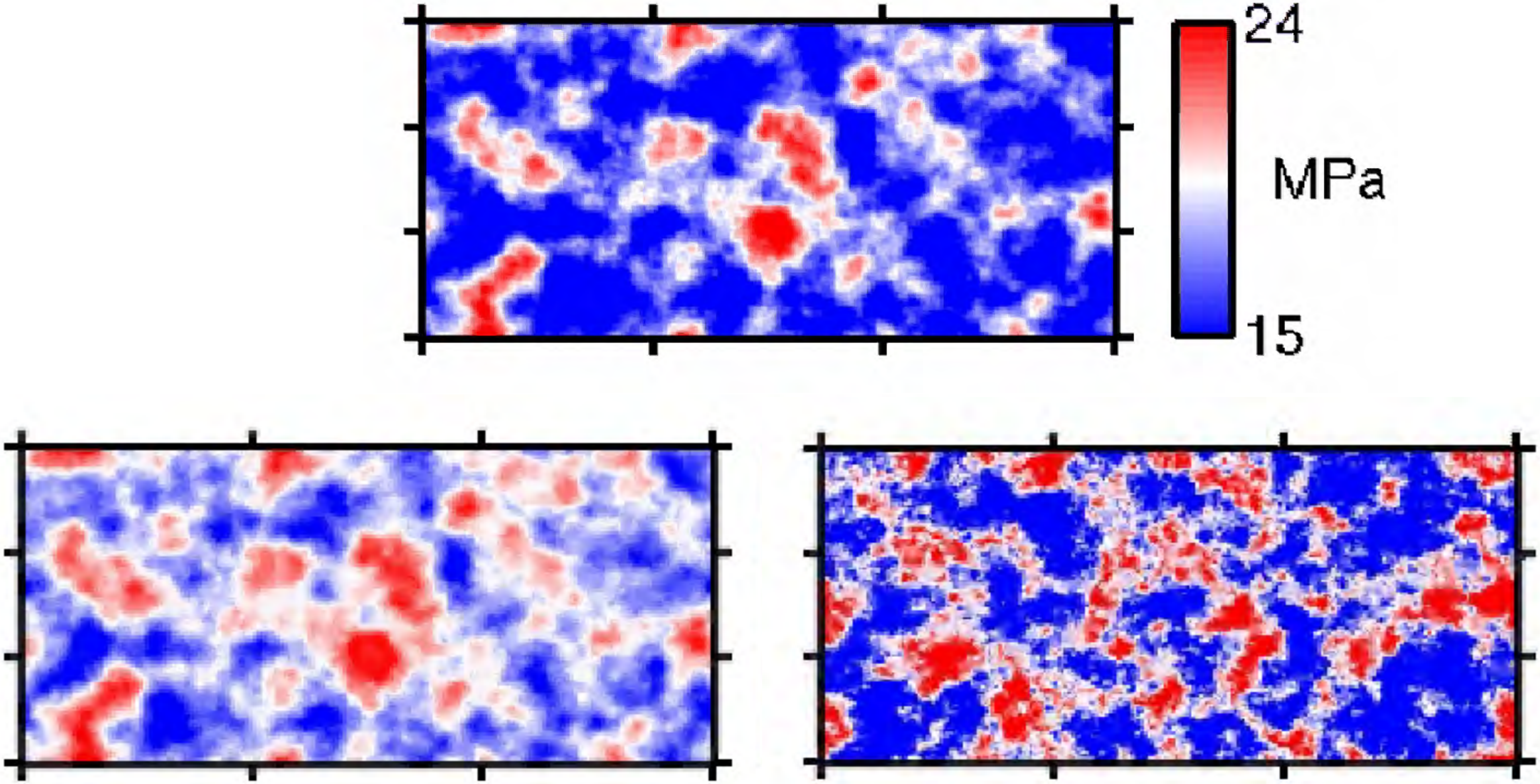


3 Parameters:
- Corner wave number
- Fractal Dimension
- Standard deviation

Ripperger, et al, 2007

Motivation

Heterogeneous initial stress in dynamic ruptures



Earthquake Dynamics

Numerical simulations of earthquake dynamics

- Given an initial stress state in the medium (on the fault), we need a constitutive relation (friction law) to solve the equation of motion
- In terms of fracture mechanics, we solve a crack-tip equation of motion considering the energy balance at the propagating crack (rupture) front

Mode I

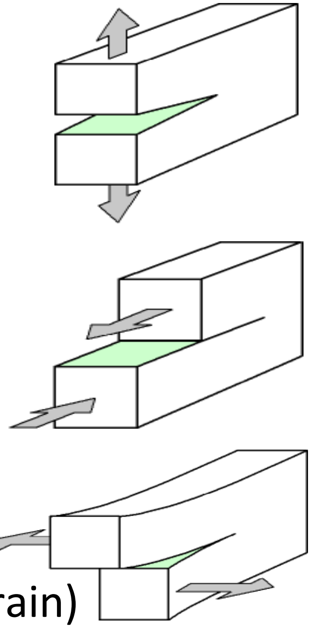
(tensile)

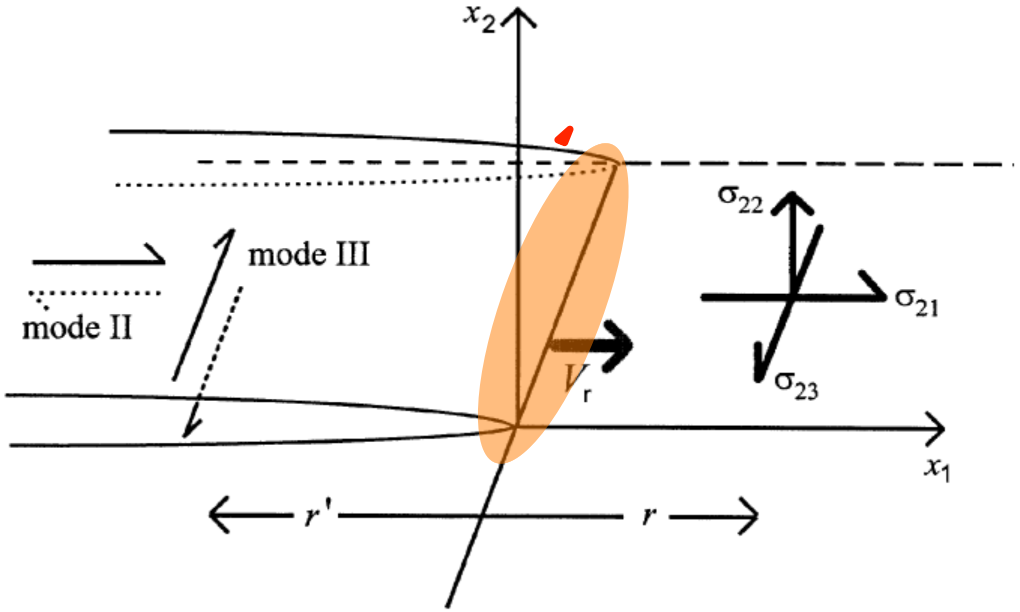
Mode II

(plane strain)

Mode III

(anti-plane strain)

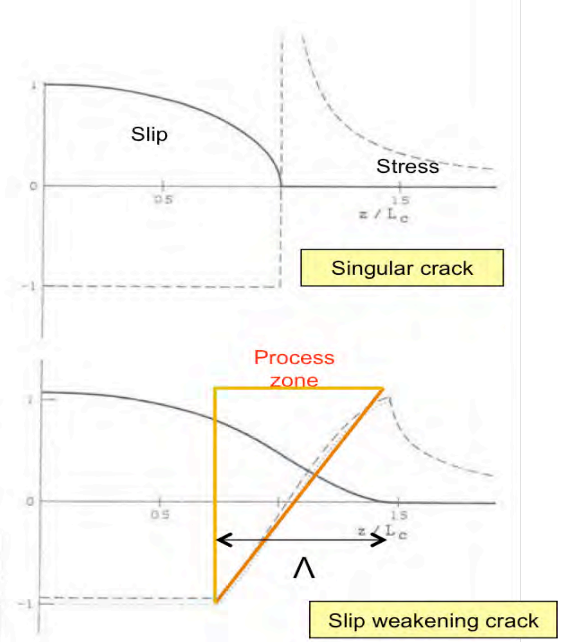


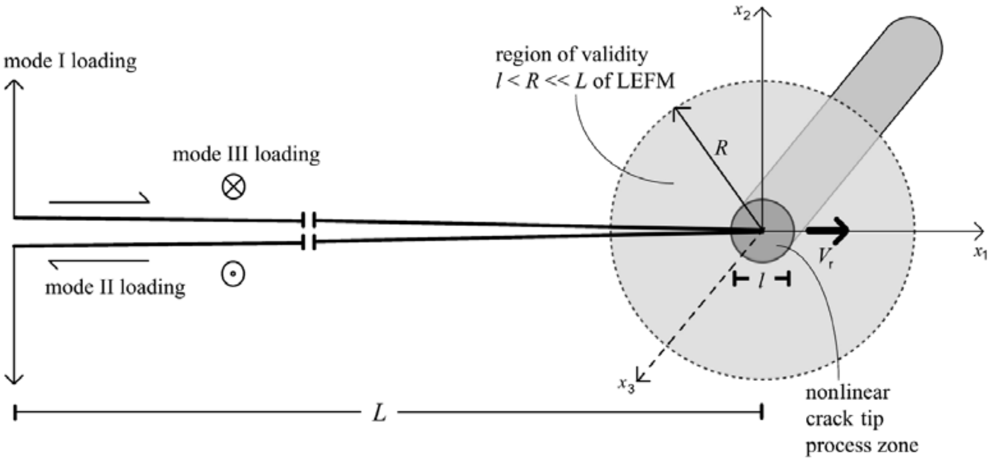


Earthquake Dynamics

Numerical simulations of earthquake dynamics

- At the tip of an idealized crack, a stress singularity exists; this needs to be relaxed or removed for practical applications
- Concept of small-scale yielding: there is a small crack-tip zone in which inelastic deformation occurs; this region is characterized by an ‘effective’ friction law. Elsewhere, the elastic solution applies

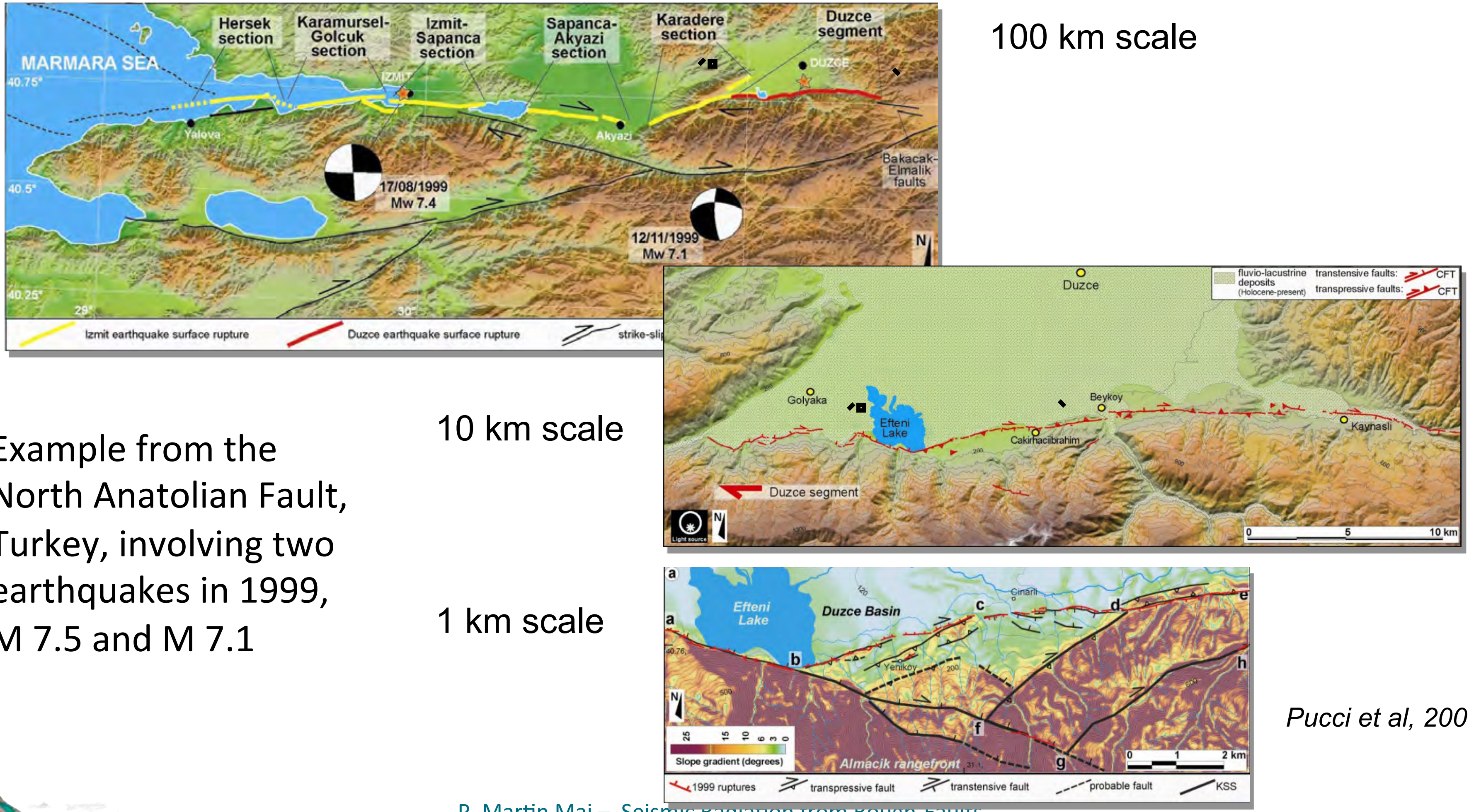




Complex Fault Geometry

Fault Segmentation

- Faults are not planar; fault networks are geometrically complex



100 km scale

10 km scale

1 km scale

Example from the North Anatolian Fault, Turkey, involving two earthquakes in 1999, M 7.5 and M 7.1

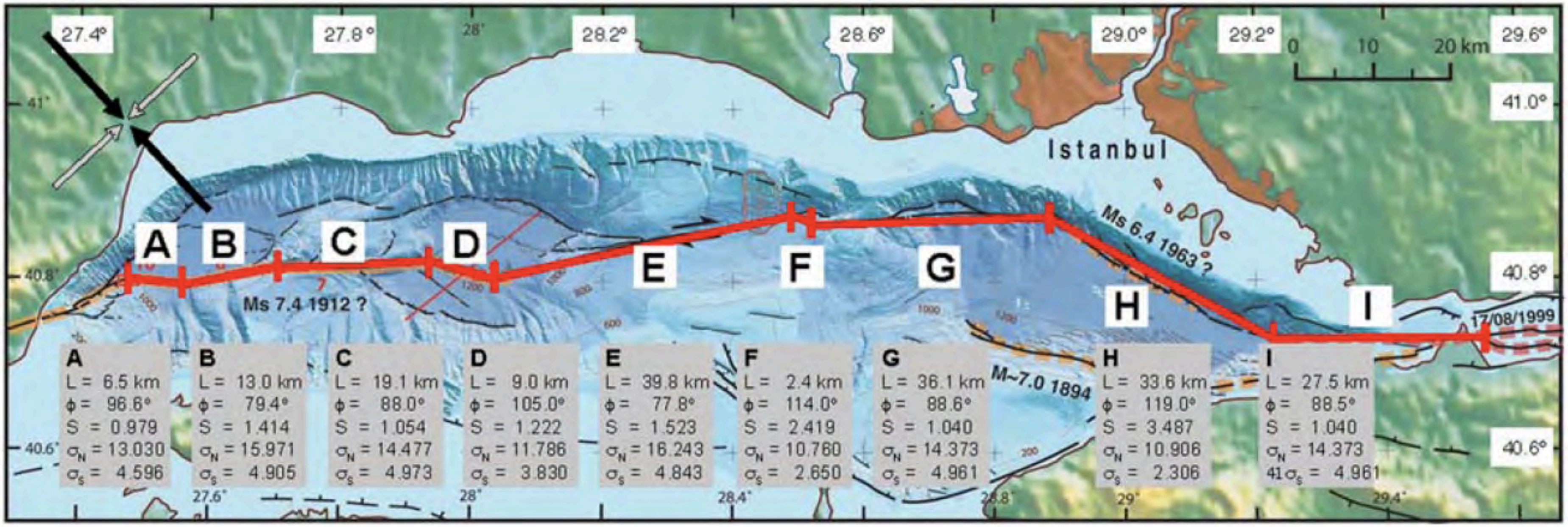
Pucci et al, 2006

Complex Fault Geometry

Fault Segmentation

- Faults are not planar; fault networks are geometrically complex

- The faults of the North Anatolian Fault Zone (NAFZ) in the Marmara Sea have ruptured in the past (1776 and before). Large earthquakes happened to the west and east of these fault in 1912 and 1999.

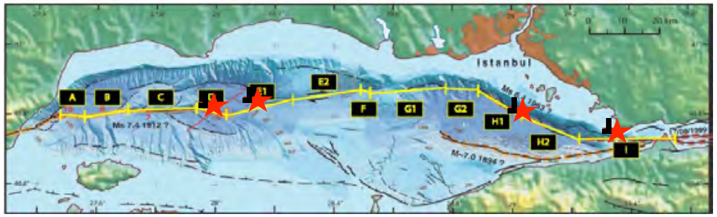


Oglesby and Mai, 2012

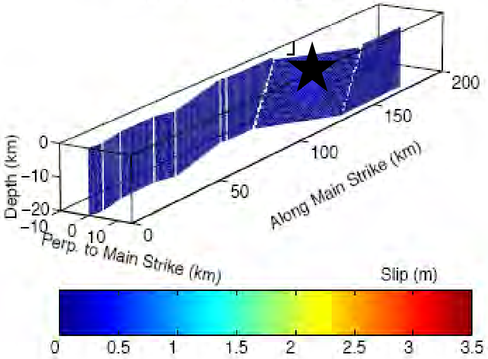
Complex Fault Geometry

Fault Segmentation

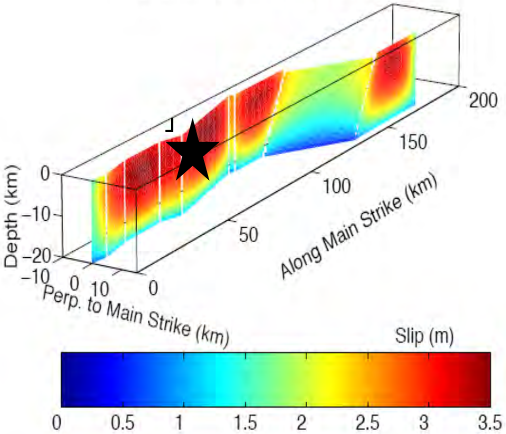
- Faults are not planar; fault networks are geometrically complex
  - Ruptures starting on segment D will break the entire fault, resulting in a M 7.8 earthquake
  - Ruptures starting on E remain smaller
  - Ruptures starting on H will not propagate: Ruptures starting on H I will remain very small



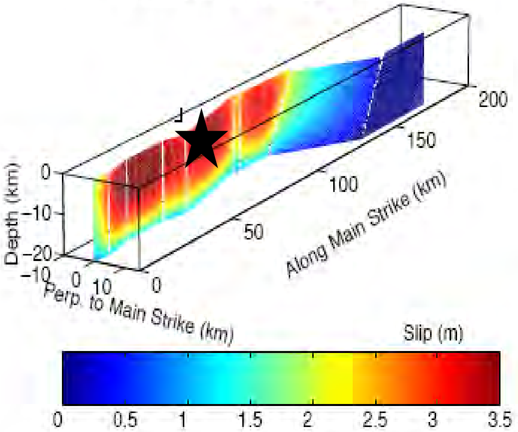
Nucleation on Segment H



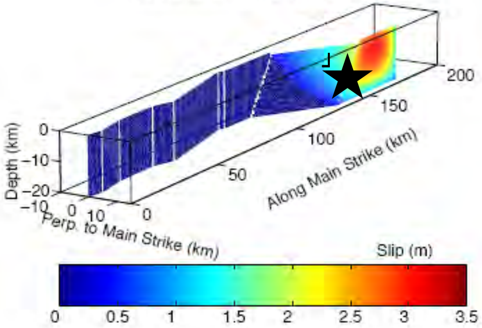
Nucleation on Segment D



Nucleation on Segment E



Nucleation on Segment I



Oglesby and Mai, 2012