Heterogeneous Initial Stress For Spontaneous Rupture Models: The 2011 Tohoku and 2008 Wenchuan Earthquakes

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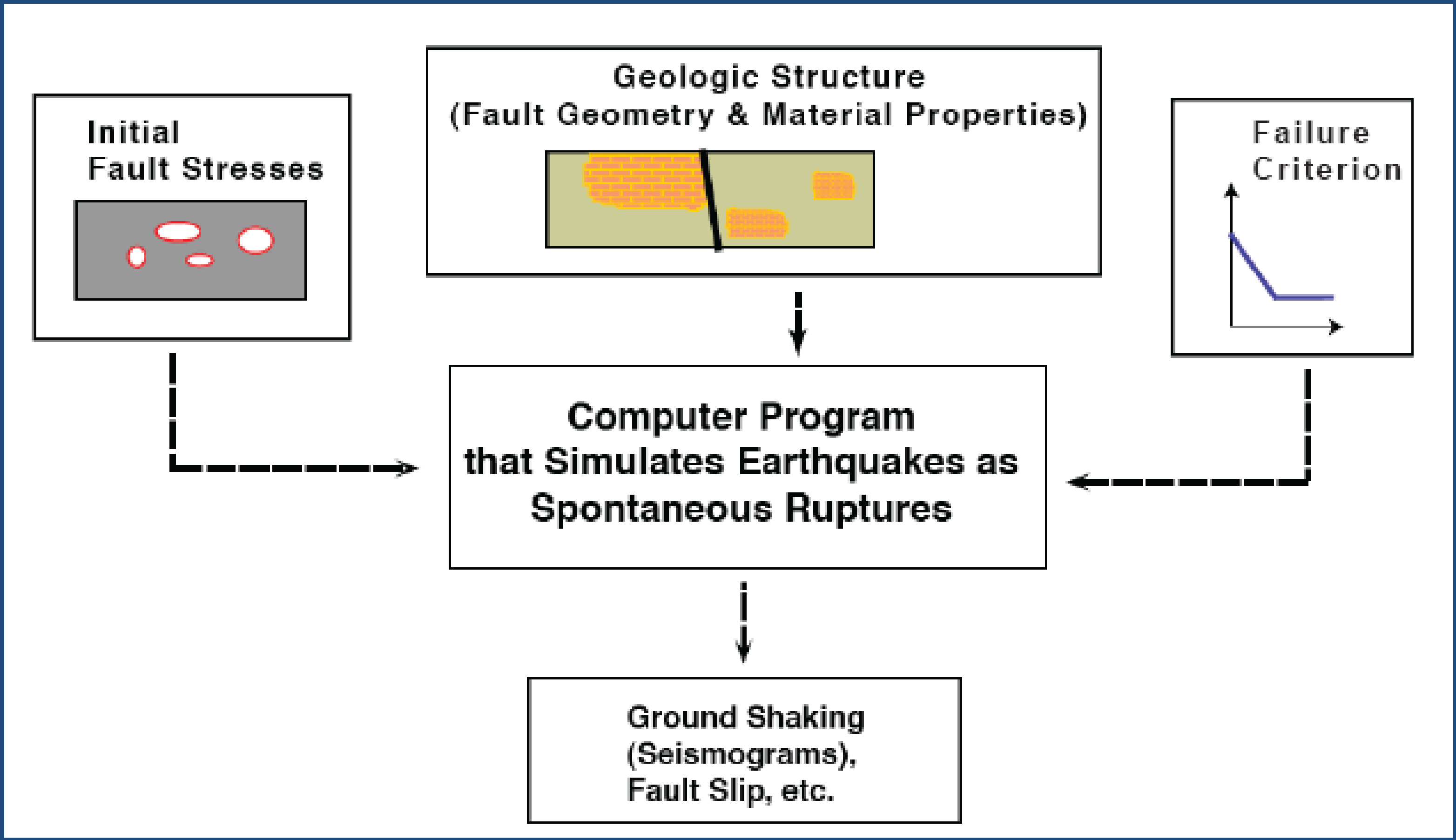
Outline

- Overview on initial stress setup for dynamic models
- EQdyna: Slip-weakening friction in an elastic or elastoplastic model
- The 2011 M9 Tohoku earthquake: roles of a possible seamount?
- The 2008 M8 Wenchuan earthquake: stress rotations?
- Concluding remarks

Overview on Initial Stress Setup

Ingredients of Spontaneous Rupture Models

- Given lab constraints on friction law and geological/geophysical constraints on geologic structure, **Initial stress is the least-constrained ingredient: most important & most flexible?**



Initial Fault Stresses

Geologic Structure (Fault Geometry & Material Properties)

Failure Criterion

Computer Program that Simulates Earthquakes as Spontaneous Ruptures

Ground Shaking (Seismograms), Fault Slip, etc.

Practice in Specifying Initial Stress

- Constant, depth-independent stress drop: elastic, strike-slip & dip-slip faulting
- Uniform regional stress field: elastic/plastic, strike-slip faulting, e.g., Rice’s group work,…
- Depth-dependent initial stress: elastic/plastic, strike-slip & dip-slip faulting, e.g., Andrews et al. (2007), Ma and Andrews (2010),…
- Heterogeneous initial stress: e.g., Day (1982), Andrews & Barall (2011), …

Heterogeneous Initial Stress

- Andrews and Barall (2011): random & self-similar (power-law) stress drop, long-wavelength stress variation, GM prediction

- Earthquake-cycle simulation: heterogeneous stress evolves over multi-cycles
  - Lapusta group's work
  - Duan & Oglesby (2005, 2006, 2007)

- Depth-dependent, nonuniform initial stress:
  - Subducted seamounts in 2011 Tohoku EQ?
  - Stress rotations in 2008 Wenchuan EQ?

EQdyna

Brief Overview

An Explicit FEM Method

- For rupture dynamics and seismic wave propagation
  - One of the codes in the SCEC validation exercise
  - Benefit a lot from our code validation exercise: Thanks to Ruth and All

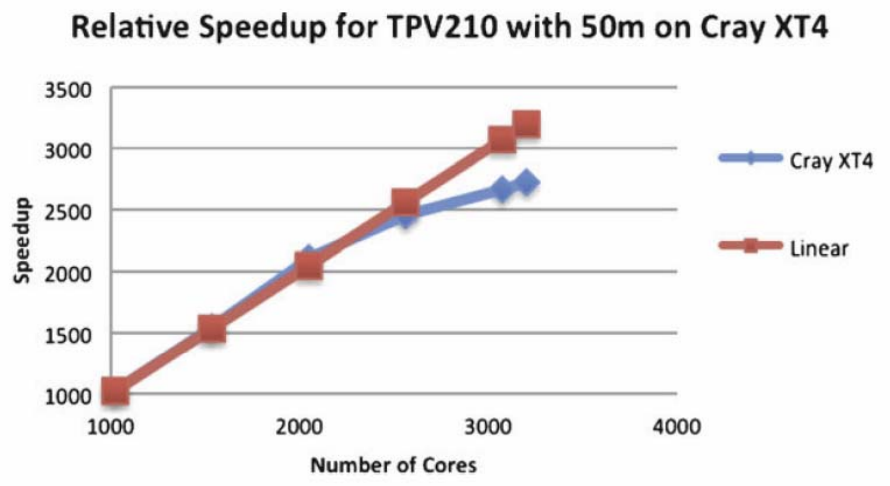
$$\rho u_{i,tt} = \sigma_{ij,j} + f_i$$

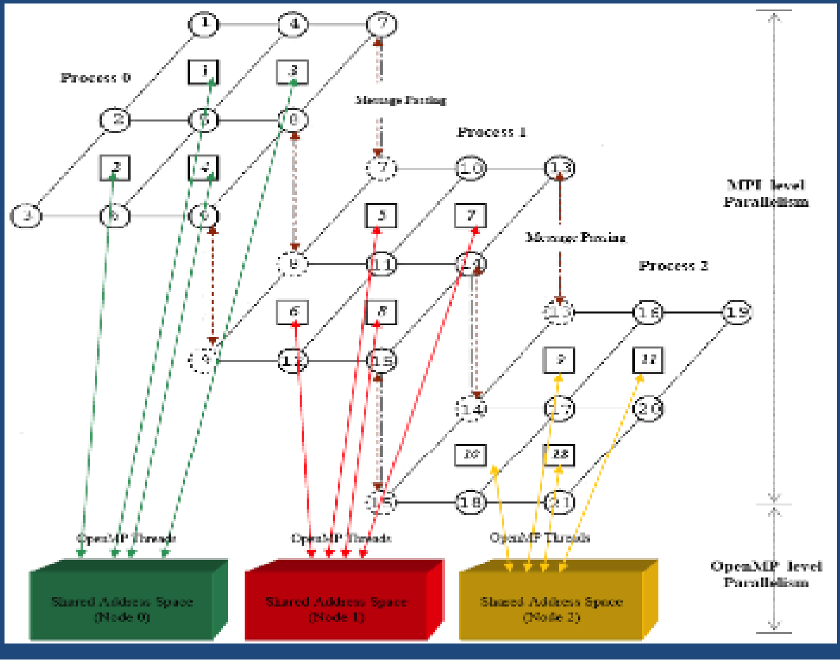
- Slip-weakening friction mainly:
  - rate-state friction in process
- TSN of Day et al. (2005)

$$\tilde{T}_\nu = \frac{\Delta t^{-1} M^+ M^- \left[\left(\dot{u}_\nu^+ - \dot{u}_\nu^- \right) + \Delta t^{-1} \left(u_\nu^+ - u_\nu^- \right) \delta_{\nu n} \right] + M^- R_\nu^+ - M^+ R_\nu^-}{a \left(M^+ + M^- \right)} + T_\nu^0, \quad \nu = s, d, n, \tag{4}$$

Hybird MPI/OpenMP Parallelization

- For spontaneous rupture modeling of recent large earthquakes: large fault dimension at reasonable element sizes
- Ground motion prediction with dynamic source characterization: high frequency
- Run on large cluster systems: EOS at TAMU, Lonestar & Kraken via NSF





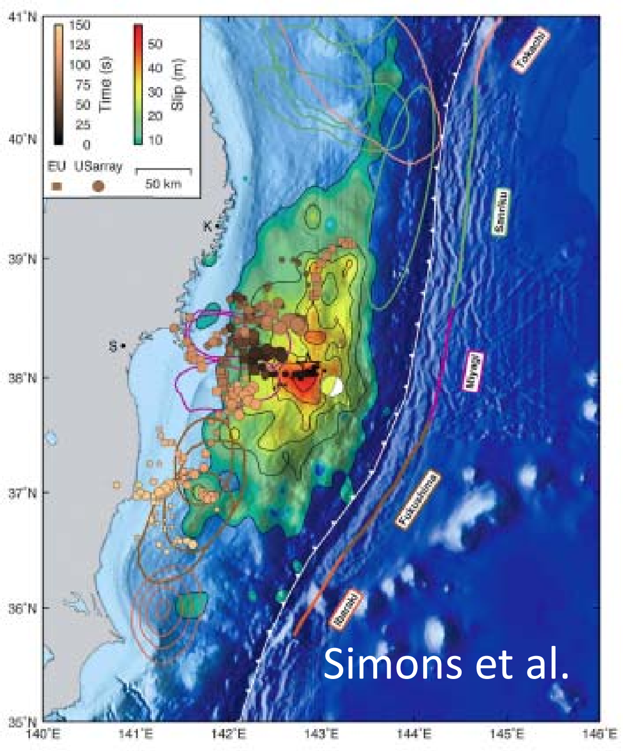
A Simulation Example

- Parallel computing: a Hybrid MPI/OpenMP approach on multicore supercomputers
  - 500 m element size on ~440kmx220km fault
  - 200 seconds dynamic simulation
  - ~580 million elements
  - ~35 hr wallclock time, ~640 GB memory using 256 cores for production runs on EOS at TAMU

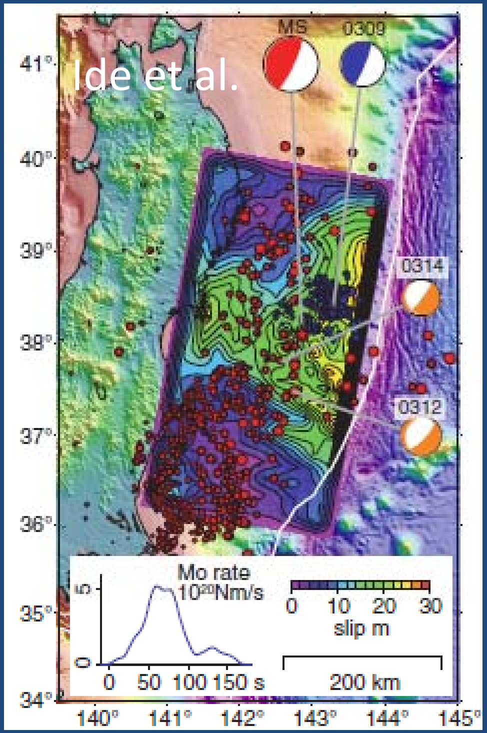
The 2011 M9 Tohoku EQ

Roles of a Possible Seamount?

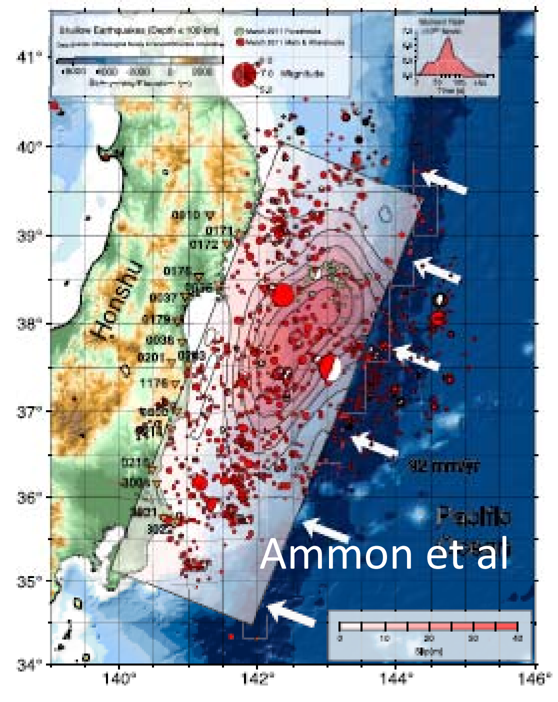
Some Kinematic Inversion Results: Slip



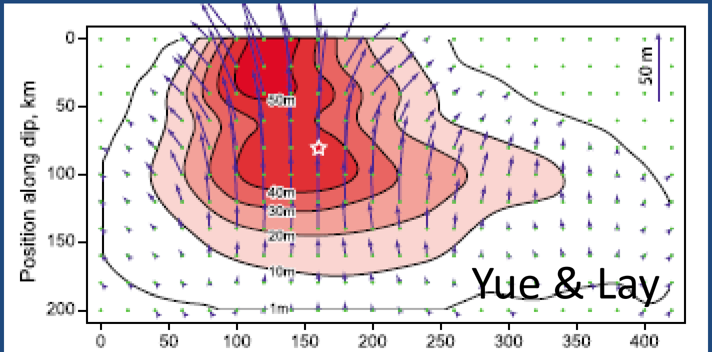
Simons et al.



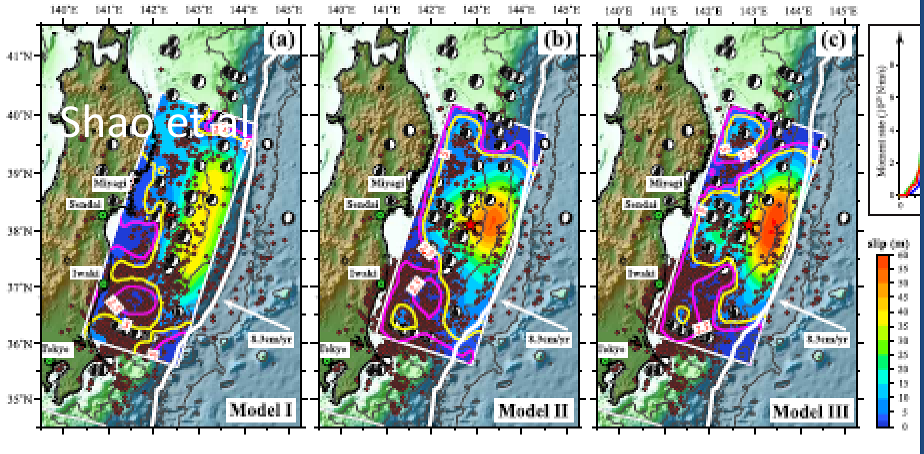
Ide et al.



Ammon et al

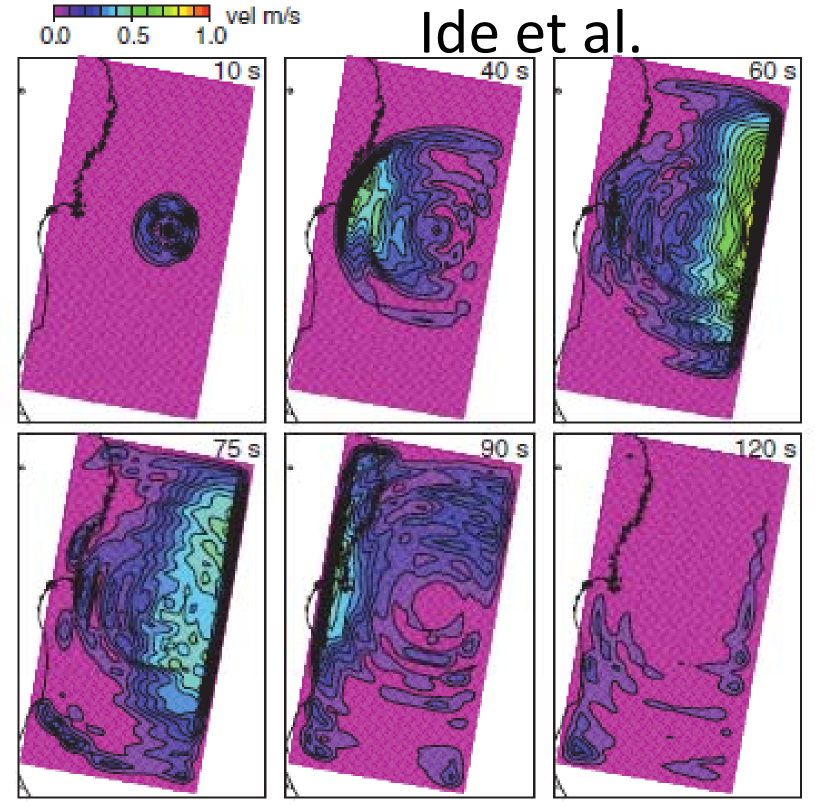


Yue & Lay

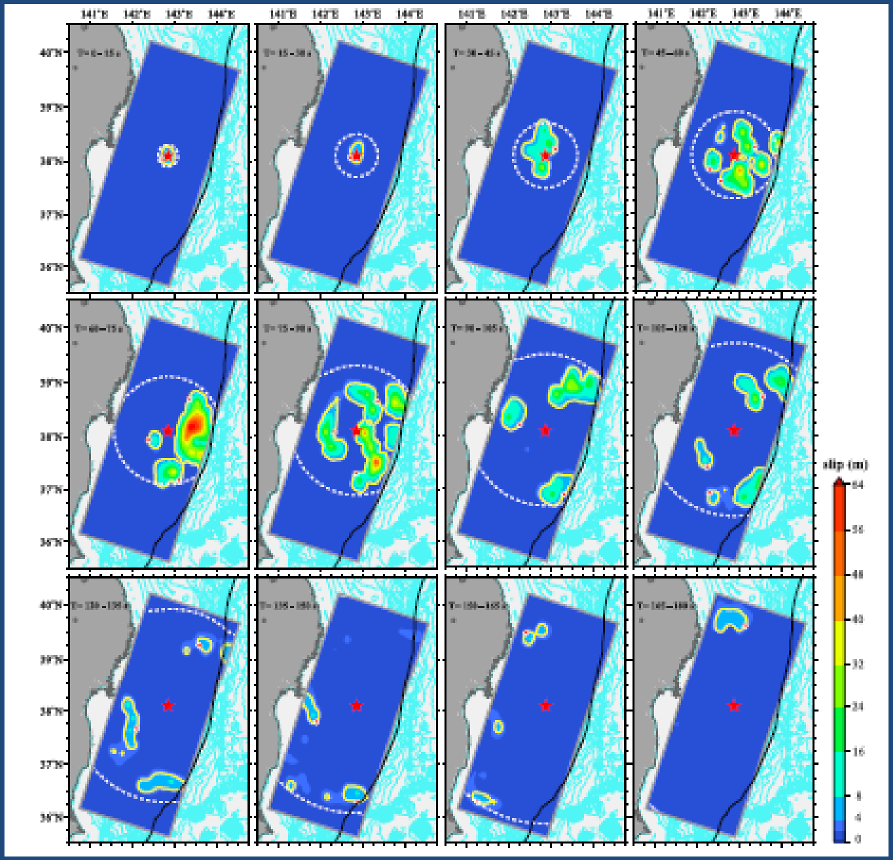


Shao et al.

Some Kinematic Results: Rupture



Ide et al.



Shao et al

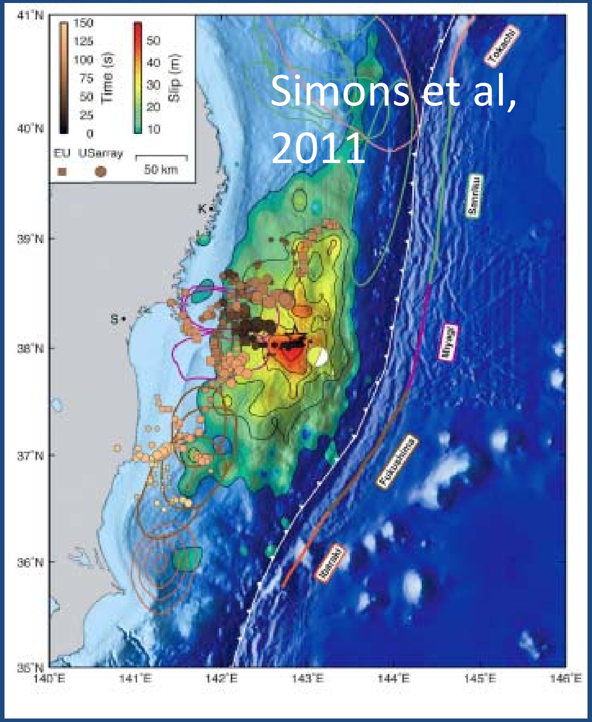
No up-dip rupture before ~40-45 seconds!

Features & Questions

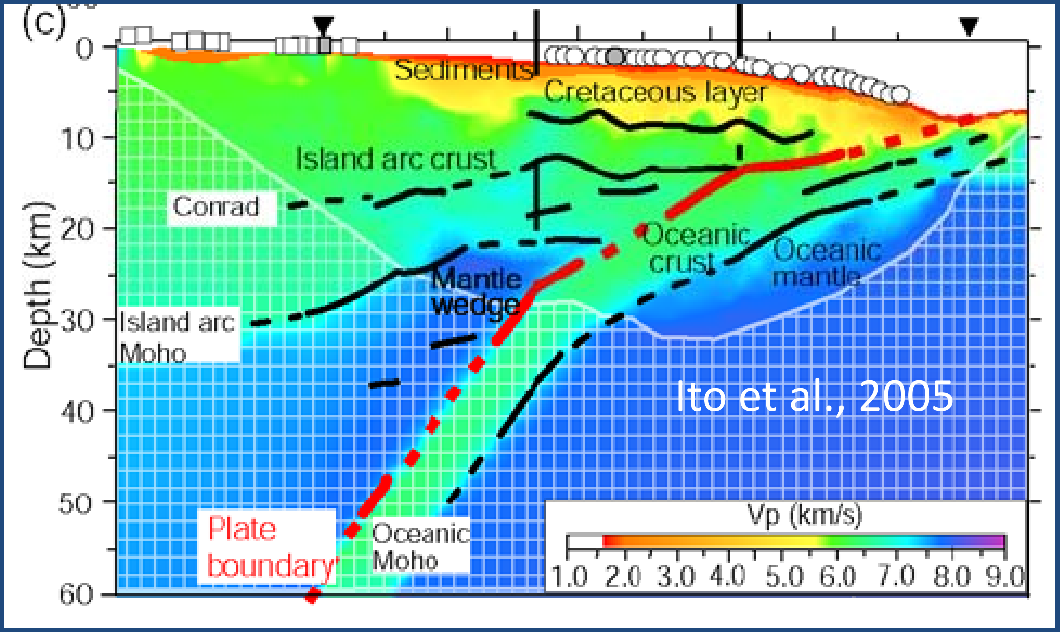
- Large Shallow Slip: 2 competing views
  - max near hypocenter: v-strengthening & stable sliding near trench?
  - max near trench: v-weakening & strain accumulation?
- Rupture propagation
  - No up-dip rupture before ~40-45 seconds: why?
  - Seafloor rupture ~60-75 seconds: strain release (+ stress drop) or passive slip (- stress drop)?
  - Deeper rupture ~90 seconds: what drives?

What Can Stall Up-Dip Rupture

- Low shear stress vs. High frictional strength
- Non-Planar fault geometry vs. Subducted seafloor features (e.g., Seamounts)



Simons et al, 2011



Ito et al., 2005

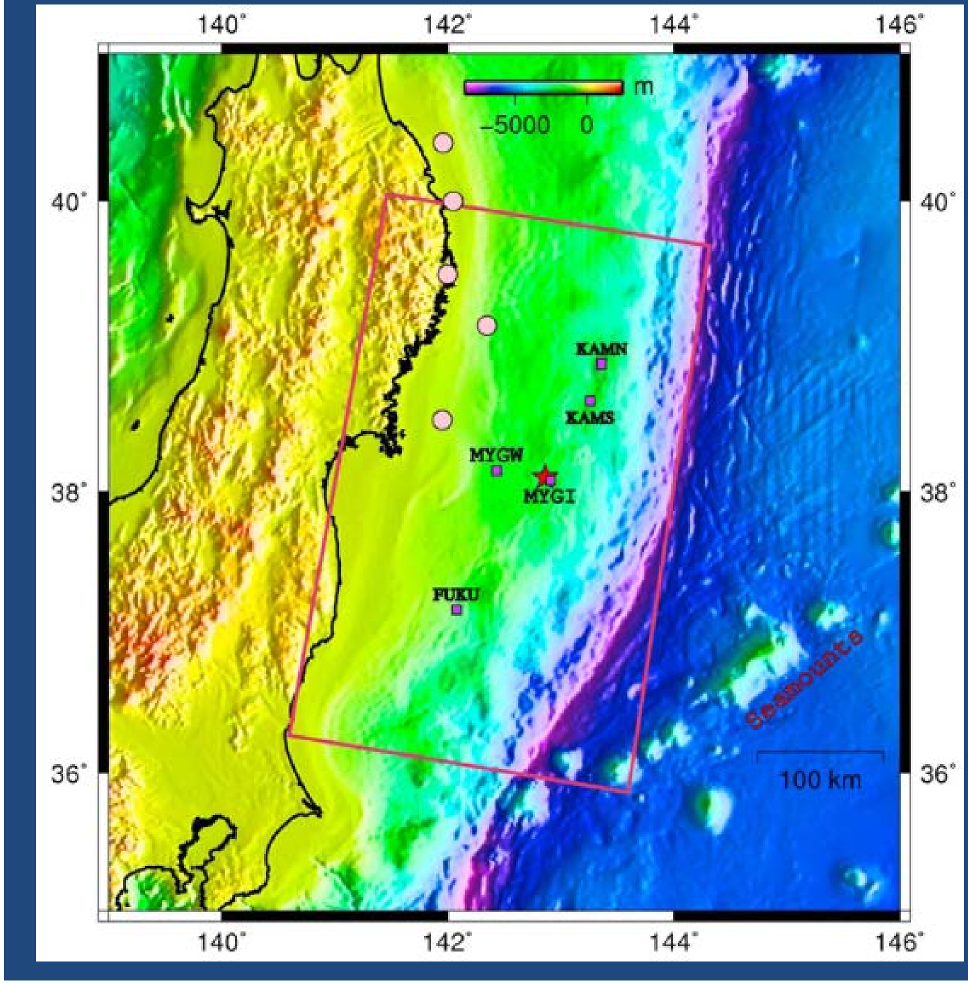
Subducted Seamounts?

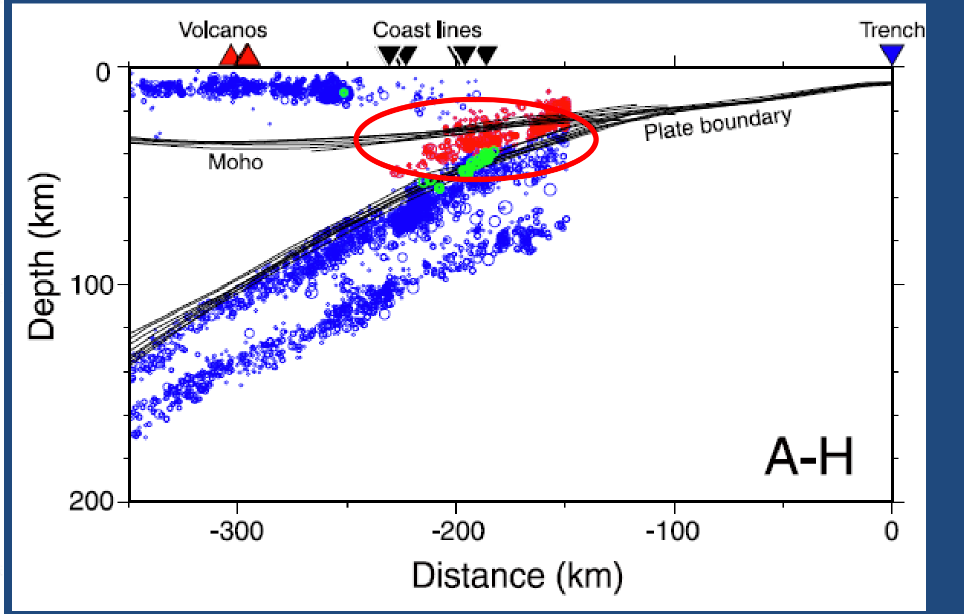
Bathymetry: ETOPO 1

- Amante & Eakins (2009)

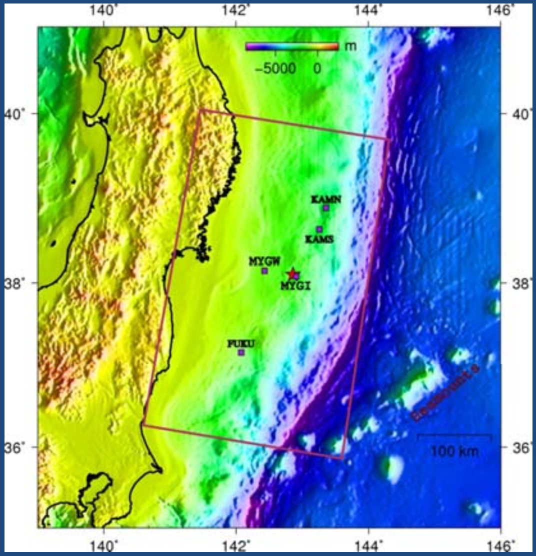
EQ clusters above the plate face

- Uchida et al (2010)

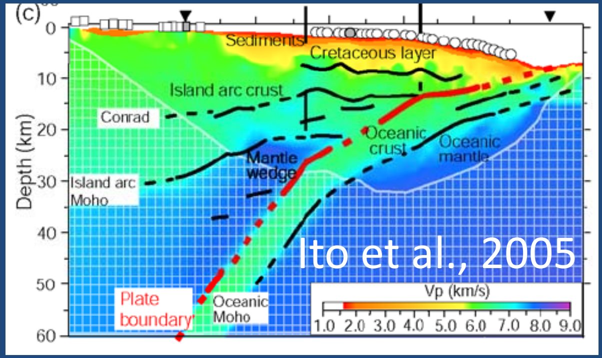




3D Spontaneous Rupture Models



- Geology Structure:
  - Fault: a 10° dipping thrust fault
  - Velocity structure: 1D
- Friction Law on Fault: Slip-weakening, +/- stress drops mimic V-weakening/strengthening
- Initial Stress: depth-dependent normal stress, pore pressure; nominal μ_0 for initial shear.



Ito et al., 2005

A Procedure of Specifying Initial Stress

- **Pure thrust faulting: max and min principal effective stresses are relevant.**

$$\sigma_3 = (1 - \lambda) g \int_0^z \rho(z') dz',$$

$$\sigma_1 = R\sigma_3,$$

$$R = [\sin(2\beta) + \mu_0(1 + \cos(2\beta))]/[\sin(2\beta) - \mu_0(1 - \cos(2\beta))].$$

$$\sigma_n = \sigma_1 \sin^2\beta + \sigma_3 \cos^2\beta,$$

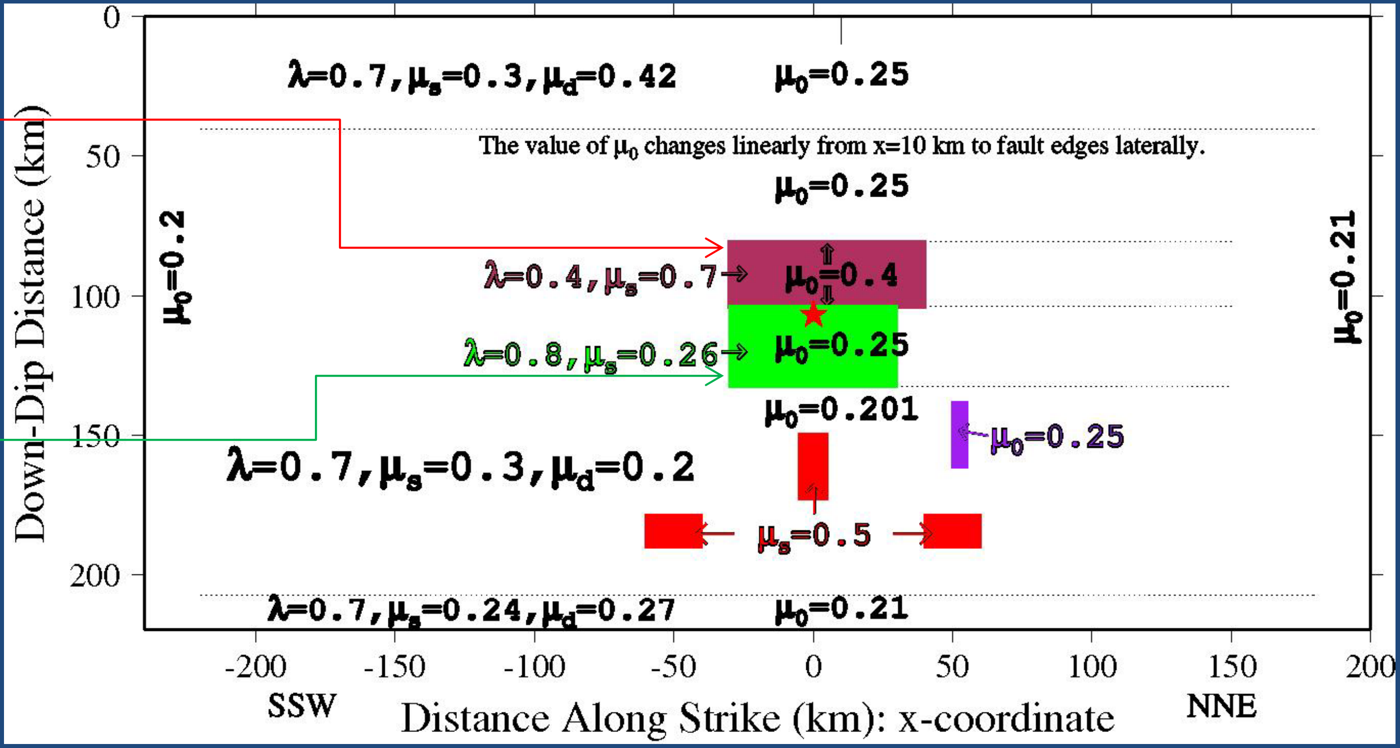
$$\tau_0 = (\sigma_1 - \sigma_3) \sin\beta \cos\beta.$$

Physical Parameters on the Fault: a Preferred Dynamic Rupture Model

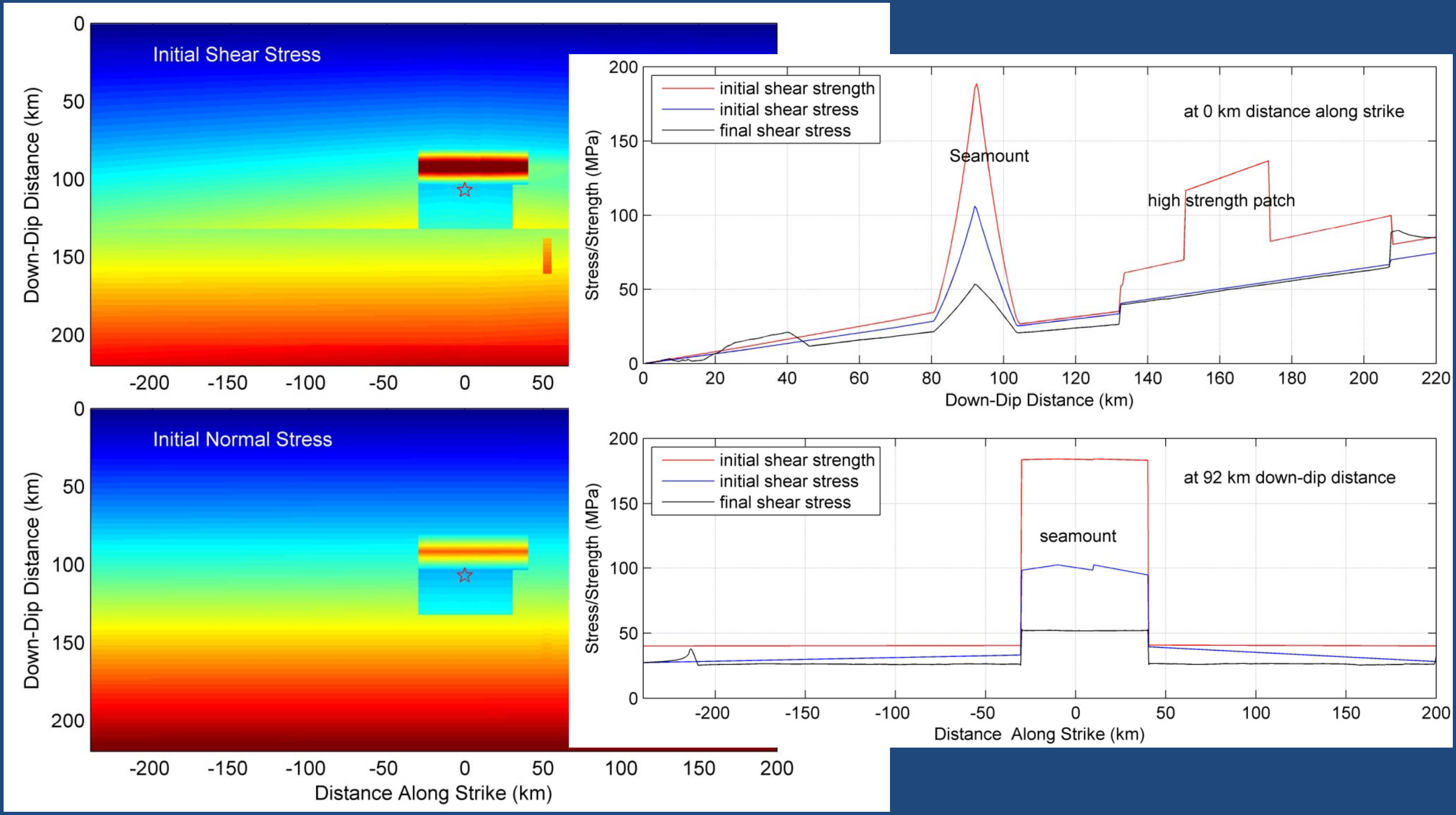
- Pore pressure: λ=pore pressure/lithostatic
- Friction coefficients: static μs /dynamic μd
- Nominal friction for initial shear stress: μ0

Seamount: low λ, high μ0, high μs

Hypocenter zone: high λ, usual μ0, low μs



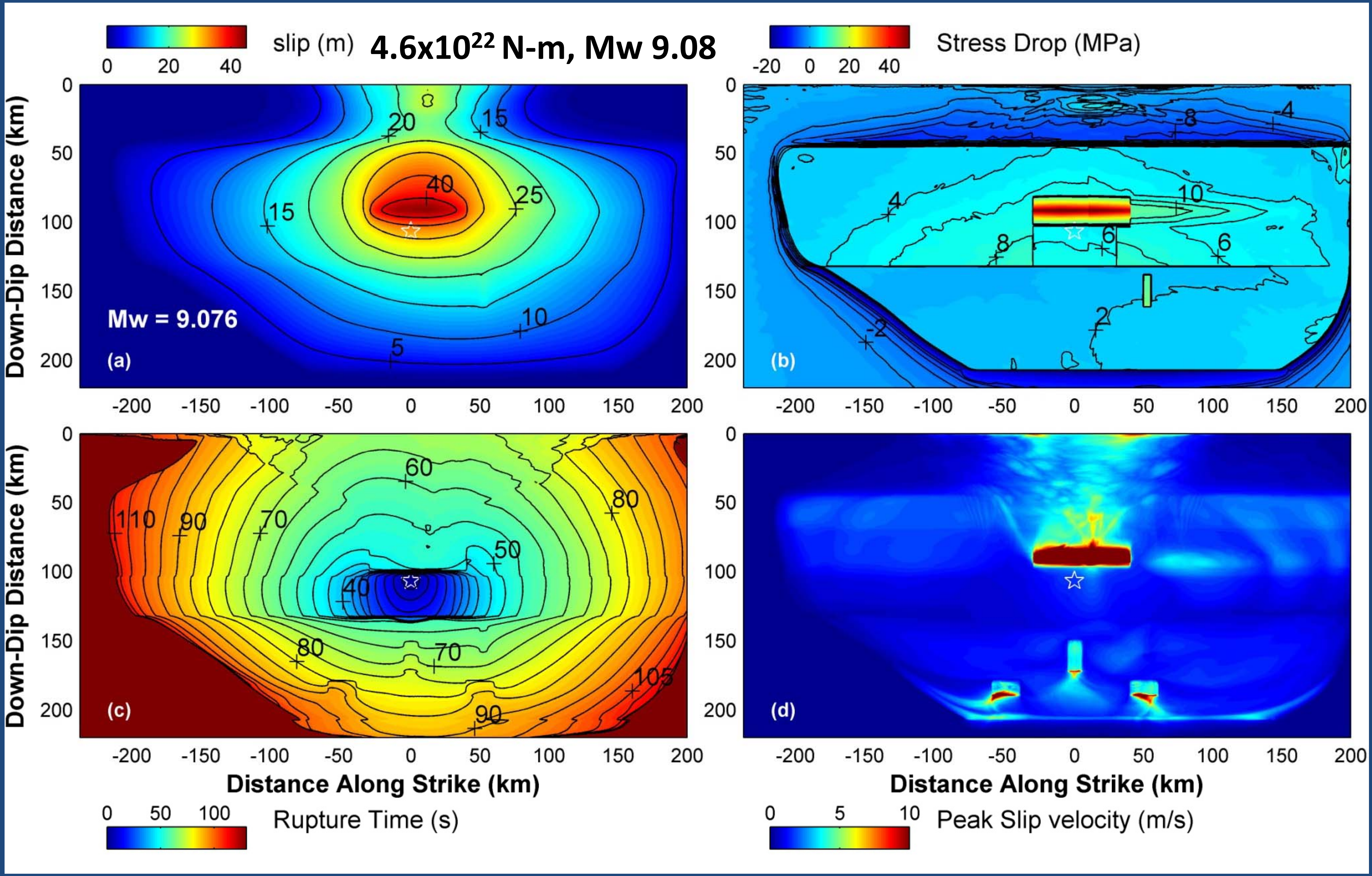
Initial Stresses on the Fault



Dynamic Rupture Propagation

A movie of slip velocity and accumulated slip from the preferred model: see preferMod.wmv

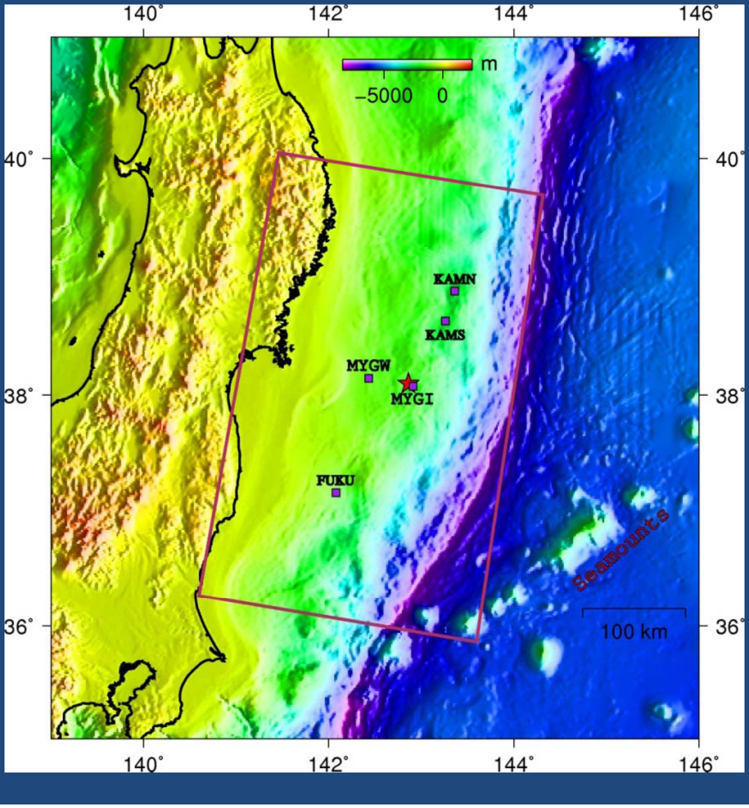
Quantities on Fault From the Model

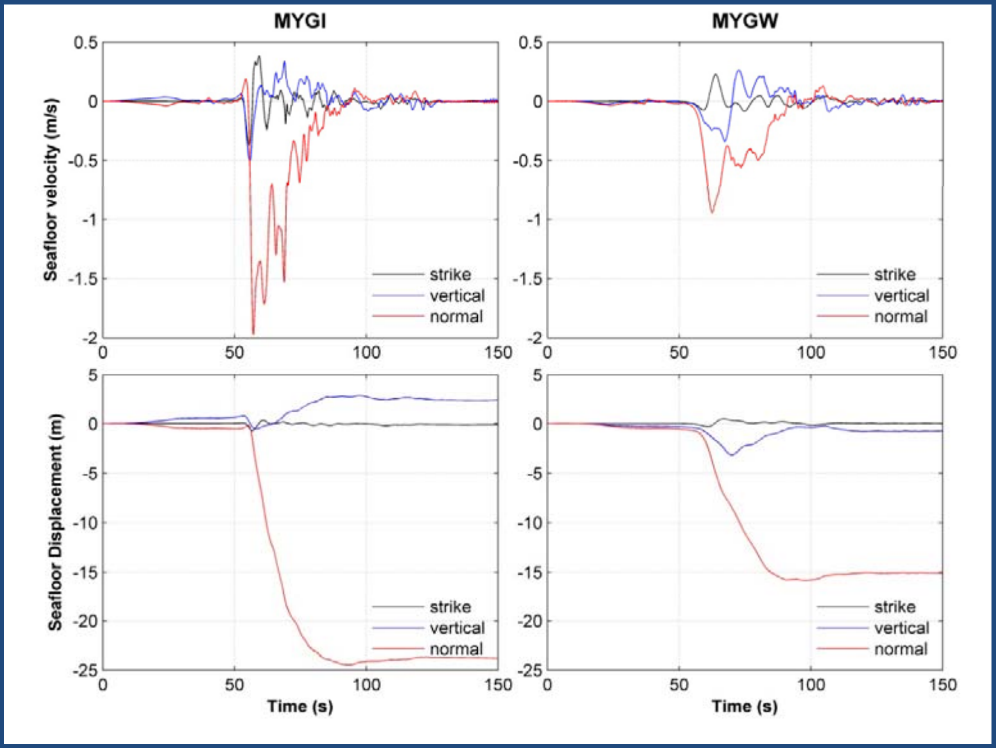


4.6x10^{22} N-m, Mw 9.08

Reproduce Epicenter Seafloor Displacements

Station	Horizontal Displacement (m)		Vertical Displacement (m)	
	Observed	Simulated	Observed	Simulated
MYGI	24	23.8	3	2.5
MYGW	15	15.0	-0.8	-0.7
KAMS	23	20.0	1.5	5.2
KAMN	15	15.1	1.6	4.3
FUKU	5	5.5	0.9	-1.3

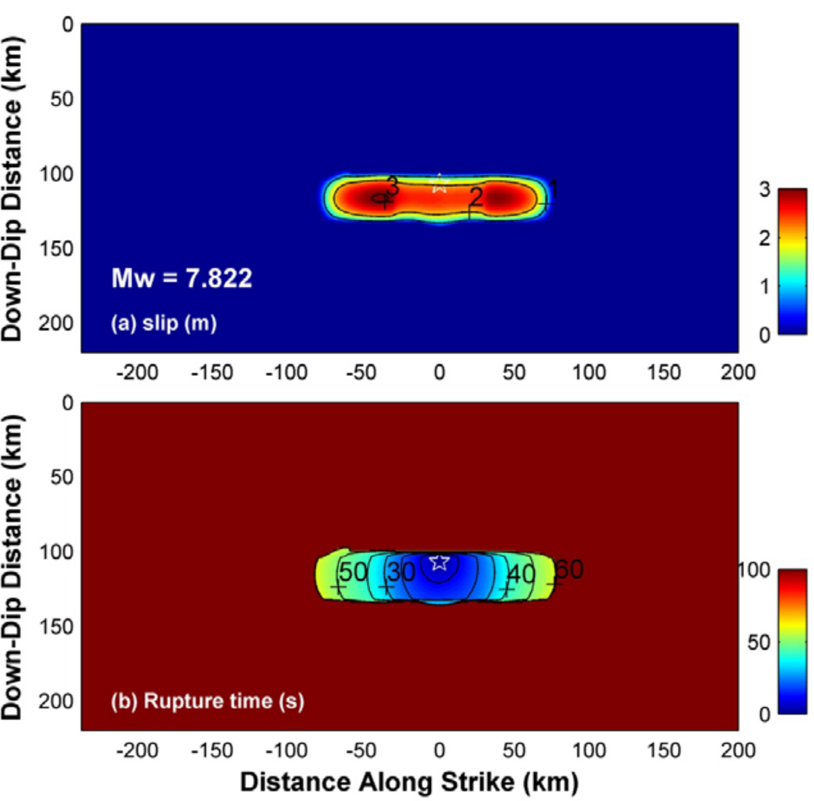




Importance of the Seamount

- Without other changes, just a longer/stronger seamount: much smaller event

A movie of slip velocity and accumulated slip: see refMod.wmv



Conclusions on the Tohoku EQ

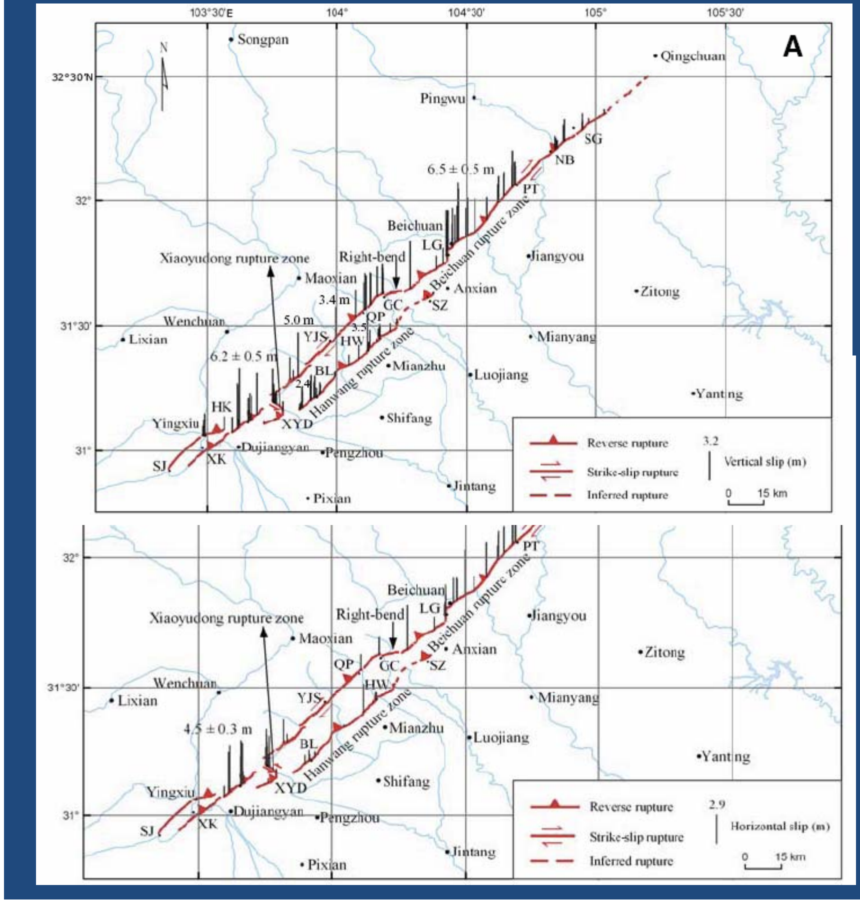
- The 2011 Mw 9.0 Tohoku-Oki earthquake may be primarily controlled by failure of a ~70 km long by 25 km wide subducted seamount.
  - Located just up-dip of the hypocenter
  - Stalled up-dip rupture: a barrier at beginning
  - Produced max slip ~50 m w/ max stress drop of ~50 MPa finally: an asperity
- Large slip near trench may be confined to a small area just up-dip of the seamount
  - Velocity-weakening (strain accumulation) near trench is not required
  - How strong velocity-strengthening (how large negative stress drop) affects the amplitude of slip there
- Parallel computing facilitates exploration of physics of megathrust earthquakes: more dynamic models needed.

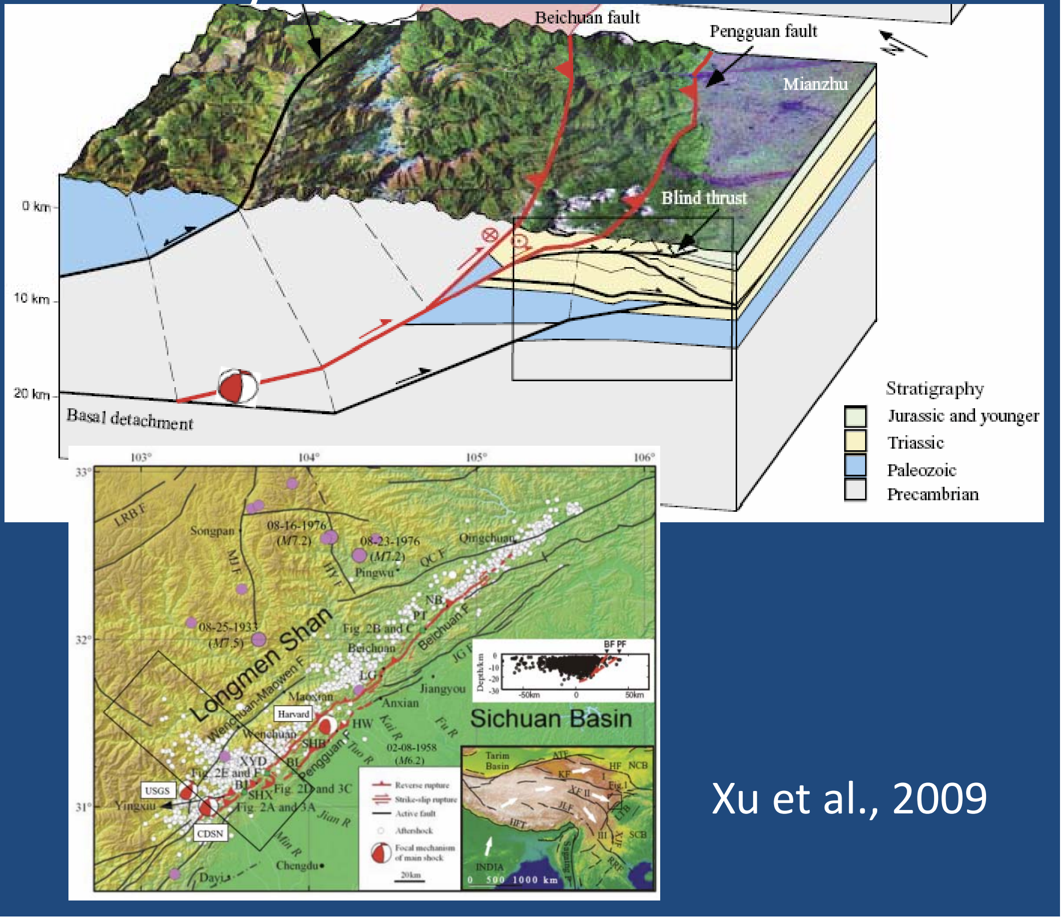
The 2008 Wenchuan EQ

Stress Rotations?

Field Observations: Surface Rupture

- Two faults ruptured: ~12 km apart on surface
  - Incomplete slip partitioning: oblique on Beichuan fault, thrust on Pengguan fault. Why?
  - Dynamic branching: how and why?





Xu et al., 2009

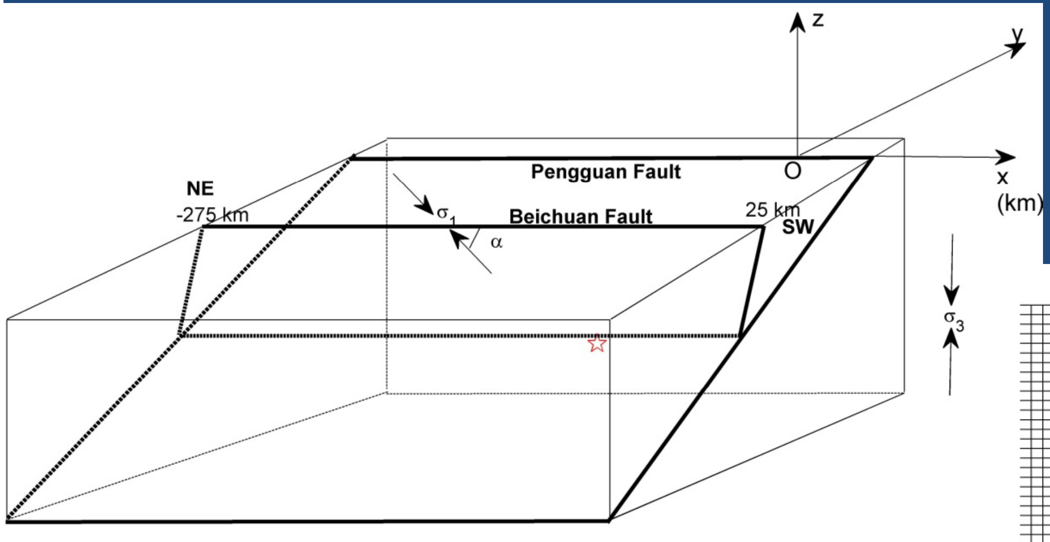
Kinematic Inversions of Seismic & Geodetic Data

- Complex spatial-temporal evolution of rupture
  - First 16 seconds on Pengguan only
  - Triggered rupture on Beichuan at ~20 s and ~40 km away

Shao et al., 2010, 2011, 2012

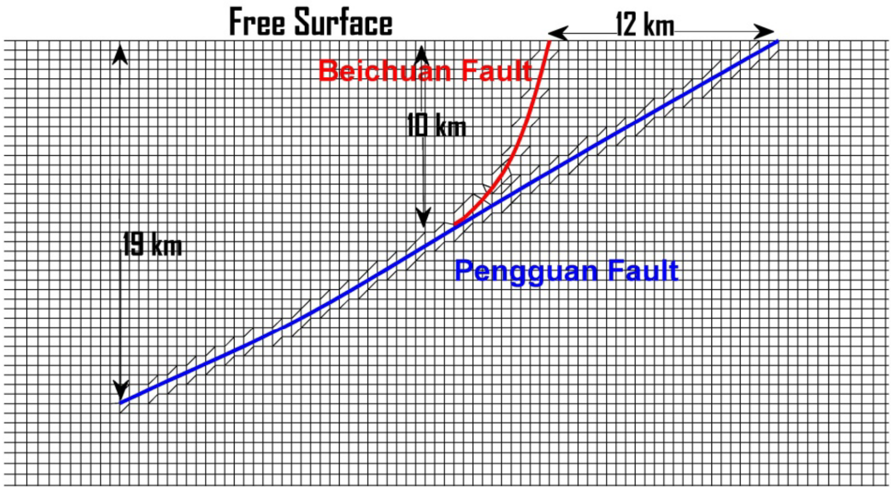
Our Branched Fault Model

- **Two smoothly curved faults: 12 km apart surface, merge at 10 km depth**
- **Material properties: homogeneous half-space w/ typical crustal rocks**
- **Friction law: time-weakening (essentially slip-weakening w/ varying D_0)**
- **Initial stress: depth-dependent effective stress**
  - **stress orientations by α : the angle between σ_1 and fault strike (focus of this study)**



Setup of initial stresses in the models: as simple as possible

(1) σ_3 is vertical: lithostatic less pore pressure.
(2) σ_1 and σ_2 are horizontal.
(3) $\sigma_2=\sigma_3$.
(4) $\sigma_1=R\sigma_3$, R>1.
(5) σ_1 makes an angle of α with the fault strike.



Uniform Regional Stress Fields

- Cannot produce incomplete slip partitioning
- Cannot produce dynamic branching

Different α for Two Faults

- Dynamic branching occurs with incomplete slip partitioning.
- But, the triggering feature reported by kinematic inversions is not produced

Preferred Model: Stress Rotations

- Incomplete slip partitioning
- Dynamic branching by triggering as reported in inversions

Conclusions on the Wenchuan EQ

- Uniform regional stress orientation along the fault system cannot produce incomplete slip partitioning and dynamic branching features observed in the event.
- Stress rotations between the two faults and along strike of the faults are needed to produce the two features.
  - Evidence: shear-wave splitting

Concluding Remarks

Heterogeneous Initial Stress for Dynamic Rupture Models

Initial Stress & Dynamic Models

- With observations of recent large earthquakes, dynamic models may allow us to infer initial stress conditions.

- Procedures for specifying initial (principal) stresses that account for depth-dependence & heterogeneities are needed in the dynamic rupture community.