Unravelling earthquake dynamics with SeisSol: Megathrust ruptures, off-fault plasticity and rough faults

Elizabeth H. Madden (Betsy)

Stephanie Wollherr, Thomas Ulrich, Alice-Agnes Gabriel

LMU
LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

lrz Leibniz-Rechenzentrum
der Bayerischen Akademie der Wissenschaften

VolkswagenStiftung

TUM
TECHNISCHE
UNIVERSITÄT
MÜNCHEN

KAUST

SEISMOLOGICAL LABORATORY
California Institute of Technology

intel

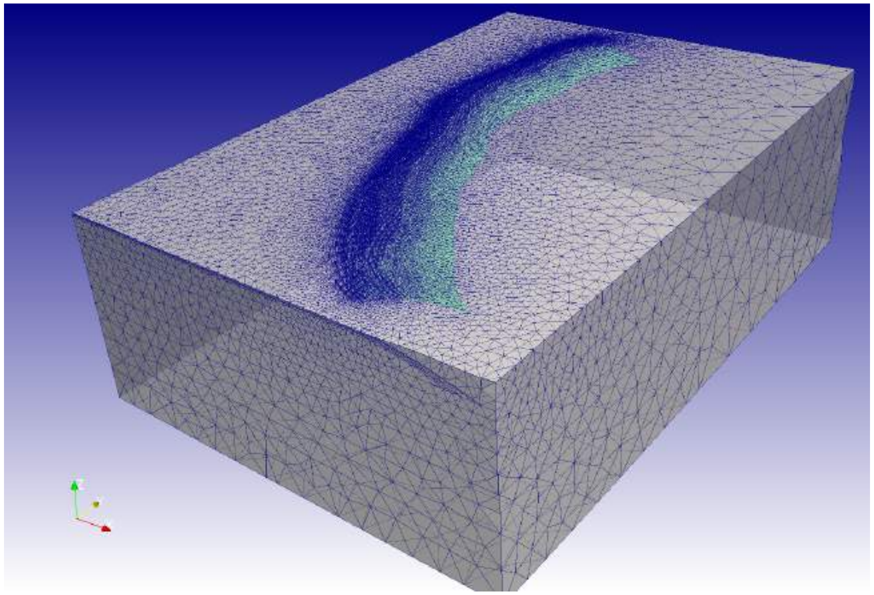
Rensselaer

IBM

ETH zürich

Earthquake models with SeisSol

- **What is SeisSol?** Seismic wave propagation and dynamic earthquake rupture code with an arbitrary high-order derivative discontinuous Galerkin (ADER-DG) scheme focusing on problems with:
  - **complex geometries** (topography, bimaterial interfaces, fault branches)
  - **heterogeneous media** (acoustic, elastic, viscoelastic, anisotropic)
  - **multi-physics** (rupture dynamics)



C. Pelties, A.-A. Gabriel, J.-P. Ampuero, Verification of an ADER-DG method for complex dynamic rupture problems, GMD, 2014

- ✓ Verified for numerically challenging fault geometries and rheologies
- ✓ Unstructured tetrahedral mesh with adaptive refinement
- ✓ On-fault solutions free of spurious oscillations even under complex geometric and physical conditions
- ✓ **SeisSol is Open Source! Contact Alice:** ***gabriel@geophysik.uni-muenchen.de*** www.seissol.org

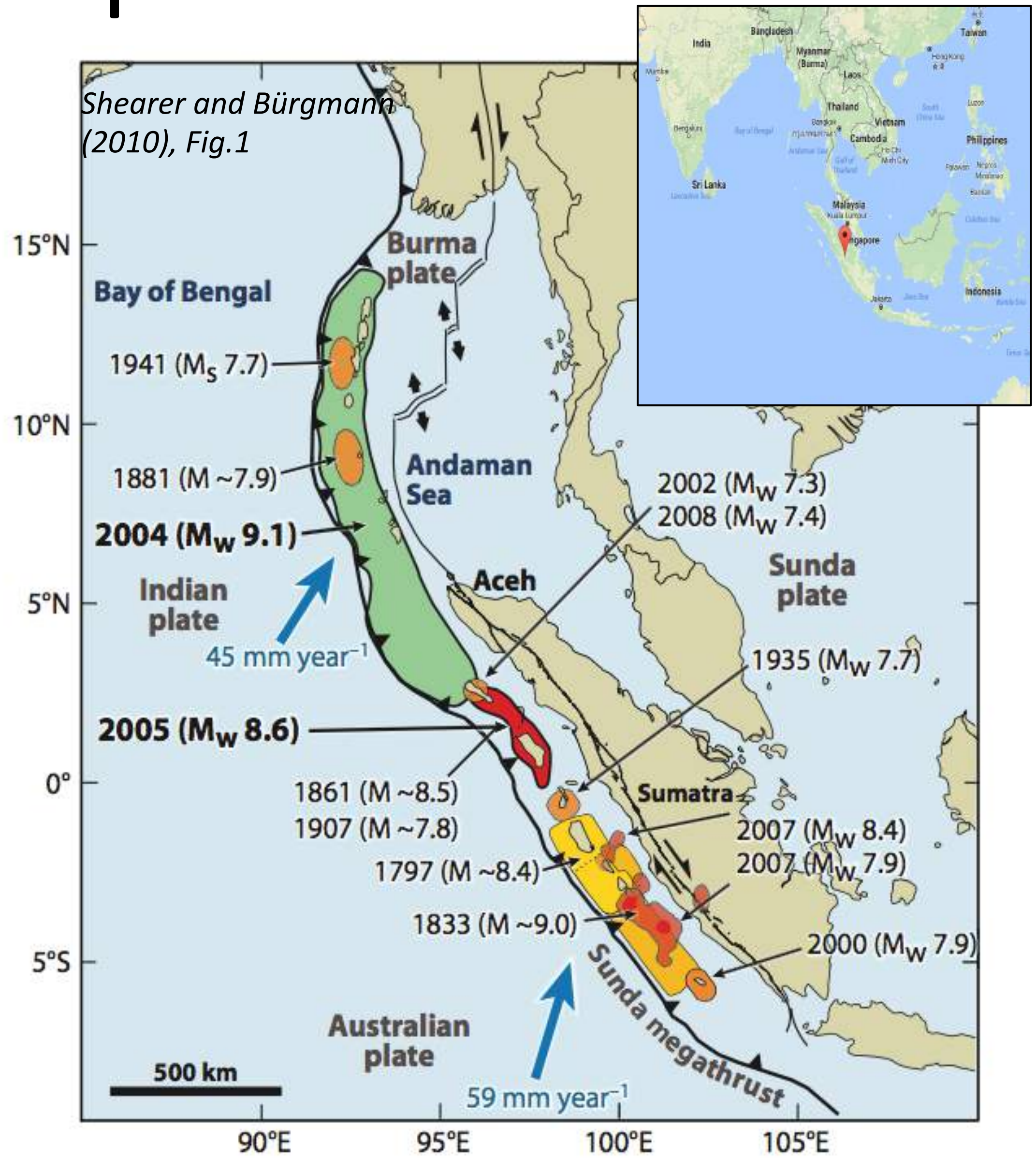
Earthquake models with SeisSol

- 2004 Sumatra earthquake
  - Influence of initial stresses on rupture dynamics of a megathrust earthquake on a complex fault
  - (Role of splay faults in seafloor displacement)

- Rough fault surfaces
- Off-fault plasticity
- SCEC benchmark Tpv35

2004 Sumatra-Andaman Earthquake

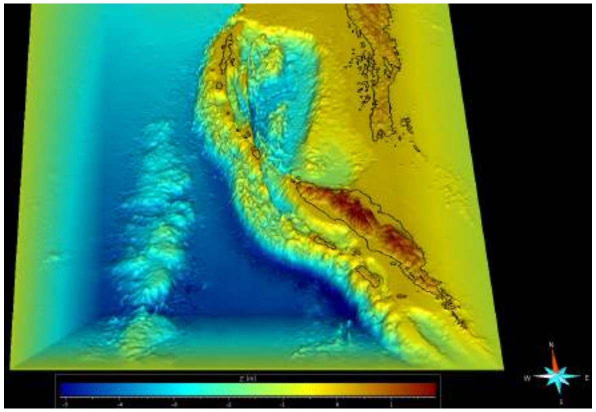
- Subduction zone:
  - Old oceanic crust
  - Slow convergence rates
- Earthquake
  - Long rupture length: 1300 to 1500 km
  - Slow rupture velocity: 2.5 km/s on average → *Shaking lasted 8 to 10 minutes*
  - Mw: 9.1 to 9.3 (depends on dip & material properties assumed)



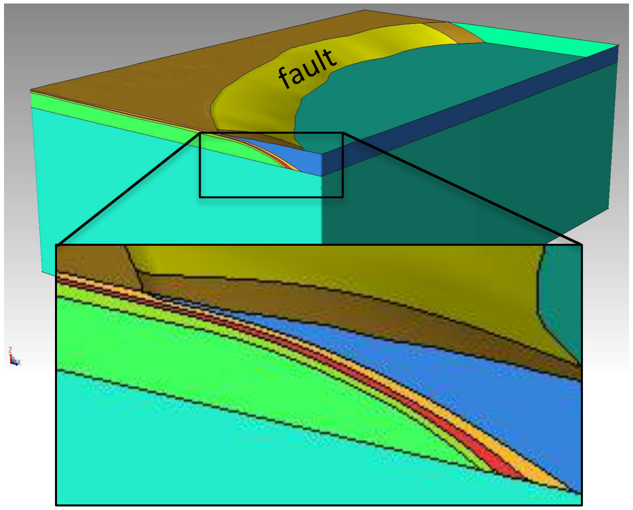
Shearer and Bürgmann (2010), Fig.1

Model input: Topo, materials, slab, stress

Topography/Bathymetry (GEBCO)
4 km resolution topography

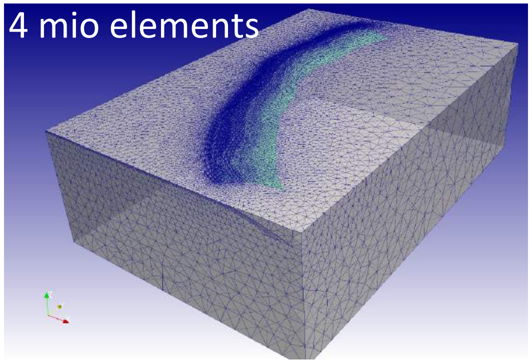


Layered material properties from "Crust 1.0" (Laske et al., 2013)

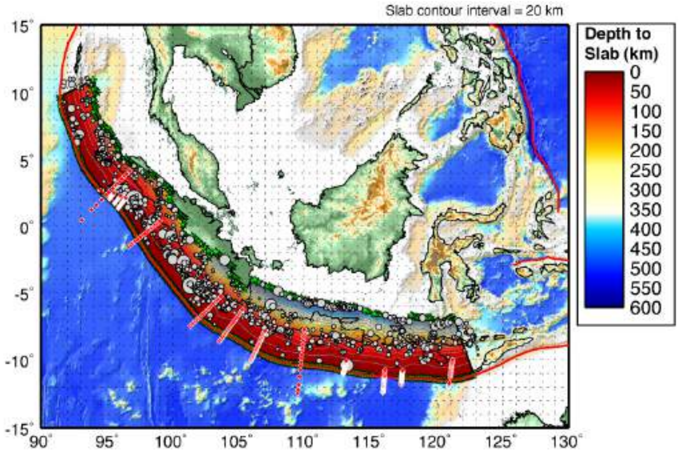


Meshed with SimModeler

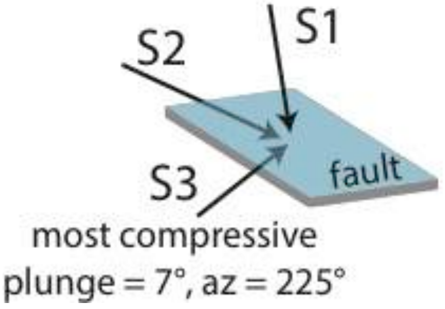
250 km off-fault
2.5 km on-fault
0.3 coarsening rate



3D slab geometry from "Slab 1.0"
(Hayes et al., 2012)



Homogeneous remote stress
Orientations from Karagianni et al., 2015: Focal mechanism inversion



$$S'(z) = \begin{bmatrix} S1 - Pf & & \\ & S2 - Pf & \\ & & S3 - Pf \end{bmatrix}$$

What do we know? Stress

Megathrust moment tensors (Hardebeck, 2015)

- Analysis of stacked events within 20 km of 9 megathrust interfaces
  - Angles between maximum compressive stress and megathrusts are optimal to moderate (30-60°)
  - Megathrust strength is similar to surrounding rock strength
  - Stress field rotates when large subduction zone earthquakes occur *(Hardebeck, 2012)*

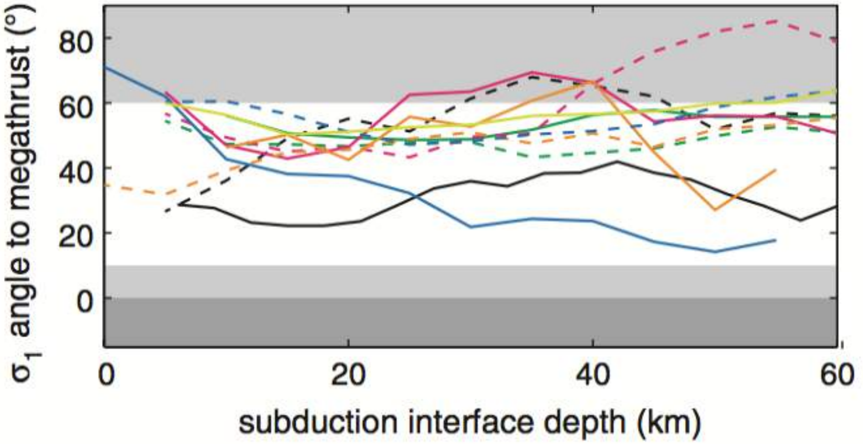
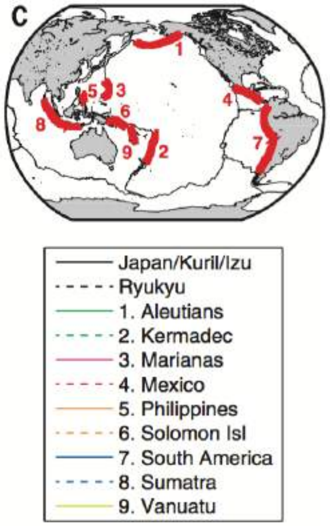


Fig.2B, C



- ➢ *Entire megathrust region is at low effective stress*
- ➢ *Megathrust supports only very low shear stresses*
- ➢ *Faults weakened by narrow zones of high fluid pressure or low friction coefficient*

What do we know? *Stress*

Drilling – Tohoku (Fulton et al., 2013)

- Japan Trench Fast Drilling Project installed a borehole temperature observatory
- Duration: 9 months, starting 16 months after M 9 earthquake
- Location: across fault near trench (slip ~50 m)

➢ Measured residual temperature gives:

- Effective shear stress, τ’ = 0.54 MPa
- Effective normal stress, σ’ = 7 MPa

(based on fault’s depth, hydrostatic pore pressure, measured densities)

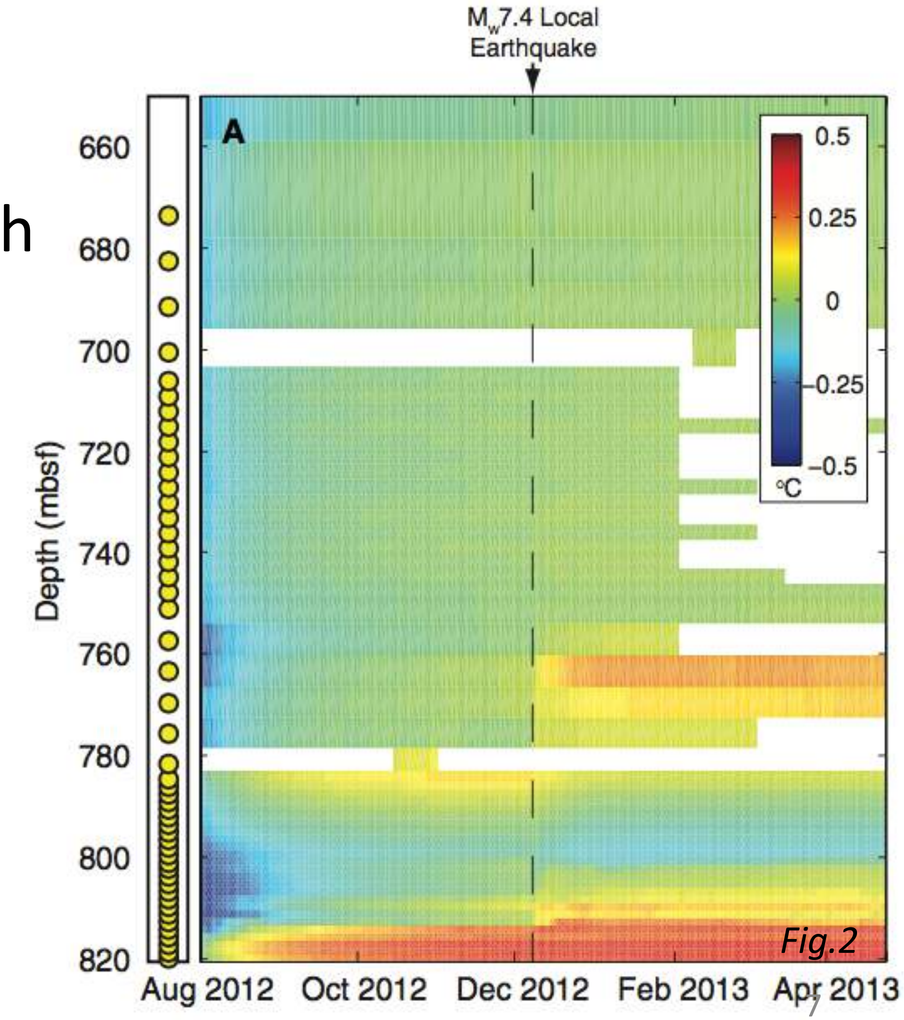


Fig.2

What do we know? *Fluid pressure*

*Pf @ subduction zones (**Husen & Kissling, 2001**; Audet et al, 2009)*

- Vp/Vs increases following the Antofagasta, Chile earthquake (M8, 30 July 1995)
  - Interseismic: high stress along subduction zone traps fluids in down-going plate, leading to high pore pressures along the megathrust - a "permeability barrier"
  - Postseismic: Vs in the overriding plate decreases as pore pressure increases due to arriving fluids that force cracks open
  - *"A pore pressure close to lithostatic pressure is needed to cause a significant increase in Vp/Vs (Eberhart-Phillips et al., 1989)."*

What do we know? *Fluid pressure*

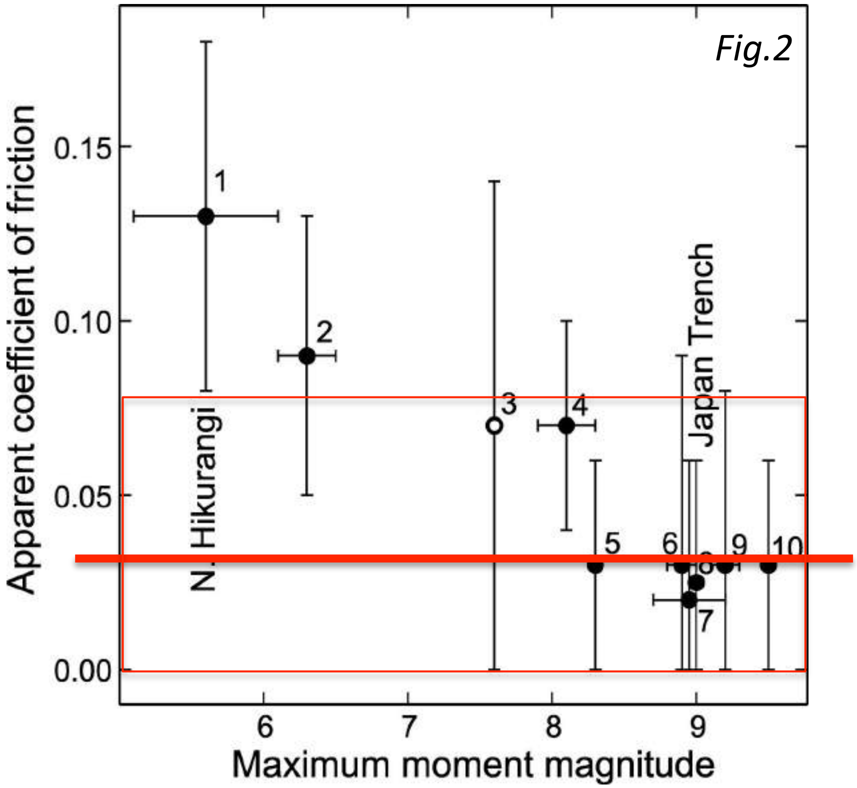
Pf @ subduction zones (Husen & Kissling, 2001; ***Audet et al, 2009****)*

- Tracking time evolution of Vp/Vs after Antofagasta, Chile earthquake (M8, 30 July 1995)
  - Interseismic: high stress along subduction zone traps fluids in down-going plate, leading to high pore pressures along the megathrust - a "permeability barrier"
  - Postseismic: Vs in the overriding plate decreases as pore pressure increases due to arriving fluids that force cracks open
  - *"A pore pressure close to lithostatic pressure is needed to cause a significant increase in Vp/Vs (Eberhart-Phillips et al., 1989)."*
- Anomalously high Poisson's ratio observed from receiver functions within subducted crust at Cascadia margin
  - High Vp/Vs ratio = high Poisson's ratio that does not match subduction zone lithology
  - Megathrust is a "low-permeability boundary"
  - *Poisson's ratio cannot be correlated precisely with pore fluid pressure b/c laboratory data is lacking, but extrapolation suggests lithostatic fluid pressures*

What do we know? *Sliding friction*

*(**Gao & Wang, 2014**; Fulton et al., 2013; DiToro et al., 2015)*

- Heat flow modeling: Most subduction zones that host megathrust earthquakes have effective friction < 0.1
  - Sumatra*:* μ’ = 0.03
  - Japan trench: μ’ = 0.025



What do we know? *Sliding friction*

(Gao & Wang, 2014; ***Fulton et al., 2013; DiToro et al., 2015****)*

- Heat flow modeling: Most subduction zones that host megathrust earthquakes have effective friction < 0.1
  - Sumatra*:* μ' = 0.03
  - Japan trench: μ' = 0.025
- Drilling @ Tohoku: Measured residual temperature suggests
  - Effective shear stress, τ = 0.54 MPa
  - Effective normal stress, σ = 7 MPa
  - ➢ Apparent coefficient of friction during sliding = μ = τ/σ ~ 0.08
    - 'Apparent': σ inferred from estimates of pore pressure and fault dip

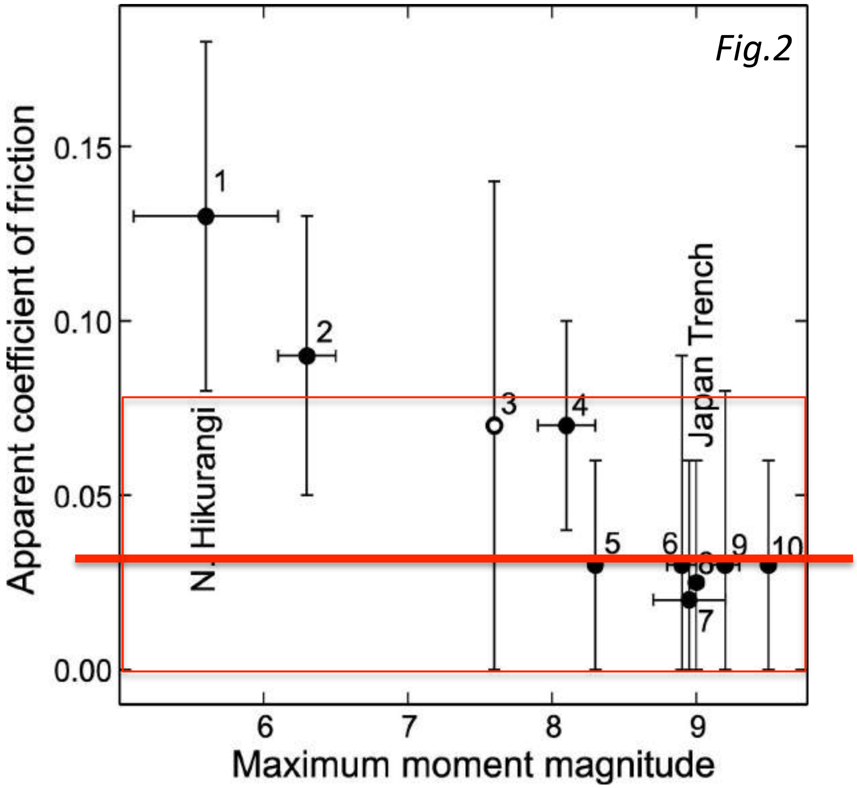


Fig.2

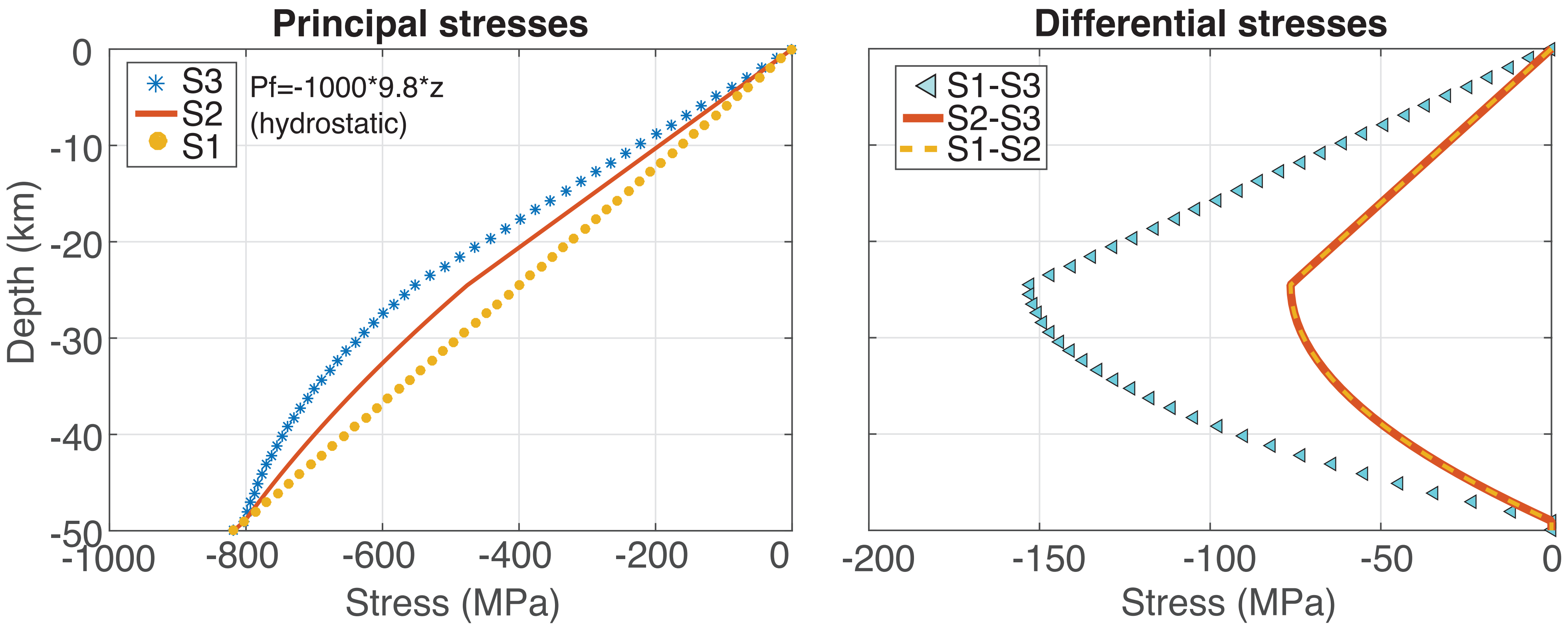
- DiToro et al. (2015): Experimental data @high slip rates, 7-15 km
  - 0.4 > μ > 0
  - friction coefficient decreases to ~10–30% of initial value during slip

Comparing 2 stress conditions

Model 1: Hydrostatic Pf

Moderate effective stress magnitudes

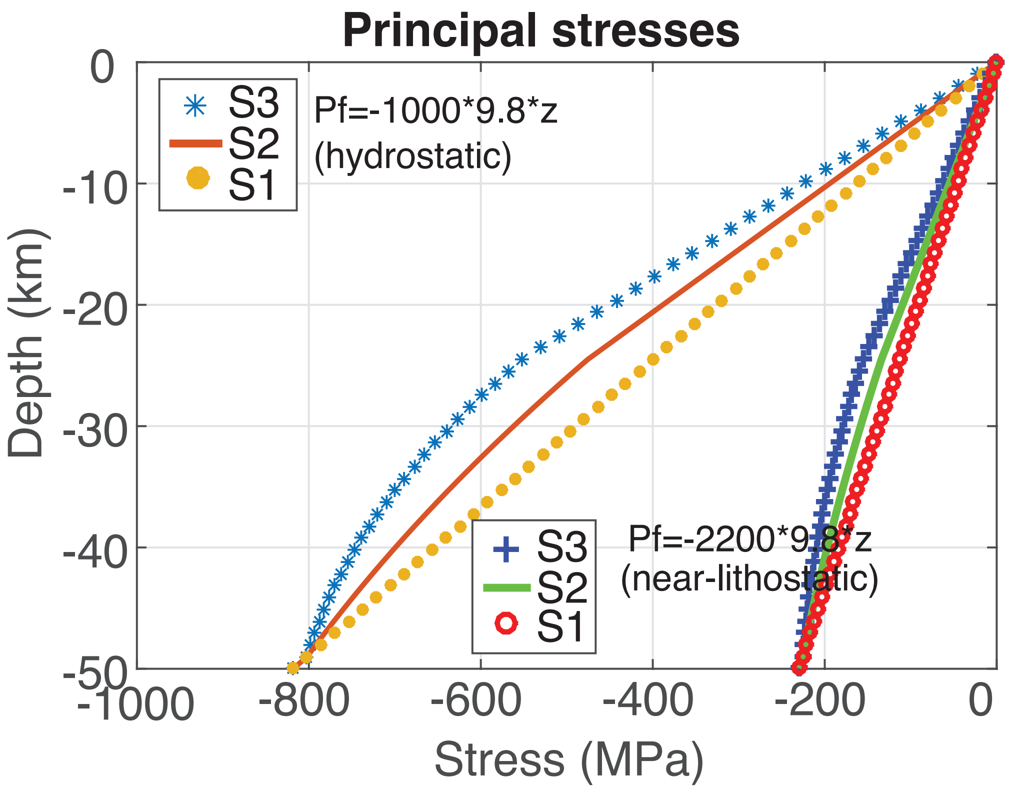
Moderate differential stress

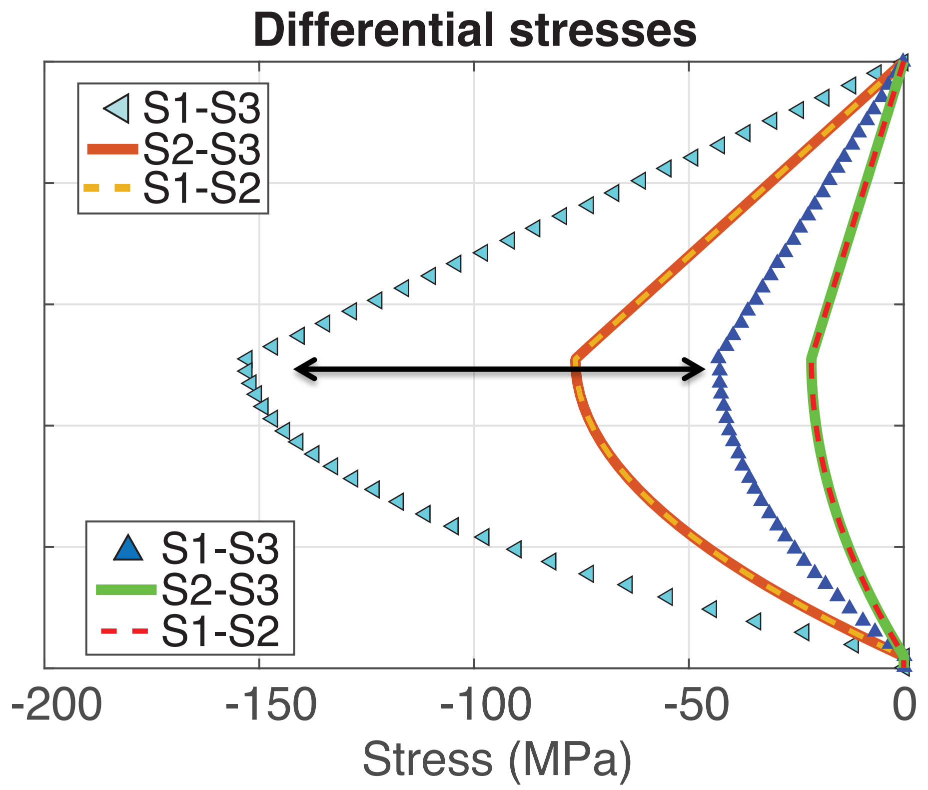


Comparing 2 stress conditions

Model 1: Hydrostatic Pf
High effective stress magnitudes
High differential stress (Sdiff)

Model 2: ~Lithostatic Pf
Low effective stress magnitudes
Low differential stress





Comparing 2 stress conditions

Model 1: Hydrostatic Pf

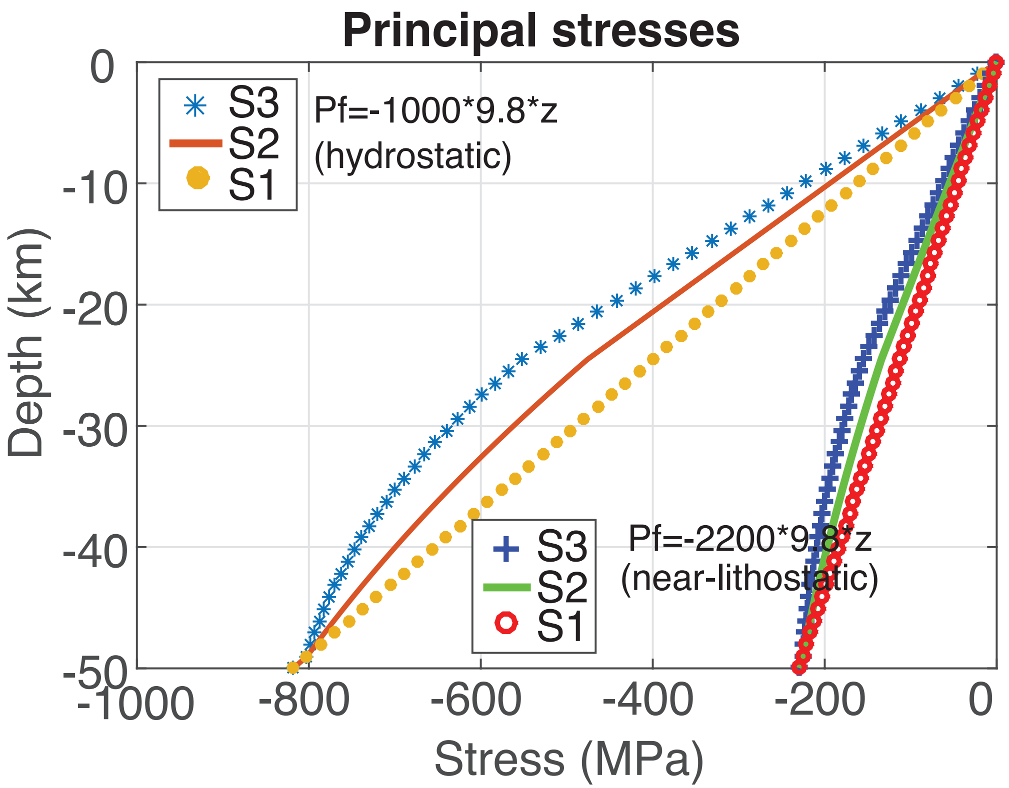
$\mu s = 0.16 \rightarrow \mu d = 0.09$

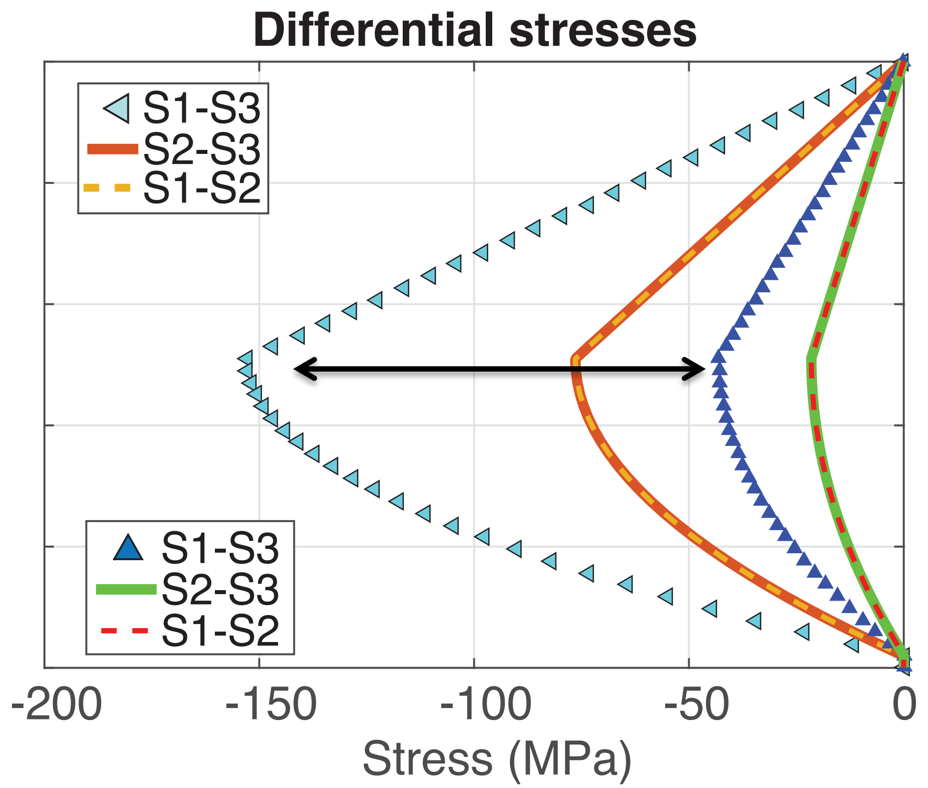
$\Delta\tau_{max}$ = 70 MPa (high)

Model 2: ~Lithostatic Pf

$\mu s = 0.14 \rightarrow \mu d = 0.08$

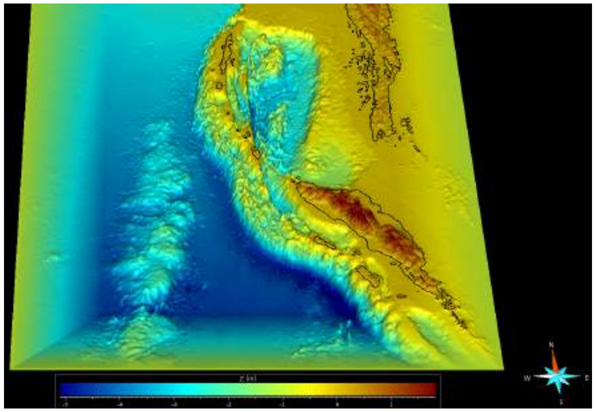
$\Delta\tau_{max}$ = 18 MPa (low)



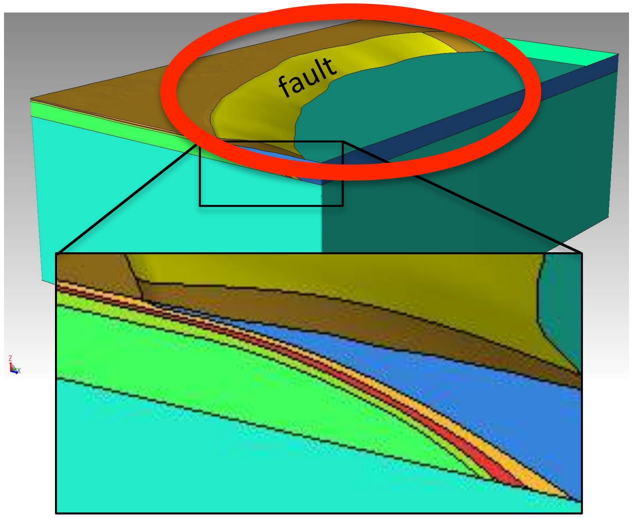


Model input: Topo, materials, slab, stress

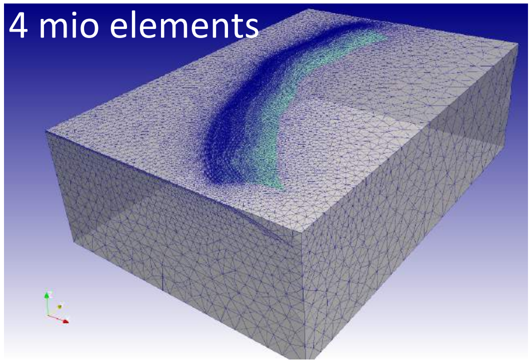
Topography/Bathymetry (GEBCO)
4 km resolution topography



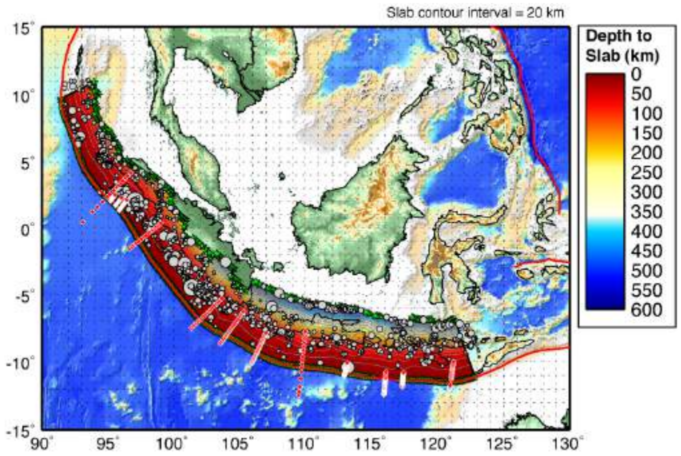
Layered material properties from "Crust 1.0" (Laske et al., 2013)



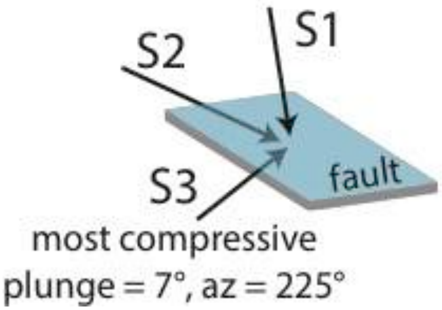
Meshed with SimModeler
250 km off-fault
2.5 km on-fault
0.3 coarsening rate



3D slab geometry from "Slab 1.0"
(Hayes et al., 2012)



Homogeneous remote stress
Orientations from Karagianni et al., 2015: Focal mechanism inversion



$$S'(z) = \begin{pmatrix} S1 - Pf & & \\ & S2 - Pf & \\ & & S3 - Pf \end{pmatrix}$$

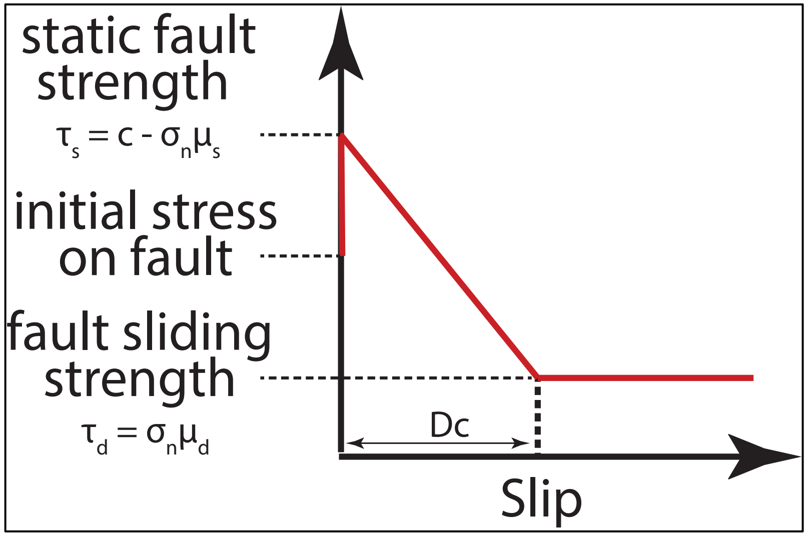
Earthquake!

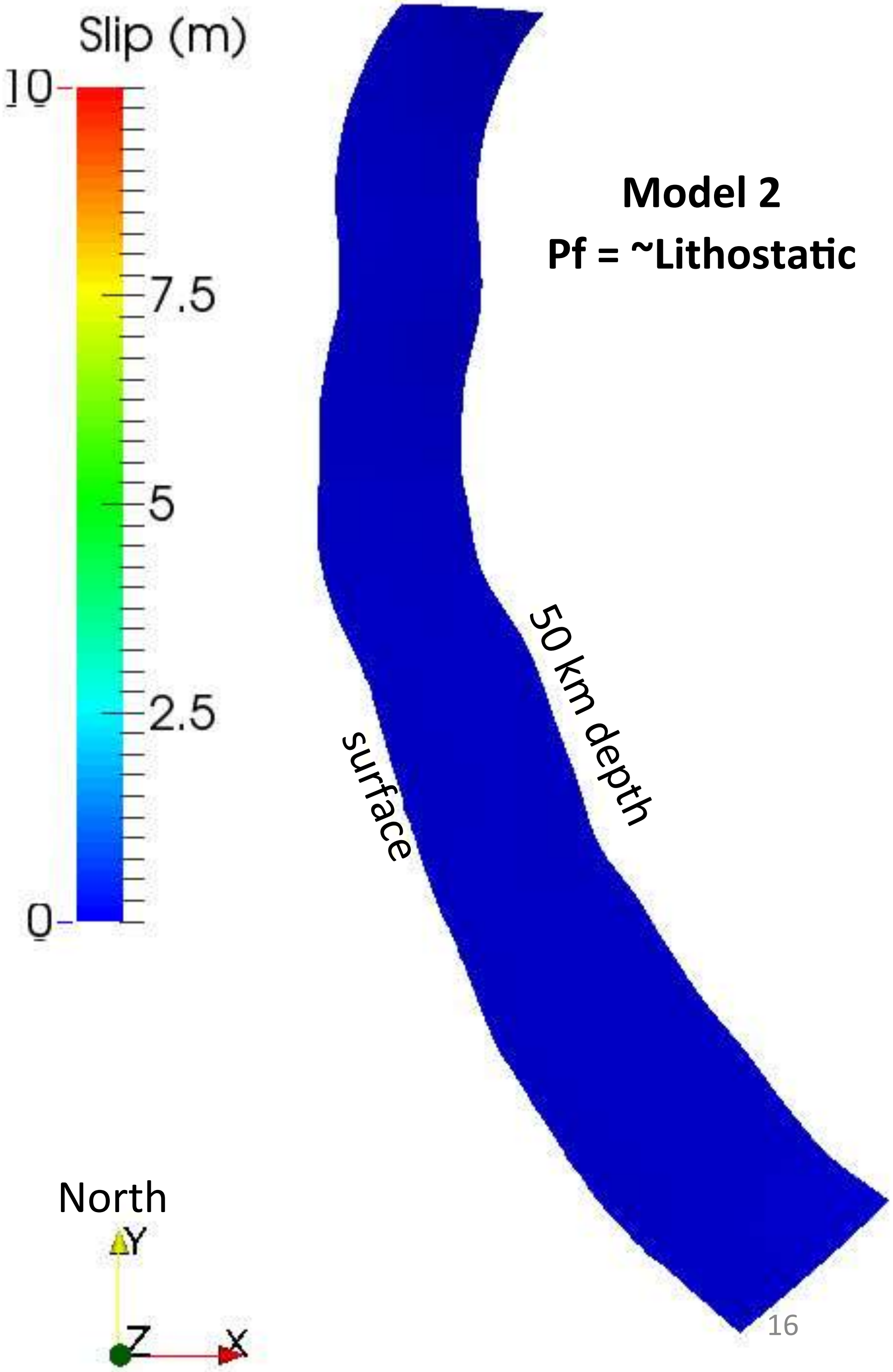
1. Forced nucleation (r = 12 km)
2. Spontaneous failure when

   $|\tau| > \text{cohesion} - \mu\sigma$

   σ: negative in compression

   cohesion = -0.4 MPa
3. Slip weakening: when slip reaches D_c = 0.8 m, μ drops



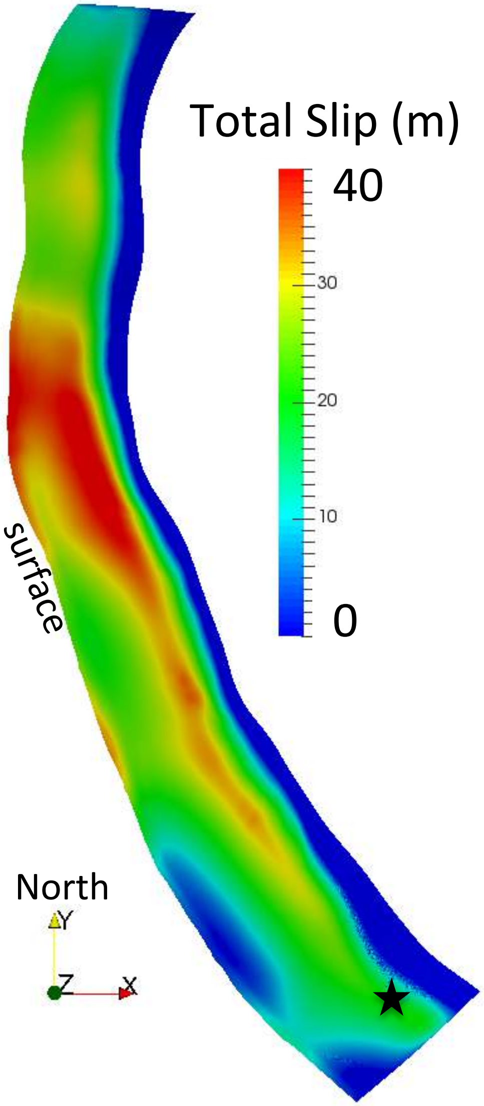


Model 2

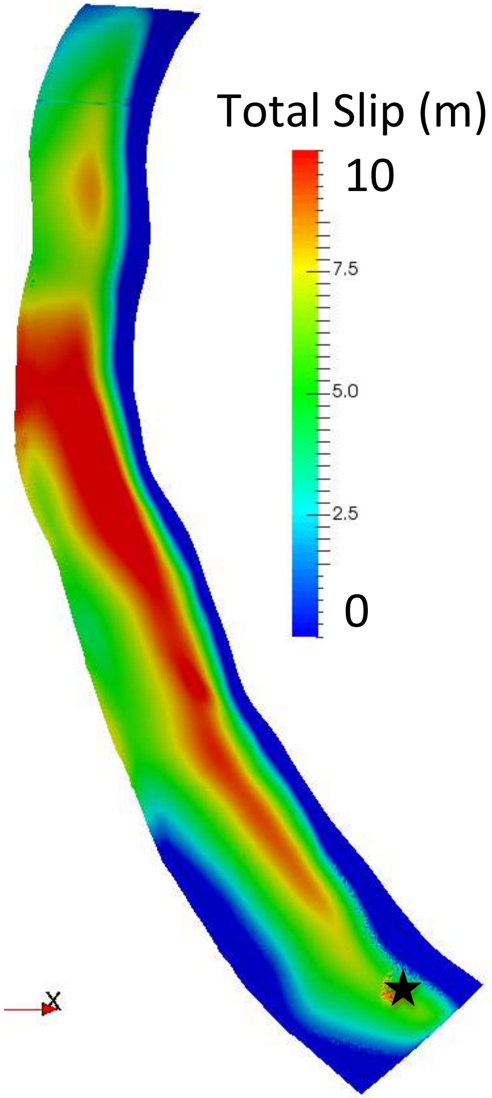
Pf = ~Lithostatic

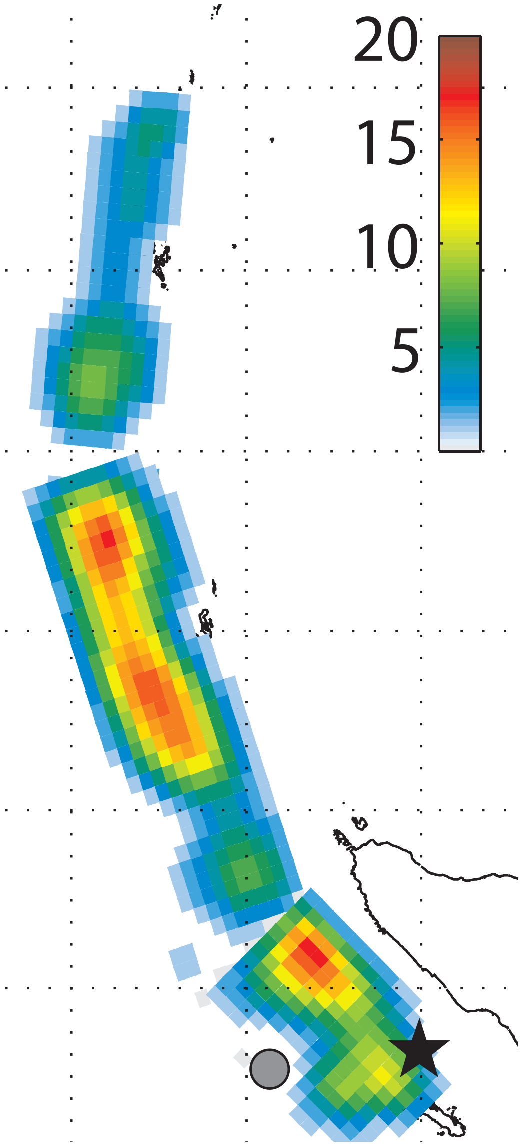
Final fault slip

Model 1: Pf = Hydrostatic



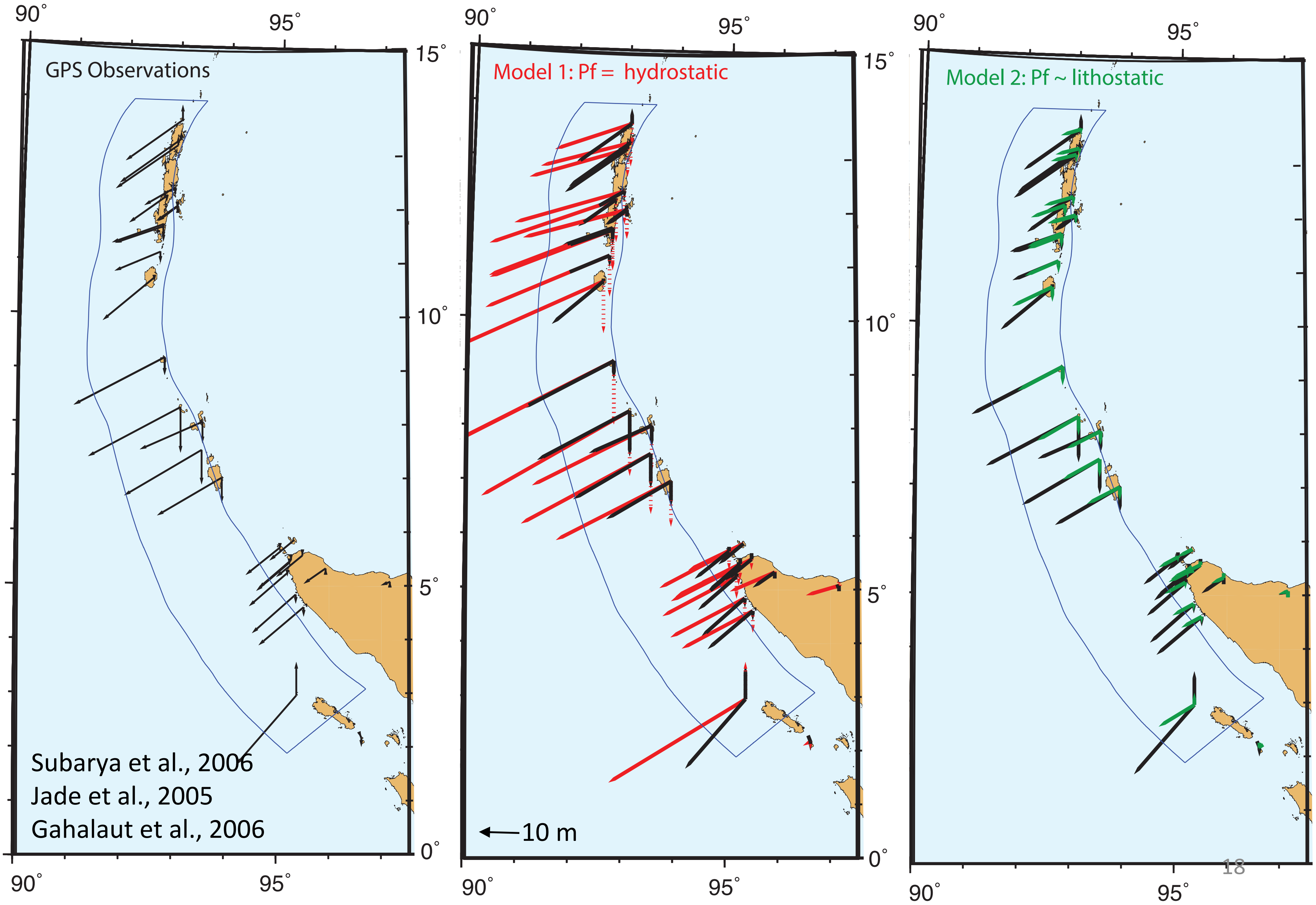
Model 2: Pf = ~Lithostatic





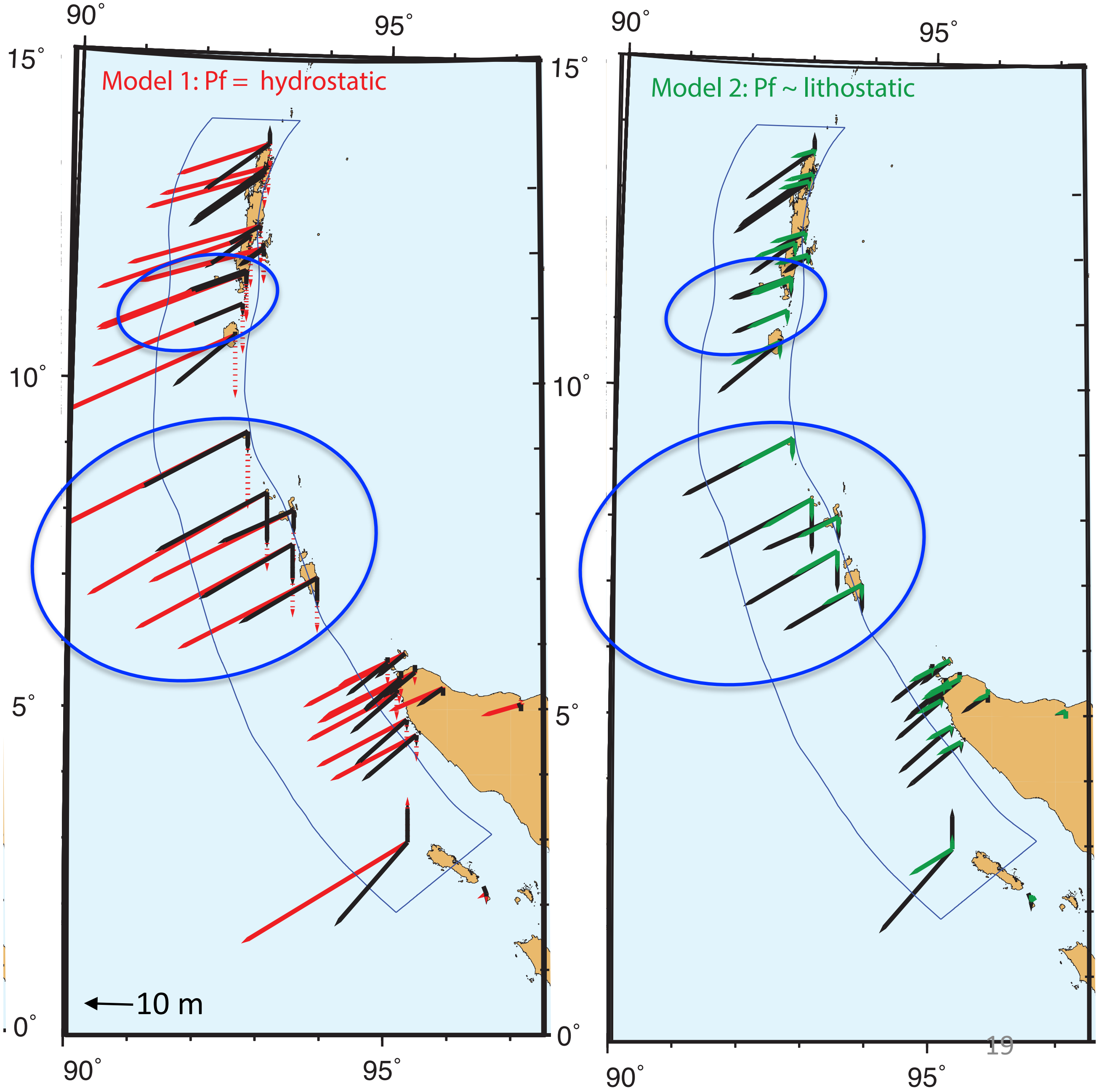
Chlieh et al. (2007)

Comparison with GPS



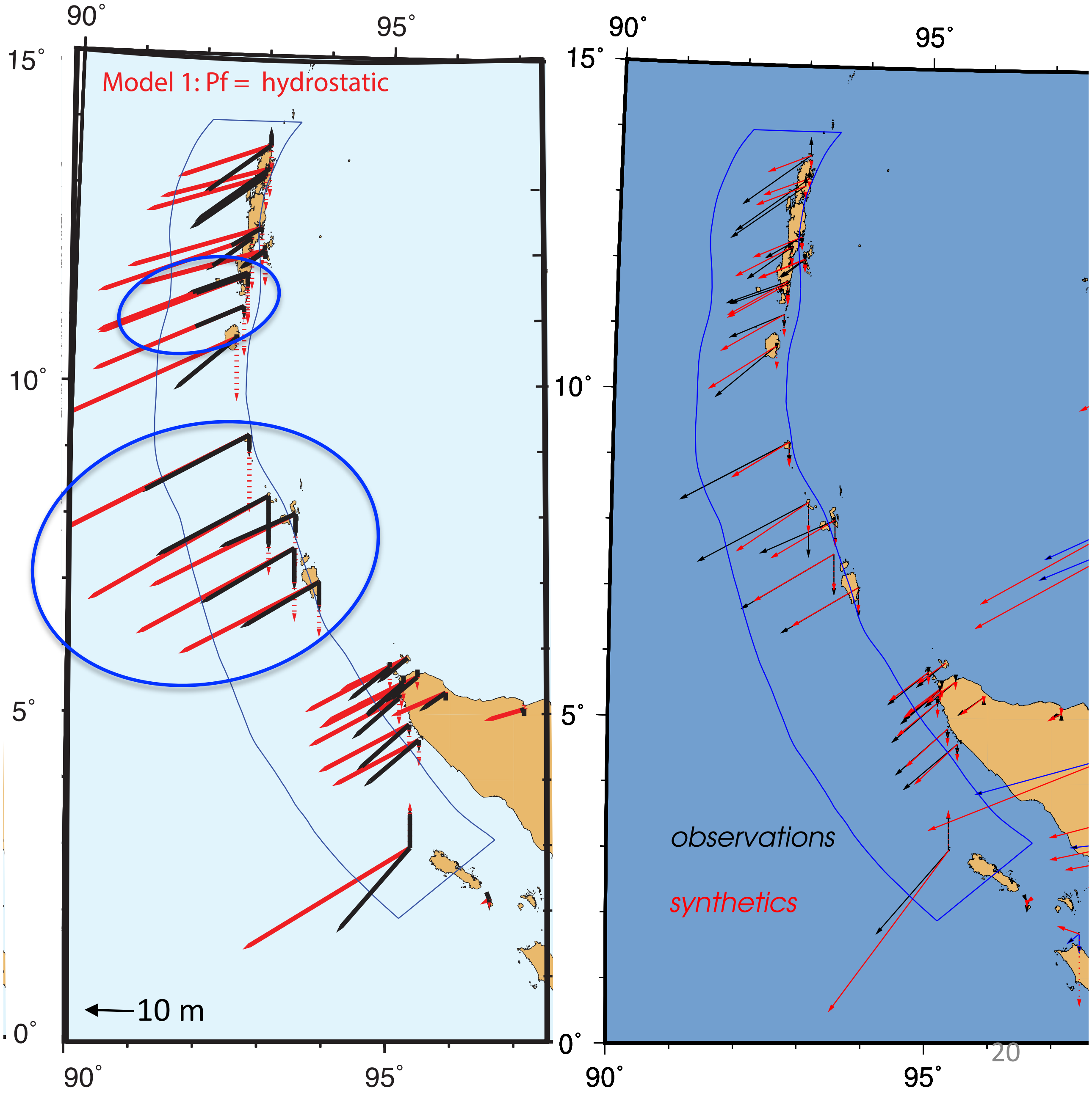
Comparison with GPS

- Models differ in magnitude only, not orientation
  - M1: too large
  - M2: too small
- Good fit to orientations along central and part of northern fault
- $P_{hydro} > Pf > P_{litho}$



Comparison with GPS

- Models differ in magnitude only, not orientation
  - M1: too large
  - M2: too small
- Good fit to orientations along central and part of northern fault
- $P_{hydro} > Pf > P_{litho}$
- Heterogeneous stress model (Ulrich)



Observation	Model 1: PF = Hydrostatic	Model 2: Pf ~Lithostatic
Final slip Max ~20 m	Too high 40 m	Too low? 12 m
GPS	Too large	Too small
	Orientations good in central and center-north parts of fault	Orientations good in central and center-north parts of fault
Avg. rupture velocity 2.5 km/sec (Ammon et al., 2005)	Too high 2.9 km/s	Too high 2.8 km/s
Magnitude M 9.1-9.3	Too large M 9.53	Within range M 9.15

Summary: *Influence of the stress field on the rupture dynamics of the 2004 M 9.2 Sumatra-Andaman EQ*

- Homogeneous remote stress field with orientation of max. compression from *Karagianni et al*. (2015) returns good surface displacement orientations relative to GPS, especially on central fault
- Dynamic friction is low, but could be even lower (0.03)
- Rule out hydrostatic pore pressure;
  - $P_{hydro} > Pf > P_{litho}$

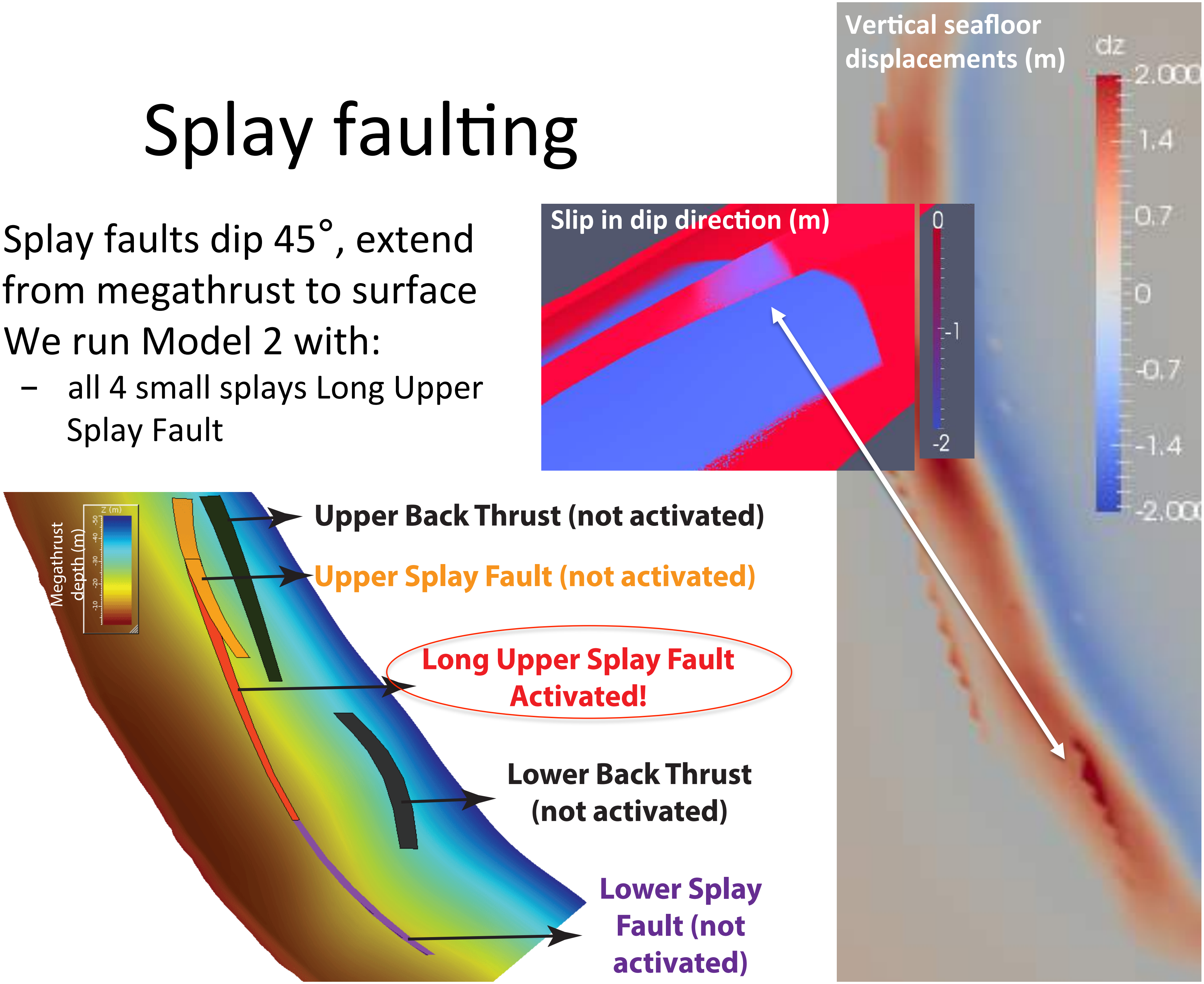
Summary: *Influence of the stress field on the rupture dynamics of the 2004 M 9.2 Sumatra-Andaman EQ*

- Homogeneous remote stress field with orientation of max. compression from *Karagianni et al*. (2015) returns good surface displacement orientations relative to GPS, especially on central fault
- Dynamic friction is low, but could be even lower (0.03)
- Rule out hydrostatic pore pressure;
  - ➢ $P_{hydro} > Pf > P_{litho}$

- M1 and M2 suggest that Sdiff and/or stress drop (effective stress mags) control rupture dynamics:
  - – M1: Pf = hydro, high Sdiff, high τ' σ'
    → *high slip, fast rupture, high stress drop, M 9.53*
  - – M2: Pf = litho, low Sdiff, low τ' σ'
    → *low slip, slow**er** rupture, moderate stress drop, M 9.15*

Splay faulting

- Splay faults dip 45°, extend from megathrust to surface
- We run Model 2 with:
  - all 4 small splays Long Upper Splay Fault



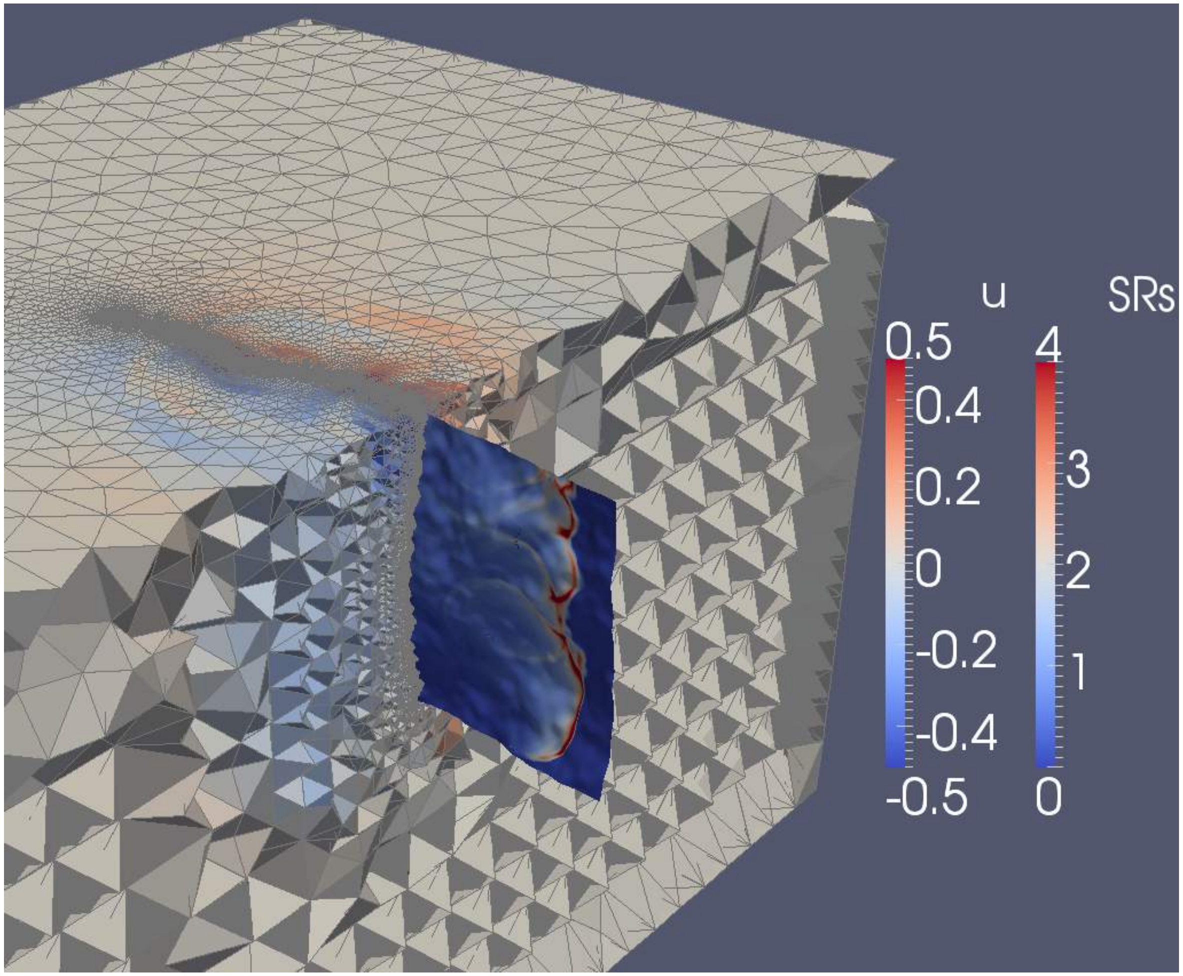
Earthquake models with SeisSol

- 2004 Sumatra megathrust earthquake
  - Influence of initial stresses & fluid pressure on rupture dynamics
  - Role of splay faults in seafloor displacement

- Rough fault surfaces
- Off-fault plasticity
- SCEC benchmark Tpv35

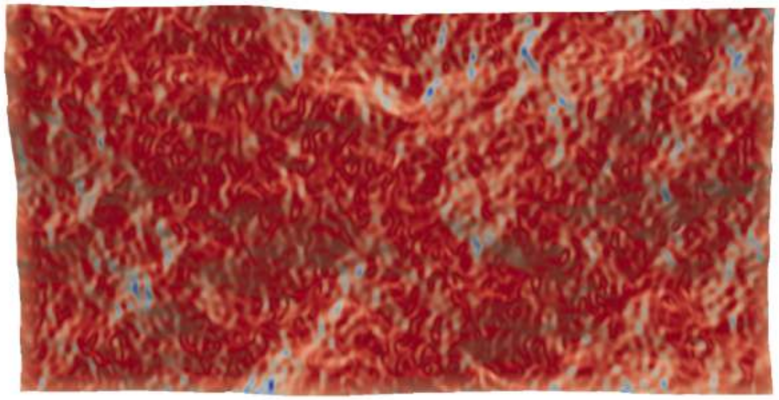
Rough faults (Ulrich & Gabriel, AGU 2016)

- Tetrahedral meshes
  - *Straight forward mesh generation with SimModeler*
- Mesh adaptivity
  - *Refined mesh on and around fault*
- Tetrahedrons are not curved, so:
  - *Finer resolution required to achieve smoothly varying surfaces*

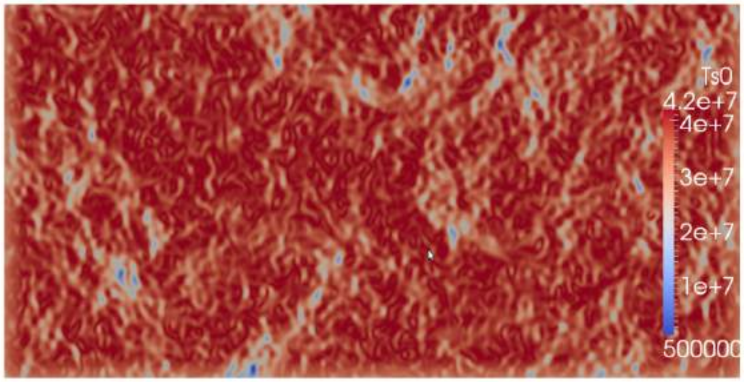


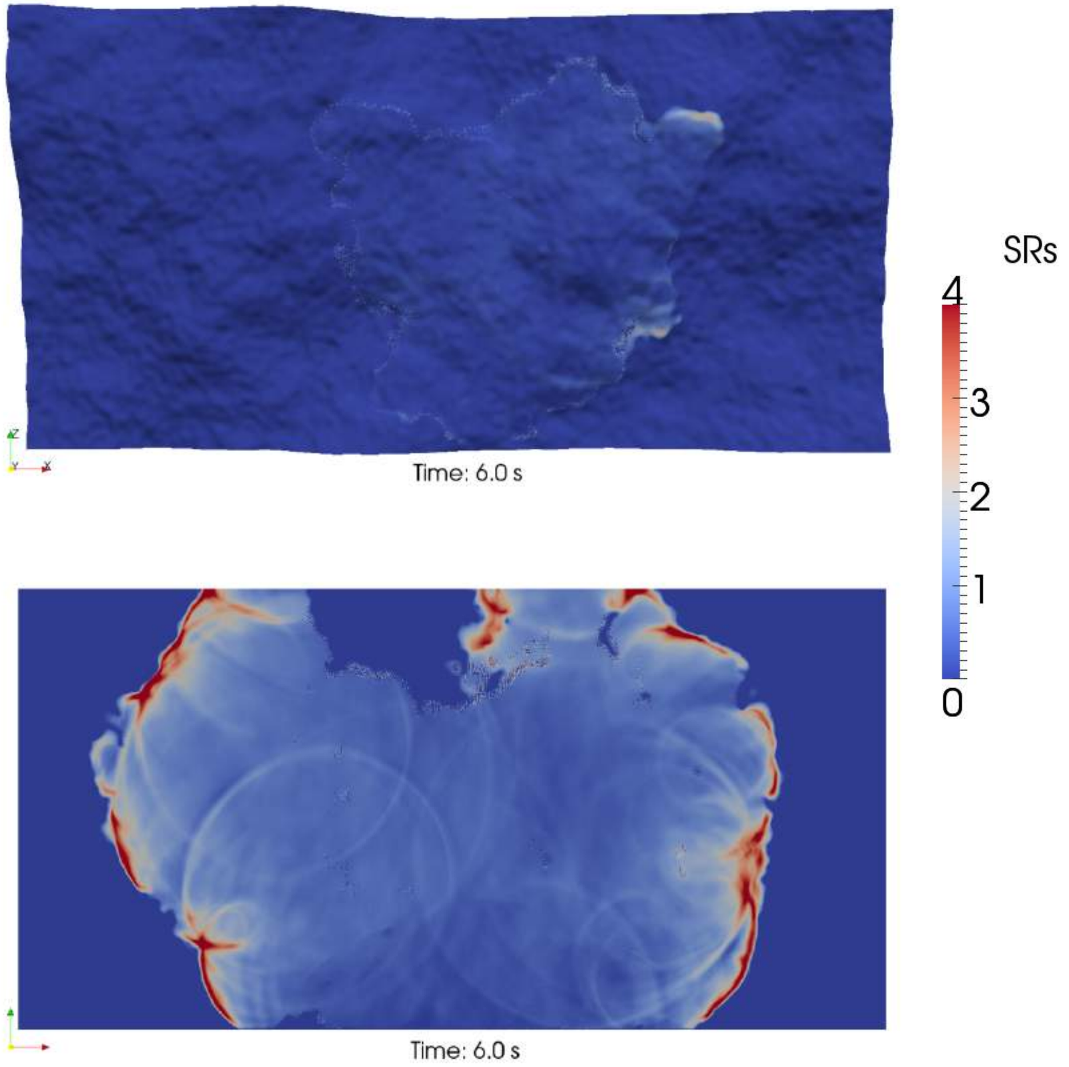
Heterogeneous stress mapping: an imperfect proxy

Modelled geometry



Projected stress on planar fault

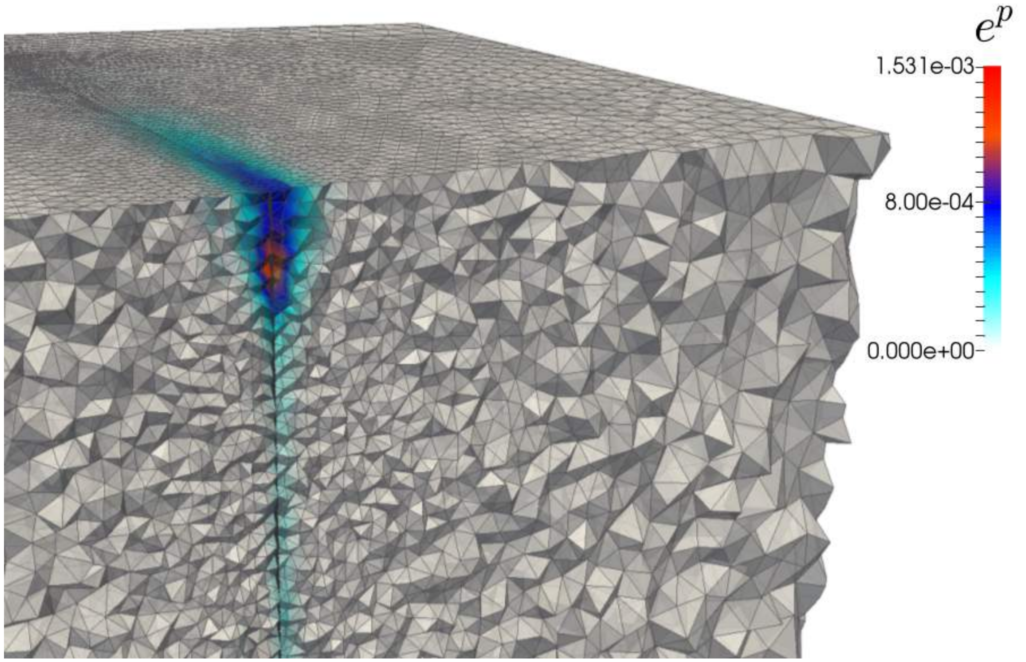




- *Variable Dc accounts for variability due to 3D geometry*

Off-fault plasticity (Wollherr & Gabriel, AGU 2016)

- Incorporation of Drucker-Prager plasticity
- Verified by benchmark TPV27 (strike-slip fault) and TPV13 (dipping fault)



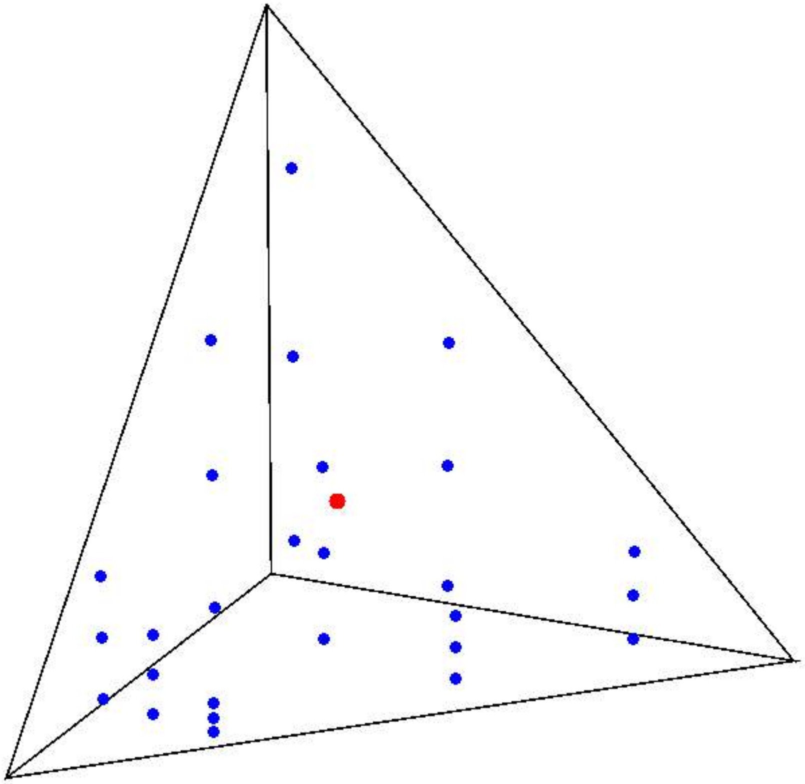
Accumulated plastic strain around the fault, TPV27

- 3D on-fault convergence tests for depth-dependent initial stresses
- Currently in use for large-scale scenarios including models of the 1992 Landers and 2004 Sumatra earthquakes

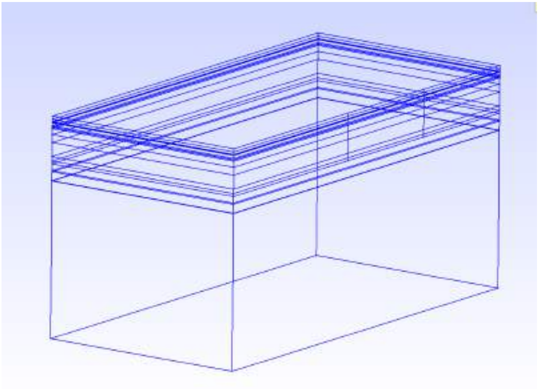
Off-fault plasticity (Wollherr & Gabriel, AGU 2016)

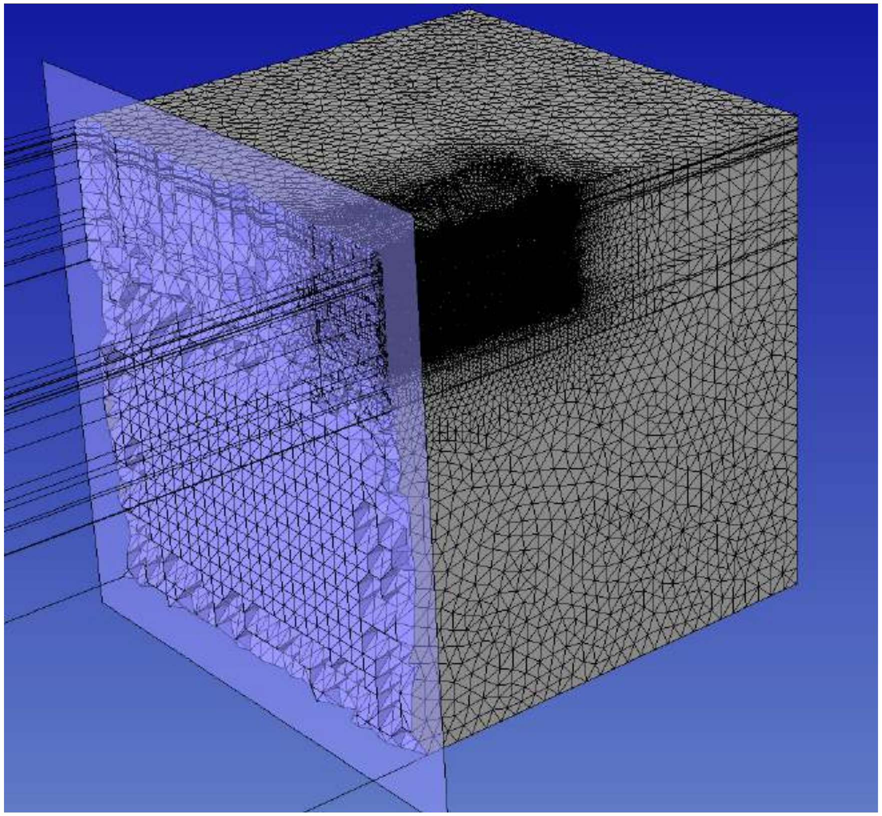
Two approaches for a modal DG method:

- Average approach: yielding checked with average stresses in each element
  - very high mesh resolution needed around the fault
- Integration points (IP) approach: yielding checked at integration points inside each element
  - faster convergence
  - more expensive relative to average approach
  - ➢ *After optimization using a code generator, IP approach is only 35-50 % more expensive relative to elastic case*



Tpv35: Parkfield M6 earthquake





- Fault is a bimaterial interface.
  - No regularization needed.
- Order 5
- Mesh → 4mio elements:
  - Resolution:
    - 200m on fault
    - 0.15 coarsening
    - 600m in a 30 km wide box around fault
  - Many layered model was more complex to mesh with coarsening than expected (no luck with open-source gmsh, SimModeler worked)

Earthquake dynamics with SeisSol: Megathrust ruptures, off-fault plasticity and rough faults

Elizabeth.Madden@LMU.de

- 2004 Sumatra EQ: *Influence of the stress field on rupture dynamics*
  - Karagianni et al. (2015) homogeneous stress orientation returns good surface displacement orientations relative to GPS, especially on central fault
  - Dynamic friction is low, but could be even lower (0.03)
  - $P_{hydro} > Pf > P_{litho}$
  - Sdiff and/or stress drop control megathrust rupture dynamics:
    - M1: P_{hydro}, high Sdiff, high stress drop, large slip, fast rupture, M 9.53
    - M2: P_{litho}, low Sdiff, moderate stress drop, low slip, slower rupture, M 9.15
  - Role of splay fault(s) & influence of rupture dynamics on tsunami generation
- Off-fault plasticity *(S. Wollherr, A.-A. Gabriel)*
  - Verified and in-use for large-scale earthquake rupture scenarios
  - Integration points relative to average approach can use a lower resolution mesh and has faster convergence, but is more expensive
- Rough faults *(T. Ulrich, A.-A. Gabriel)*
  - Rquires fine mesh discretization to limit sharp edges on the fault
  - Heterogeneous stress mapping is an imperfect proxy for modelling dynamic rupture along a rough fault