Stochastic slip distributions on non-planar faults described by unstructured mesh

S. Murphy, Ifremer
A. Herrero, INGV

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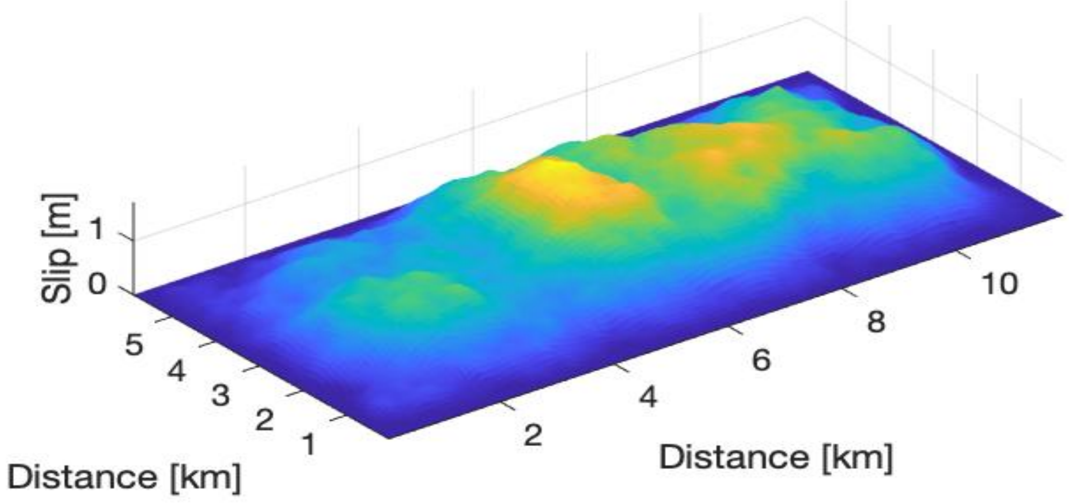
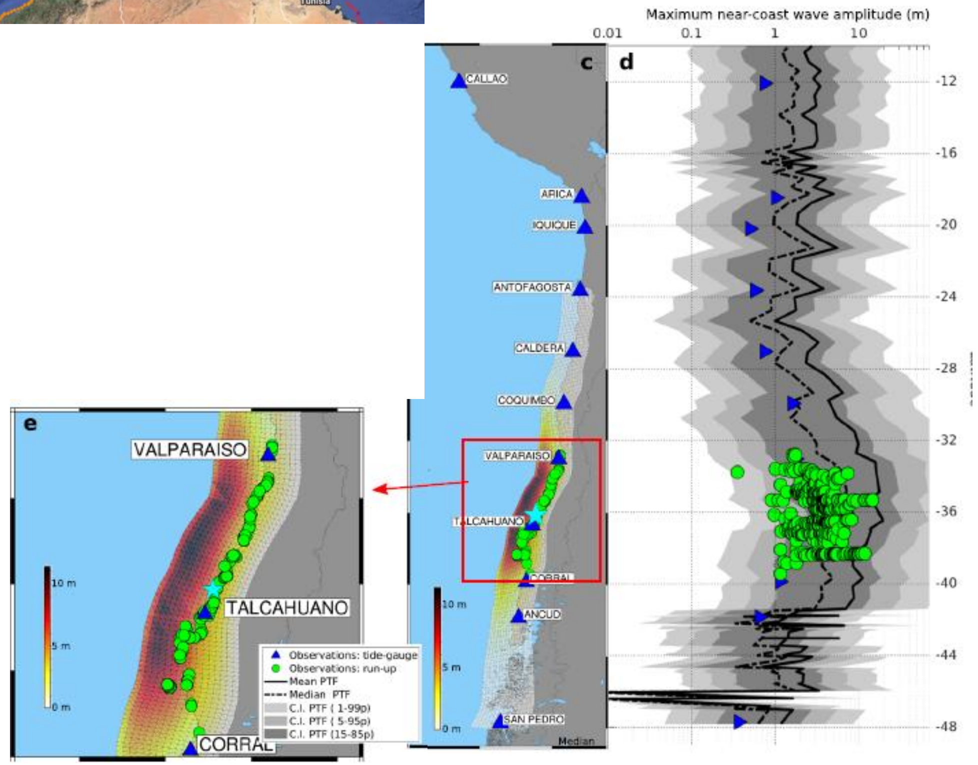
Motivation

Produce rapid stochastic slip distributions containing information from observations

Use in : kinematic slip inversion
hazard assessment
tsunami forecasting



TSUMAPS-NEAM:
tsumaps-neam.eu

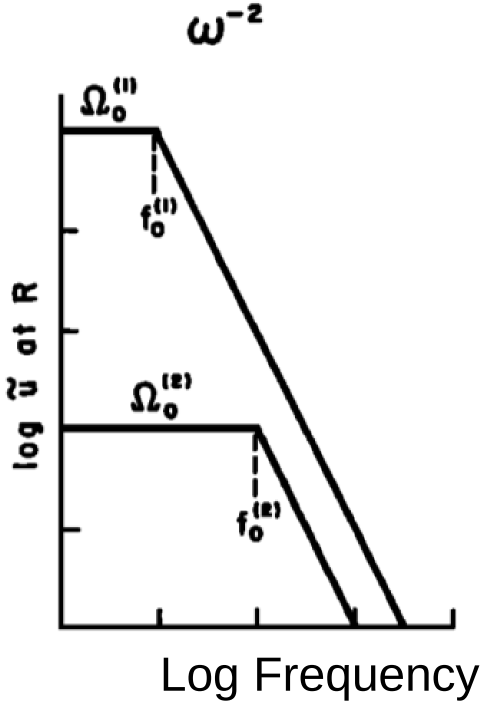


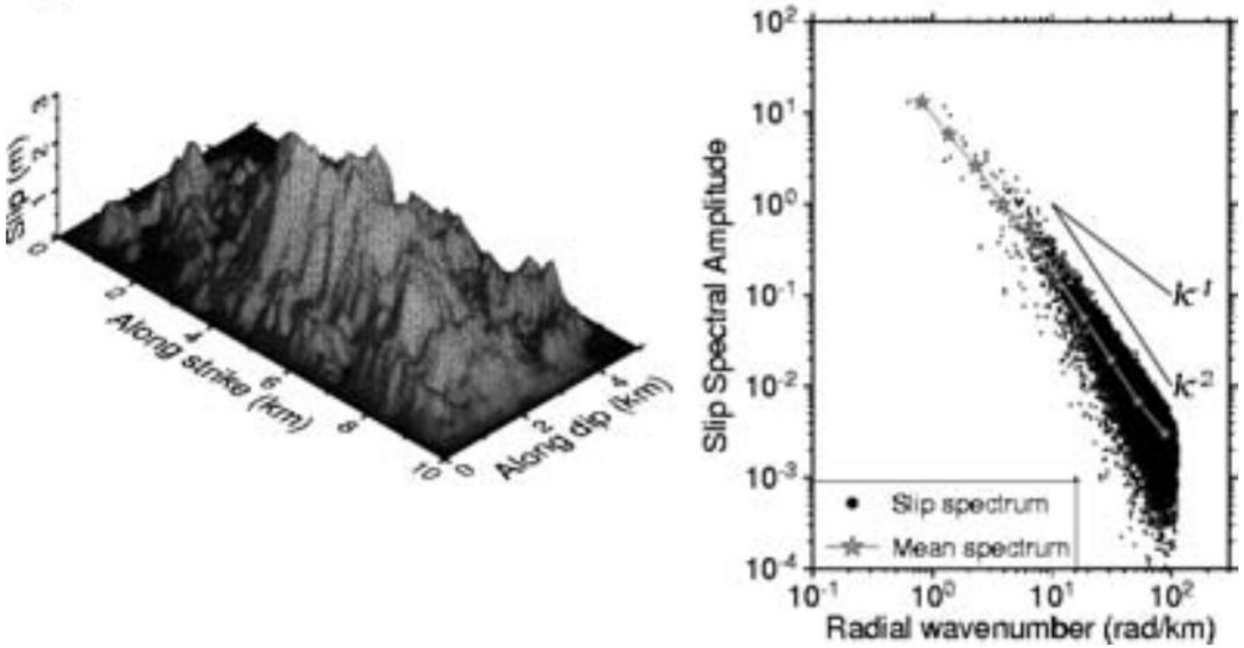
Selva et al., 2021

Why power law slip distributions?

Power law scaling of ground motion can be interpreted as being a feature of a k^{-2} slip spectra

$$\tilde{\Delta u}_L(k) = C\,\frac{\Delta\sigma}{\mu}\,\frac{L}{k^2},$$





VOL. 84, NO. B5 JOURNAL OF GEOPHYSICAL RESEARCH MAY 10, 1979

b Values and $\omega^{-\gamma}$ Seismic Source Models: Implications for Tectonic Stress Variations Along Active Crustal Fault Zones and the Estimation of High-Frequency Strong Ground Motion

THOMAS C. HANKS

U.S. Geological Survey, Menlo Park, California 94025

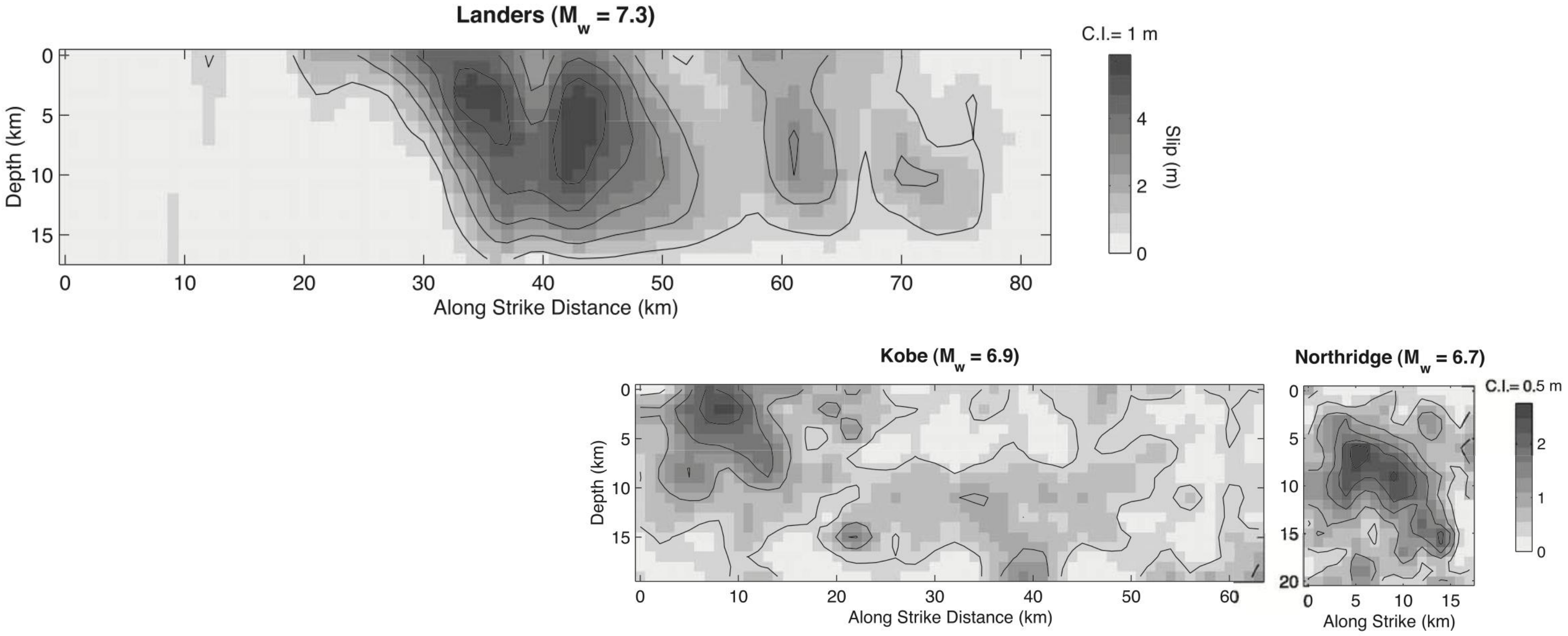
Bulletin of the Seismological Society of America, Vol. 84, No. 4, pp. 1216–1228, August 1994

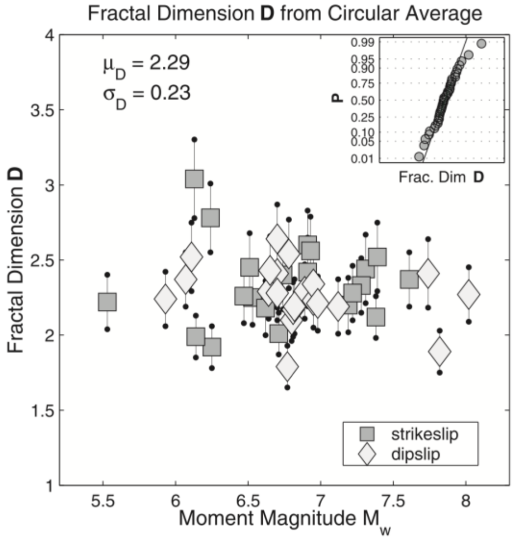
A Kinematic Self-Similar Rupture Process for Earthquakes

by A. Herrero and P. Bernard

Similar v self-affine slip

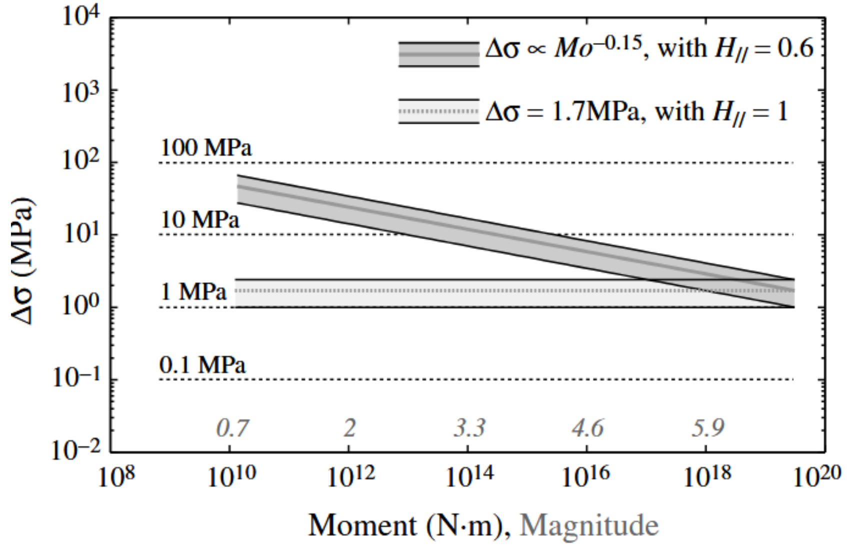
Statistical analysis suggests self-affine rather than self-similar

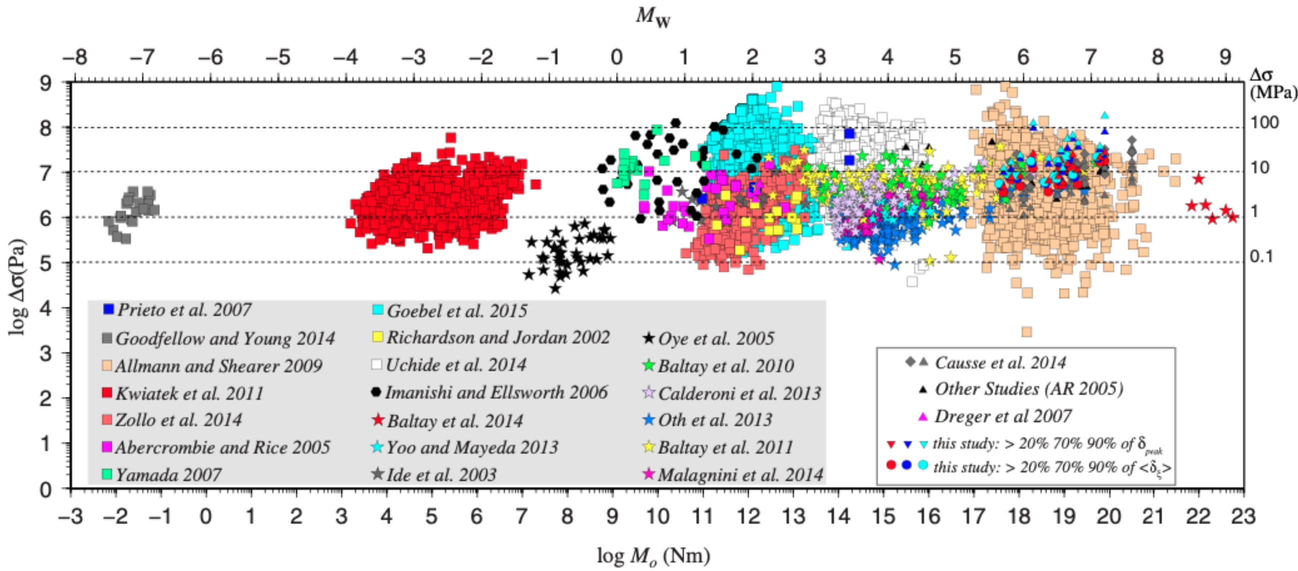




Mai and Beroza, 2002

Candela et al, 2011

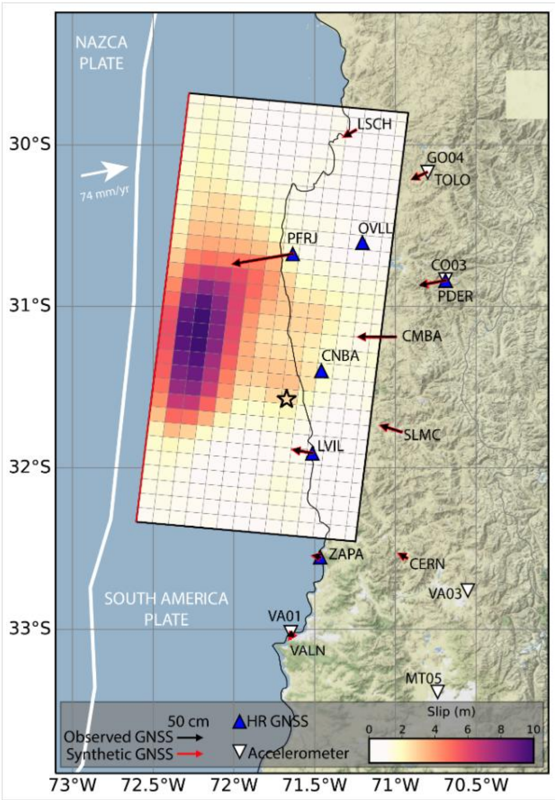




Cocco et al, 2016

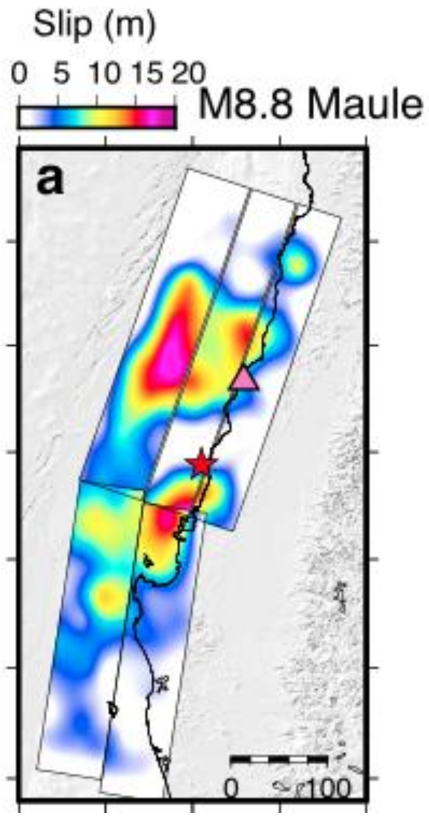
Description of fault surface

Hetergeneous Planar Fault



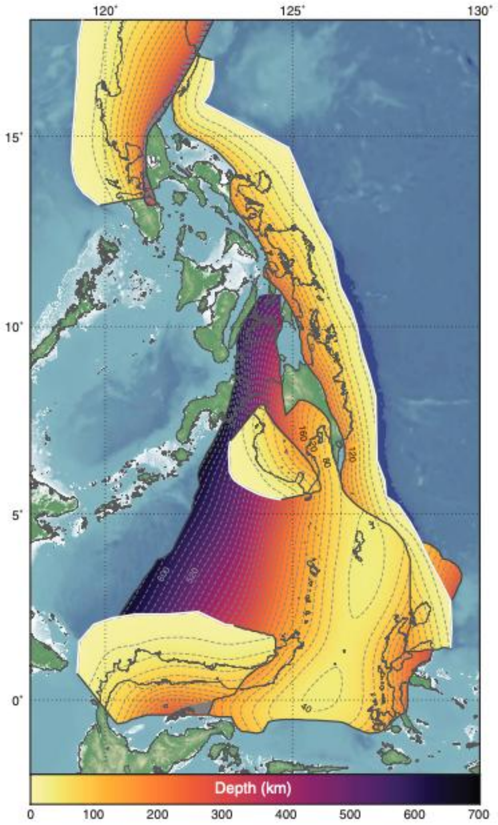
Goldberg et al. 2022

Multi-planar faults



Melgar and Hayes, 2018

Hetergeneous Non-Planar Fault

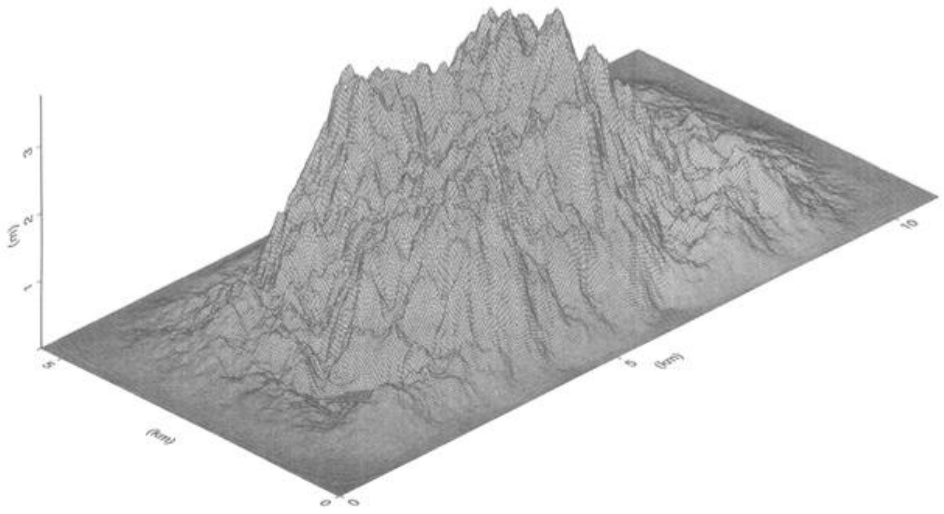


Slab 2.0 (Hayes,2018)

Generating stochastic slip distributions

Fourier Domain

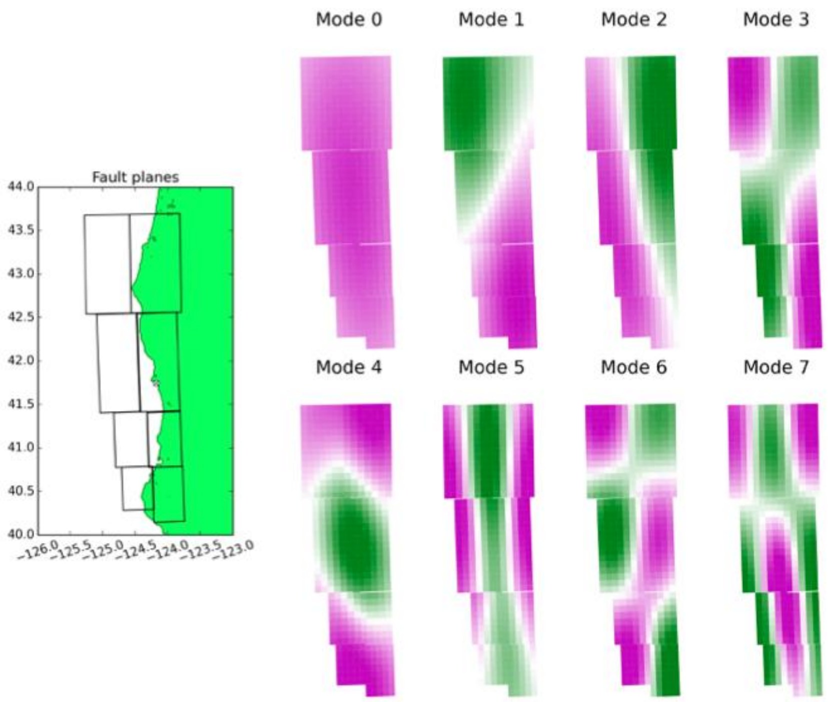
$$\tilde{\Delta u}_L(k) = C\,\frac{\Delta\sigma}{\mu}\,\frac{L}{k^2}$$



Herrero and Bernard, 1994

Karhunen-Loève Expansion

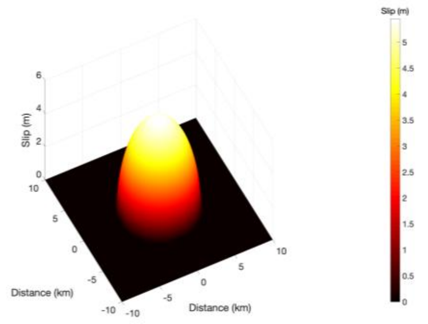
$$\boldsymbol{s} = \boldsymbol{\mu} + \sum_{k=1}^{N} z_k \sqrt{\lambda_k}\,\boldsymbol{v}_k.$$



LeVeque et al., 2016

Composite Source Model

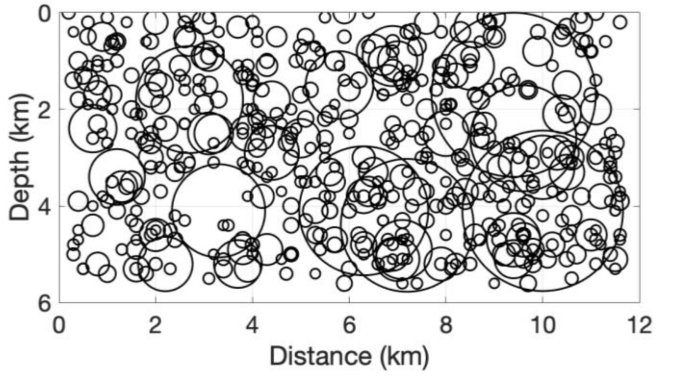
Subevent of slip

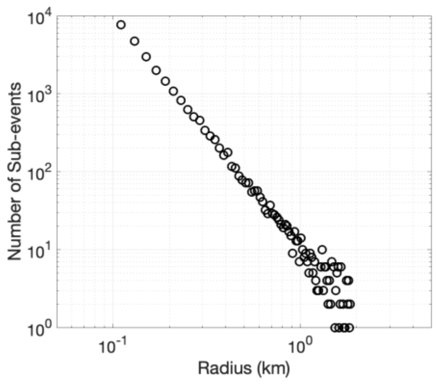


$$u(r) = \frac{24}{7\pi}\frac{\Delta\sigma}{\mu}\sqrt{R^2 - r^2} \qquad r < R$$

Ruiz et al. 2011;

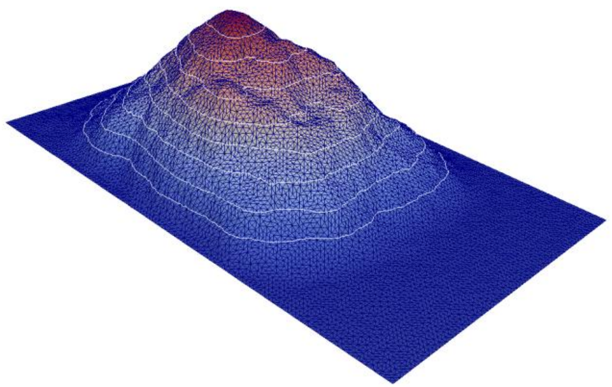
Distibution of subevents

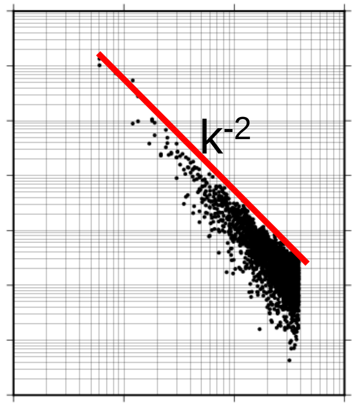




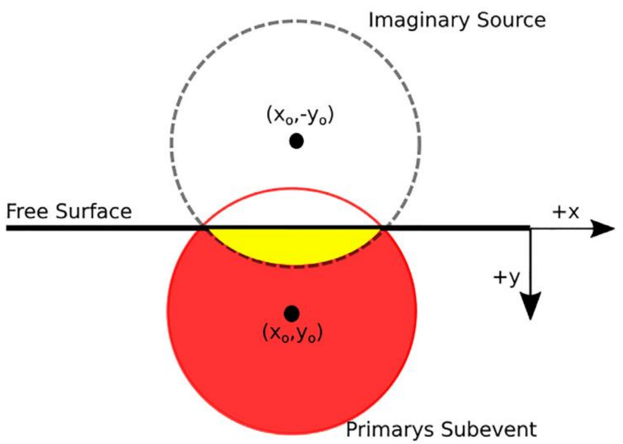
Zeng et al. 1994

Summation of subevents

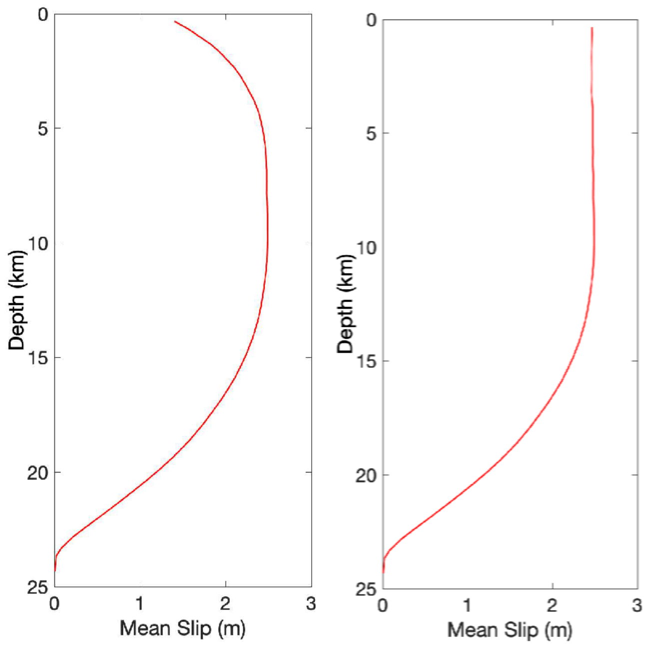




Better accounting for surface rupture

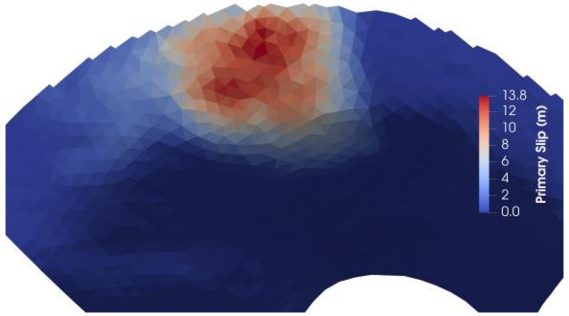


- Slip near surface decreases in standard model
- ‘Reflect’ slip patches back onto fault
- Removes depth dependance of slip near surface



Murphy and Herrero, 2020

Primary Slip Contribution



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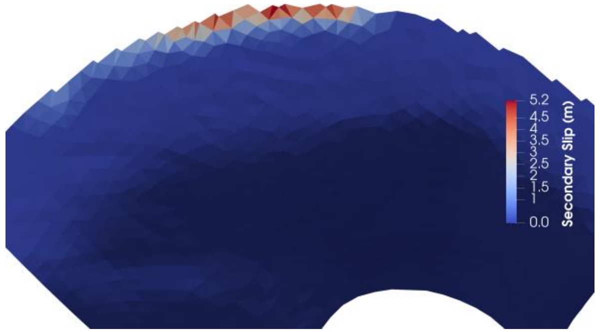
Reflected Slip Contribution



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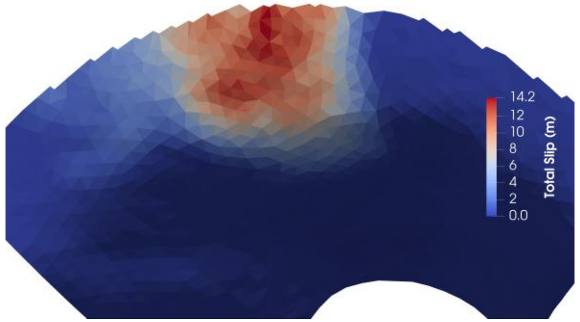
Final Slip Distribution

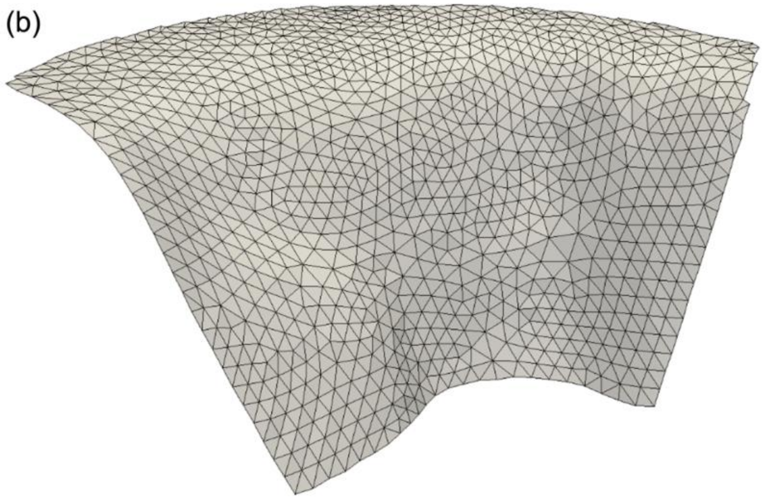


Ifremer

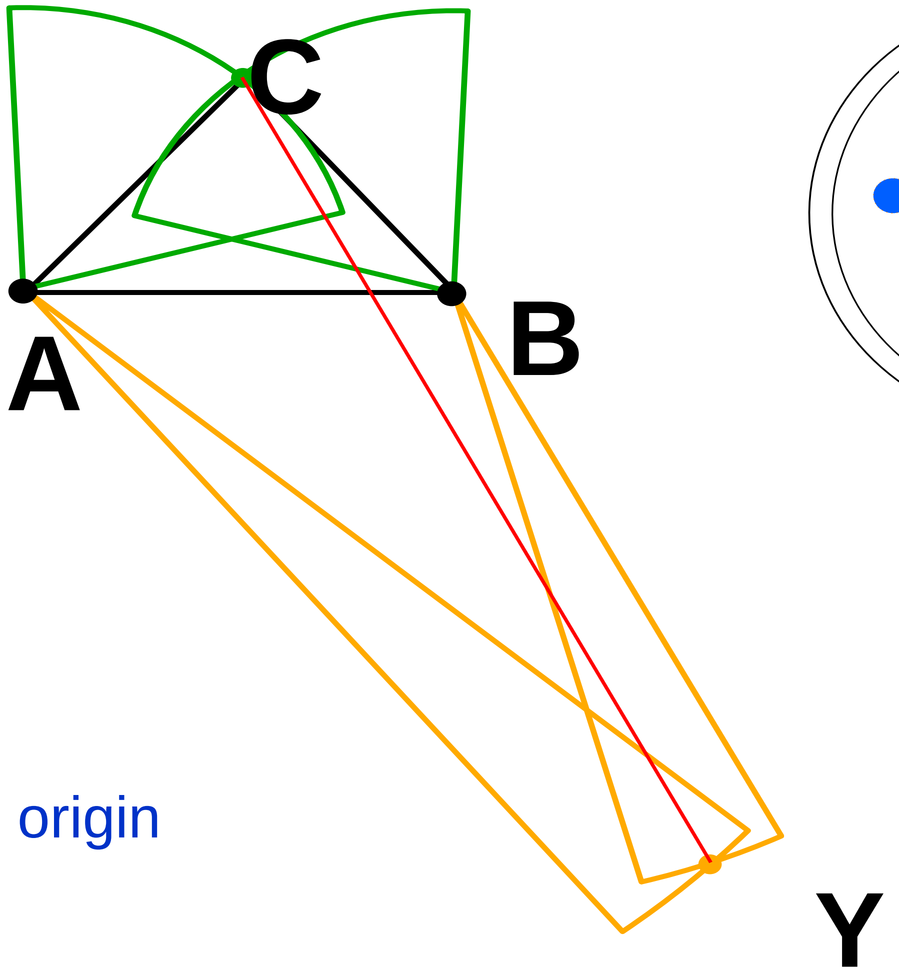
Calculating distance across a surface

Trilateration technique

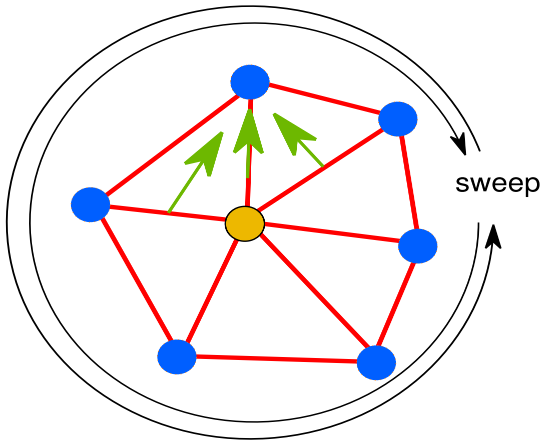
Unstructured Mesh

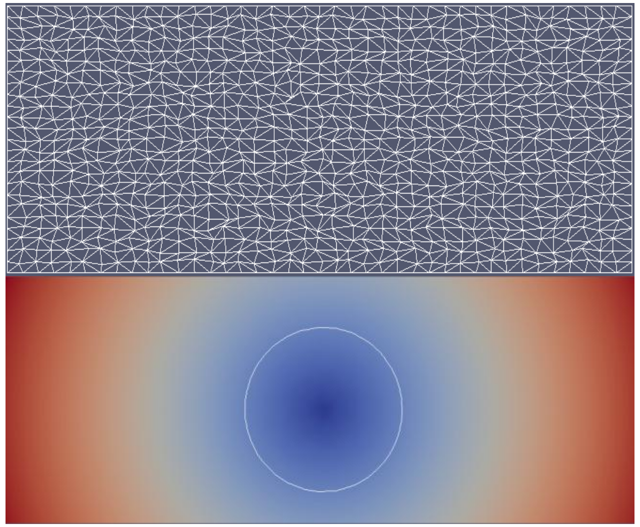


Local Level



Global Level





1) Reconstruct element
2) Locate apparent distance to origin

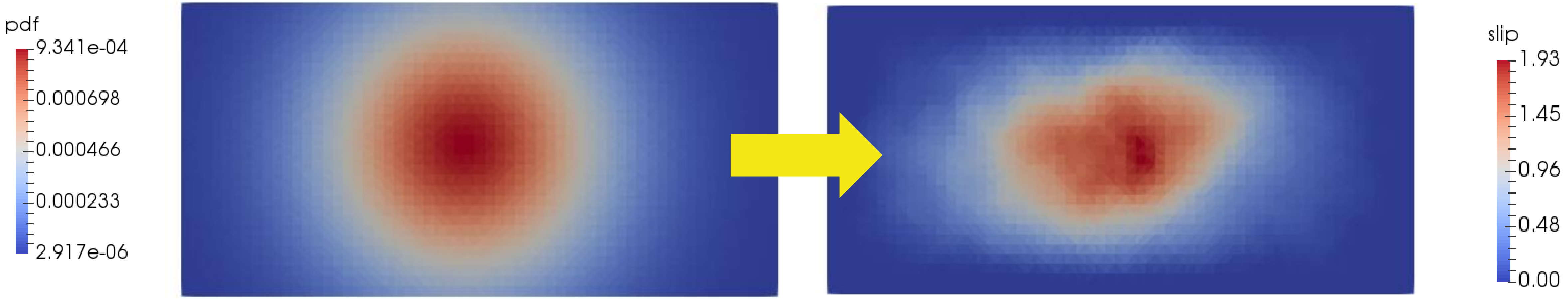
Herrero et al.,2018

Stochastic Slip: Composite Source Model

Advantages:

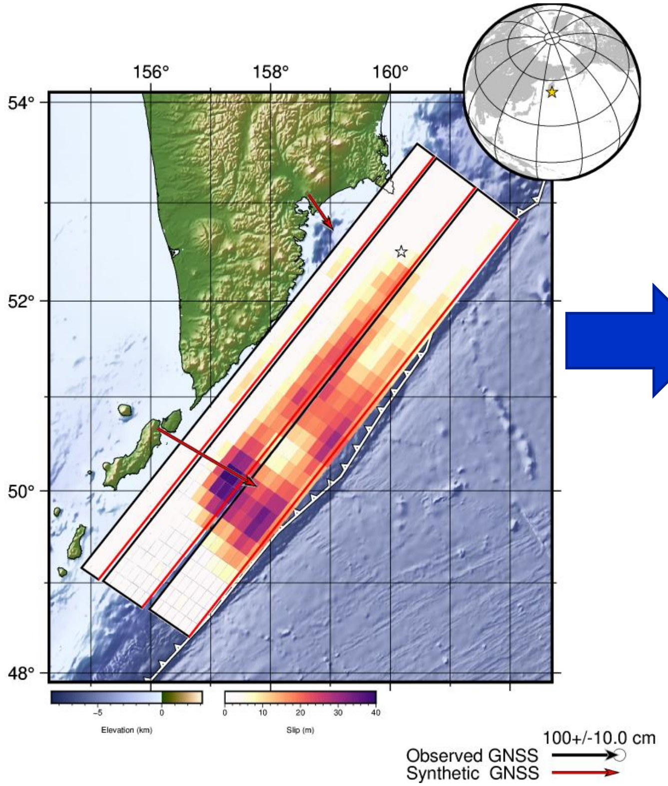
1) no negative slip
2) can be applied on non-planar surfaces
3) natural way of controlling low wavelengths of slip

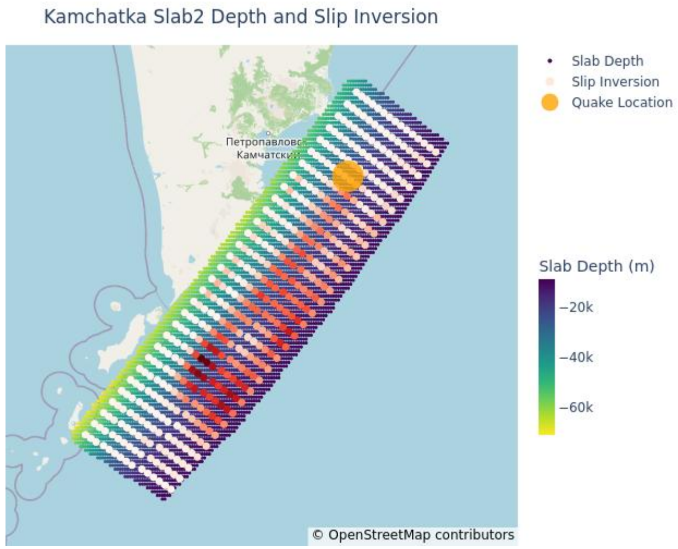
PDF for placement of subevents

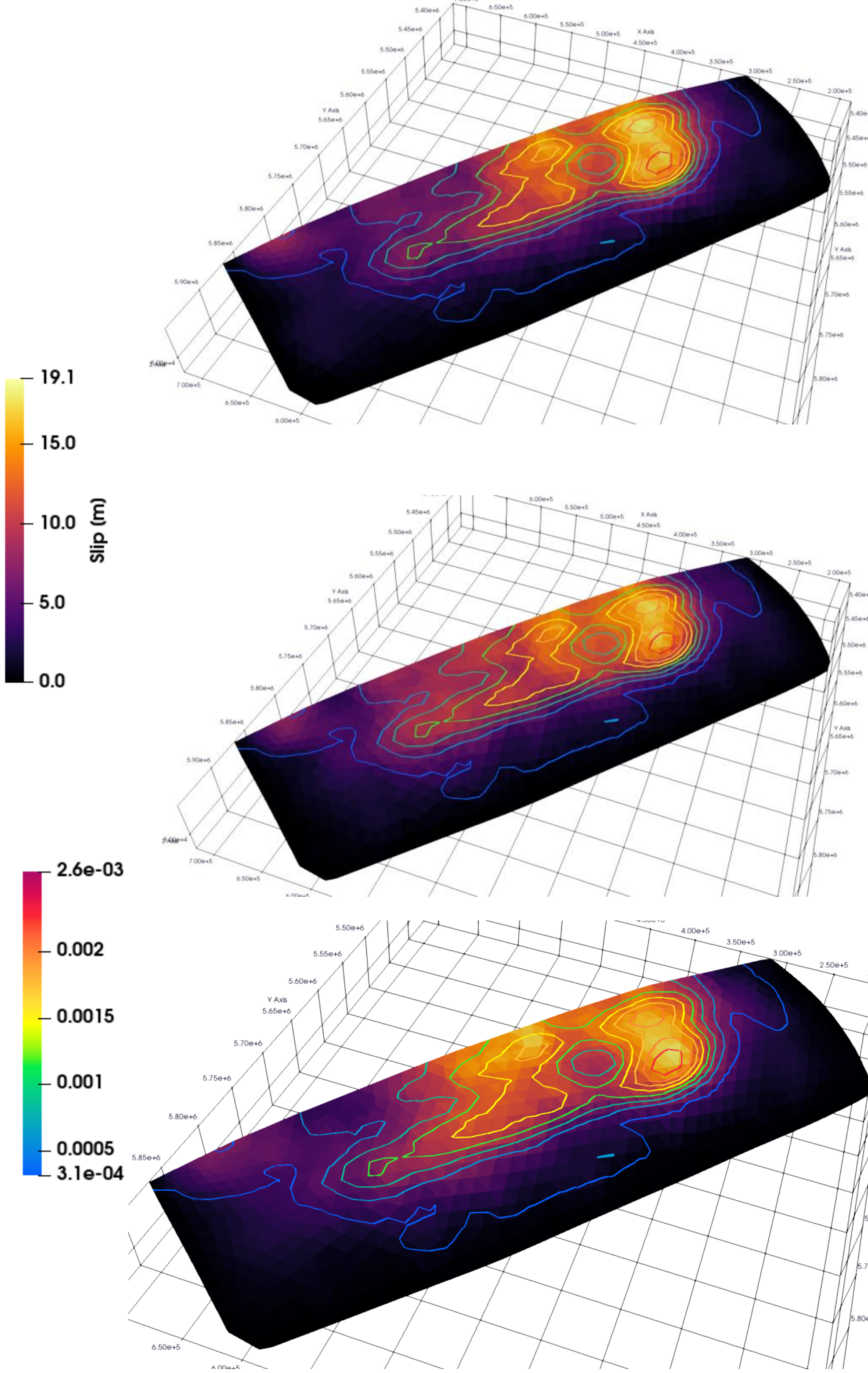


PDF for subevent placement

- M8.8 Kamchatka 2025 Earthquake
- USGS Finite Fault solution exists for planar faults
- But Slab 2.0 (Hayes et al., 2018) provides a non-planar representation of subduction zones







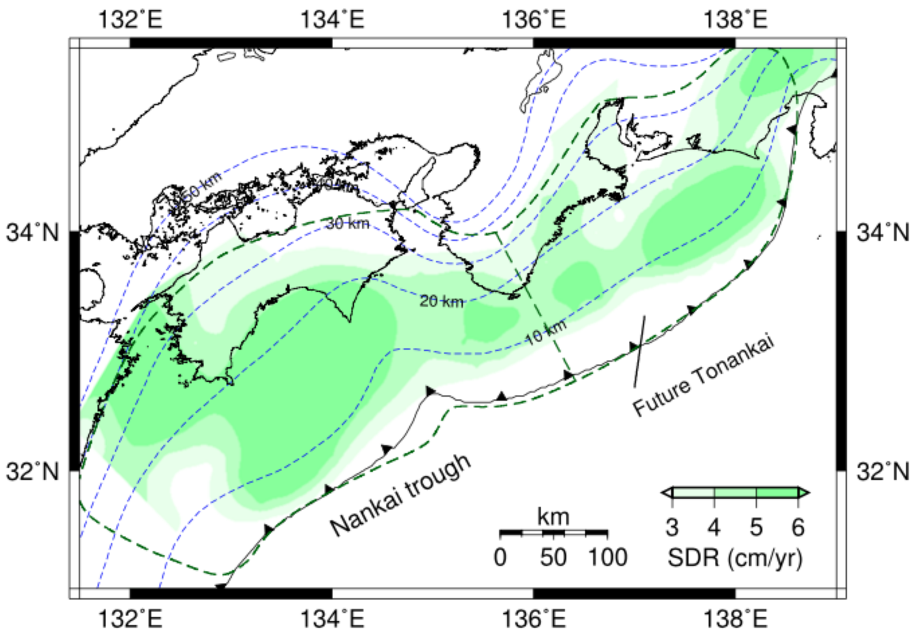
https://earthquake.usgs.gov/earthquakes/eventpage/us6000qw60/finite-fault

PDF for subevent placement

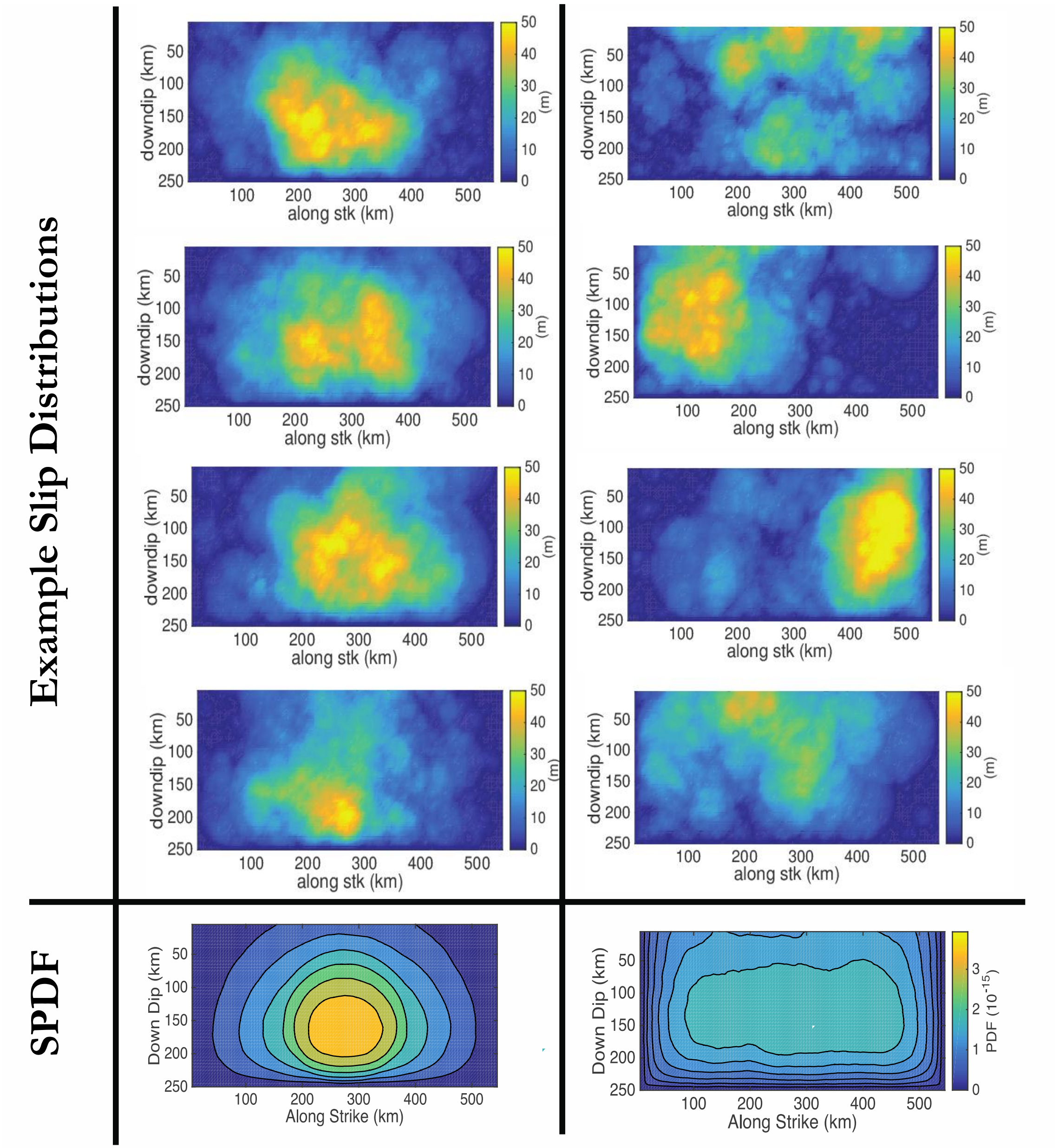
Different pdfs for different situations:

- Slip inversion : depending on uncertanity
- Tsunami hazard : completely unknown
  - Near surface amplifcation
  - Slip deficit / coupling

Important to check ensemble matches expectation



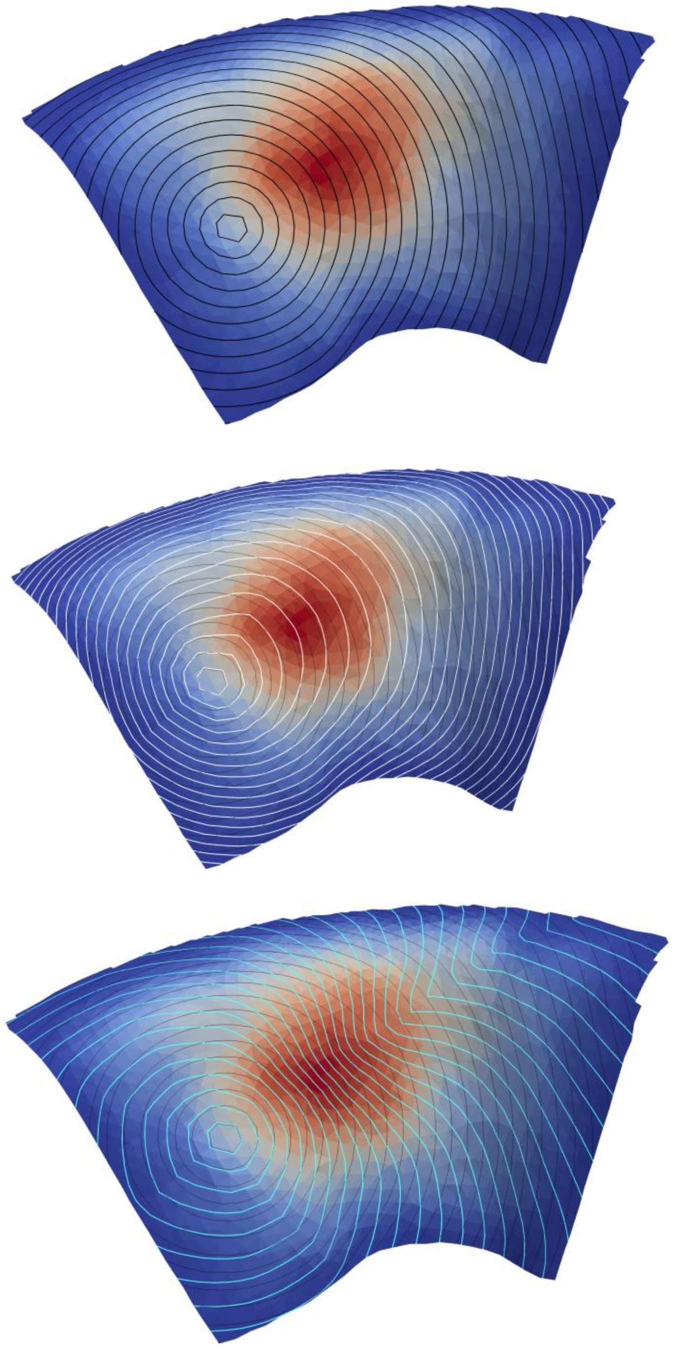
Nakano et al., 2020



Murphy et al., 2016

Ifremer

Rupture Time Across Fault

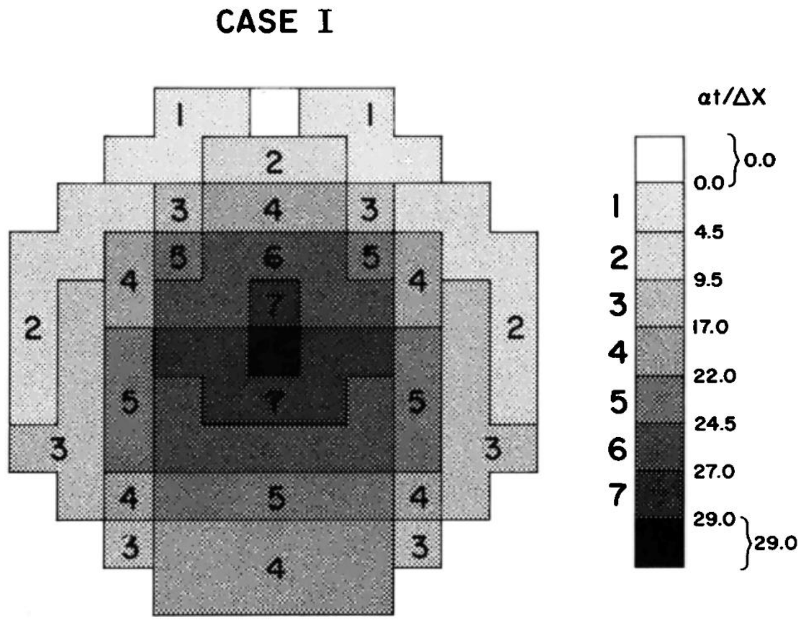


Rupture velocity can be simple or complex

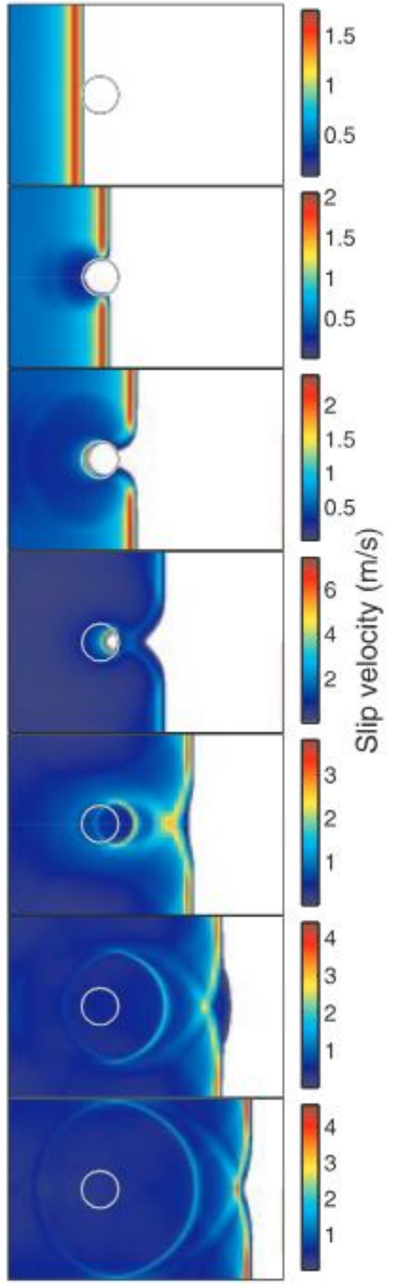
$$v_r = c$$

$$v_r(z) \propto z^n$$

$$v_r(\delta) \propto \delta^n$$



Das and Kostrov, 1983



Dunham et al., 2003

k223d

- Code available on github : https://github.com/s-murfy/k223d
- A simplified input is used with many options given default values
- Stand alone Fortran version
  - Input done through command line
  - Mesh information passed through vtk files

```
k223d.x mw=6.9 in=input.vtk out=output.vtk
```

```
k223d.x mw=6.9 < input.vtk > output.vtk
```

- C API wrapper
  - Directly callable from Python, Julia, C, C++
  - Everything passed through interface

```python
import k223d

# Minimal: slip distribution only
slip, _ = k223d.compute_source(points, cells, mw=7.0)

# With surface rupture and rupture time
slip, time = k223d.compute_source(
    points, cells, mw=7.0,
    surface_nodes=surface_nodes,  # indices of nodes on the free surface
    velocity=cell_vel,            # rupture velocity per cell [m/s]
    time=itime                    # initialisation time per node
)
```

- Happy to work on adding new features

Conclusions

- The aim is to produce rapid stochastic slip distributions but include as much physics as possible

- Slip distributions exhibits power law scaling, self-similar slip can be theoretically linked to self similar ground motion and the stress drop in independent of size

- Composite source model combined with trilateration technique allows us to produce self-similar slip distributions on more realistic (non-planar) surfaces

- Possible to include more rupture physics into models, e.g. near surface slip amplification, rupturing around barriers

- Two approaches compliment each other:
    - Kinematic sim's can be used to add stochastic high frequency to dynamic simulations
    - Dynamic simulations can be used to inject more physics into kinematic simulations.

Thank you for your attention