Dynamic Source Inversion of an Intermediate-Depth Earthquake: a Slow and Inefficient Rupture with Large Stress Drop and Radiated Energy

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Numerical Modeling of Earthquake Motions: Waves and Ruptures
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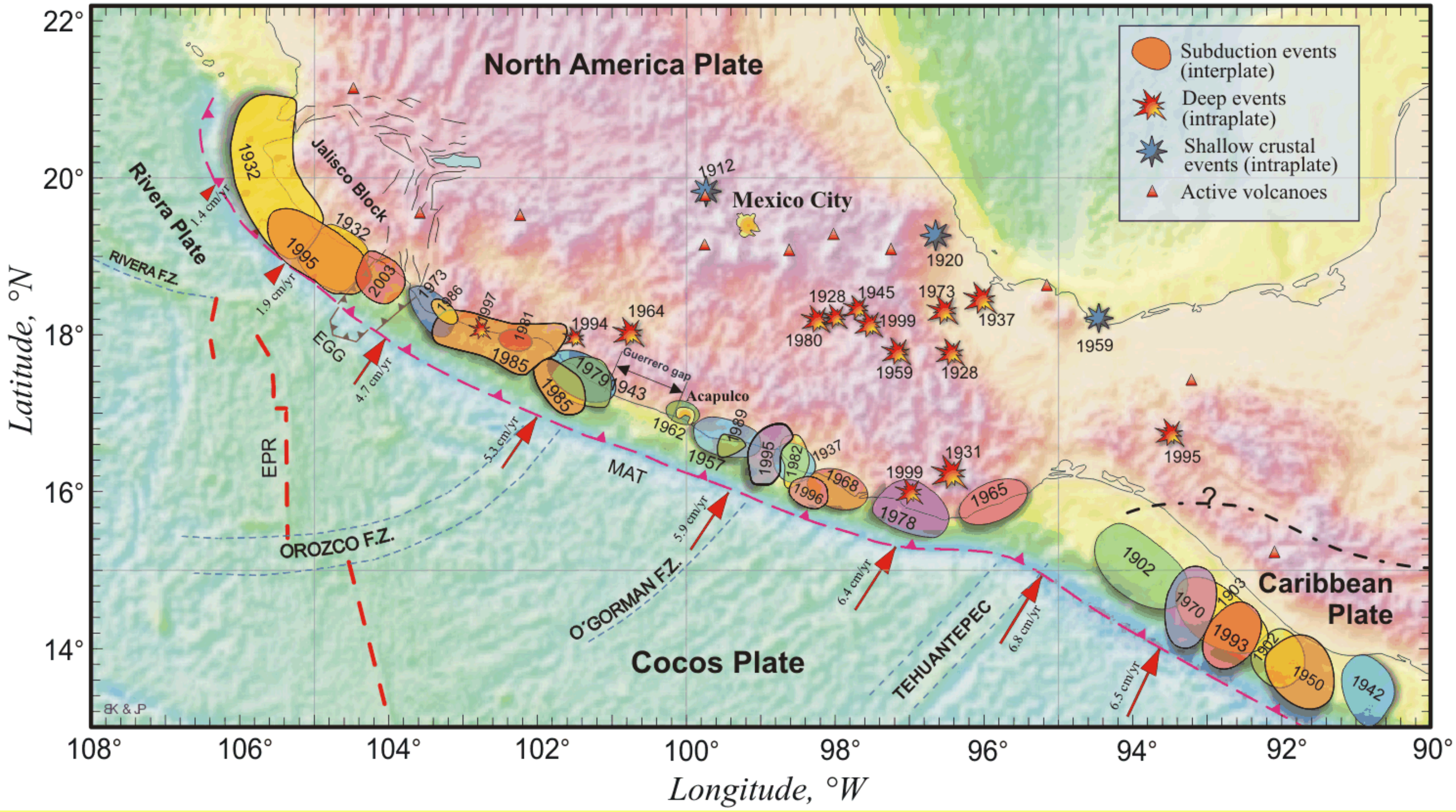
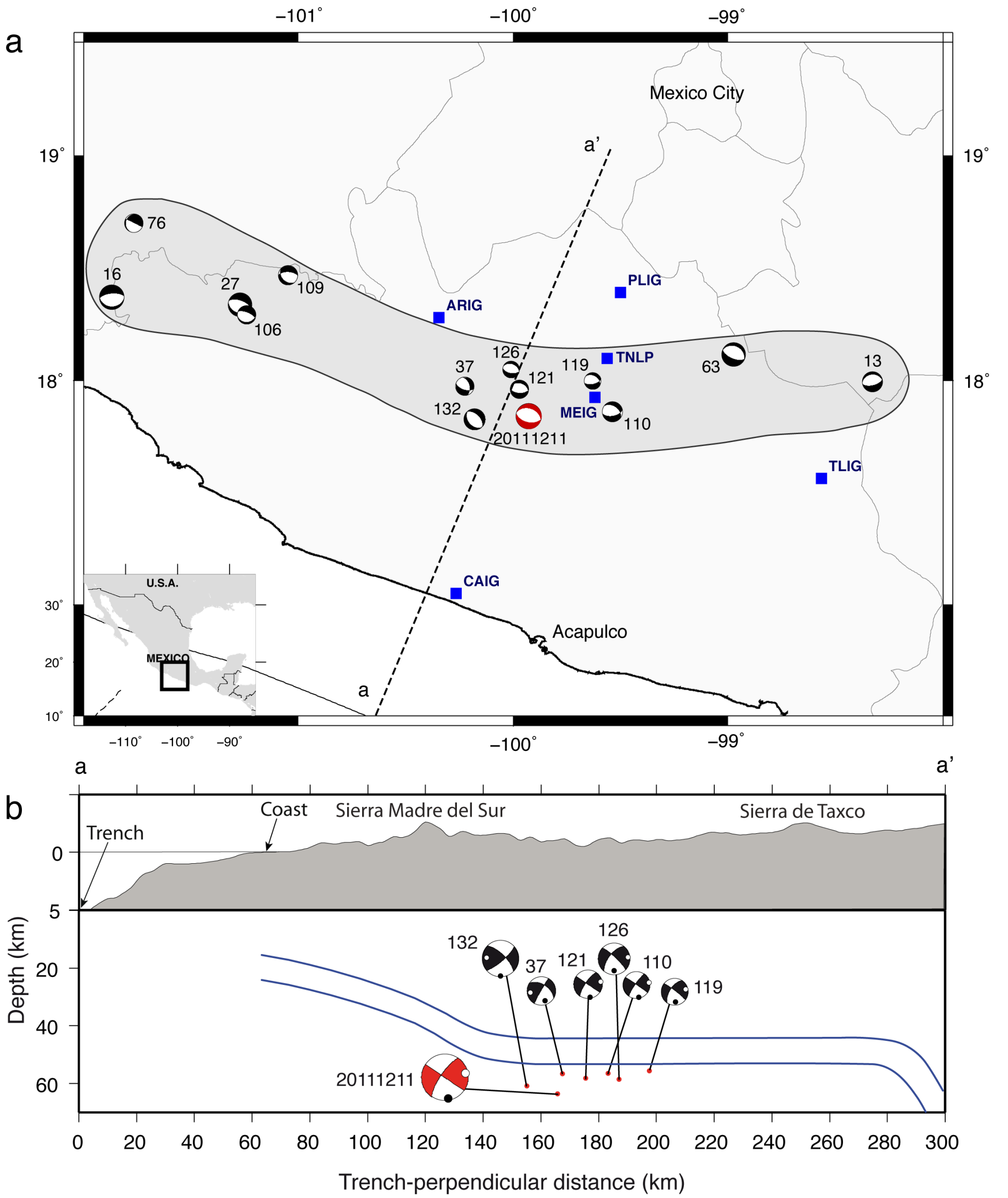
Seismotectonic Setting in the South of Mexico

Inter- vs. Intra-plate Earthquakes



Kostoglodov and Pacheco

Down Dip Intraslab Extensional (Normal) Earthquakes in Guerrero



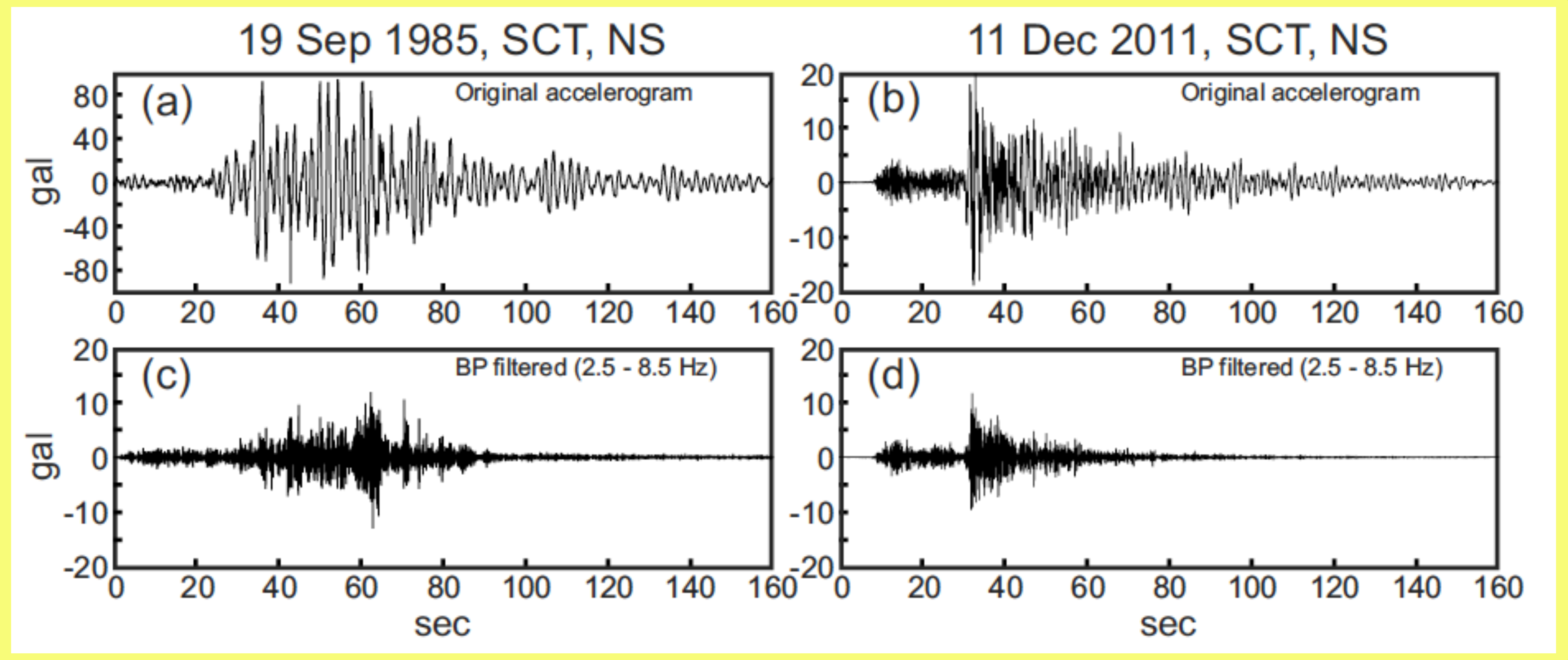
Earthquakes Features:

- Inslab normal faulting
- Down-dip extensional regime
- Deeper than 50 km
- ~150 km or further from the trench
- High stress drops (~30 MPa, e.g. García et al., 2004)

Modified from Pacheco and Singh, 2010

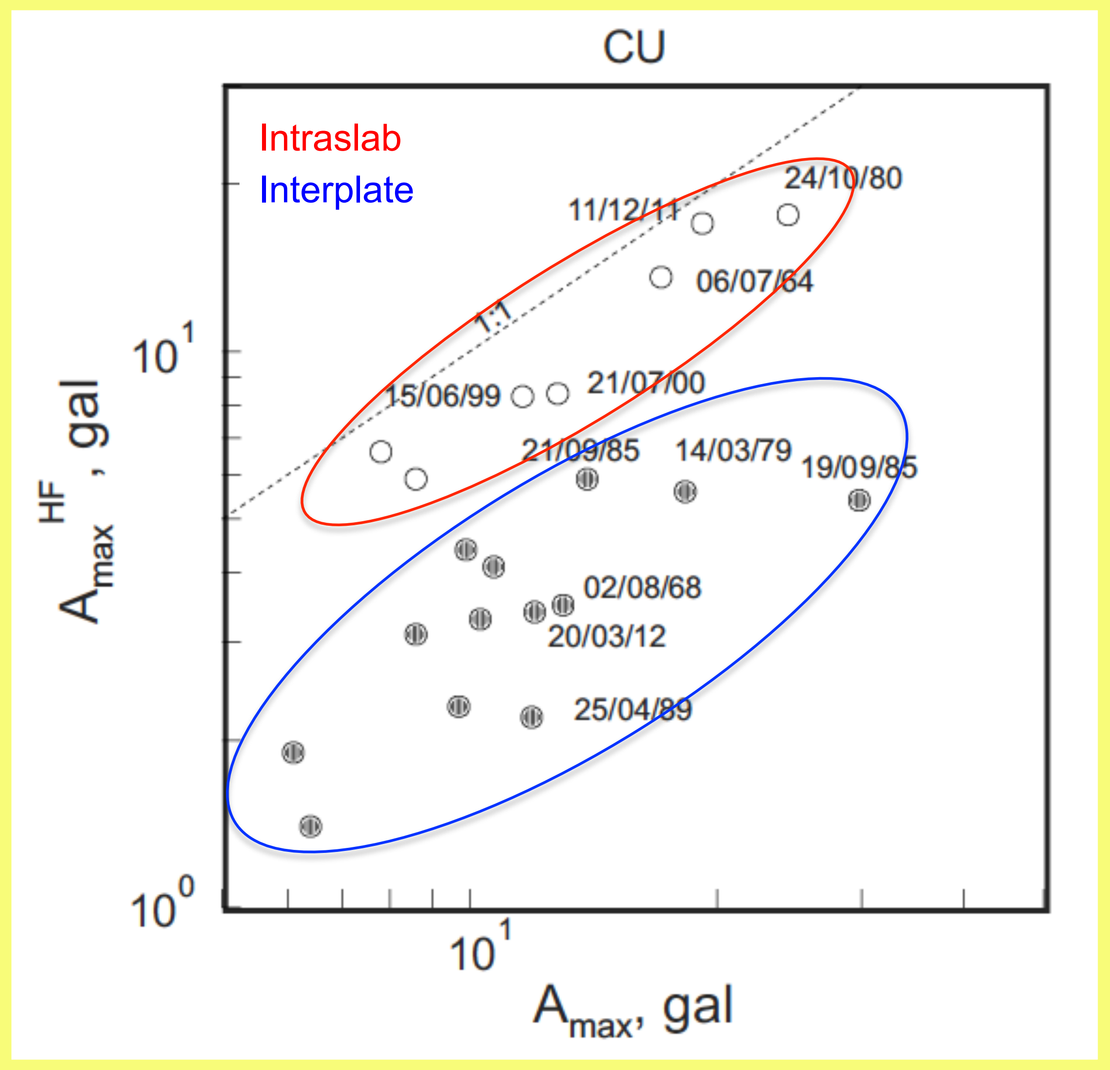
Seismic Hazard from Intermediate-Depth Earthquakes in Mexico City

M8.1 Interplate vs M6.5 Intraplate



Singh et al., 2013

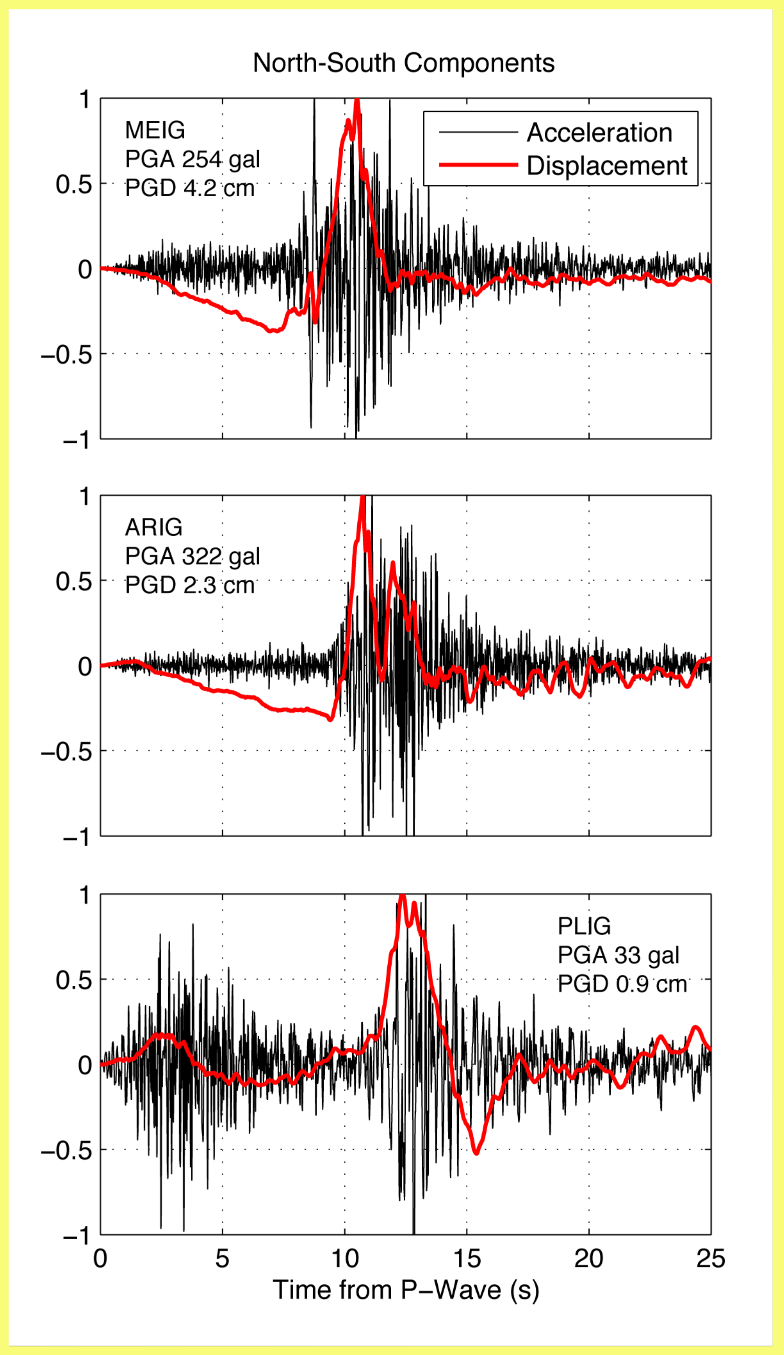
Seismic Hazard from Intermediate-Depth Earthquakes in Mexico City



The 20 earthquakes with PGA > 6 gal in the last 55 years in Mexico city

Intermediate-depth events produce larger PGA at high frequencies (i.e., between 2.5-8.5 Hz) in hard rock sites.

Singh et al., 2013

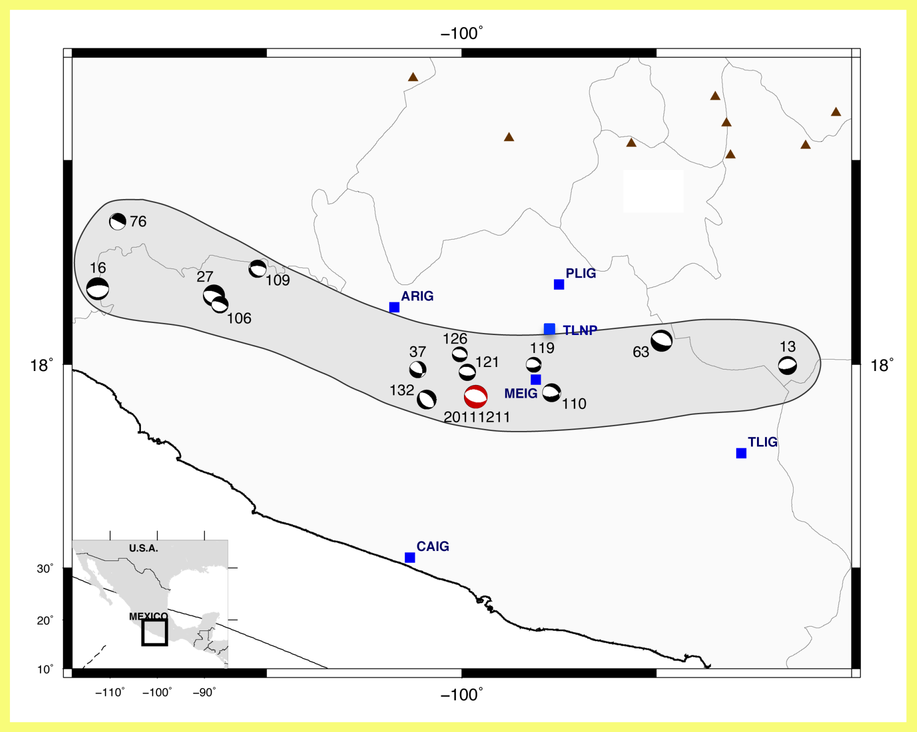


M6.5 Zumpango Earthquake of December 11, 2011

(Near-Field Seismograms)

- Eastward source directivity
- S-wave nodal radiation at PLIG
- Double time integration from accelerations

Stations Array

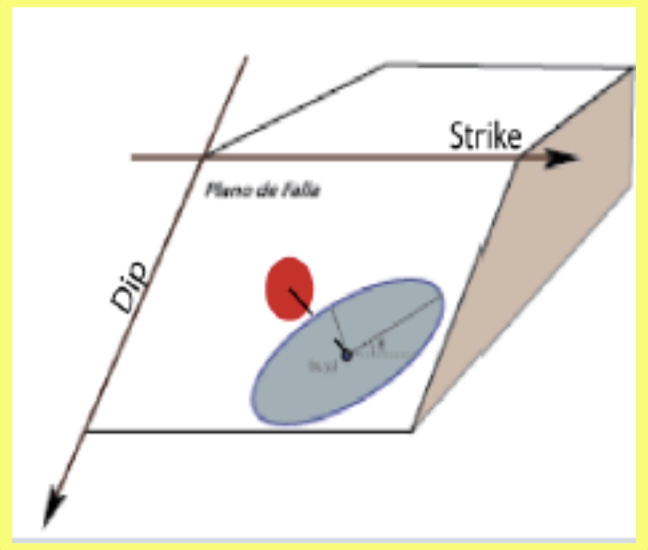


Content of the Talk

1. Dynamic source model parameterization
2. Derivation of some fundamental source parameters
3. Parallel genetic algorithm for the inversion of source dynamics
4. Results and some comparisons with global data

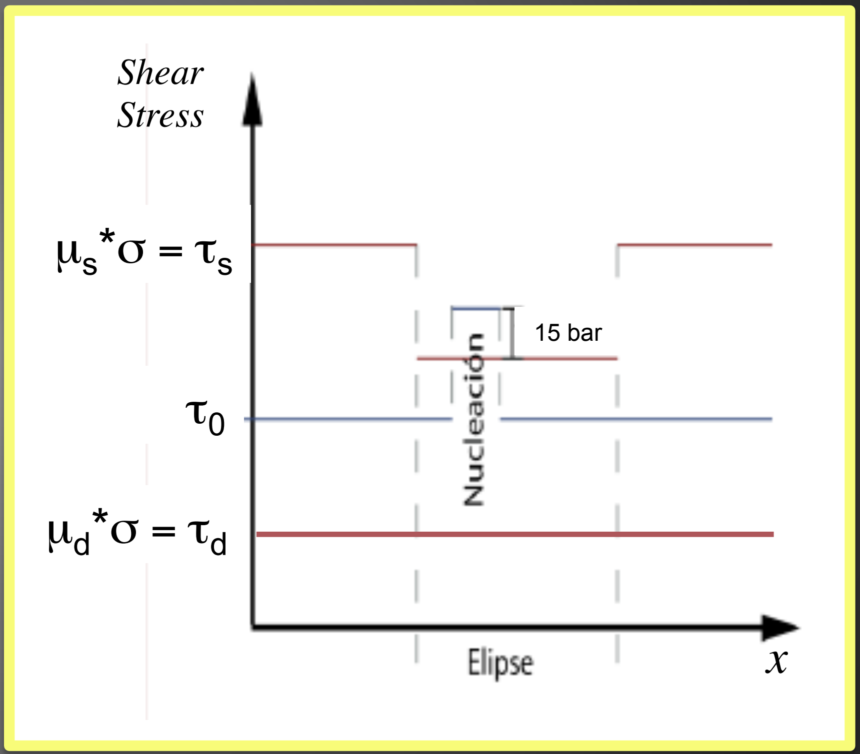
Dynamic Source Model

Elliptical Rupture Patch



After Di Carli et al. (2010)

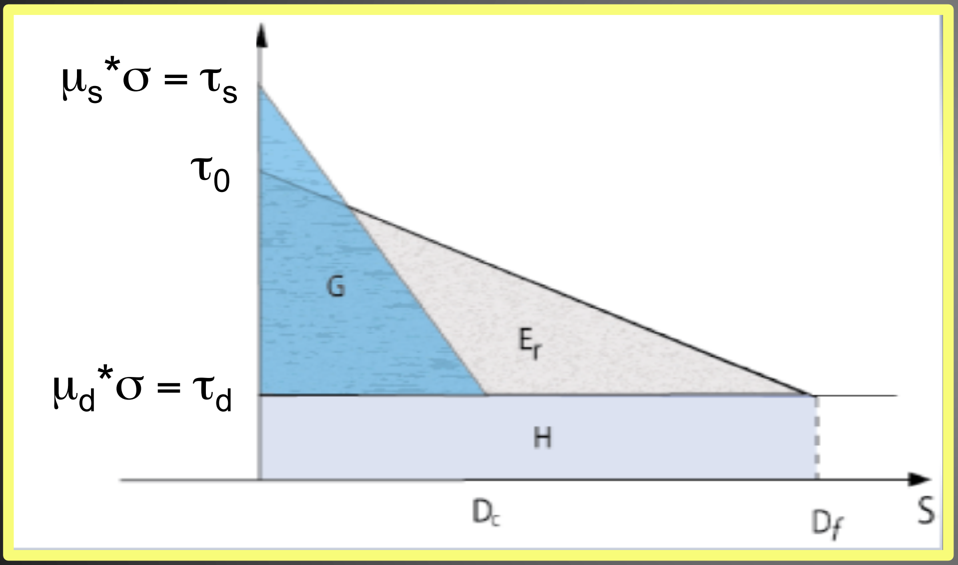
Barrier Model: Initial Stress Conditions



- Elliptical-shaped source model
- Few model parameters
- Similar to Brune's source model
- Spontaneous rupture propagation

Dynamic Source Model Parameterization

Friction Law: Linear Slip-Weakening



Ida, 1972

Nine Model Parameters

- Semi-axis of the ellipse
- Coordinates of the ellipse in the fault plane
- Ellipse inclination angle
- Stress drop ($\Delta\tau = \tau_0 - \tau_d$) inside and outside nucleation
- Friction coefficient increment ($\Delta\mu$)
- Slip weakening distance (D_c)

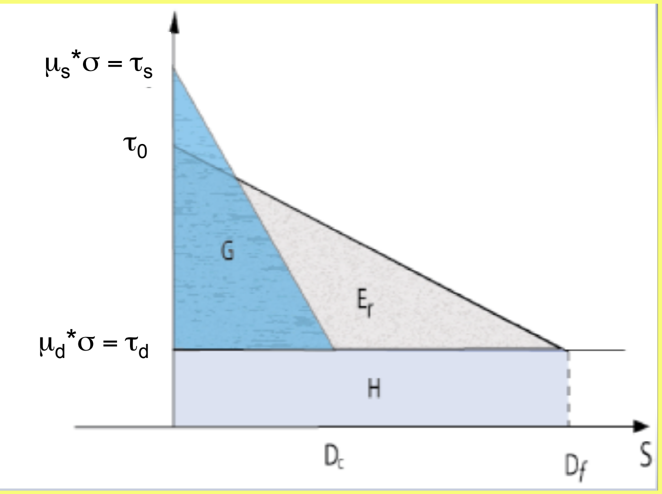
Computational Model

The 3D elastodynamic equations along with the constitutive friction law are solved using the Staggered-Grid Traction-at-Split Nodes (SGSN) method (Dalguer and Day, 2007).

Estimation of Dynamic Source Parameters

Total energy change (Volterra relationship)

$$\Delta W = -\frac{1}{2}\iint S_f(\boldsymbol{\tau}_0 + \boldsymbol{\tau}_1)\boldsymbol{\nu}\, d\Sigma,$$



Total energy dissipation

$$\iint d\Sigma \int_{t_0}^{t_1} \boldsymbol{\tau}(t)\dot{S}(t)\boldsymbol{\nu}\, dt,$$

From energy balance, the radiated energy is thus given by

$$E_r = \frac{1}{2}\iint S_f(\boldsymbol{\tau}_0 + \boldsymbol{\tau}_1)\boldsymbol{\nu}\, d\Sigma - \iint d\Sigma \int_{t_0}^{t_1} \boldsymbol{\tau}(t)\dot{S}(t)\boldsymbol{\nu}\, dt.$$

That in terms of the stress drop becomes (Rivera and Kanamori, 2005)

$$E_r = A\left\{\frac{1}{2}(\tau_0 - \tau_d)S_f - \int_{t_0}^{t_1}[\tau(t) - \tau_d]\dot{S}(t)\, dt\right\},$$

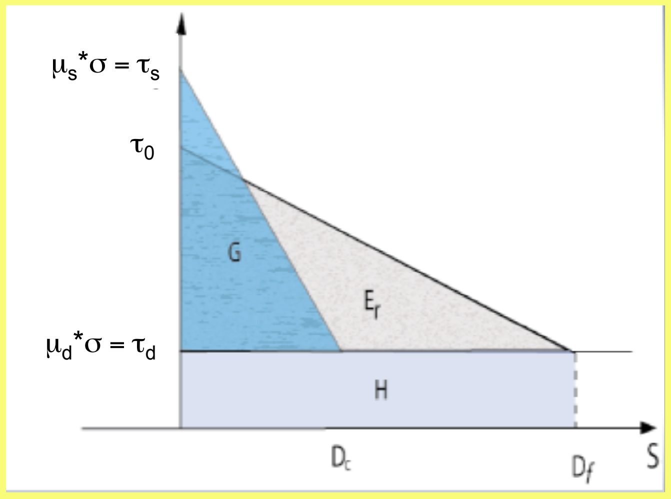
Estimation of Fundamental Source Parameters

Radiated energy (repeated)

$$E_r = A\left\{\frac{1}{2}(\tau_0 - \tau_d)S_f - \int_{t_0}^{t_1}[\tau(t) - \tau_d]\dot{S}(t)dt\right\},$$

Radiated energy in terms of the stress drop
and the slip-weakening distance

$$E_r = A\left\{\frac{1}{2}(\tau_0 - \tau_d)S_f - \int_0^{D_c}[\tau(S) - \tau_d]dS\right\}.$$



Where the fracture energy is given by

$$G = \int_0^{D_c}[\tau(S) - \tau_d]dS,$$

Radiation Efficiency

$$\eta_r = \frac{E_r}{E_r + G},$$

Undimensional Kappa

$$\mathrm{K} = \frac{\Delta\tau}{\mu(\mathbf{S}+1)} \cdot \frac{L}{D_c},$$

Madariaga and Olsen, 2000

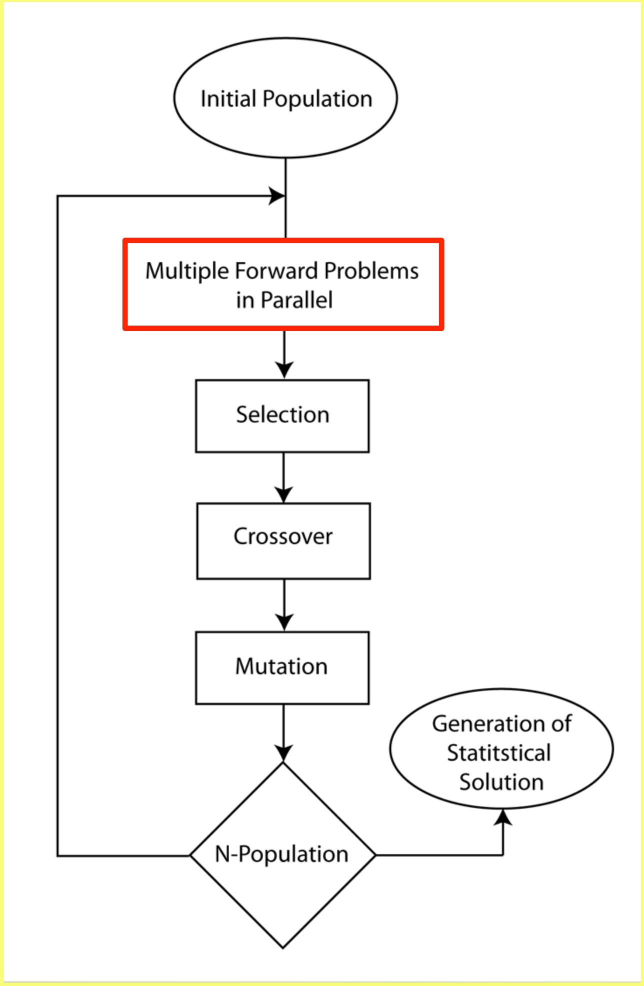
where

$$\mathbf{S} = (\tau_s - \tau_0)/\Delta\tau$$

Andrews, 1976

A New Parallel Genetic Algorithm

GA Flux Diagram



Initial Population

Multiple Forward Problems in Parallel

Selection

Crossover

Mutation

N-Population

Generation of Statitstical Solution

After Holland, 1975

Algorithm features:

- Parallel program for solving multiple forward-problems simultaneously
- Selection through biased roulette criterion (Goldberg, 1989)
- One- or two-bit crossover
- Decreasing mutation probability
- Identification of non-rupturing models to avoid useless computations
- No computation of repeated models

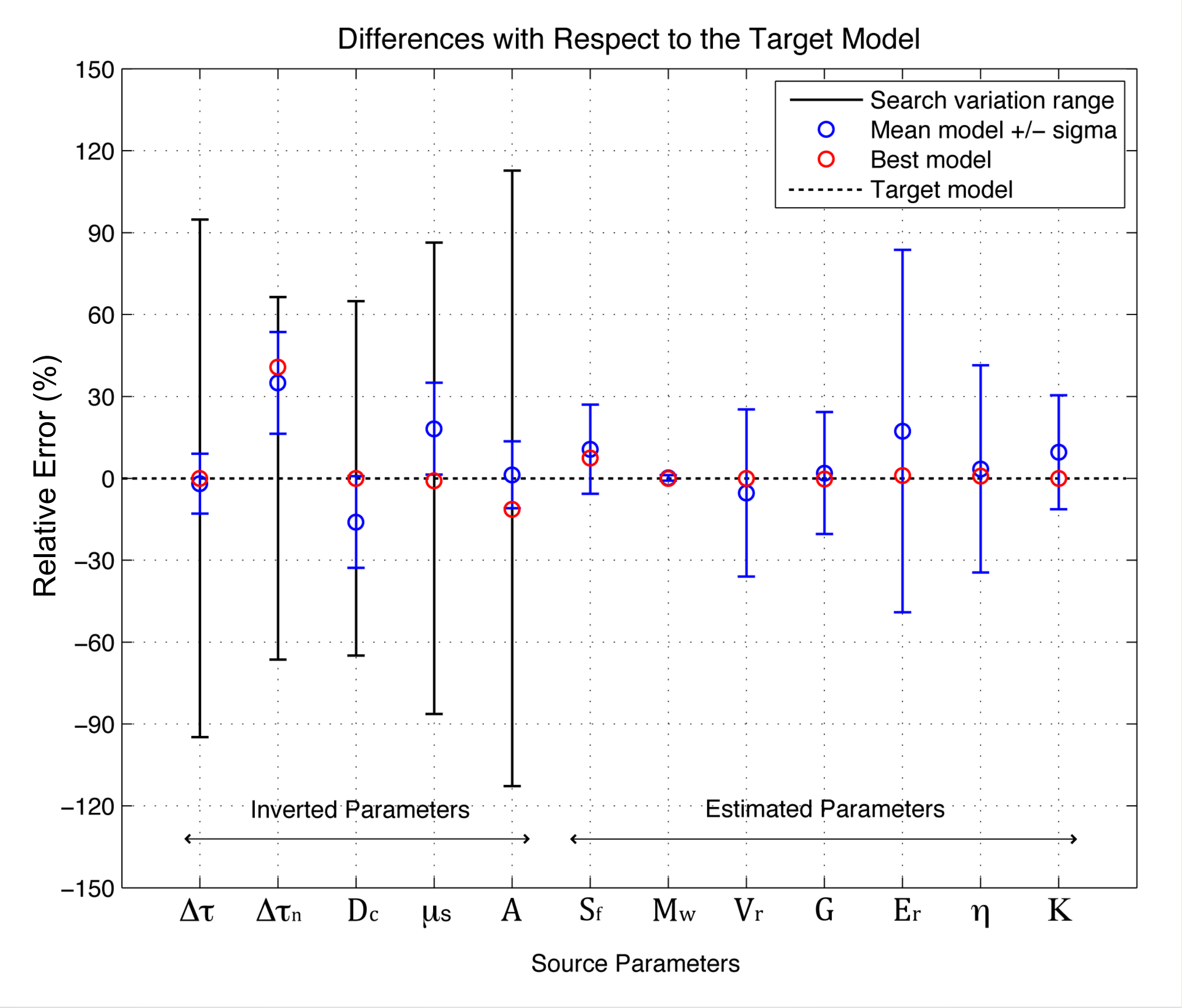
Misfit Function

$$M = 0.5\left[1 - \frac{cross(d_s - d_o)}{auto(d_s) + auto(d_o)} + \frac{|\delta\tau| - \tau_c}{2\tau_c}\right]$$

Díaz-Mojica et al., JGR, 2014

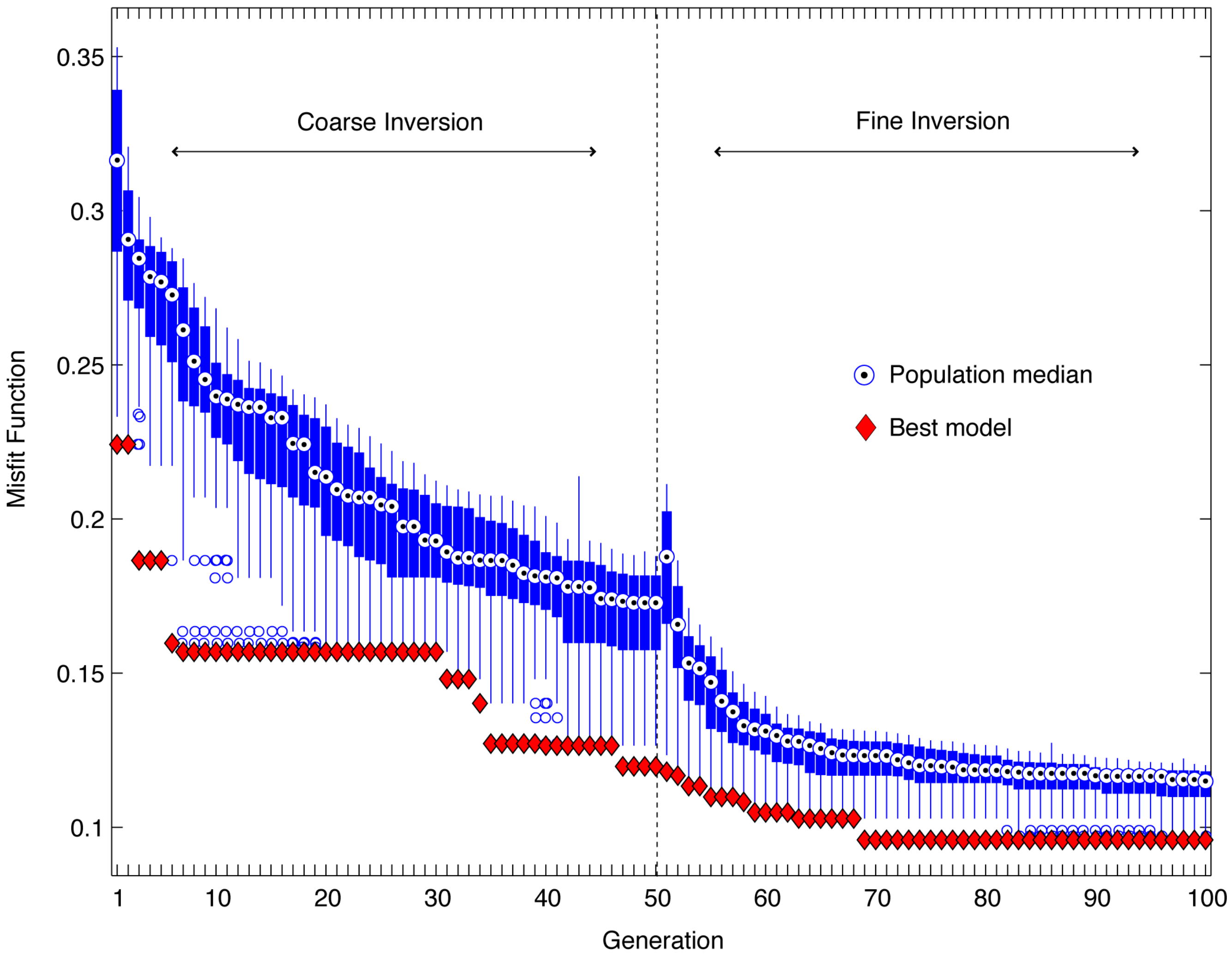
Synthetic Inversion Test: Source Parameters

Best fitting model within the 10% of the target solution, while the mean source model is within the 25% of the target.



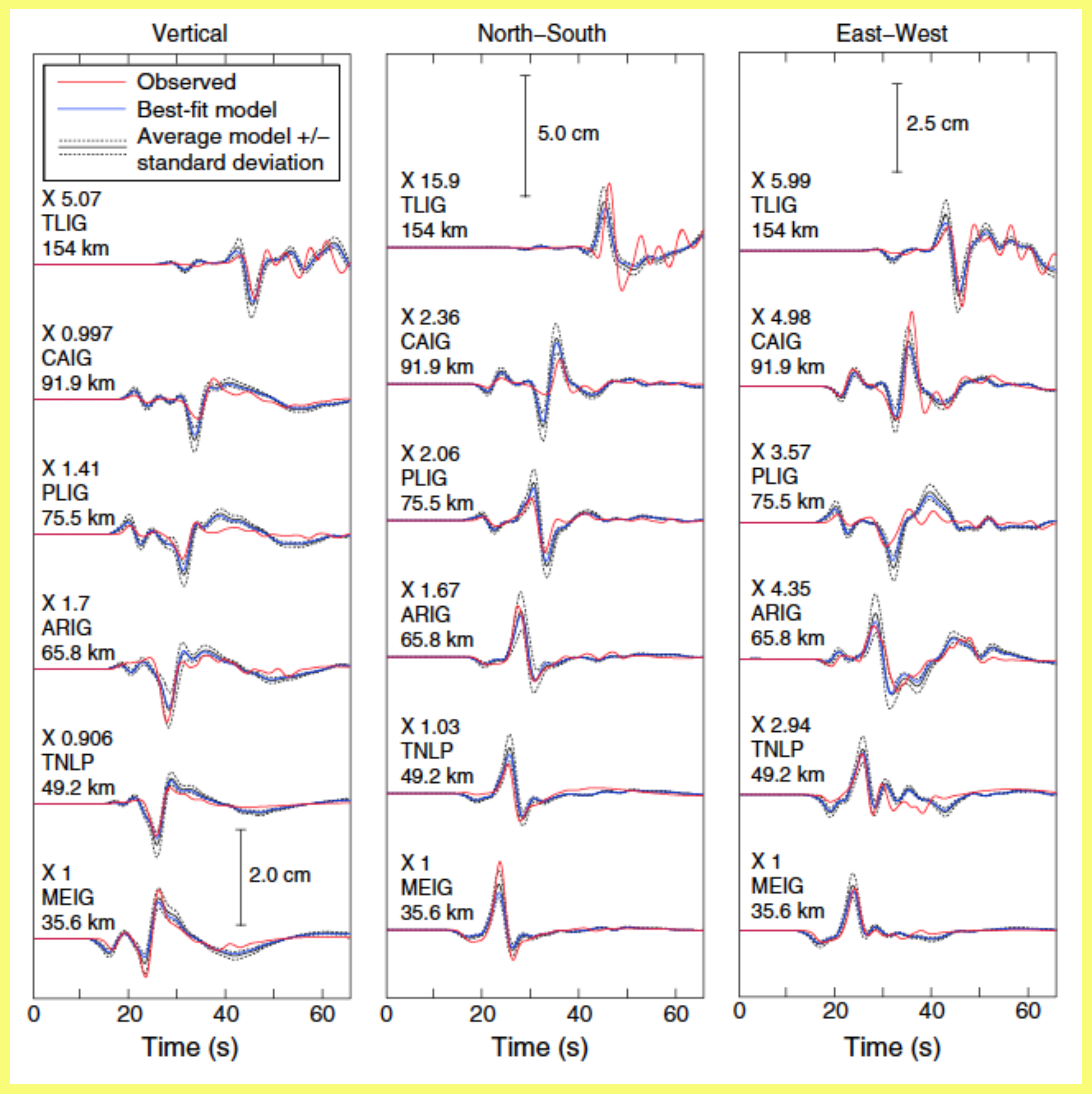
M6.5 Zumpango Earthquake: Inversion Results

Multiscale Inversion Approach



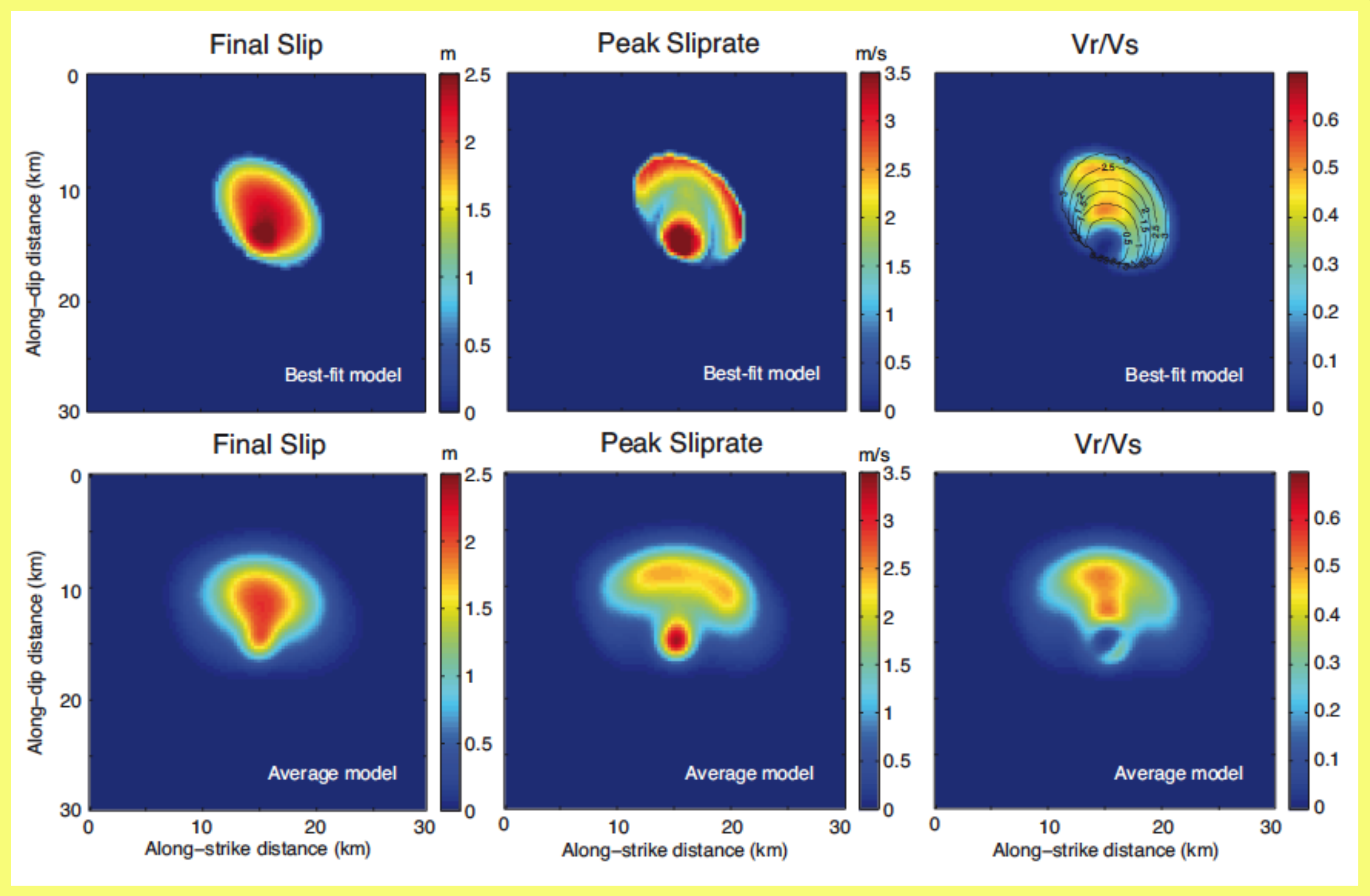
M6.5 Zumpango Earthquake: Seismograms Fit

Band-pass filter 0.02 < f < 0.2 Hz



M6.5 Zumpango Earthquake: Inversion Results

Fault Solutions (300 selected models from 50,400 trials)



- Upward and eastward source directivity
- Two main radiation patches
- Subshear source velocity

Zumpango Earthquake Source Parameters

Díaz-Mojica et al., JGR, 2014

Low Values (typical of tsunami earthquakes)

Rupture Velocity: Vr/Vs = 0.47 ± 0.09

Radiation Efficiency: $\eta = 0.26 \pm 0.10$

Typical Values (comparable to interplate earthquakes)

Radiated Energy: Er = (5.4 ± 3.1) x 10^{14} J

Ratio: Er/M0 = 5.7 x 10^{-5}

Radiation Efficiency

$$\eta_r = \frac{E_r}{\Delta W_0} = \frac{E_r}{E_r + G}$$

Very High Value (i.e., G = 2.7 Er)

Fracture Energy: G = (14.4 ± 3.5) x 10^{14} J

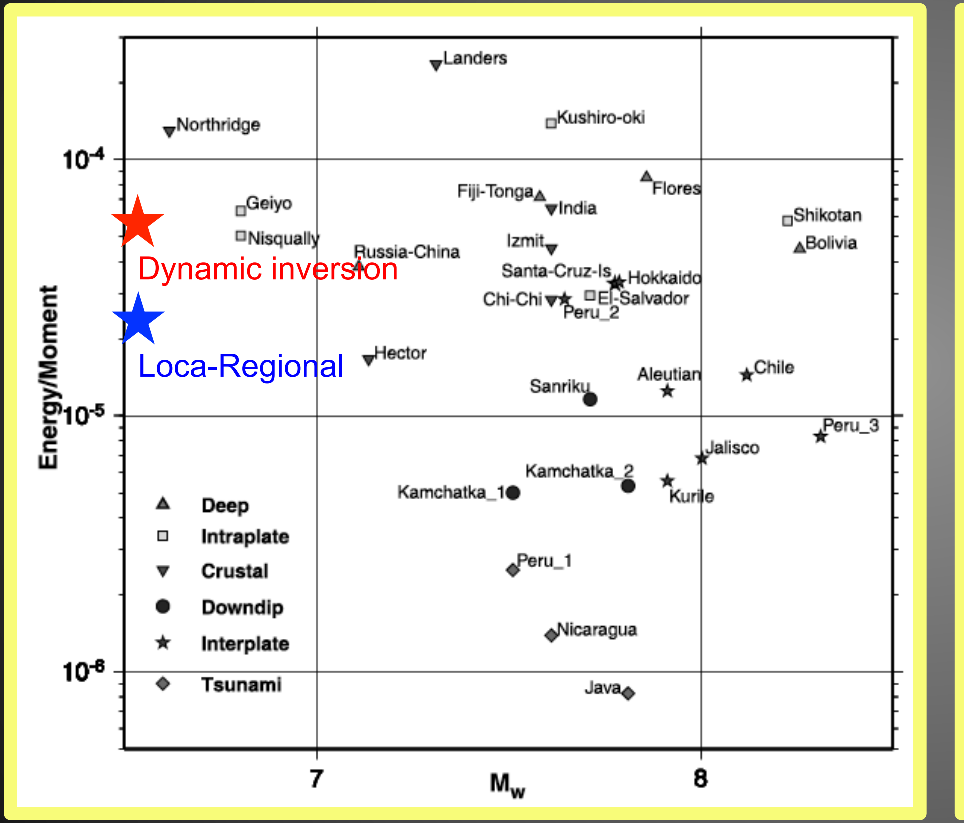
73% of the available potential energy for dynamic faulting was not radiated and dissipated in the focal region.

Stress Drop: $\Delta\tau$ = 29.2 ±6.2 MPa

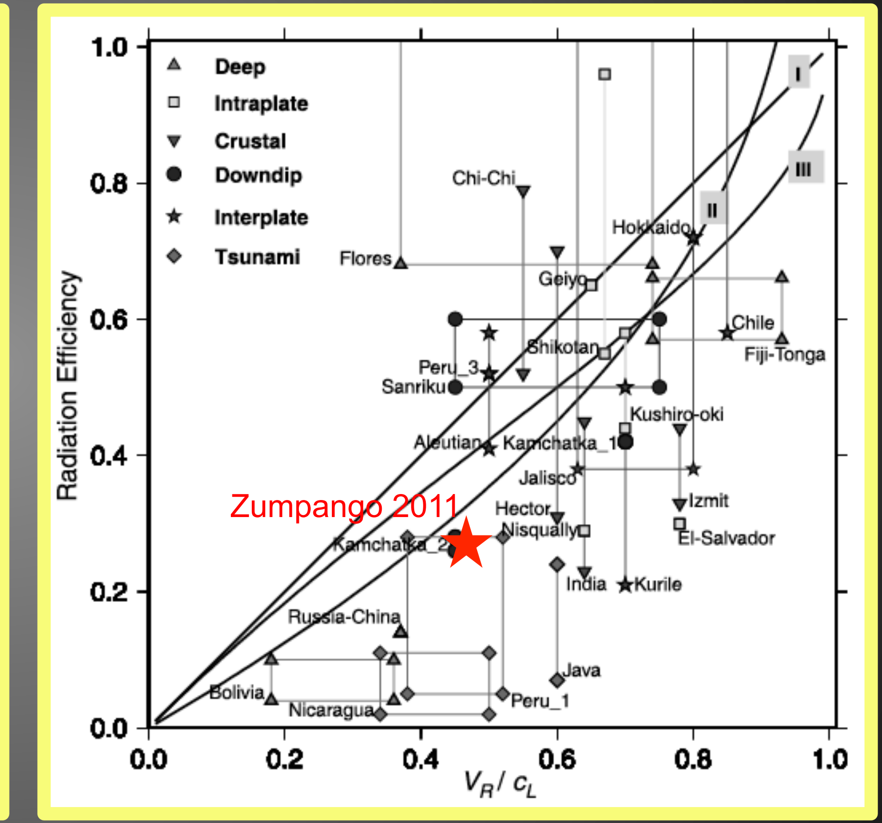
High Value (i.e., ~4 time larger than interplate earthquakes)

M6.5 Zumpango Earthquake: Inversion Results

Radiated Energy

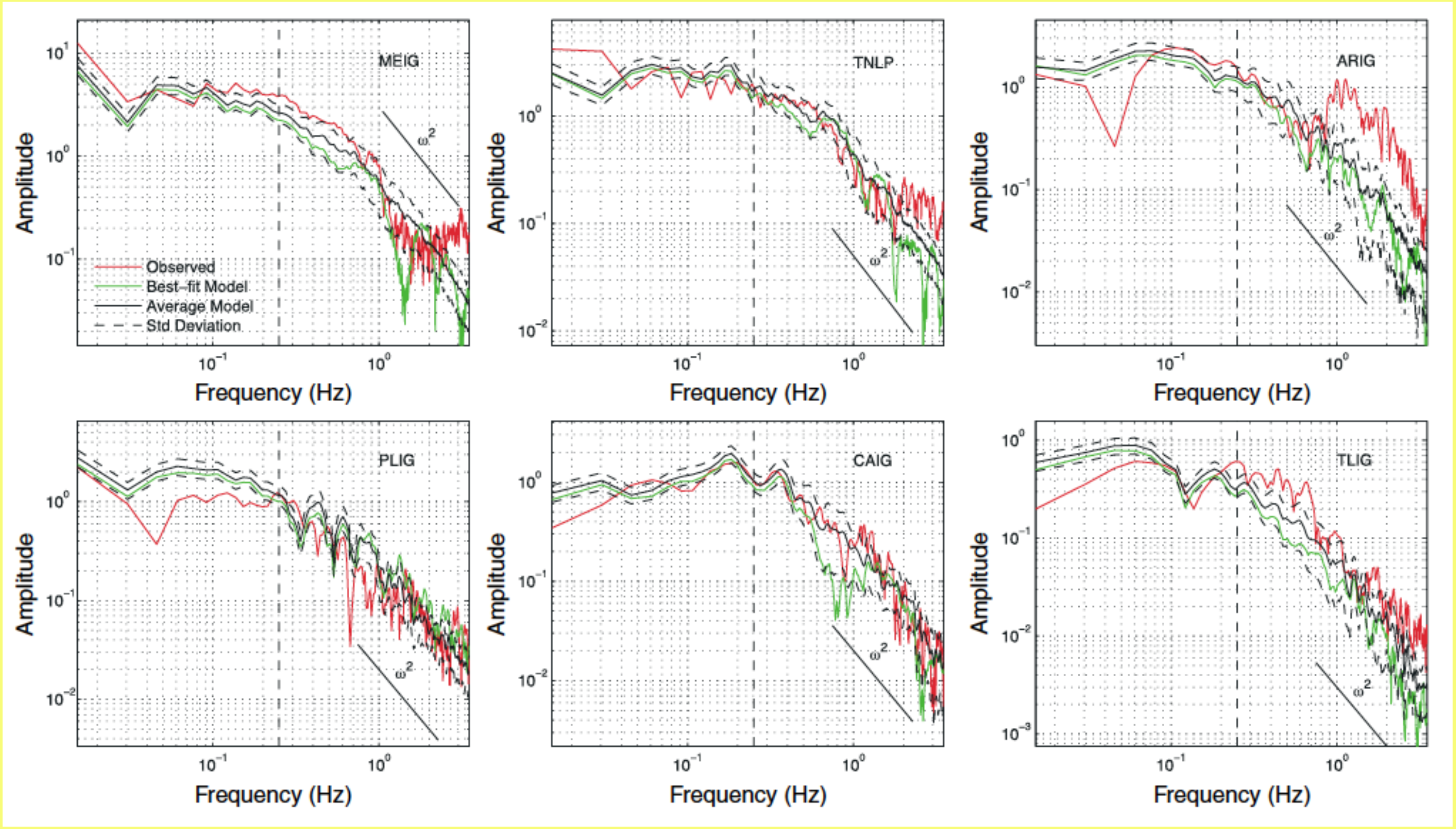


Radiation Efficiency and Rupture Velocity



(Venkataraman and Kanamori, 2004)

Source Multiscale Causality



From Brune's source model, less than 18% of the total Er is contained below f_c (Singh and Ordaz, 1994). In this case, $f_c = 0.47$ Hz, and the inversion cutoff is 0.25 Hz.

Conclusions

1. We have introduced a parallel genetic algorithm for imaging the earthquake source dynamics by following an elliptical dynamic-rupture-patch approach and the SGSN finite difference method.

2. The dynamic source inversion of the Zumpango earthquake revealed a rather low rupture velocity (Vr/Vs = 0.47 ± 0.09) with very low radiation efficiency (0.26 ± 0.10) and large stress drop (29.2 ±6.2 MPa).

3. Fracture energy ((14.4 ± 3.5) x 10^{14} J) was about three times larger than the radiated energy (G=2.7Er), although the later was estimated as (5.4 ± 3.1) x 10^{14} J, which is high and imply a very energetic earthquake where 73% of the available energy dissipated in the focal region.

Conclusions

4. The Zumpango earthquake and both the deep 1994 Bolivian earthquake (Mw8.3; depth = 637 km) and the Bucaramanga nest share some fundamental features (i.e., slow rupture speed, low radiation efficiency, high stress drop and small rupture area).

5. The dynamic source inversion yielded reliable estimates that depend on time scales much shorter than the shortest period in the observed seismograms, revealing a multiscale causality of our model.

This work has been published in JGR last year:

Díaz-Mojica, J., V. M. Cruz-Atienza, R. Madariaga, S. K. Singh, J. Tago, and A. Iglesias (2014), Dynamic source inversion of the M6.5 intermediate depth Zumpango earthquake in central Mexico: A parallel genetic algorithm, J. Geophys. Res. Solid Earth, 119, 7768–7785, doi:10.1002/2013JB010854.

Thank you