The 2018 Mw 7.5 Palu Earthquake
and
the Slowness-Enhanced Back-projection

Han Bao (UCLA)

J.P. Ampuero (IRD/UCA, Géoazur)

L. Meng, G. Peltzer. (UCLA)

E. Fielding, C. Liang, C. Milliner (JPL, Caltech)

Overview

Part 1: Palu Earthquake

- Static Observations
  - Radar and image satellites
- Dynamic Observations
  - Teleseismic Back-projection
  - Surface Mach wave/Mach cone
- Implications

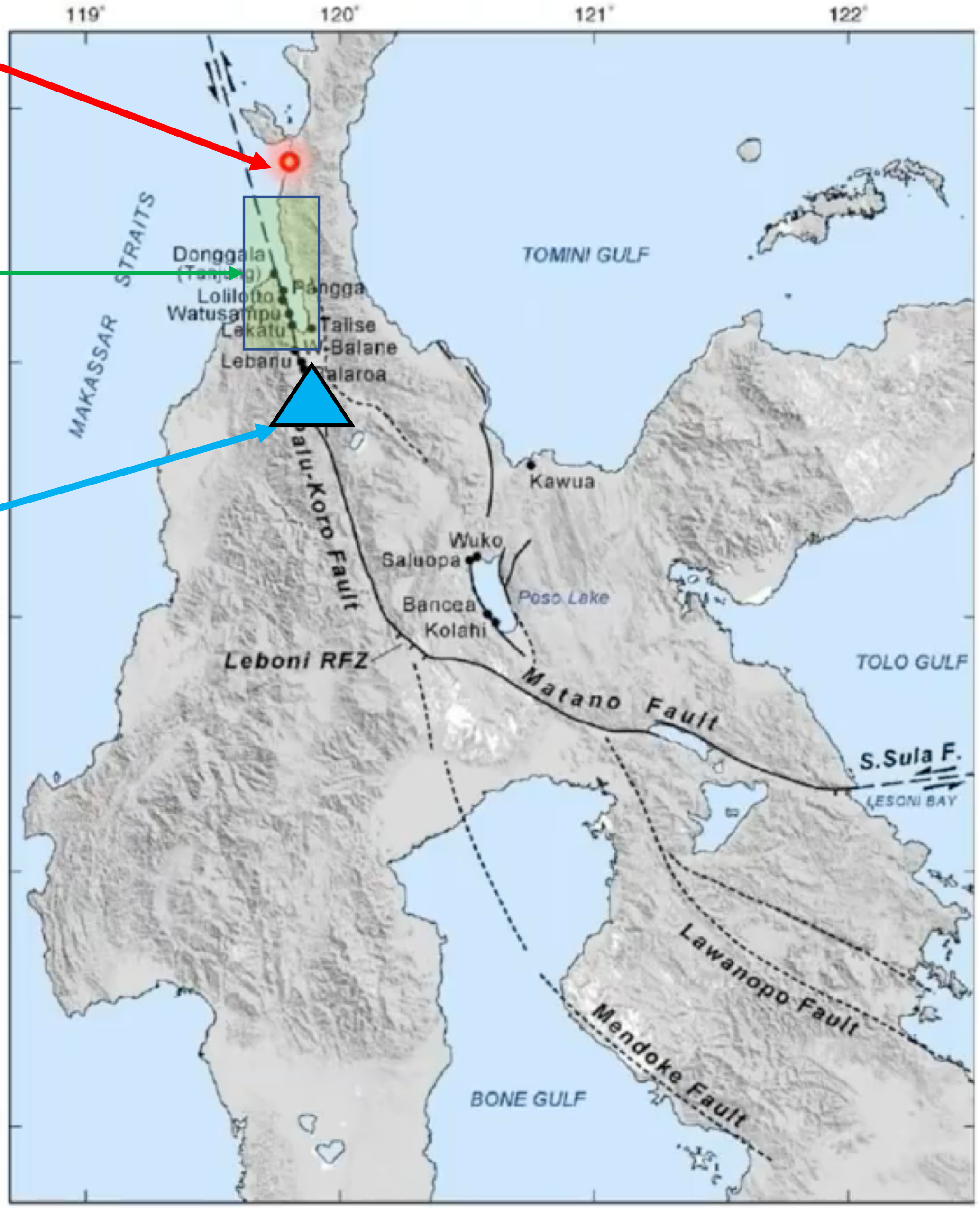
Part 2: SEBP

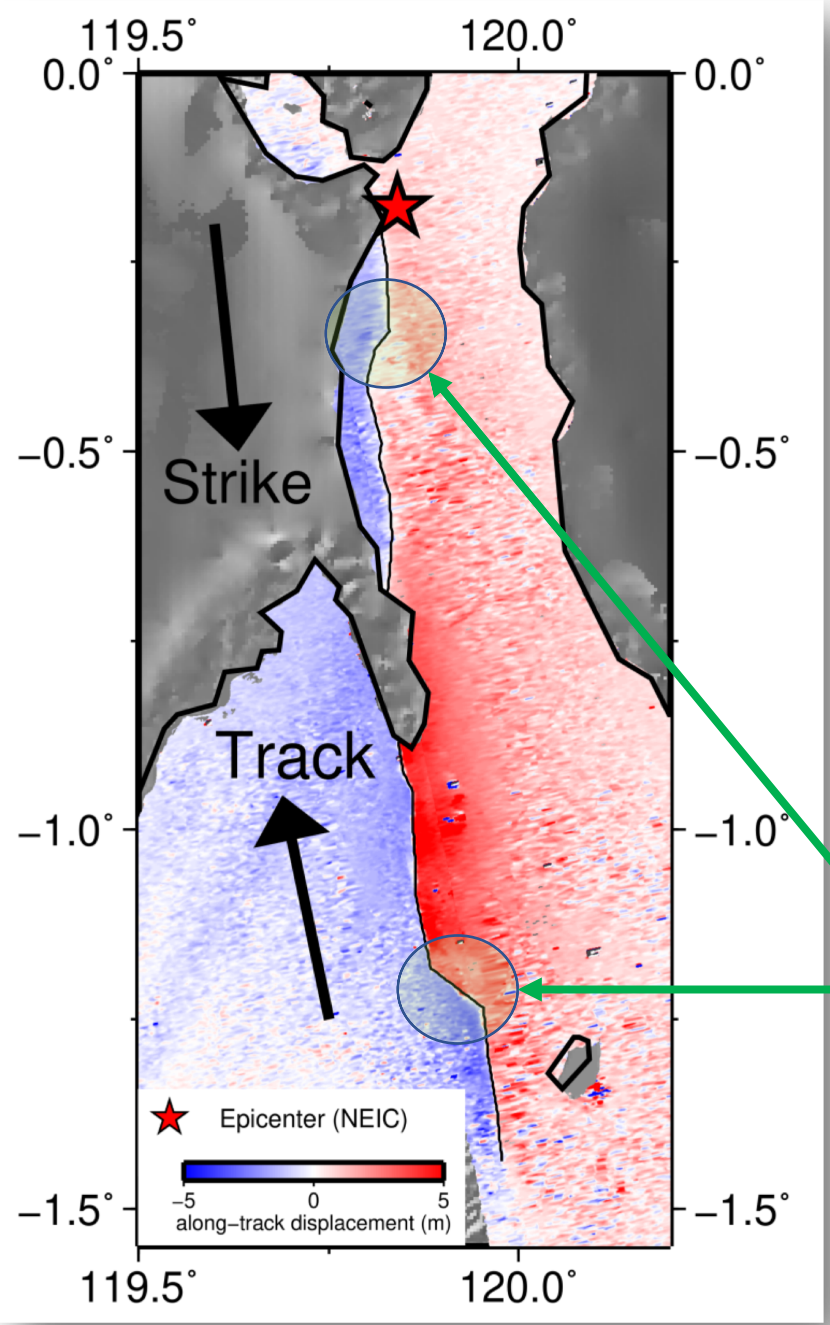
- Slowness-Enhanced Backprojection
  - Improvement of accuracy
  - Better source properties estimation
- Optimization and Application

Epicenter

Palu Bay

Palu City



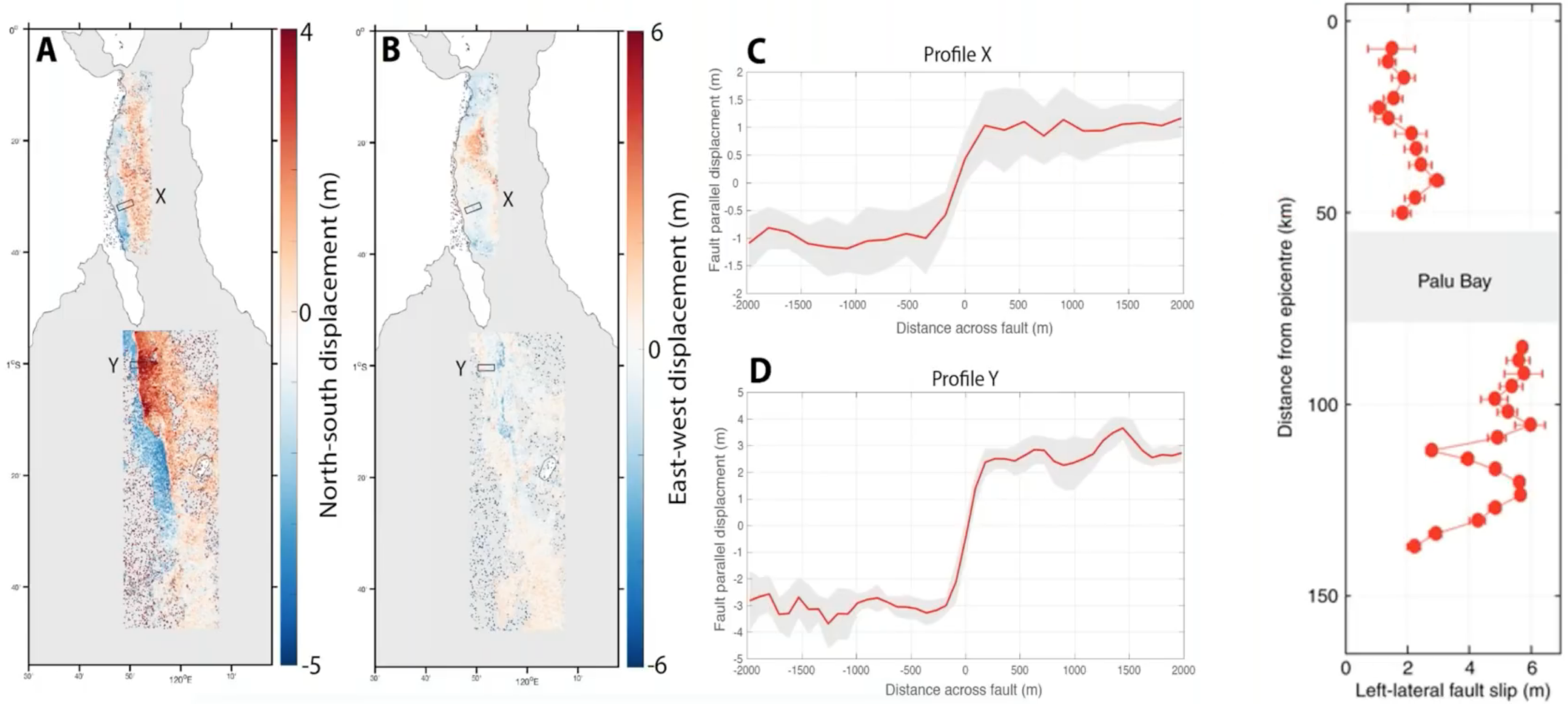


Remote sensing observations of surface rupture

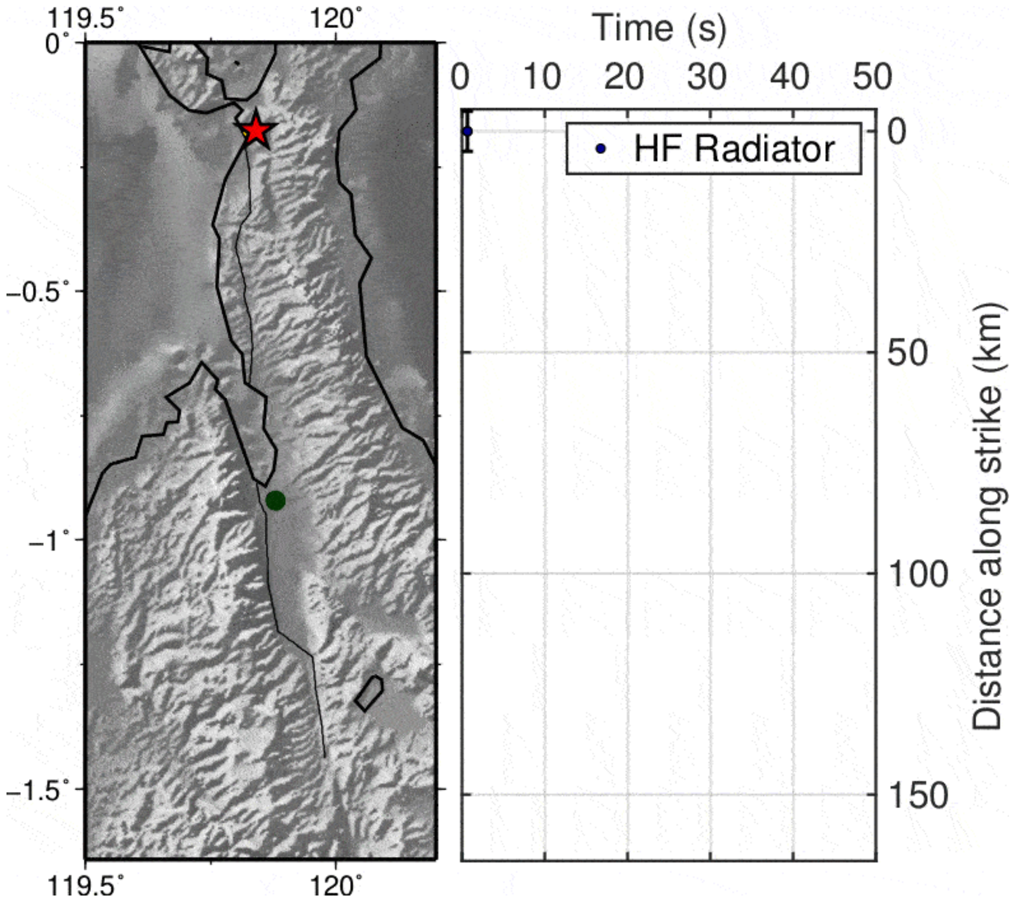
- Along-track displacement from ALOS-2
- Southward rupture length ~150 km
- Large slip (~6m) in Palu city
- Some portions of the fault are quite straight, but there are also visible bends and kinks.

Remote sensing observations of surface rupture

Optical pixel tracking analysis of Sentinel 2 and Planet Labs images



Teleseismic observations of rupture speed
1. Back-projection rupture imaging



Slowness-enhanced Back-projection (SEBP)

Southward rupture length ~150 km

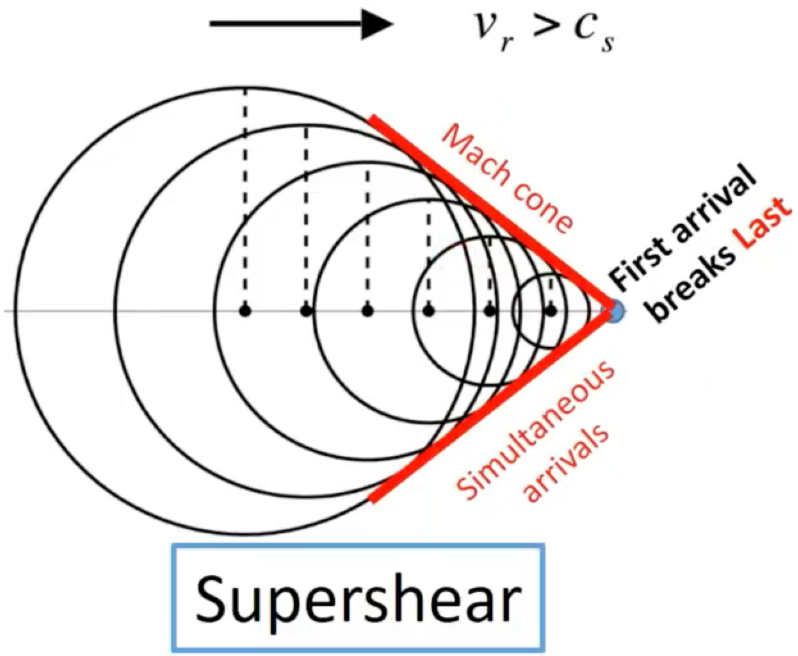
A **supershear** earthquake:
Rupture speed faster than S waves

Steady and fast rupture despite large fault bends

Local Vs = 3.6 km/s
(Crust 1.0)

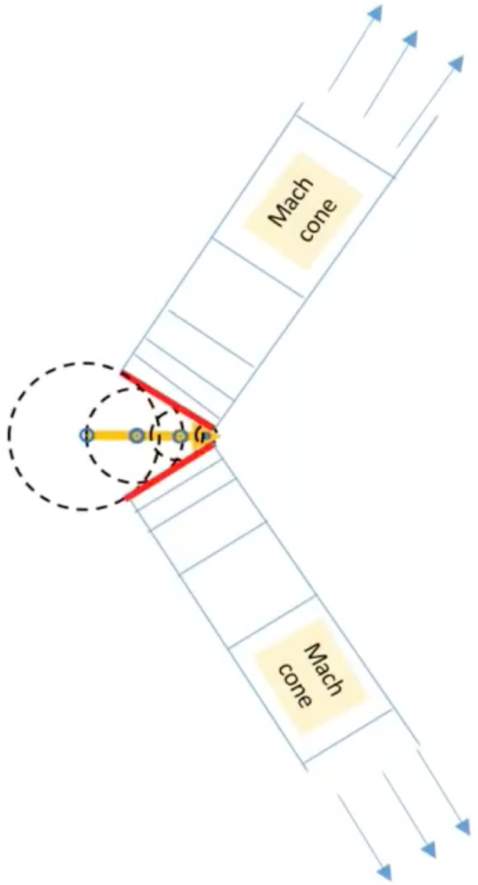
Teleseismic observations of rupture speed
2. Surface wave Mach cone

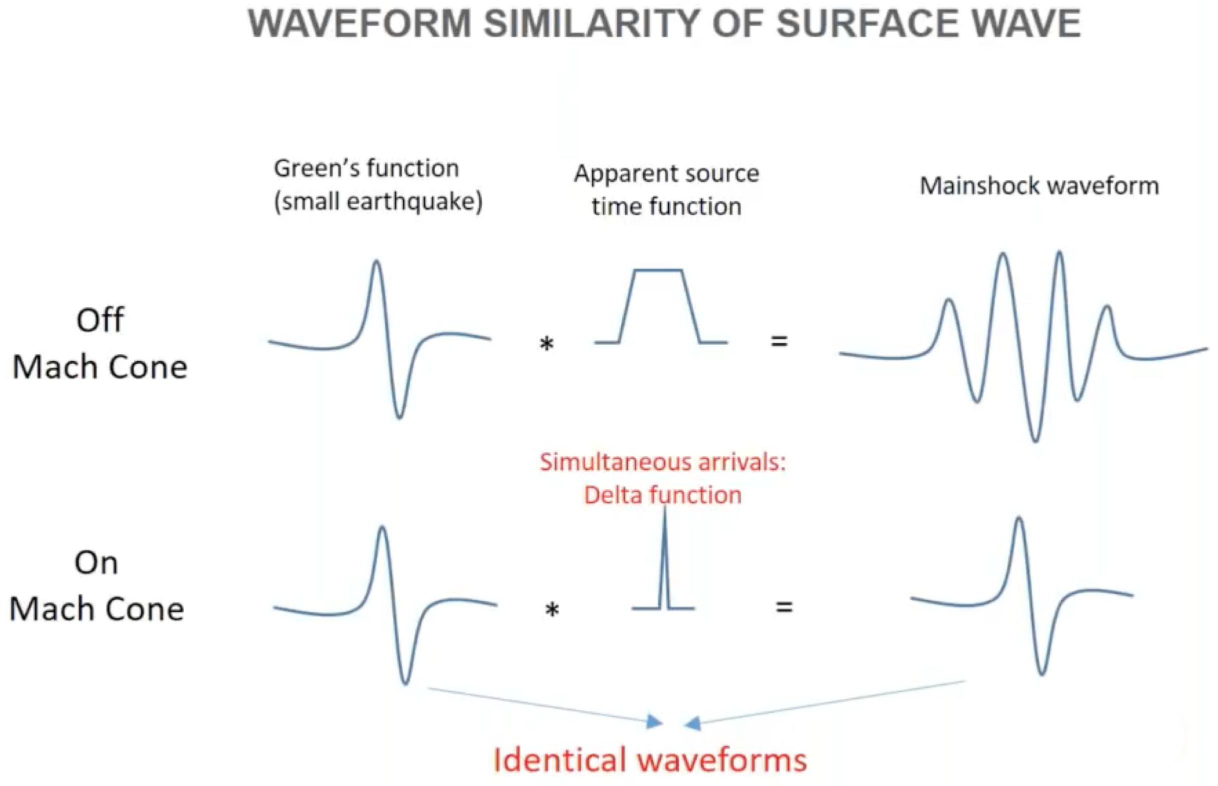
Sonic boom generated by
supersonic jet plane



Modified from Eric Dunham's website

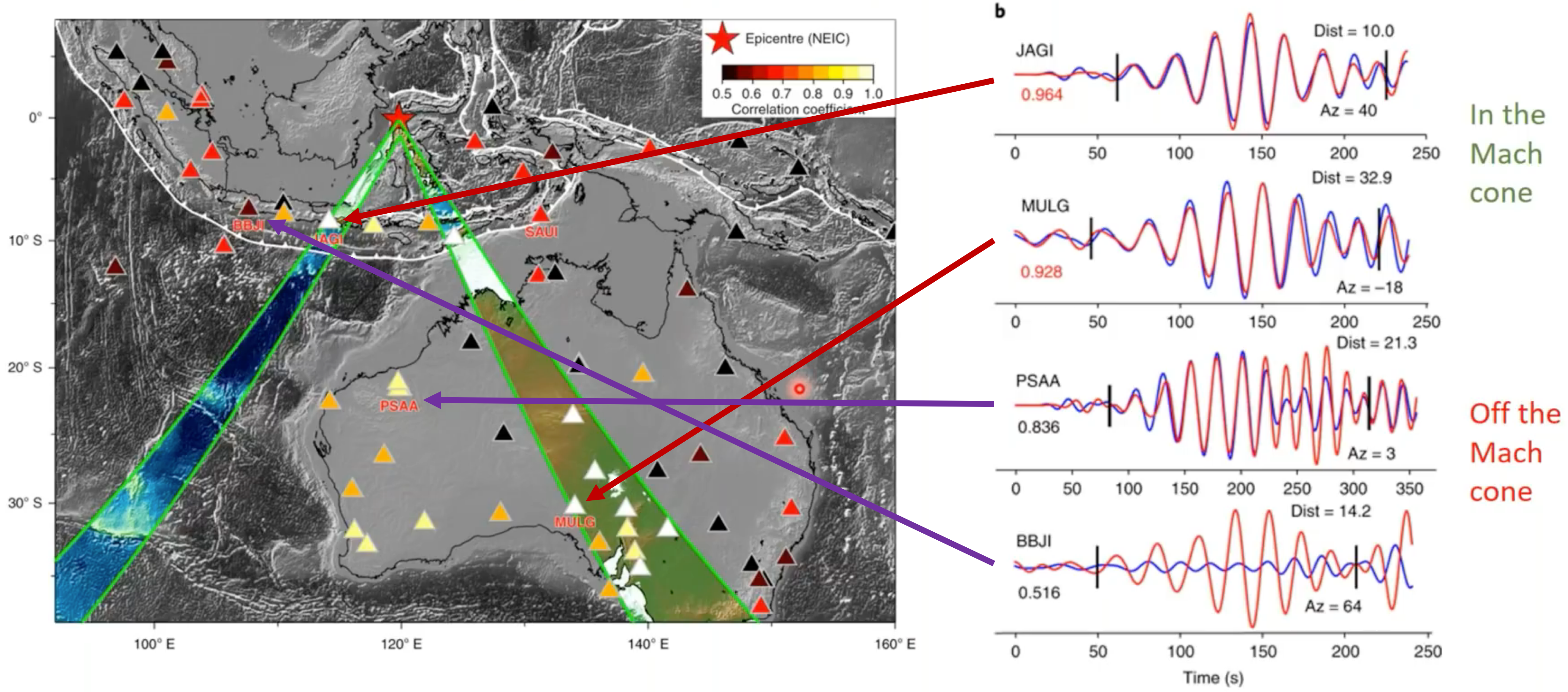
Teleseismic observations of rupture speed
2. Surface wave Mach cone



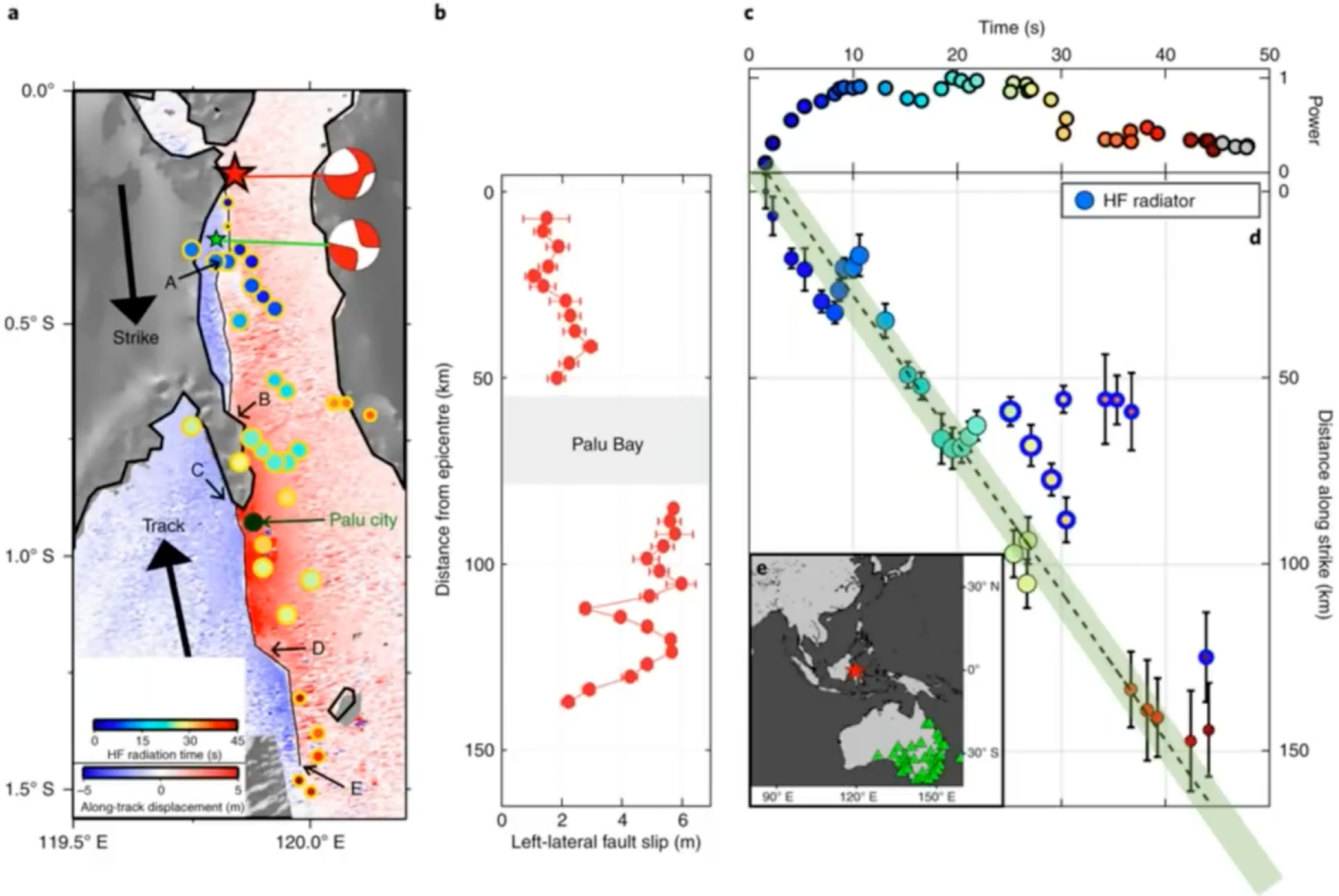


Following Vallée and Dunham, 2012

Teleseismic observations of rupture speed
2. Surface wave Mach cone



Teleseismic observations of rupture speed



Rupture speed ≈ 4.1 km/s

Fast speed from early on

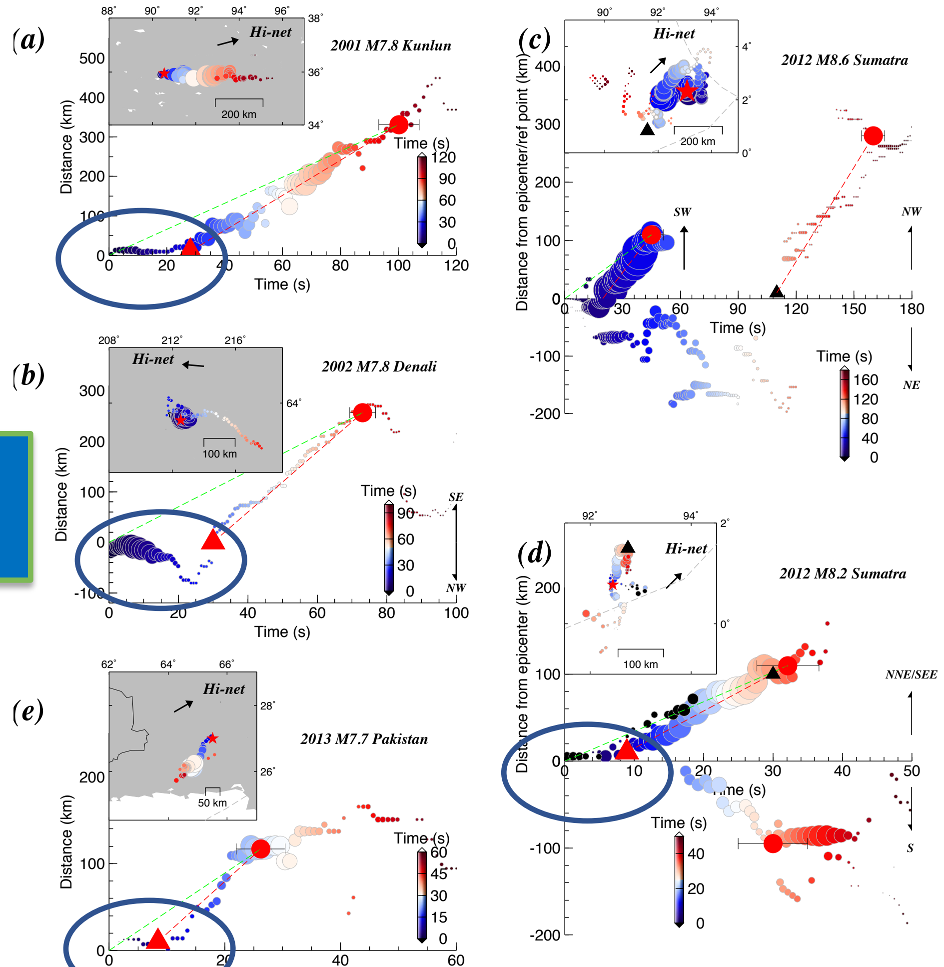
Steady despite fault bends

Overview

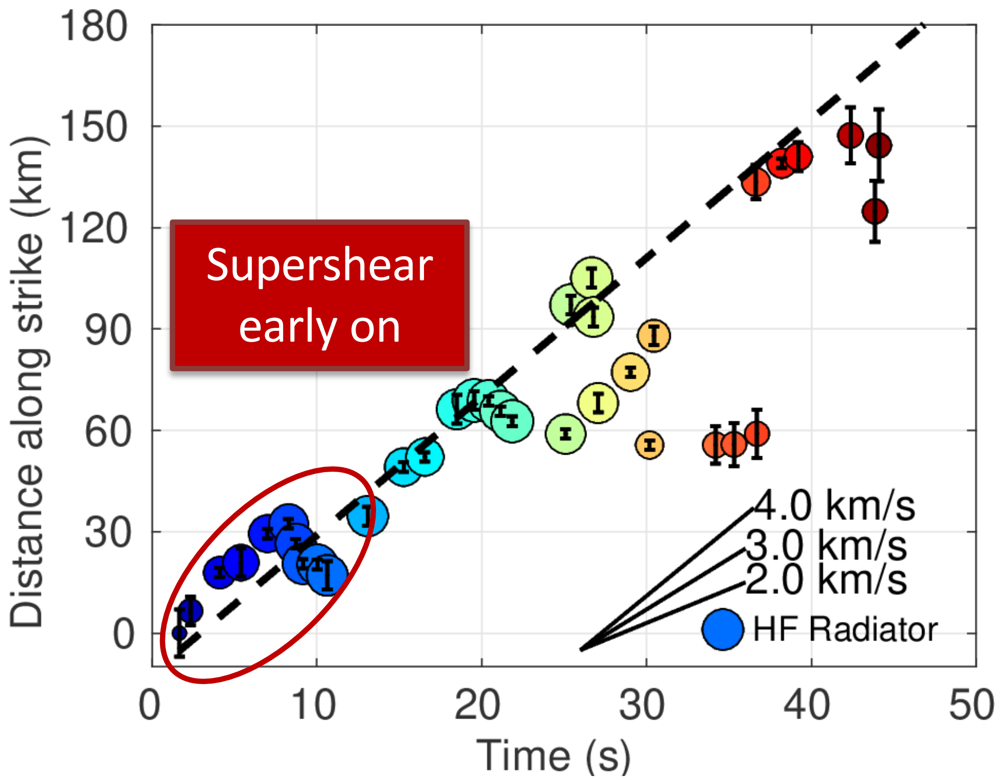
- Static Observations
- Dynamic Observations
- Implications
  - Short transition distance
  - Unstable supershear speed
  - Steady supershear despite kinks

Early Supershear Ruptures

Subshear initiation



Wang et al., 2016



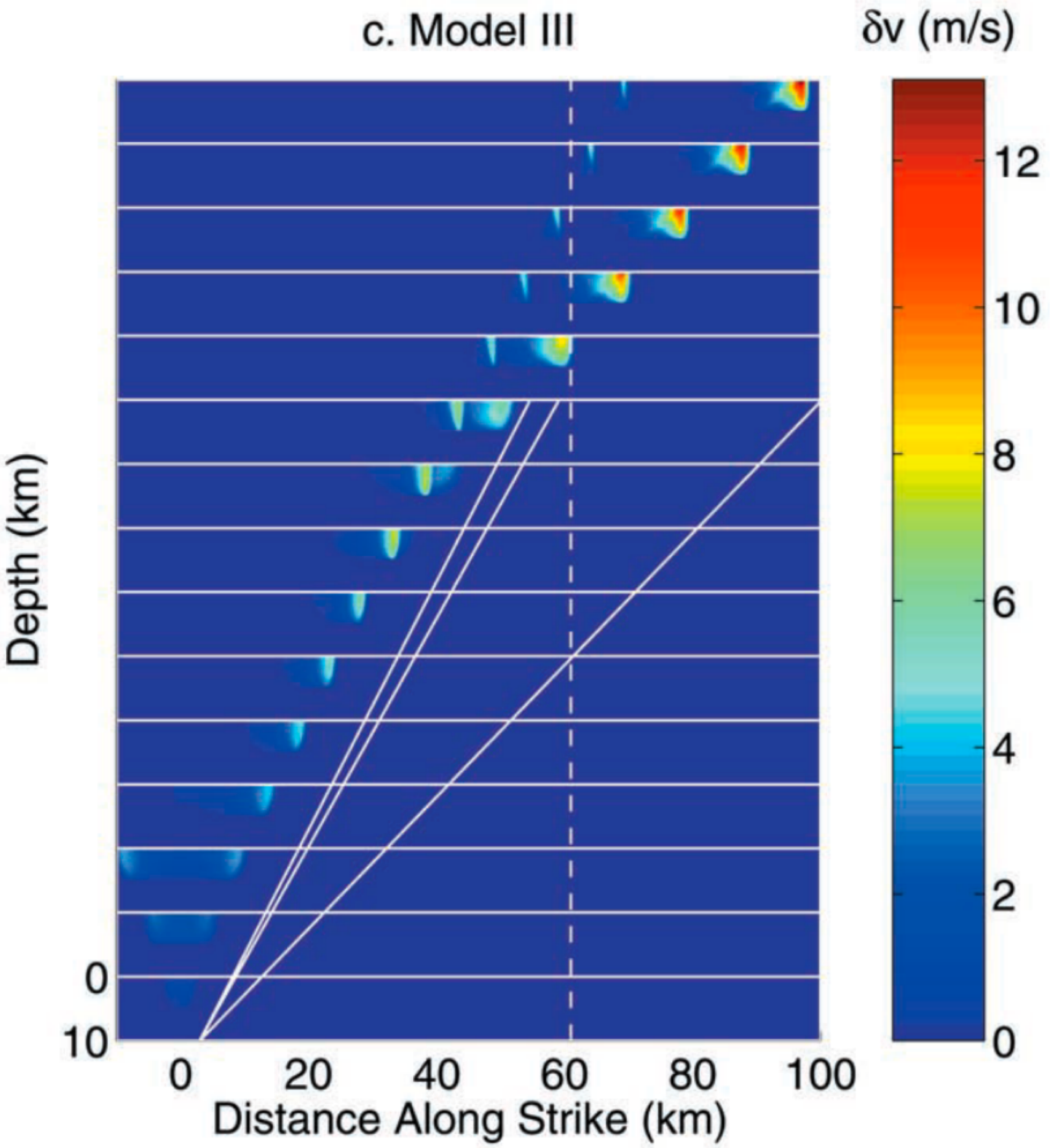
Daughter-Crack

- Dynamic Stress Transfer

Elastic wave transmit stress with a speed faster than rupture propagation

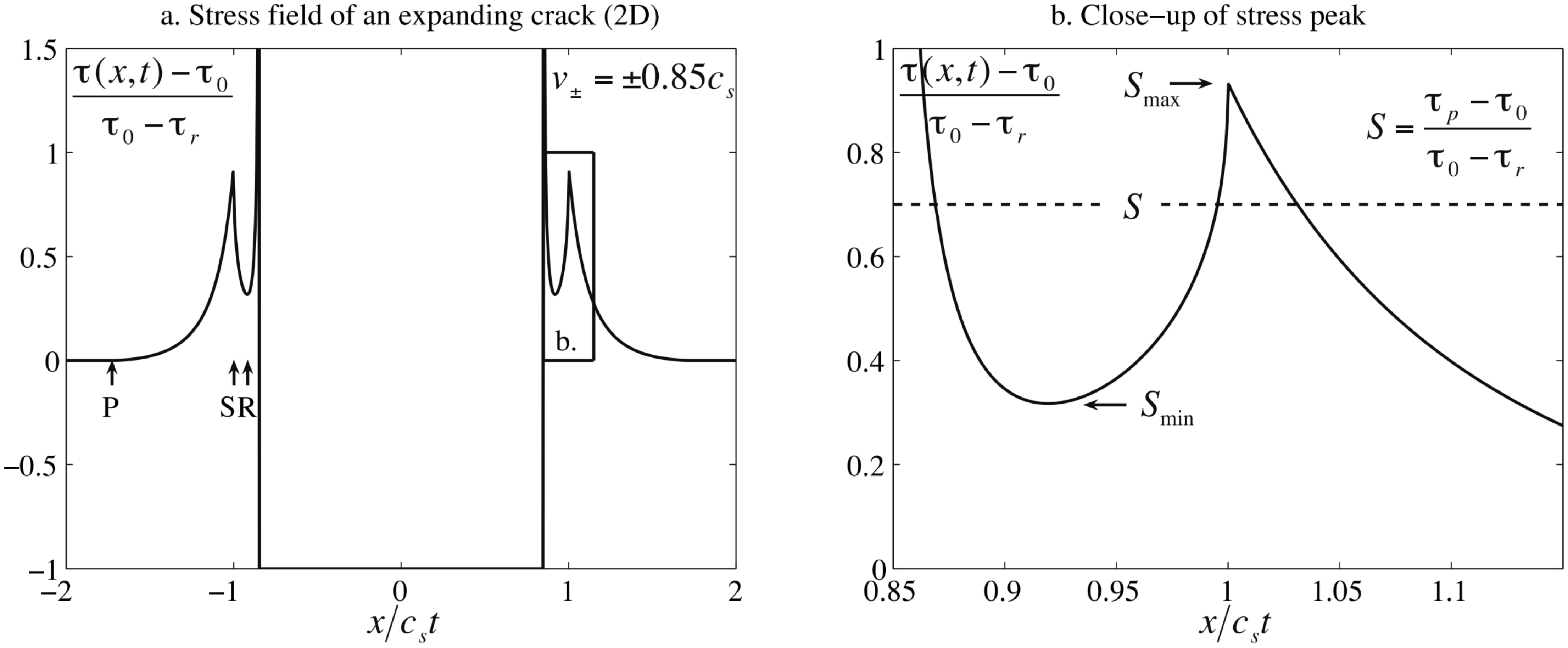
- Exceeding peak strength of the fault

- Initiating slip with a Daughter-Crack



Dunham & Archuleta (2004)

Daughter-Crack

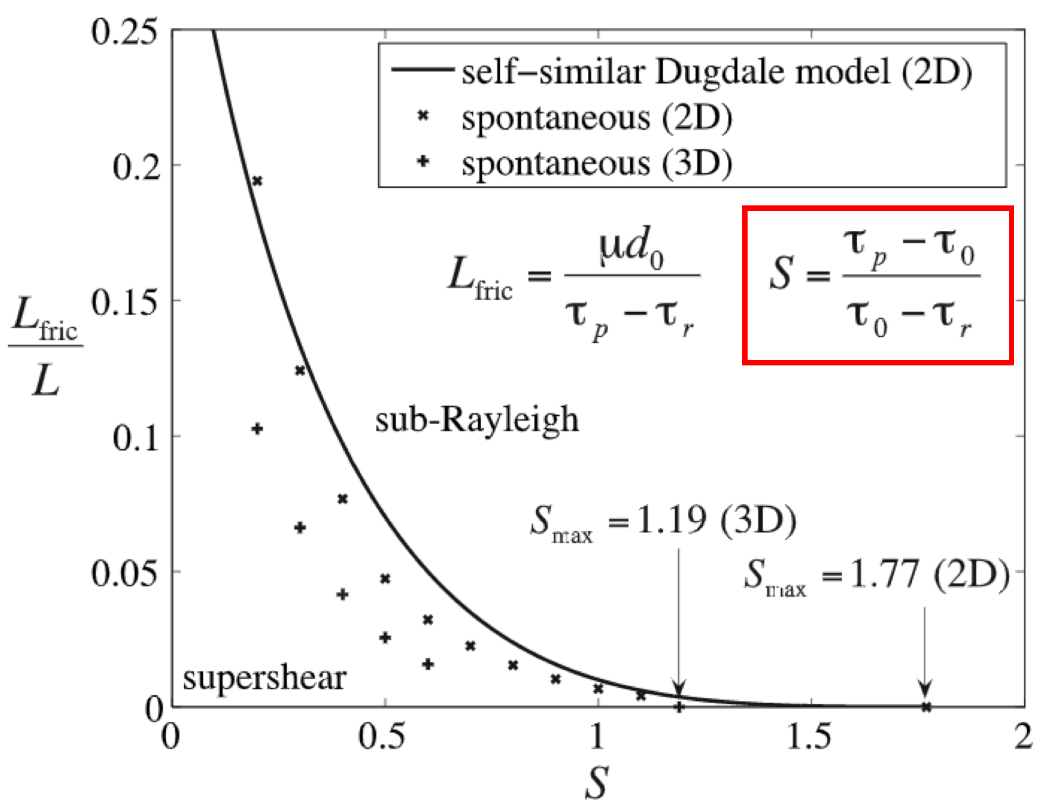


Dunham, 2007

Interpretations

Supershear Transition length as a function of seismic S ratio

Normalize Transition Distance



Higher initial stress

Dunham, 2007

Transition distance can be caused by:

- high initial shear stress level
- short critical slip-weakening distance

Possibly high initial **stress concentrations** due to the M6.1 foreshock or to fault roughness.

Supershear earthquakes

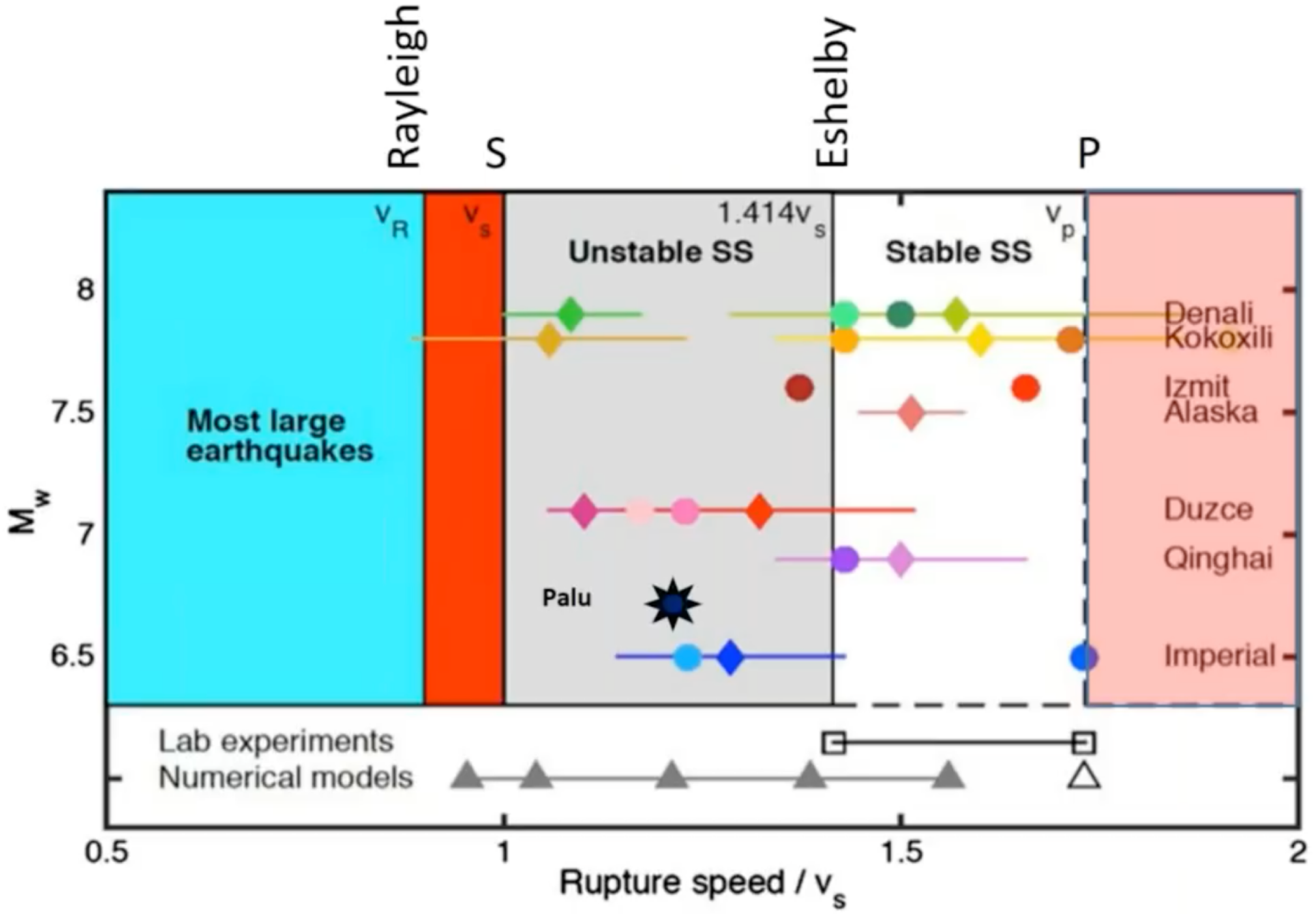
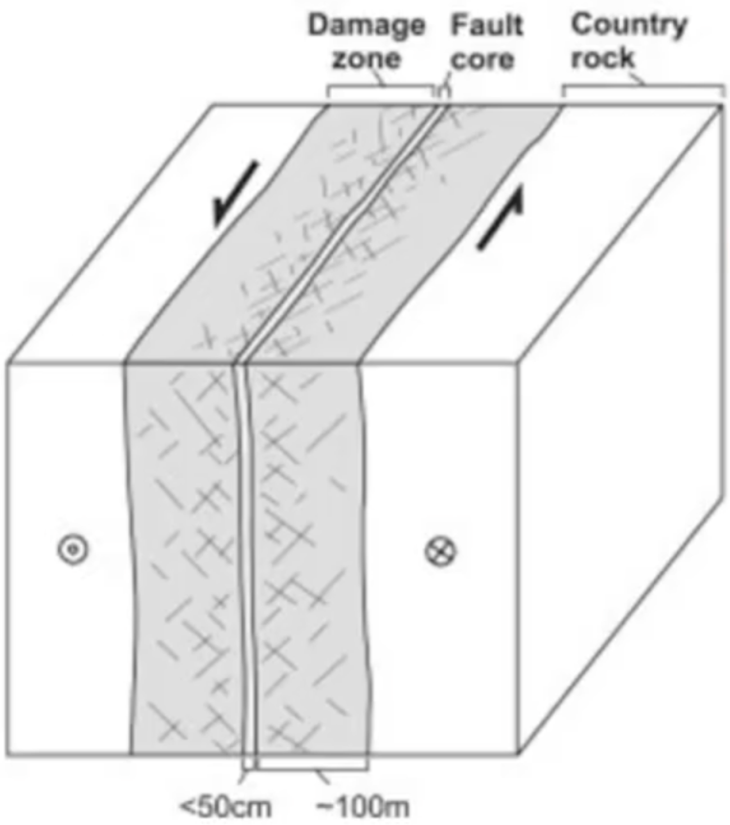


Figure modified from Huang et al., 2016

Damaged Fault Zone

Punchbowl fault, CA
(Chester and Chester, 1998)

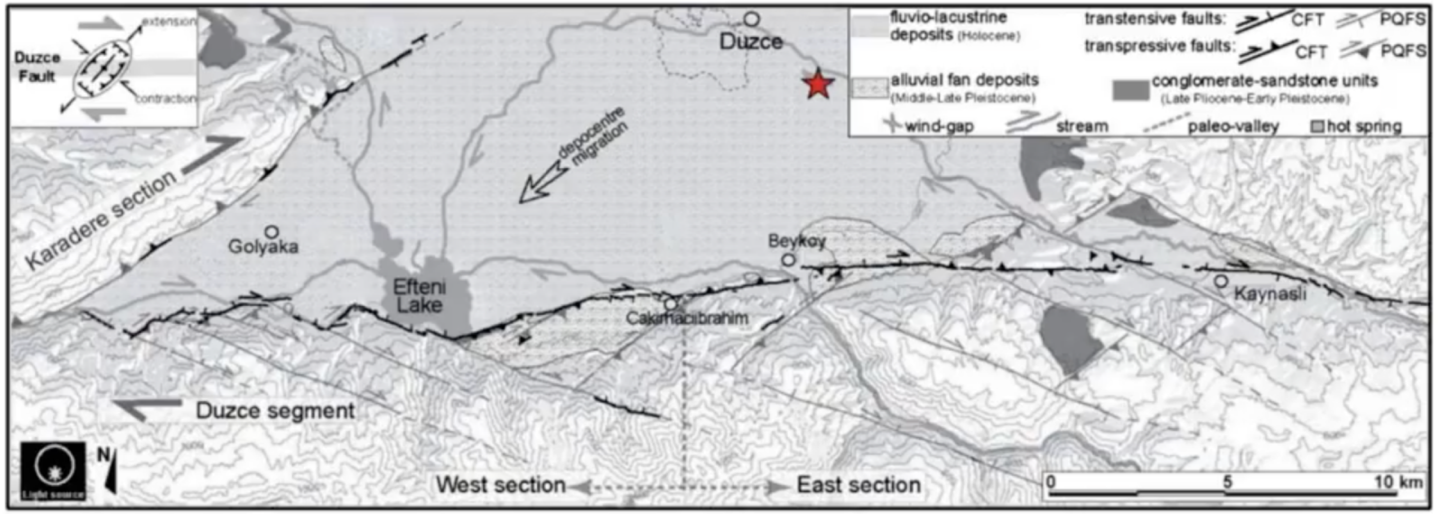


Y. Huang and J.P. Ampuero (2012)

- Easily **30% drop** of the seismic wave speed.
- **Shorten** the transition distance

Supershear earthquakes

1999 Mw 7.6 Izimit

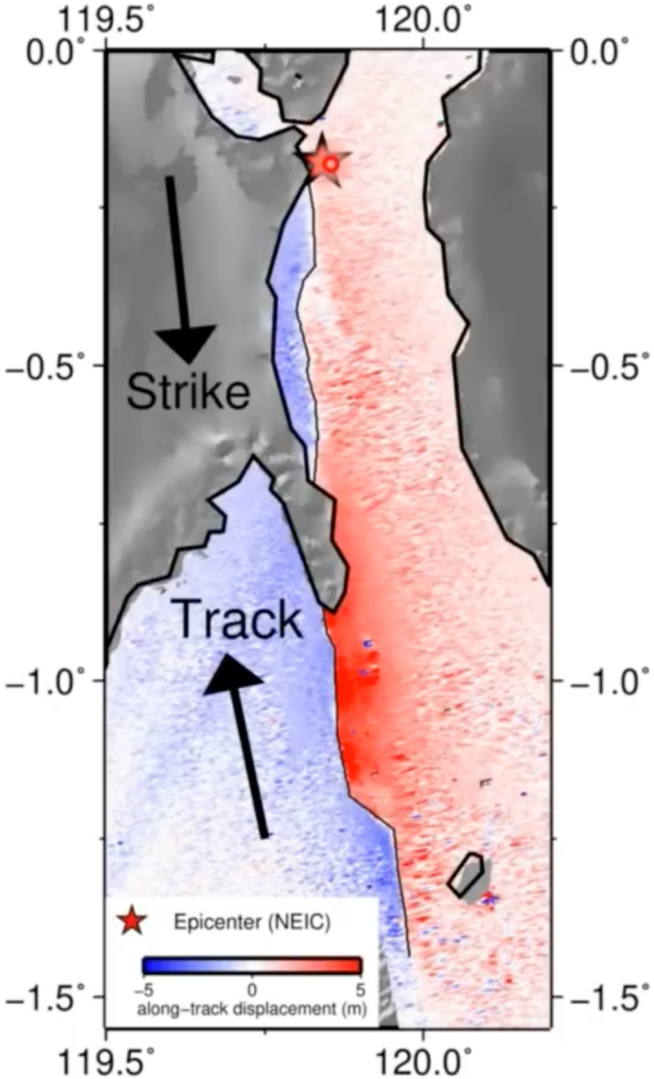


staircase trajectory

sub-Rayleigh

straight trajectory

supershear

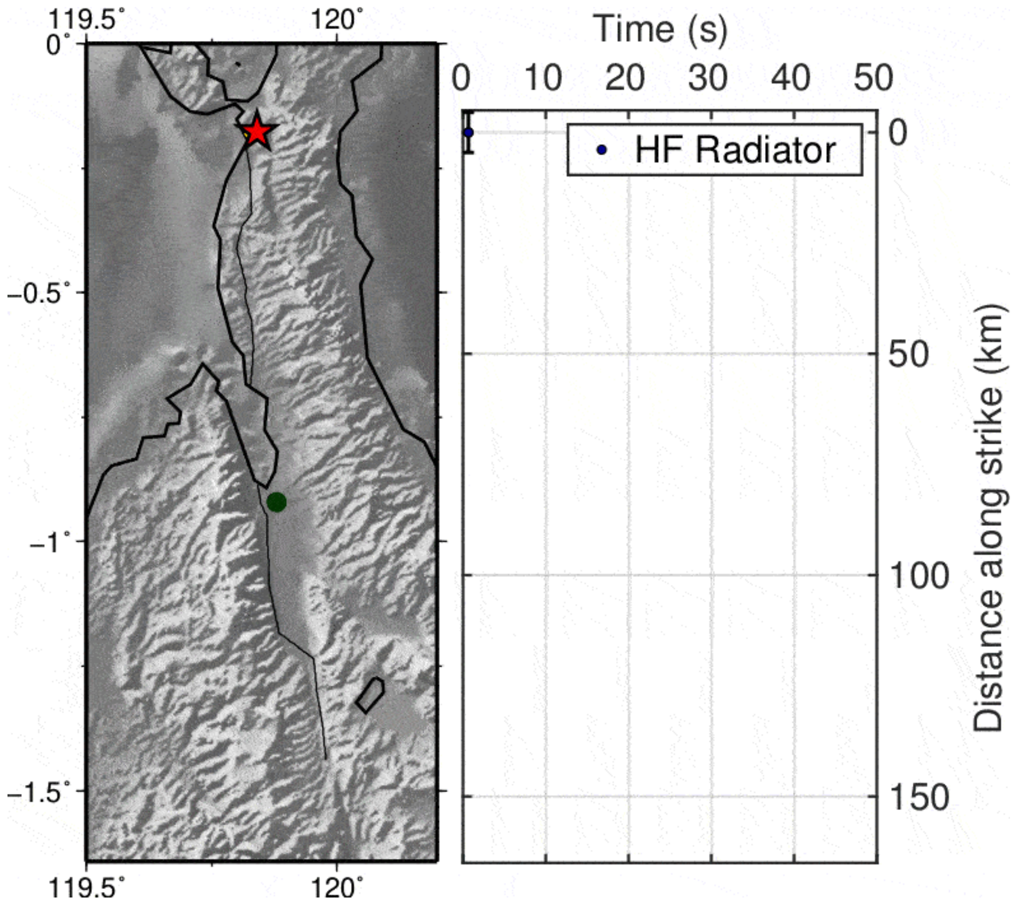


"In all the documented observations of supershear ruptures, a striking common feature is the simple geometry of the fault. Its surface expression is always remarkably straight and continuous."

(Bouchon et al, 2010)

Supershear rupture of the 2018 Mw 7.5 Palu earthquake

Summary



- Observations:
  - A supershear earthquake from early on
  - Steady and fast despite major fault bends
  - Supershear but slower than expected
- Open questions:
  - What is the condition of the local damage zone?
  - Did supershear contribute to a cascade of secondary effects?

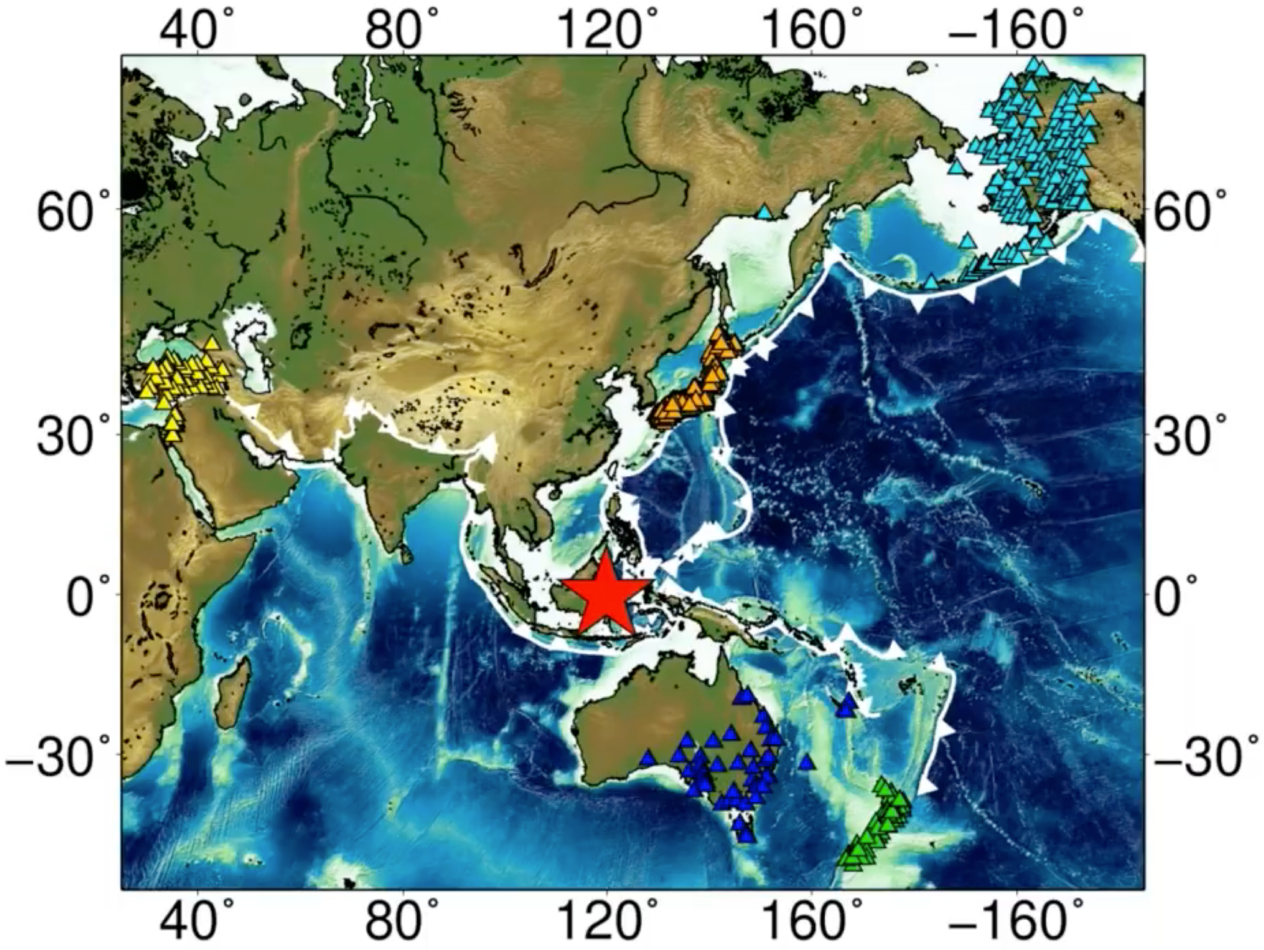
    (shaking -> submarine landslide -> tsunami)

Extra Slides for question: Palu

Extra Slides for question: Back-projection

Arrays we considered:

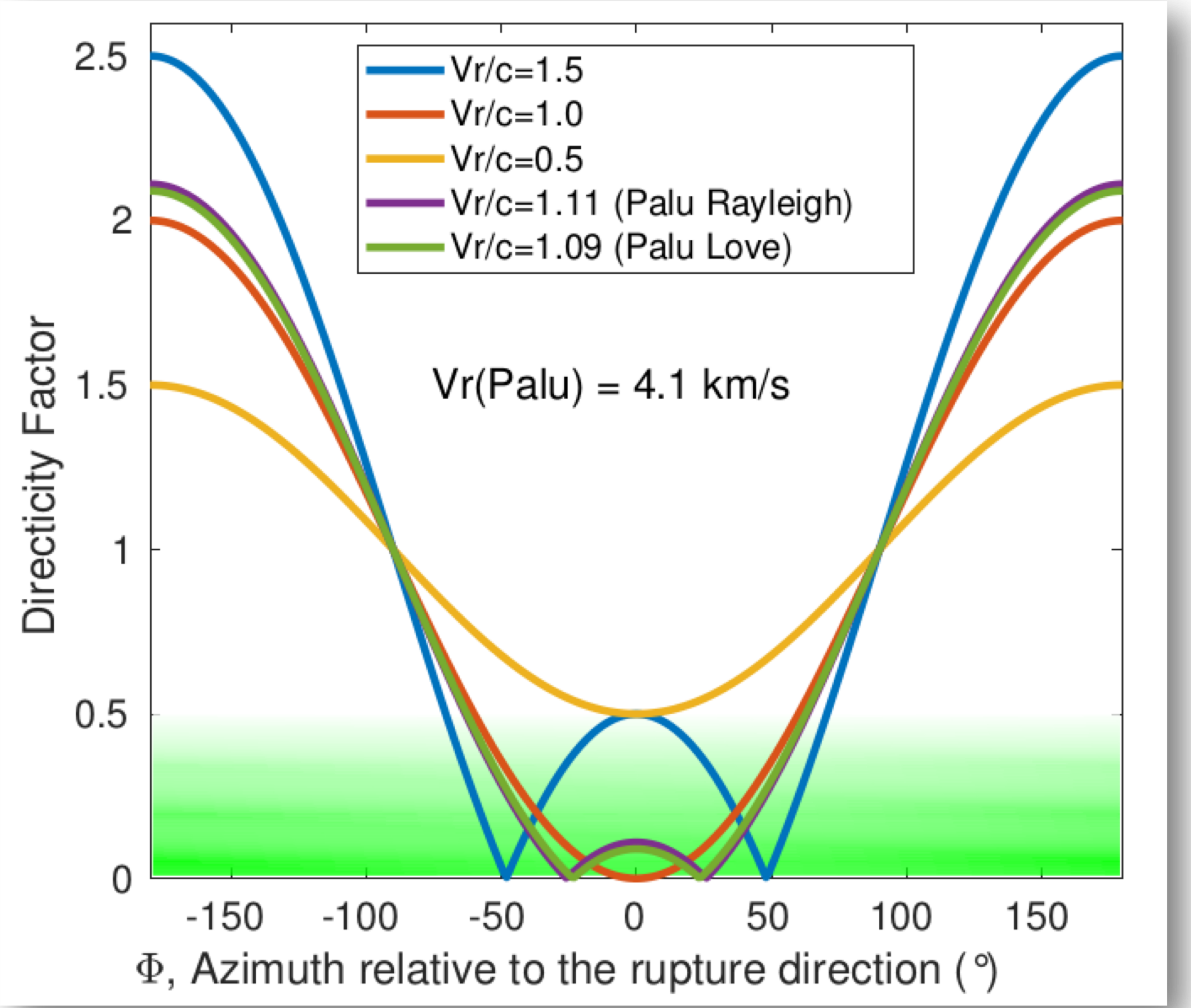
Australia
New Zealand
Turkey
Japan
Alaska



Directivity Factor (D)

$$\left[1 - \frac{v_r \cos\phi}{c(\omega)}\right]$$

Spectral Stretching
Spectral Compressing



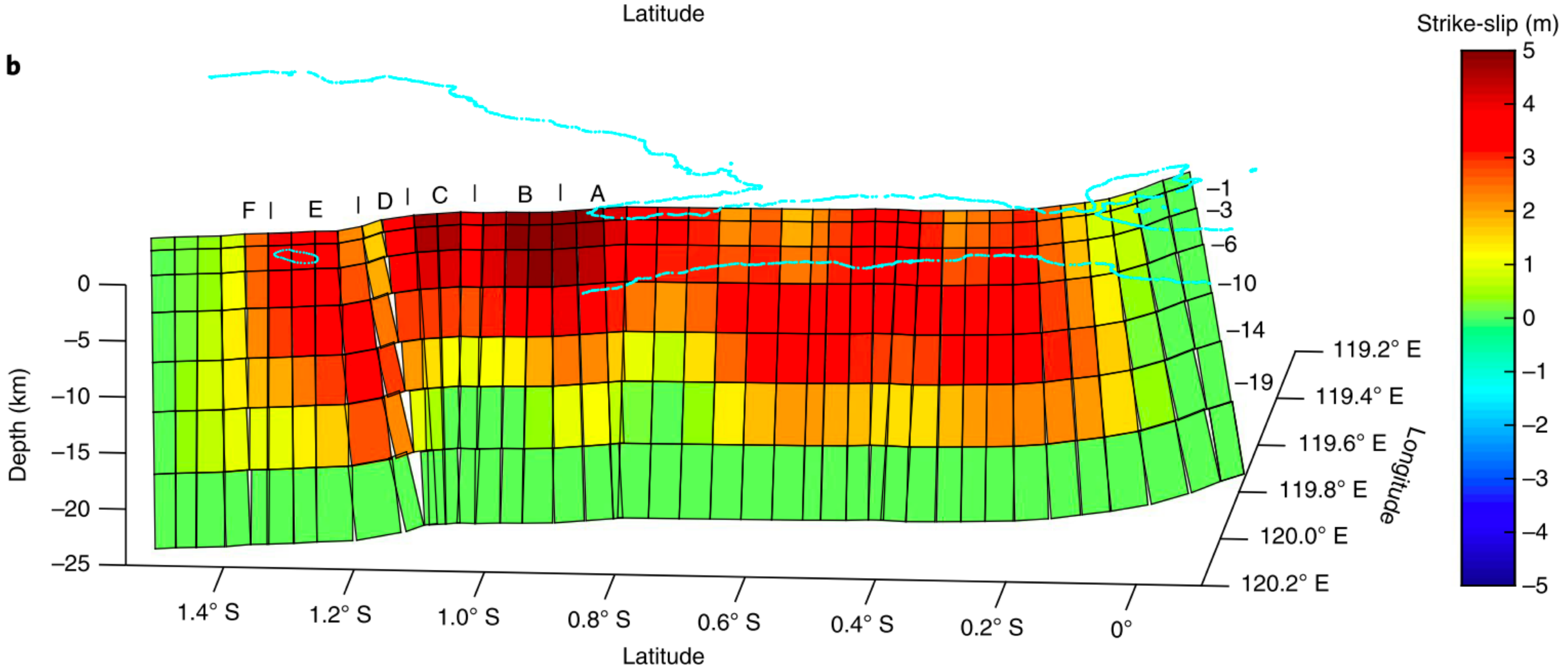
The Mw 7.5 Palu earthquake, 28/09/18

Tsunami

AFP

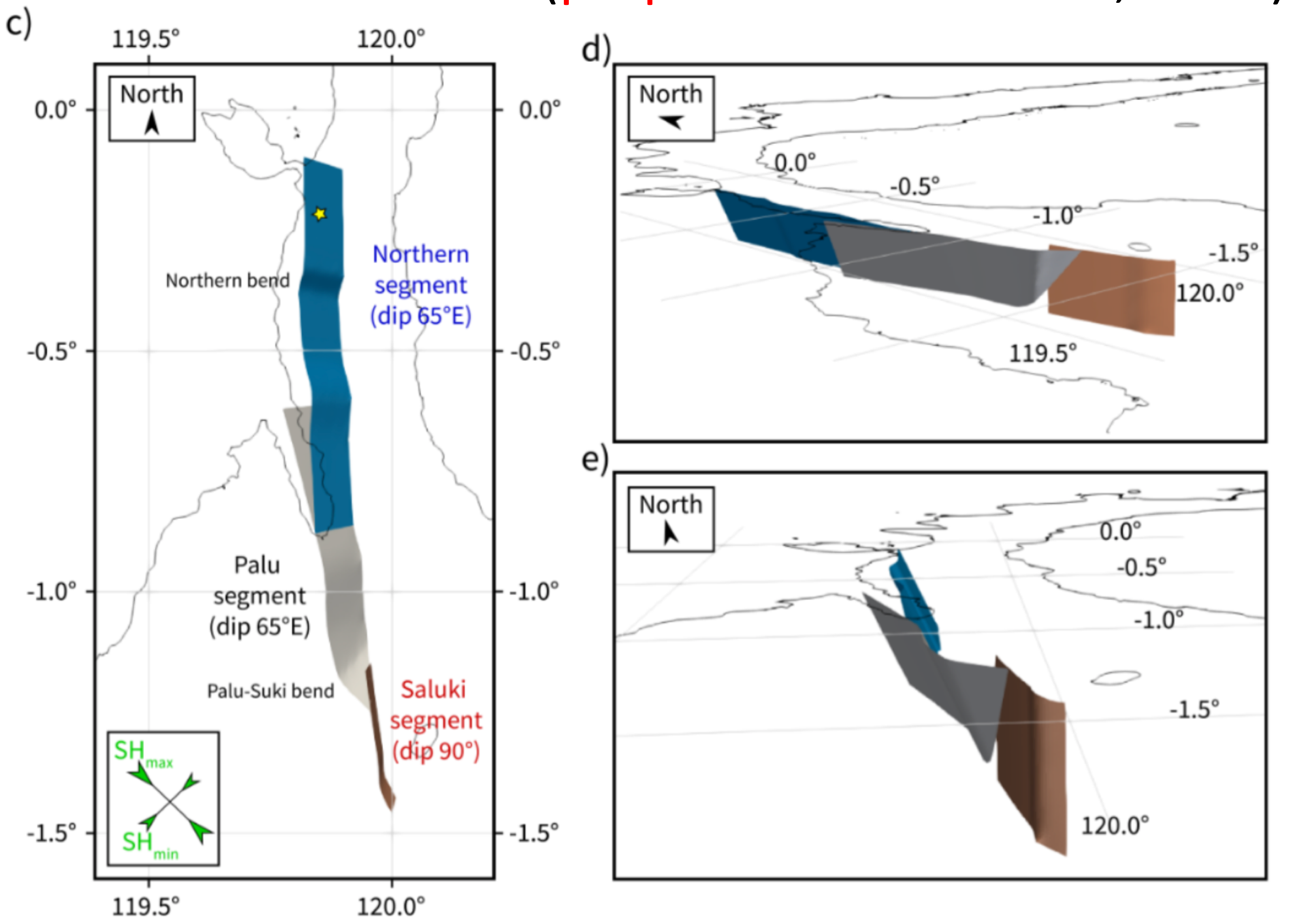
Landslides/liquefaction

Reuters

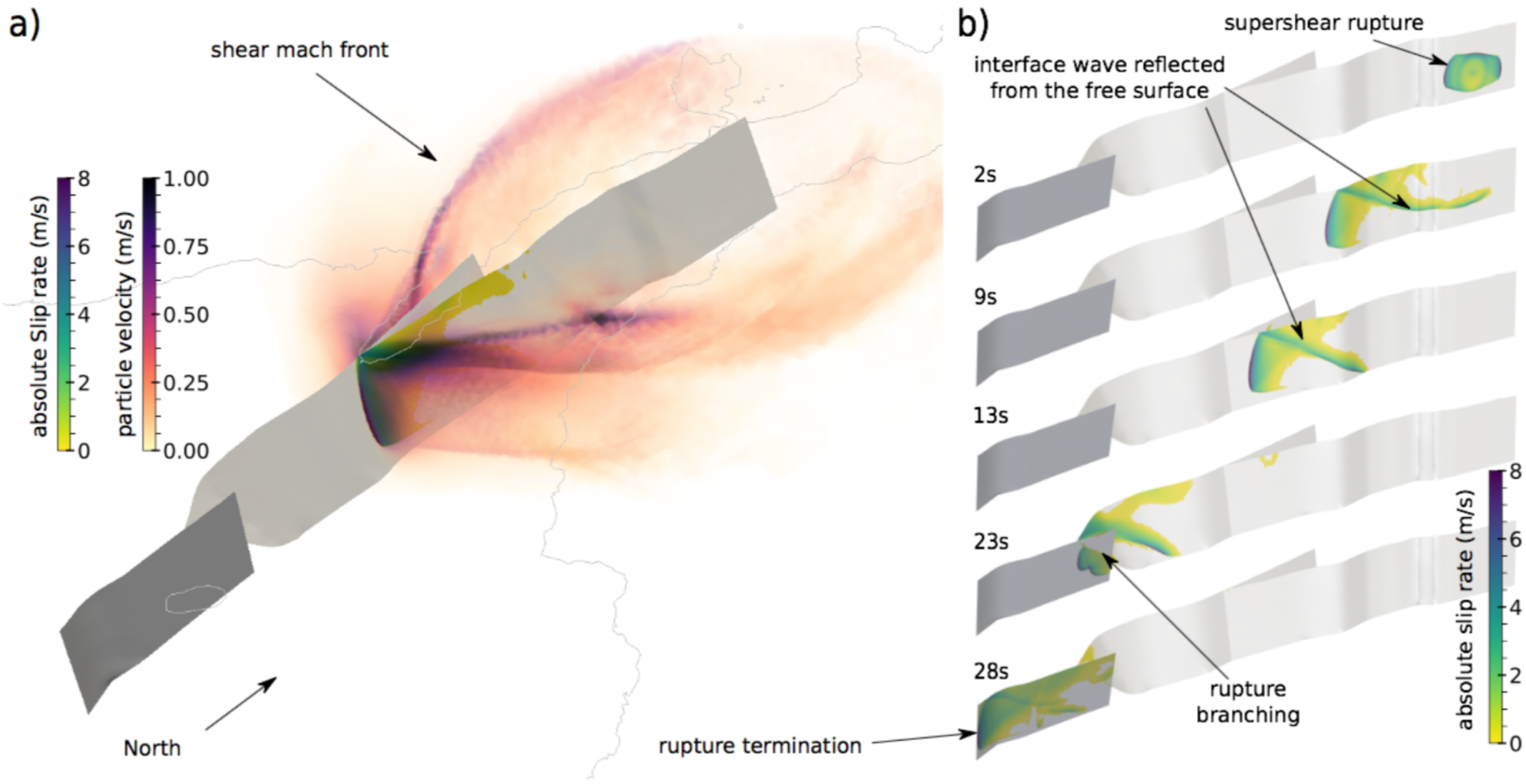


Socquet et al. (Nat Geo, 2019)

Ulrich et al. (preprint on EarthArXiv, 2019)



Ulrich et al. (preprint on EarthArXiv, 2019)



Overview

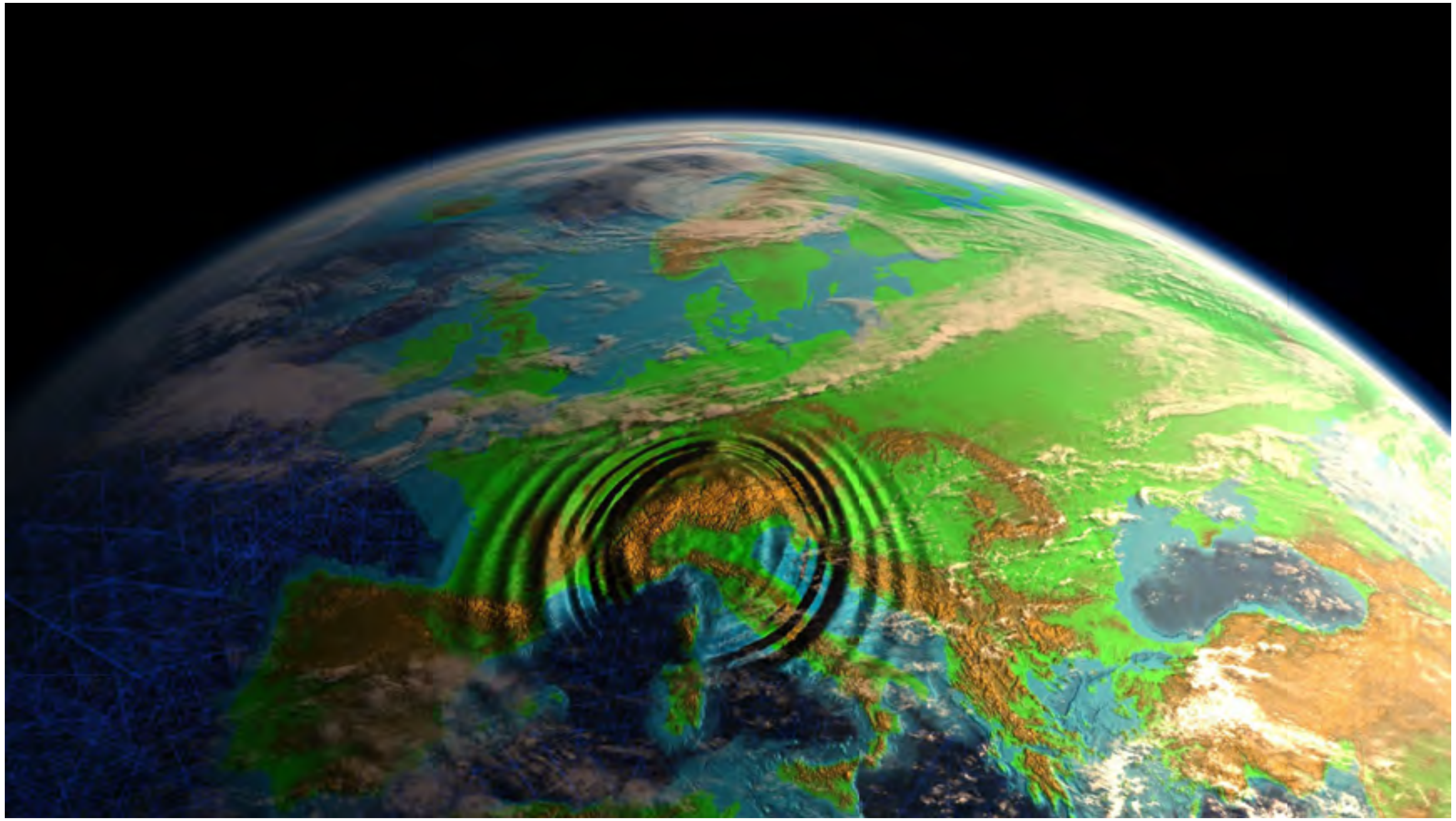
Part 1: Palu Earthquake

- Static Observations
  - Radar and image satellites
- Dynamic Observations
  - Teleseismic Back-projection
  - Surface Mach wave/Mach cone
- Implications

Part 2: SEBP

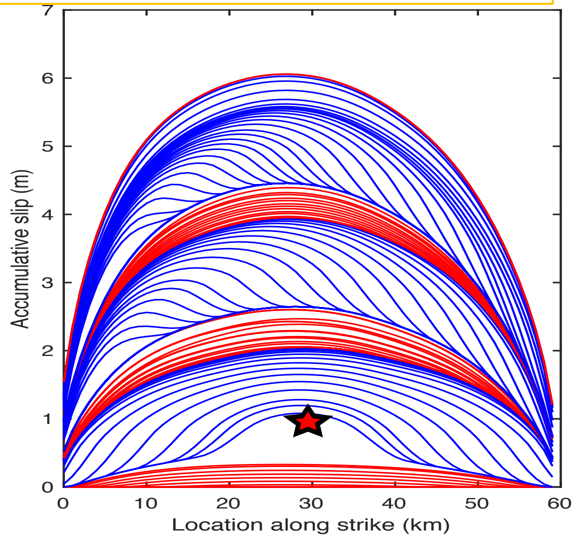
- Slowness-Enhanced Backprojection
  - Improvement of accuracy
  - Better source properties estimation
- Case Applications

motivation

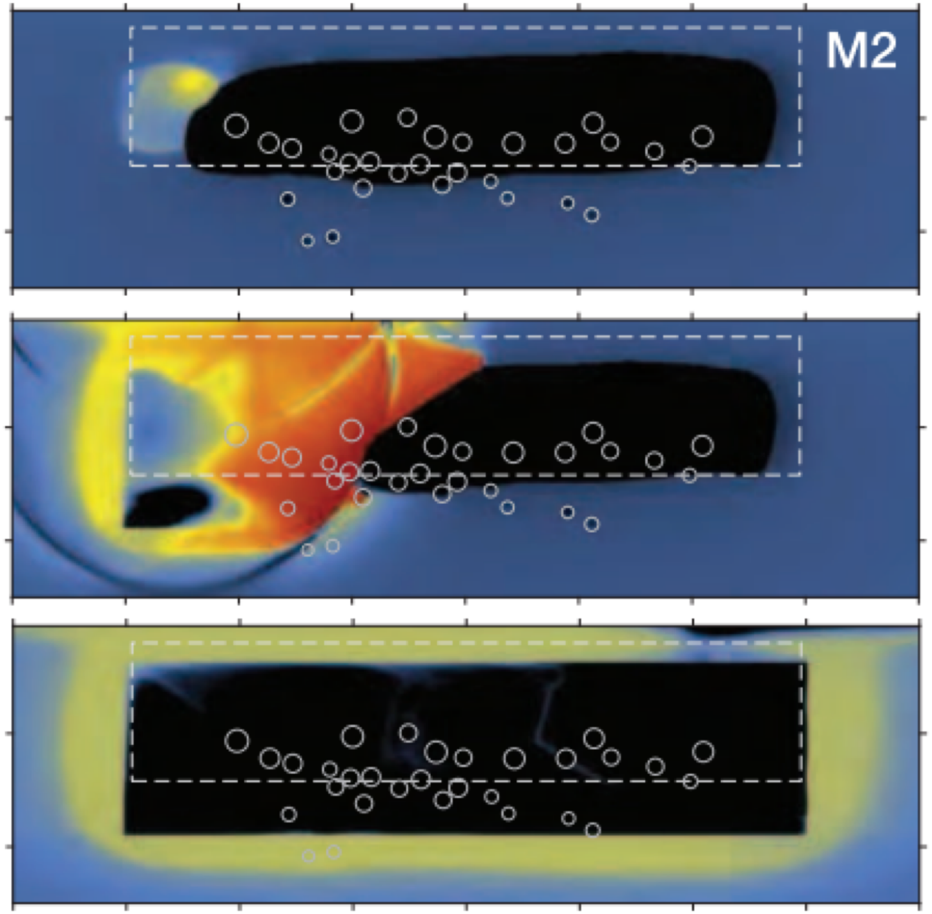


A better understanding of earthquake sources

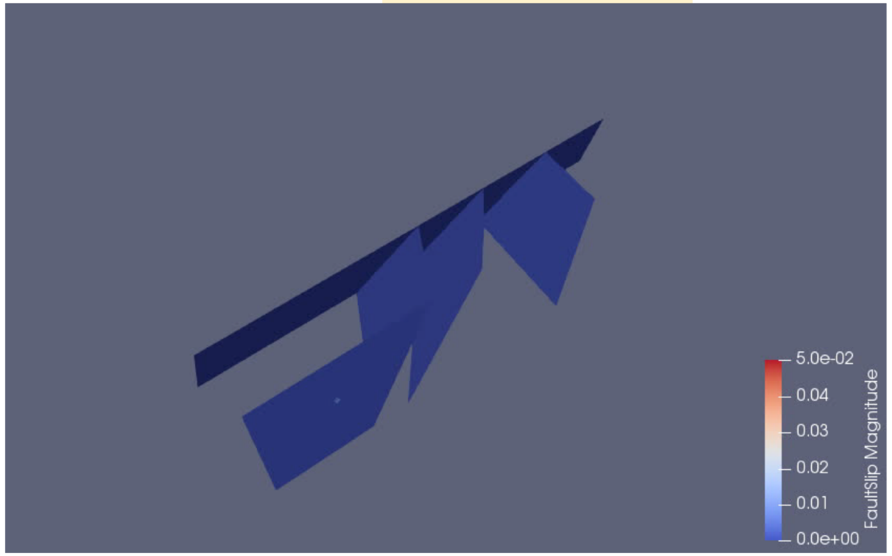
Earthquake Cycle



Xie and Meng



Jiang and Lapusta (2016)



(Zhang, Wu, Meng, Kyriakopoulos, Oglesby, Fang)

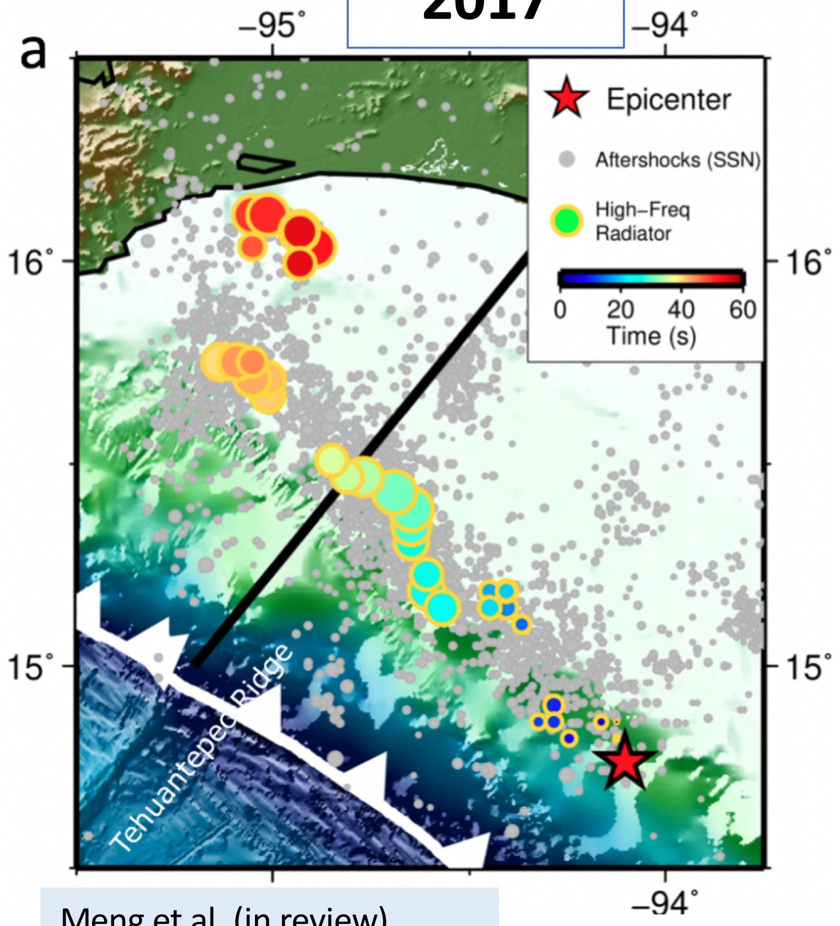
Rupture propagation

challenge:

Observation’s uncertainty

- Rupture properties:
  - Length?
  - Direction?
  - Speed?

Mexico 2017

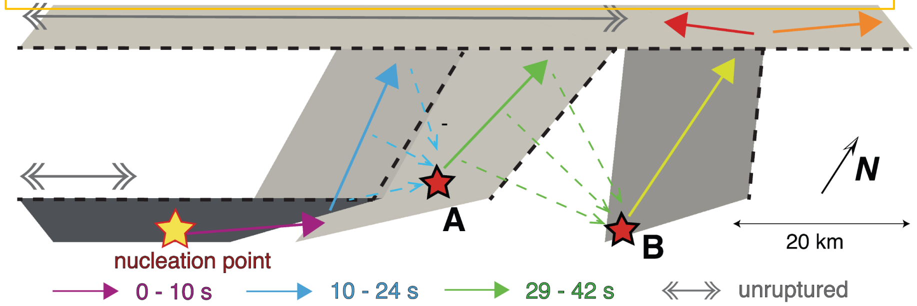


Meng et al. (in review)

challenge:

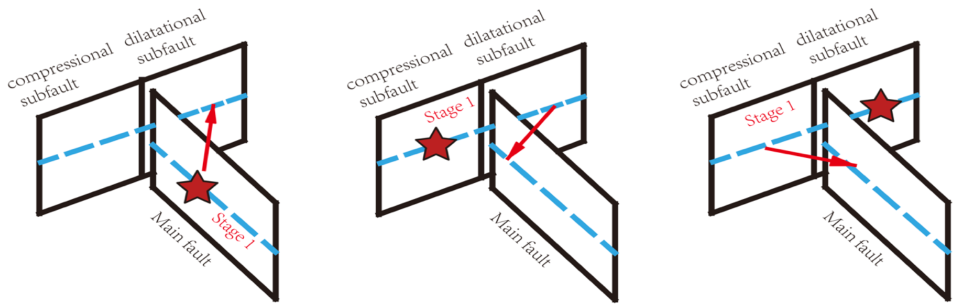
Observations' fall-behind

Dynamic model of the 2016 Mw 7.8 Kaikoura earthquake



(Zhang, Wu, Meng, Kyriakopoulos, Oglesby, Fang)

Earthquake Cycle Simulation of 2012 Mw 8.6 Indian-Ocean earthquake



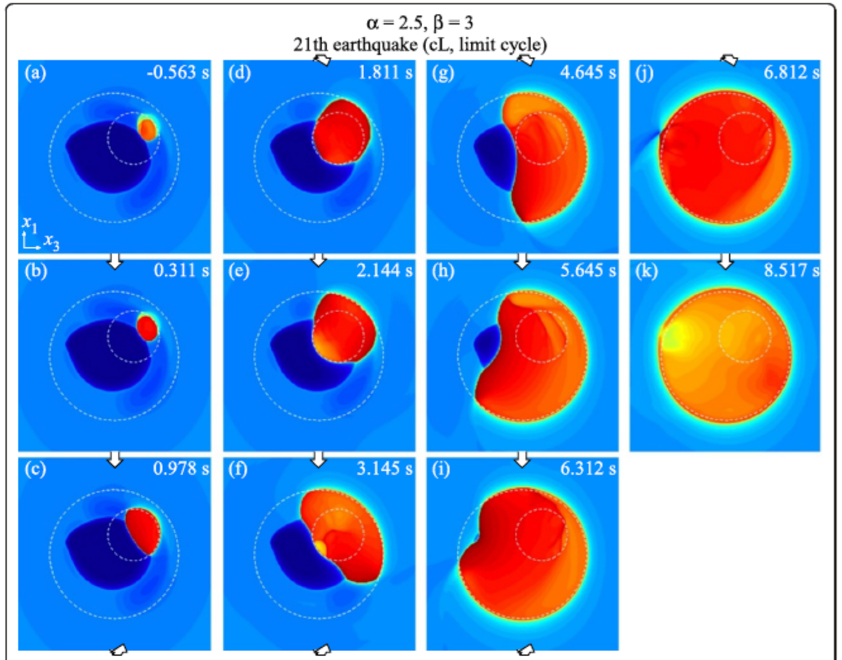


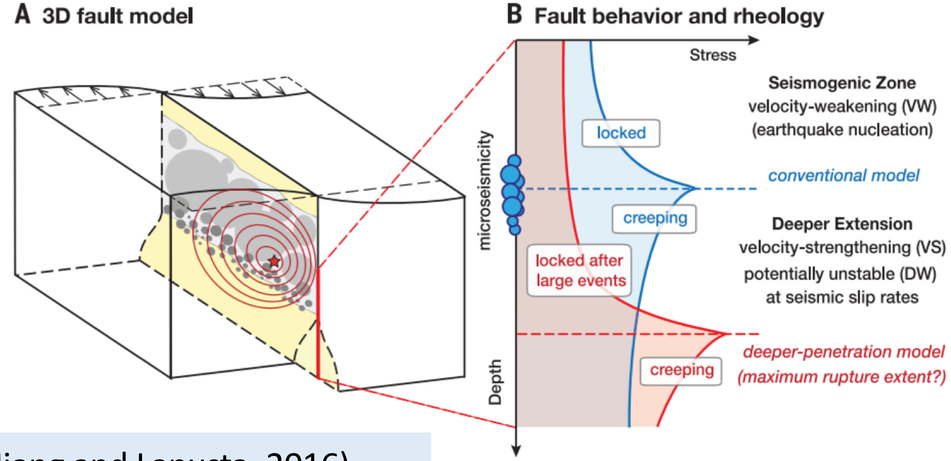
Figure 10 cL for $\alpha < \beta$. (a, b, c, d, e, f, g, h, i, j, k) Snapshots of the slip rate distribution during a typical cascade-up L event for $\alpha = 2.5$ and $\beta = 3$. The time after the moment acceleration exceeds threshold 10 PNm/s^2 is indicated in each panel. The color scale is the same as in Figure 3.

(Noda et al., 2014)

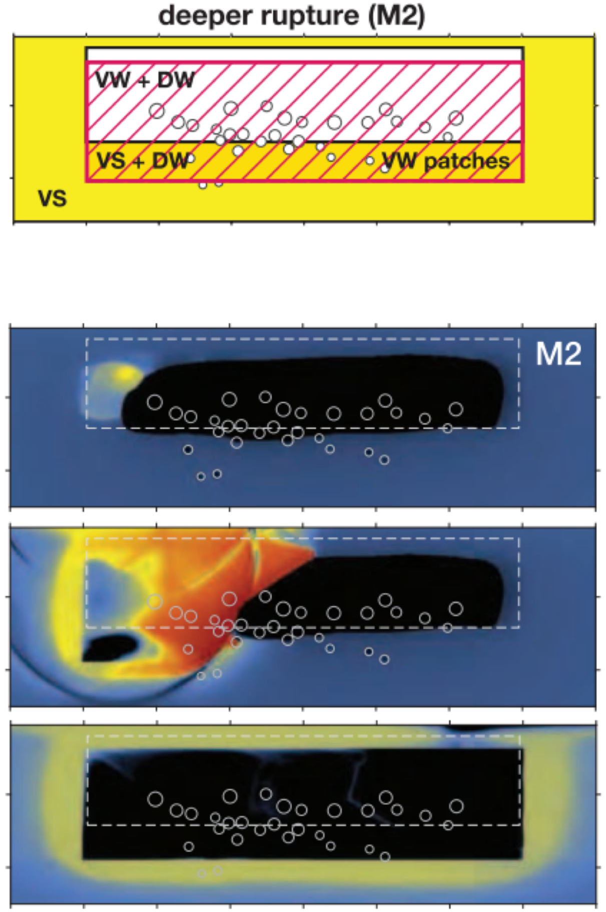
Interpretation of earthquake physics

- How Deep can Rupture Go?

Why silent inter-seismic?



(Jiang and Lapusta, 2016)

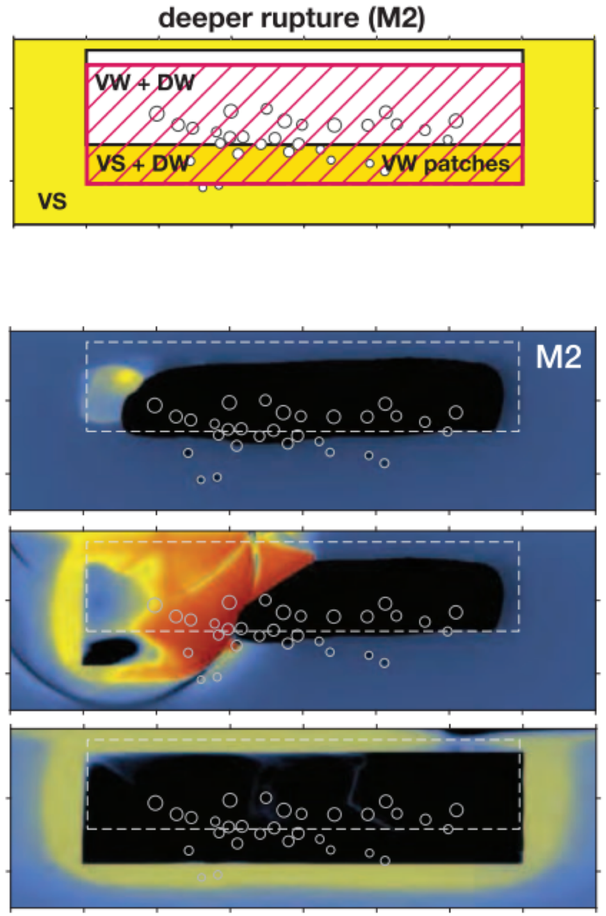


(Jiang and Lapusta, 2016)

Additional dynamic weakening at high slip-rate promotes deeper rupture penetration

Interpretation of earthquake physics

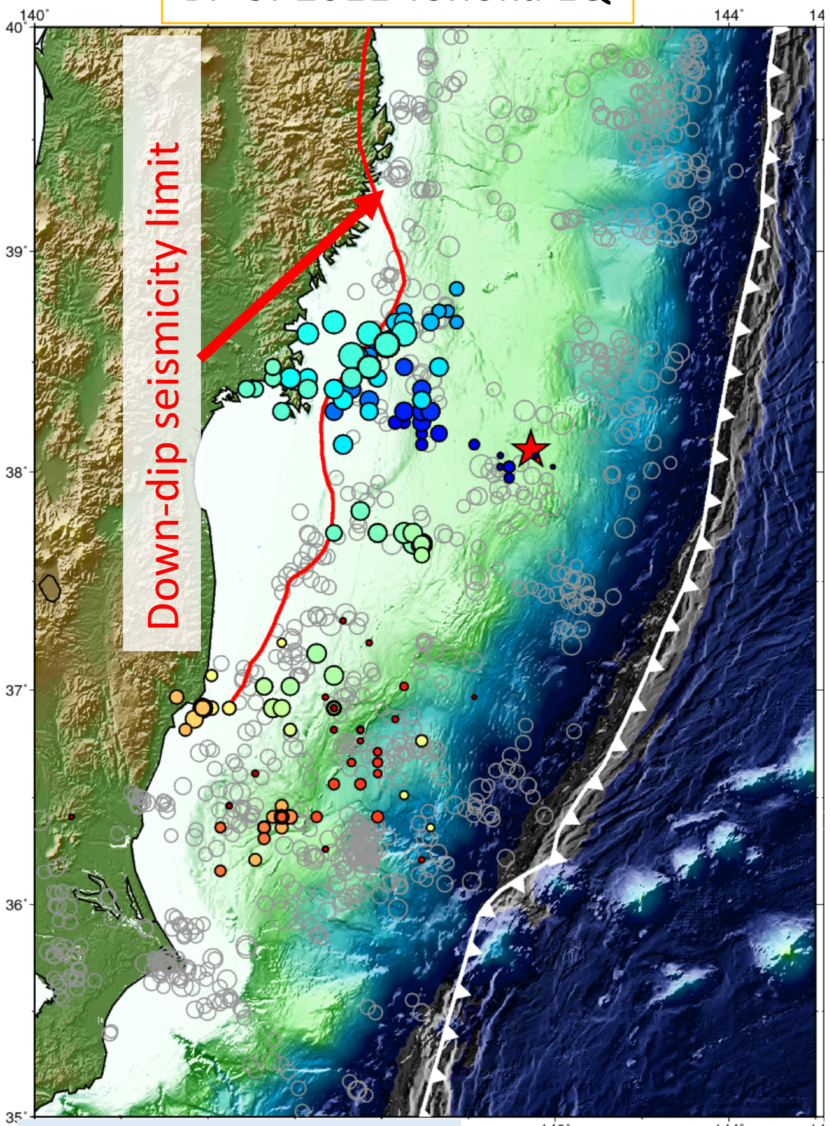
Also the case for subduction zone?



(Jiang and Lapusta, 2016)

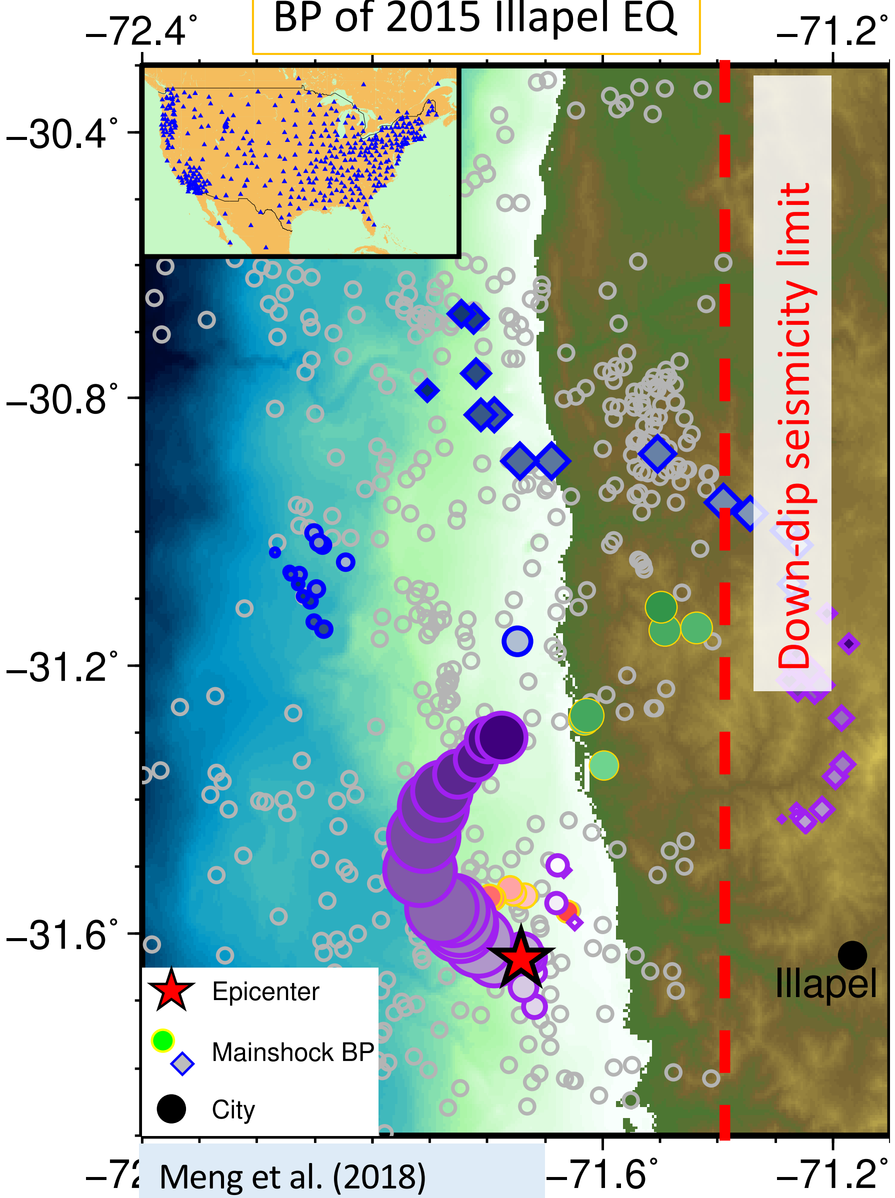
Interpretation of earthquake physics

BP of 2011 Tohoku EQ



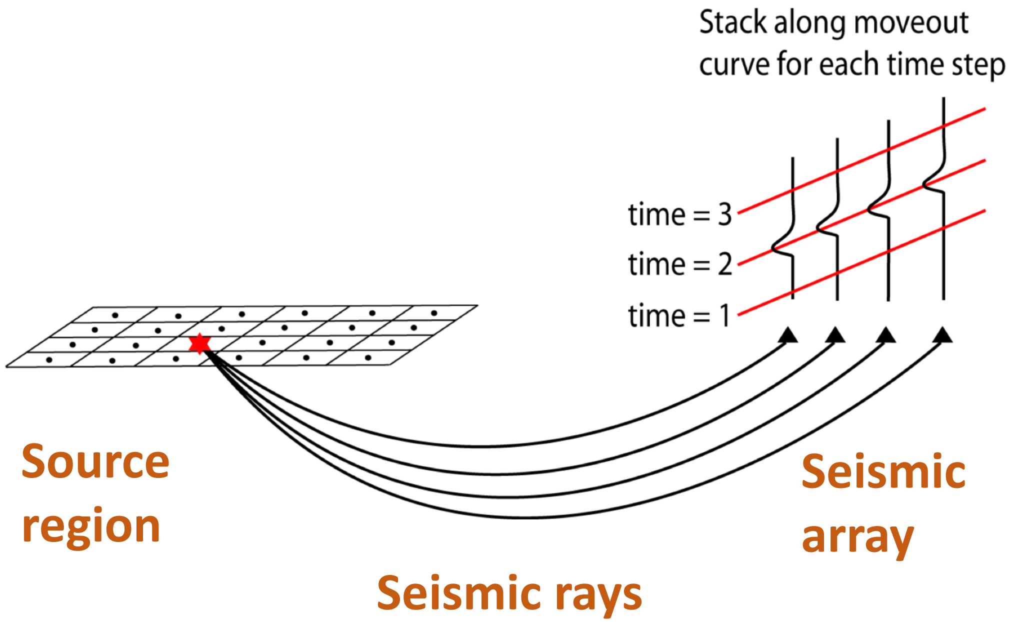
Bao and Meng (in prep)

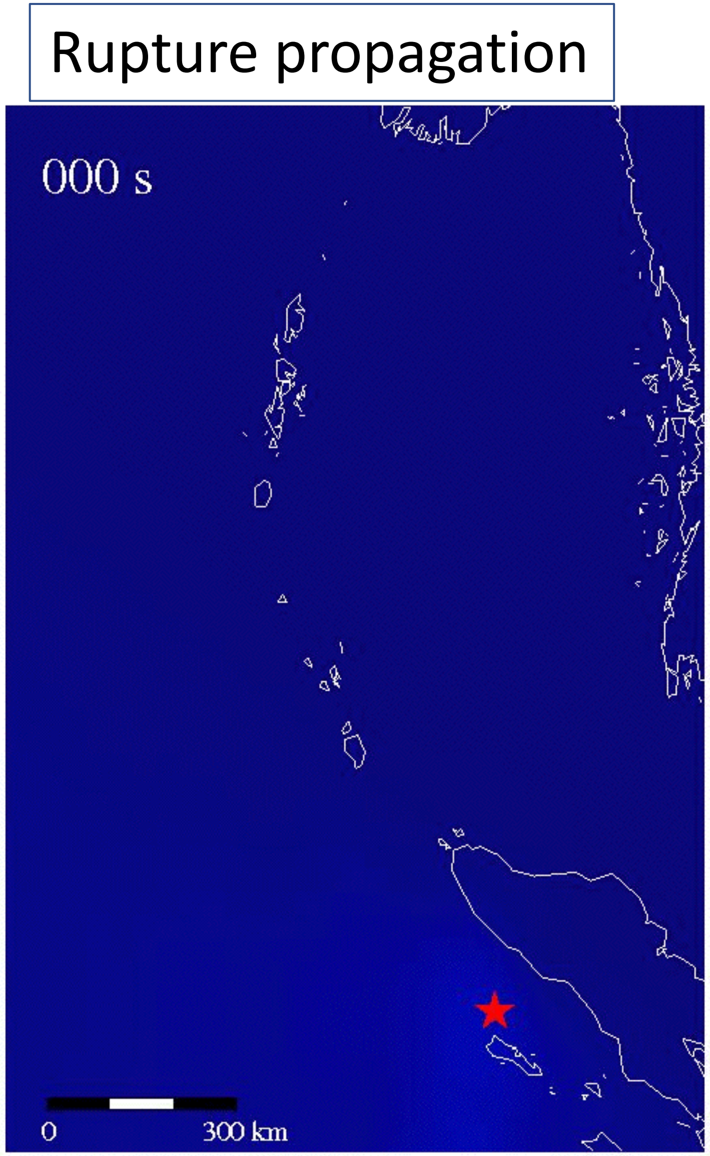
BP of 2015 Illapel EQ



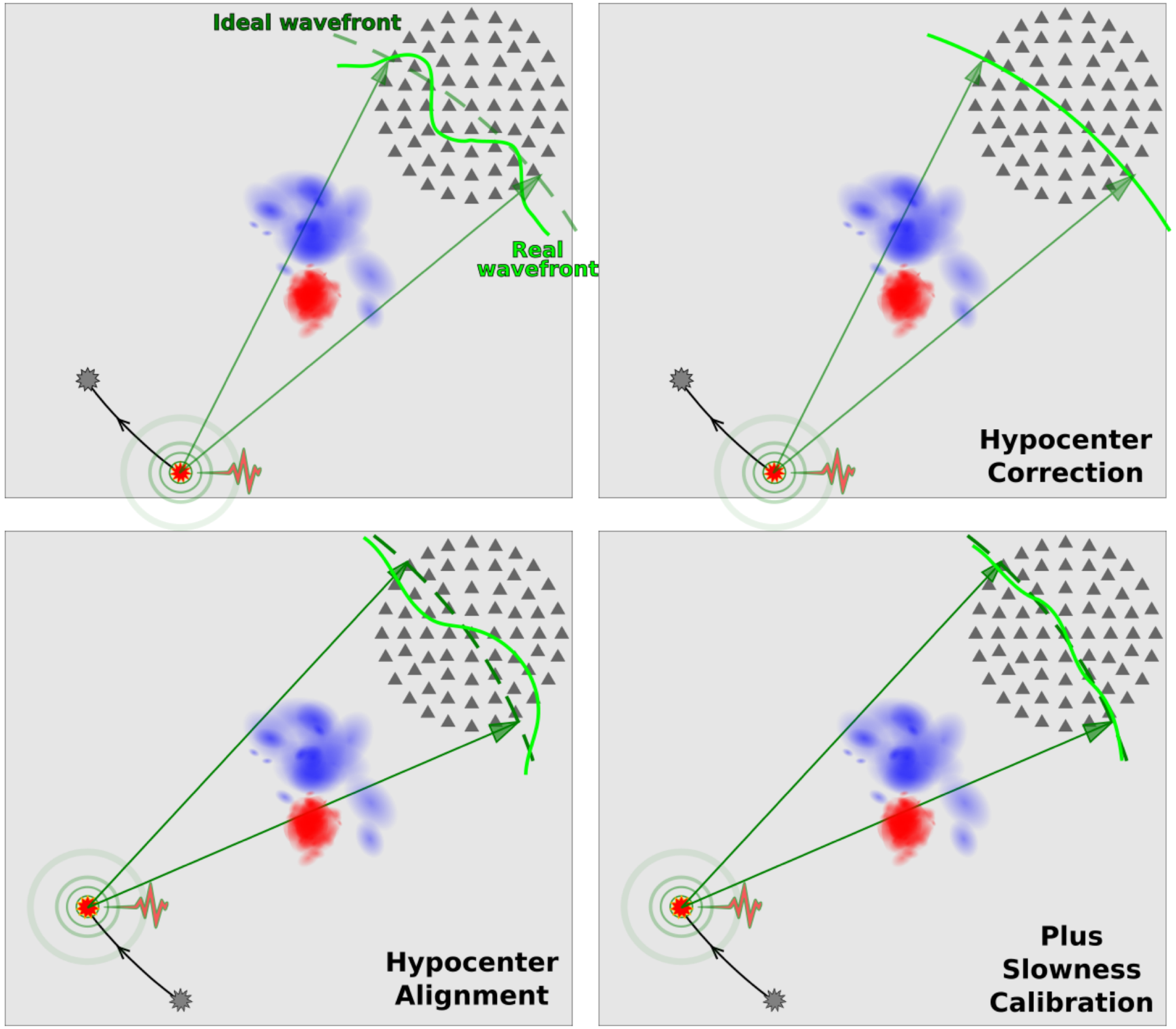
Meng et al. (2018)

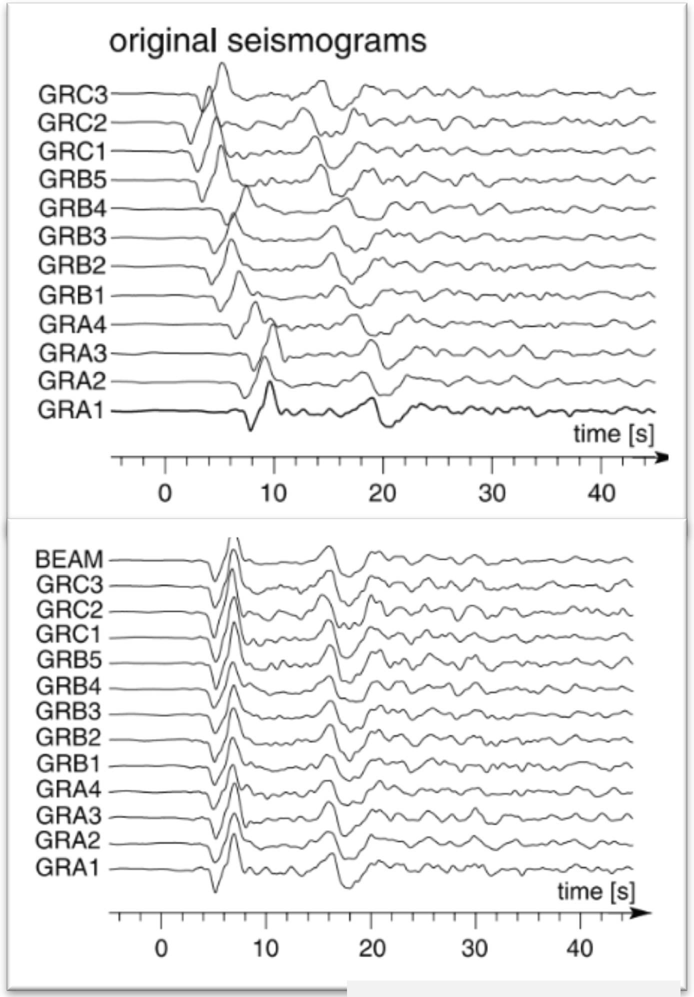
Back-projection (BP)



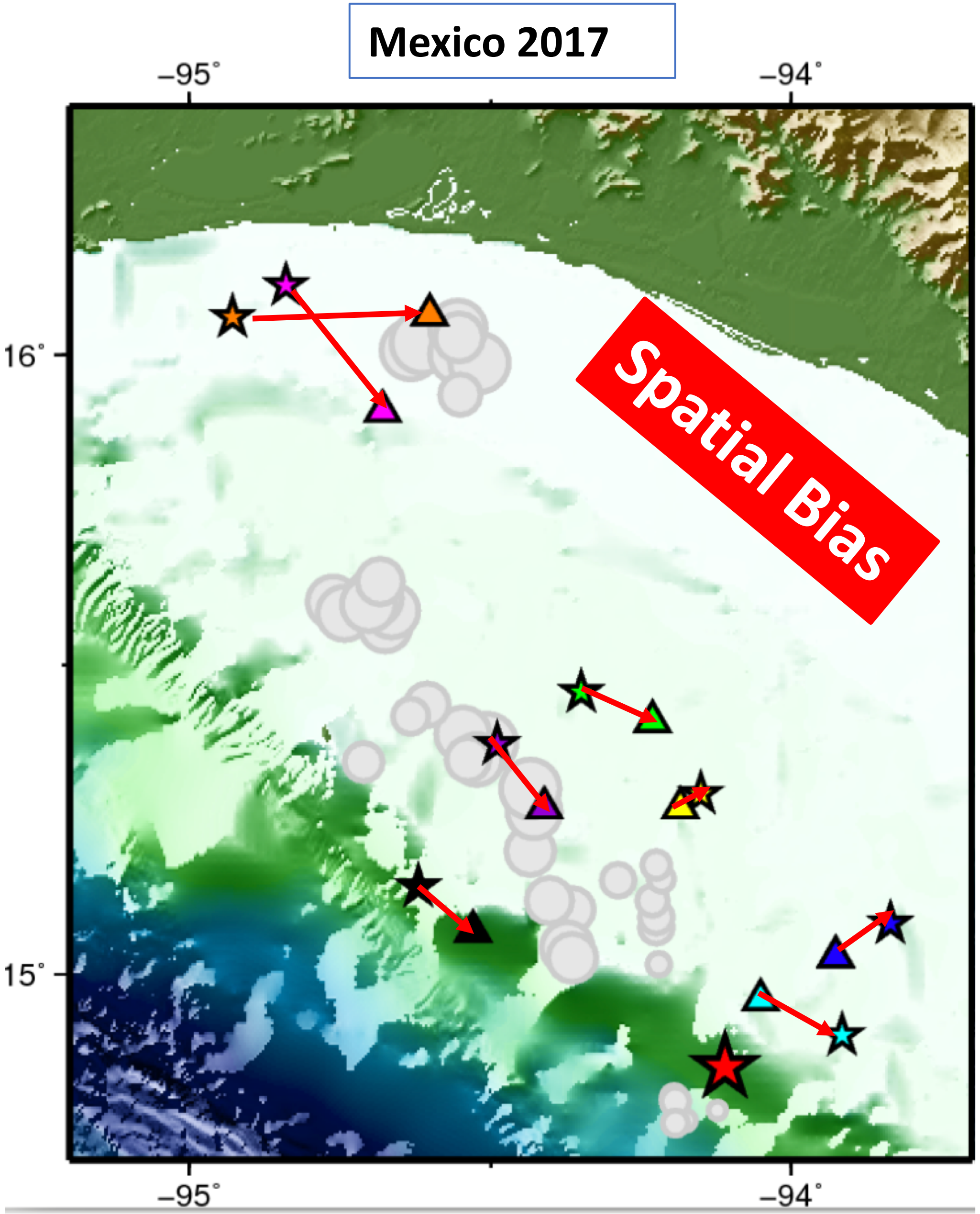


Back-projection (BP)

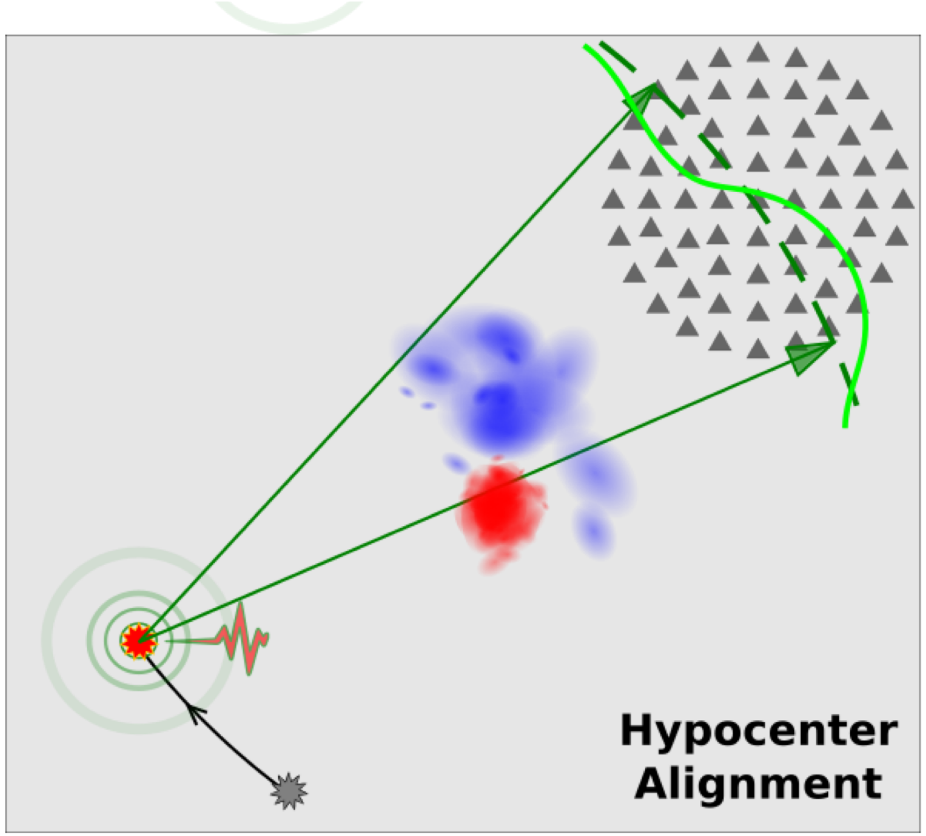




Thomas (2001)



Meng and Bao (In review)



$$\delta T_j(\xi) = \delta T_j(\xi_h) + \boxed{\left[\delta T_j\left(\xi_{C_k}\right) - \delta T_j(\xi_h)\right]} + \boxed{\delta \overrightarrow{S_j^{NS}}}\left(\vec{\xi} - \vec{\xi}_{C_k}\right)^{NS} + \boxed{\delta \overrightarrow{S_j^{EW}}}\left(\vec{\xi} - \vec{\xi}_{C_k}\right)^{EW}$$

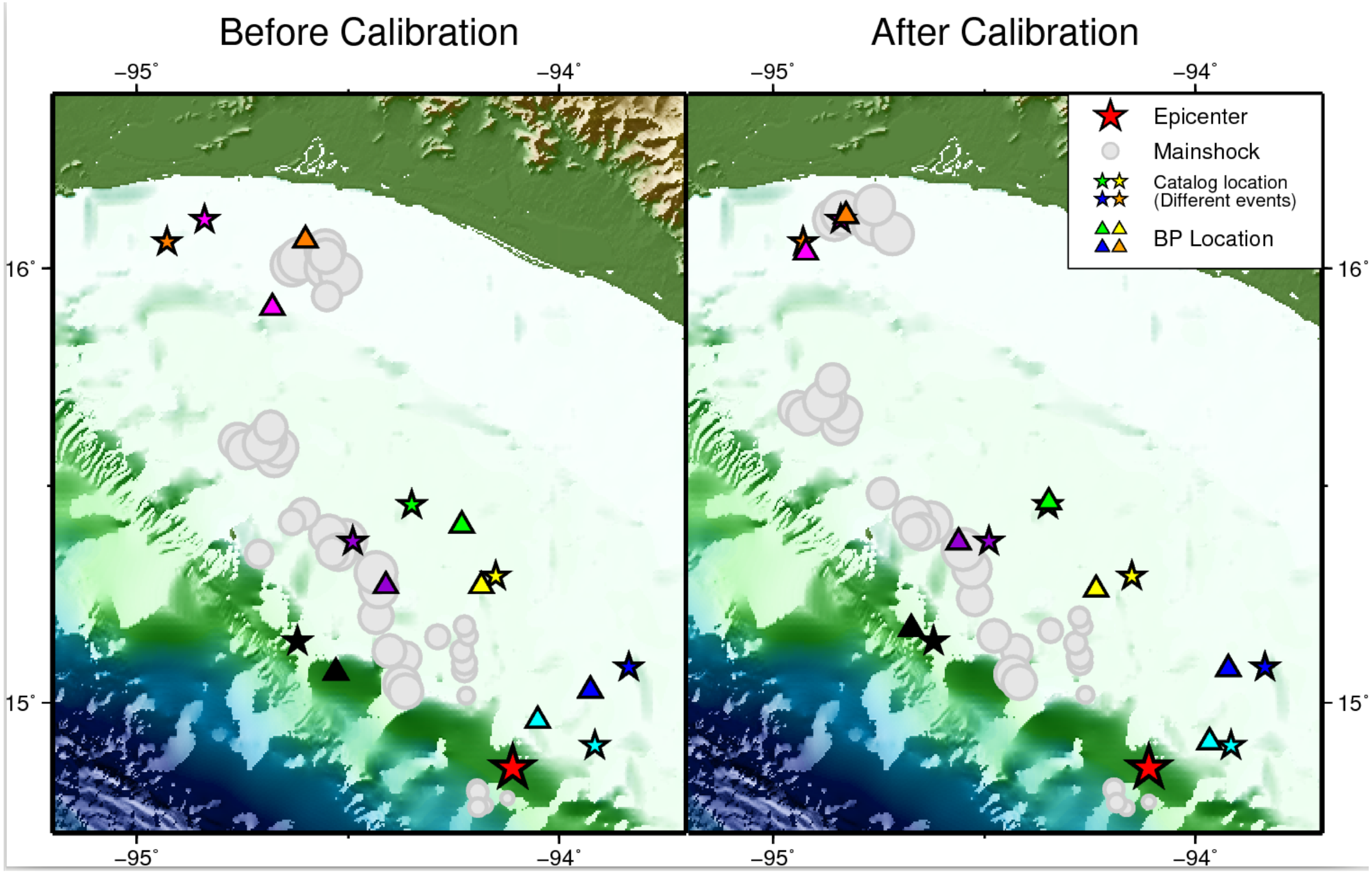
Solvable with least square inversion

Averaged Regional Time Error (1st order)

Spatial varied Time Error (2nd order)

Meng and Bao (**in prep**. 2019)

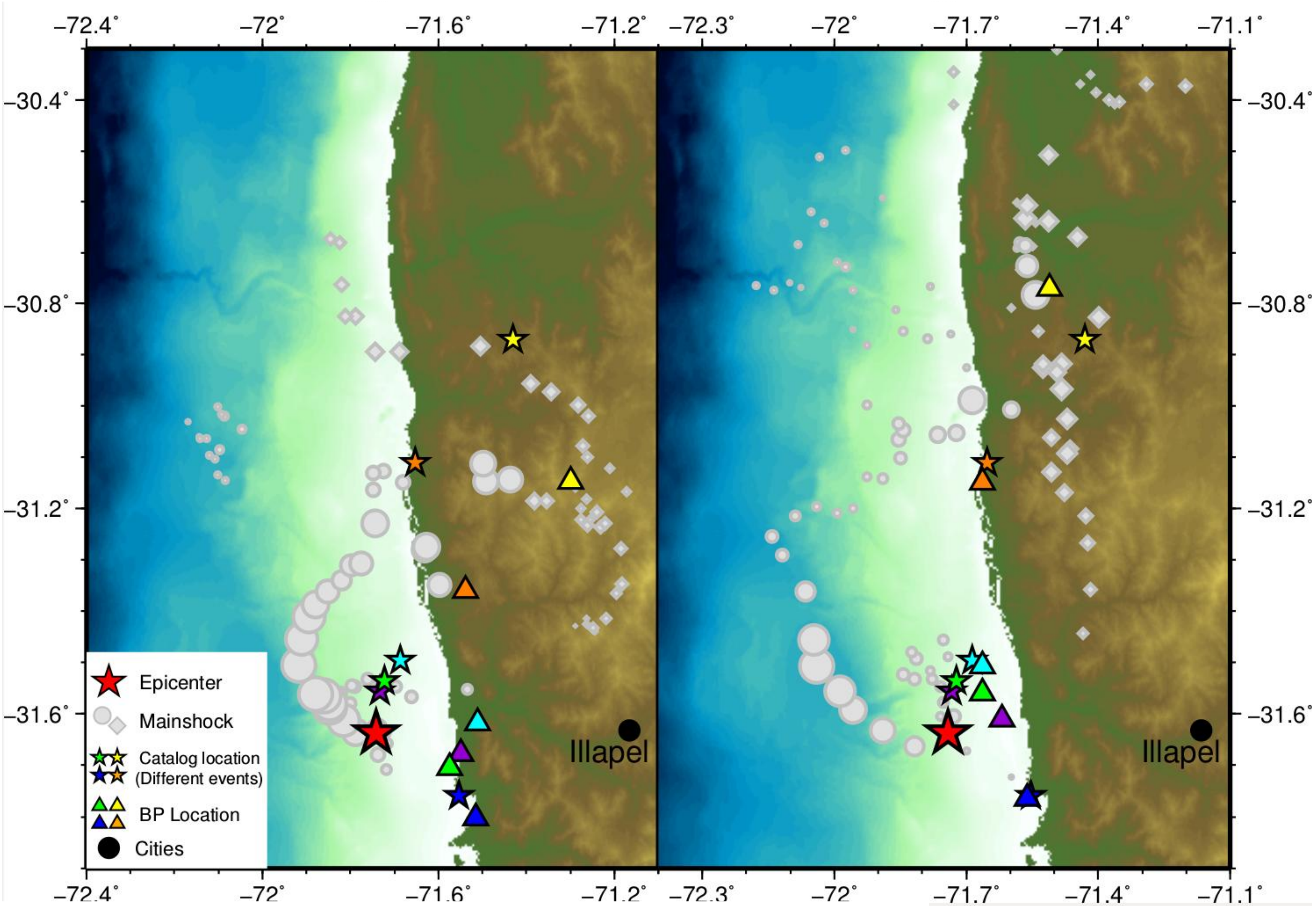
2017 Mw 8.2 Tehuantepec



RMS Error ： 21 km -> 8 km

Meng and Bao (2019)

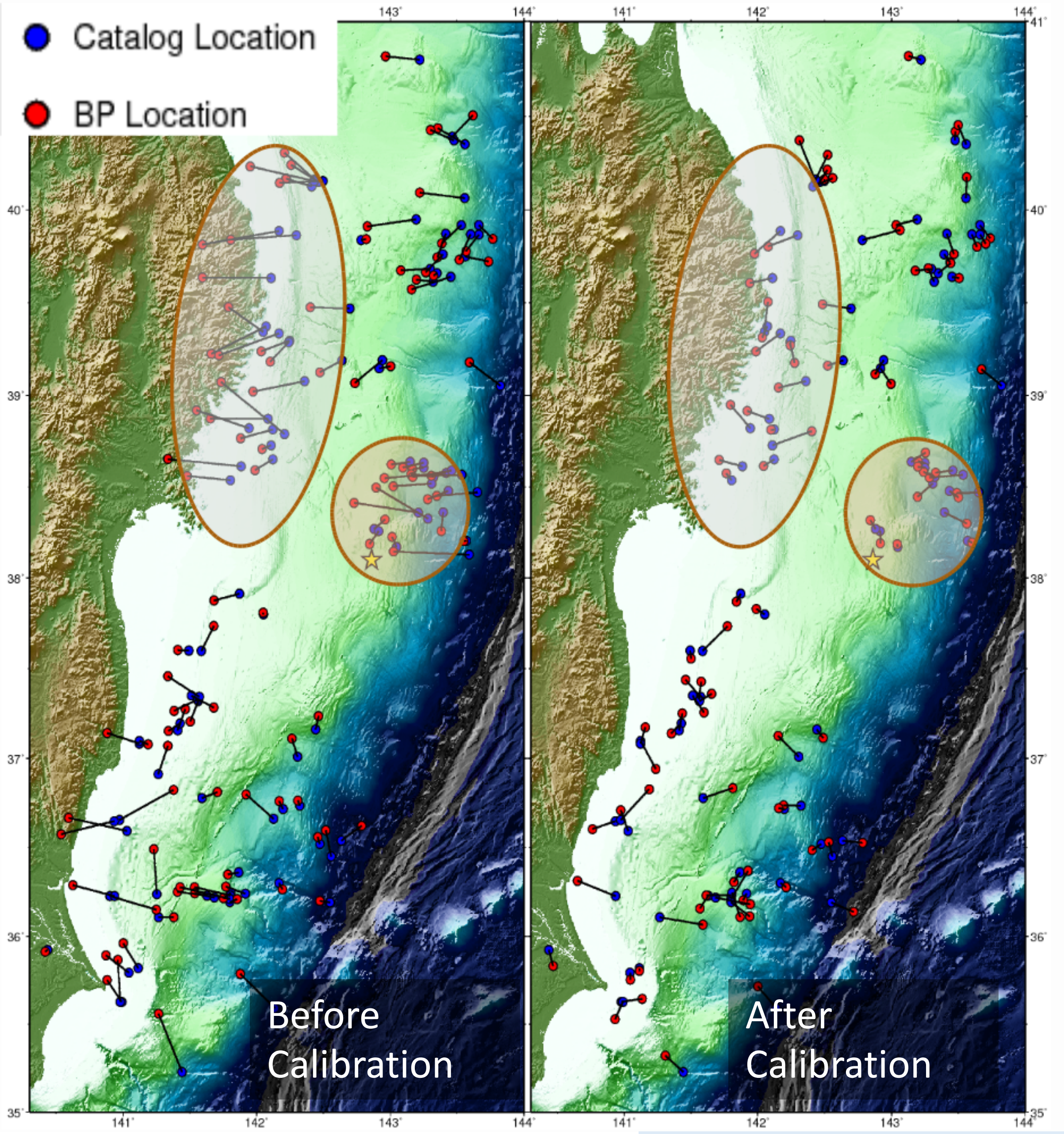
2015 Mw 8.3 Illapel

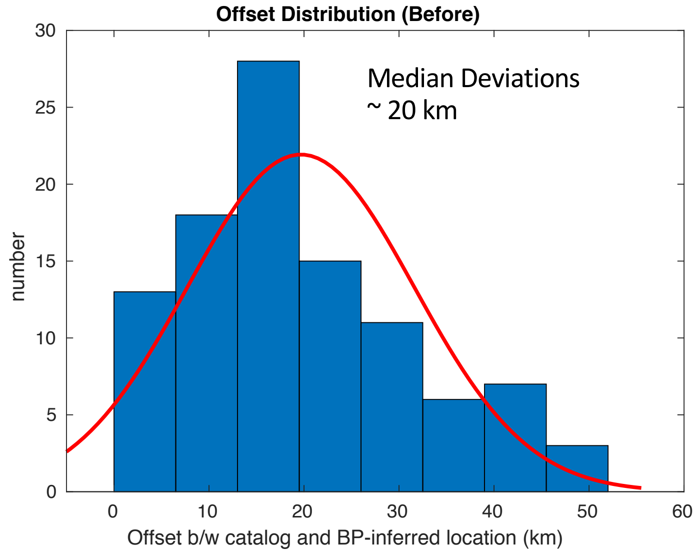


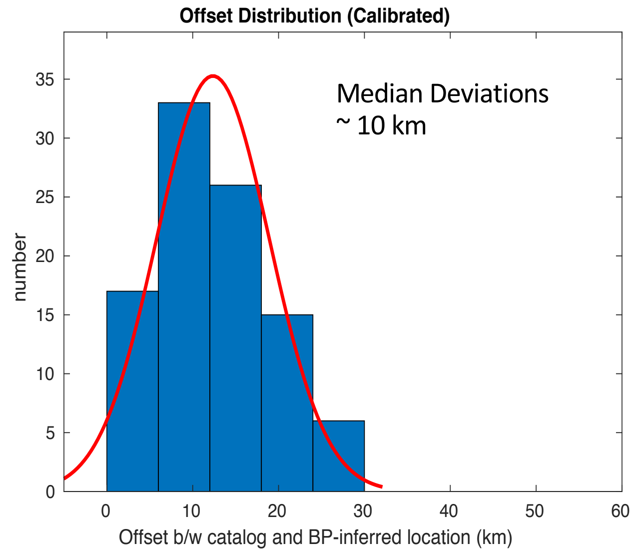
RMS Error：24 km -> 8 km

Meng and Bao et al. (2018)

2010 Mw 9.1 Tohoku







Bao and Meng (**in prep**. 2019)

Overview

Part 1: Palu Earthquake

- Static Observations
  - Radar and image satellites
- Dynamic Observations
  - Teleseismic Back-projection
  - Surface Mach wave/Mach cone
- Implications

Part 2: SEBP

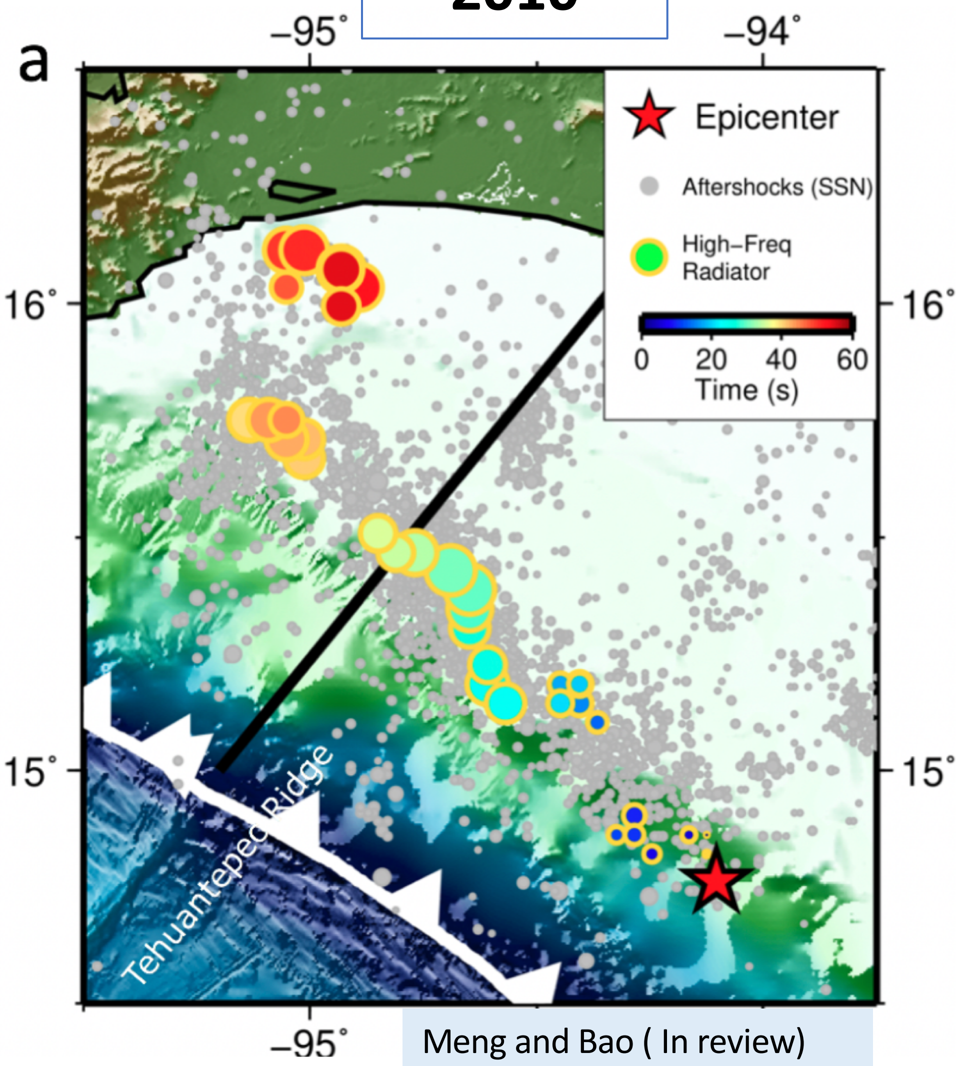
- Slowness-Enhanced Backprojection
  - Improvement of accuracy
  - Better source properties estimation
- Case Applications

Impact on interpretation of earthquake physics

More accurate estimate of *Rupture Properties*:

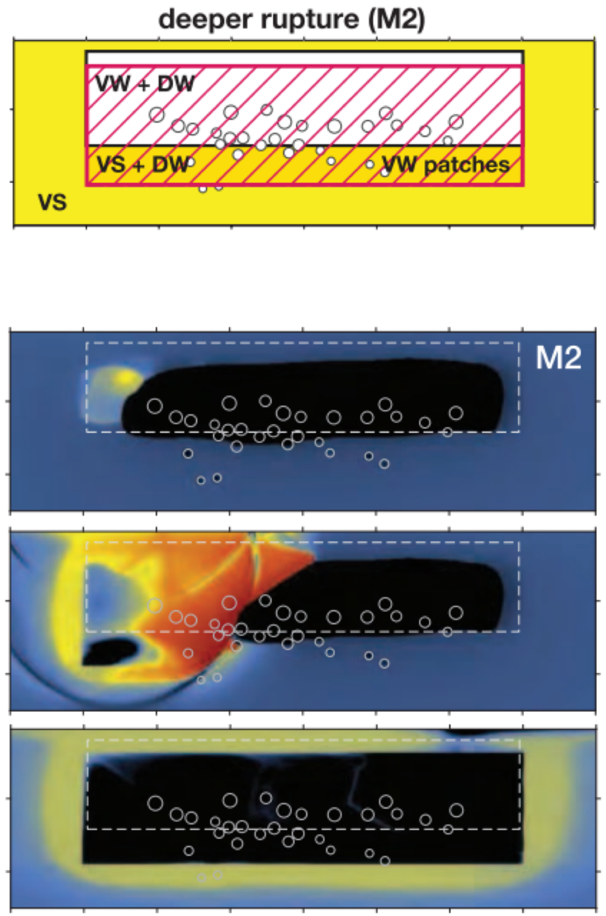
- Length
- Direction
- Speed

Chile 2010



Meng and Bao (In review)

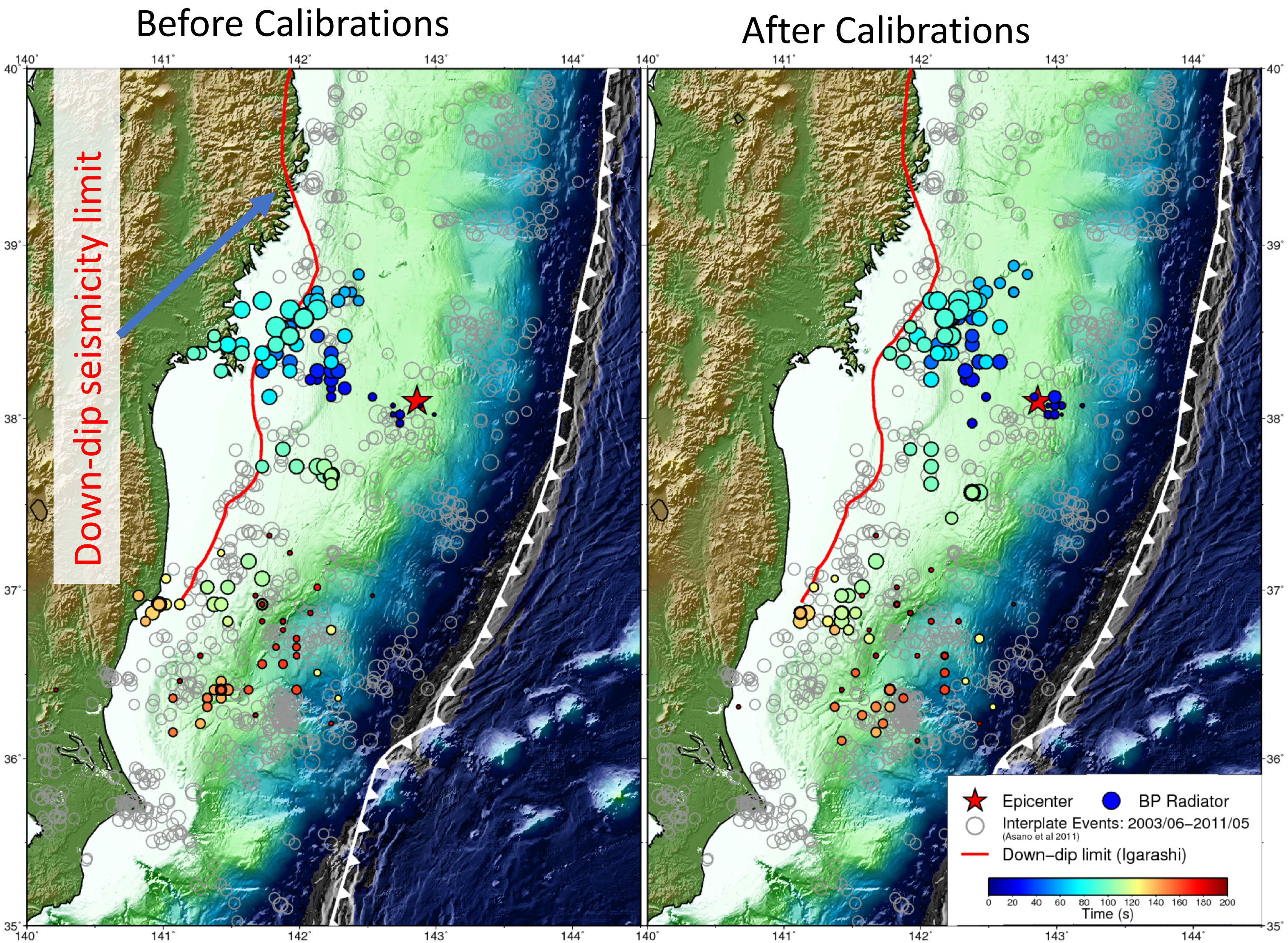
How Deep can Rupture Go?



(Jiang and Lapusta, 2016)

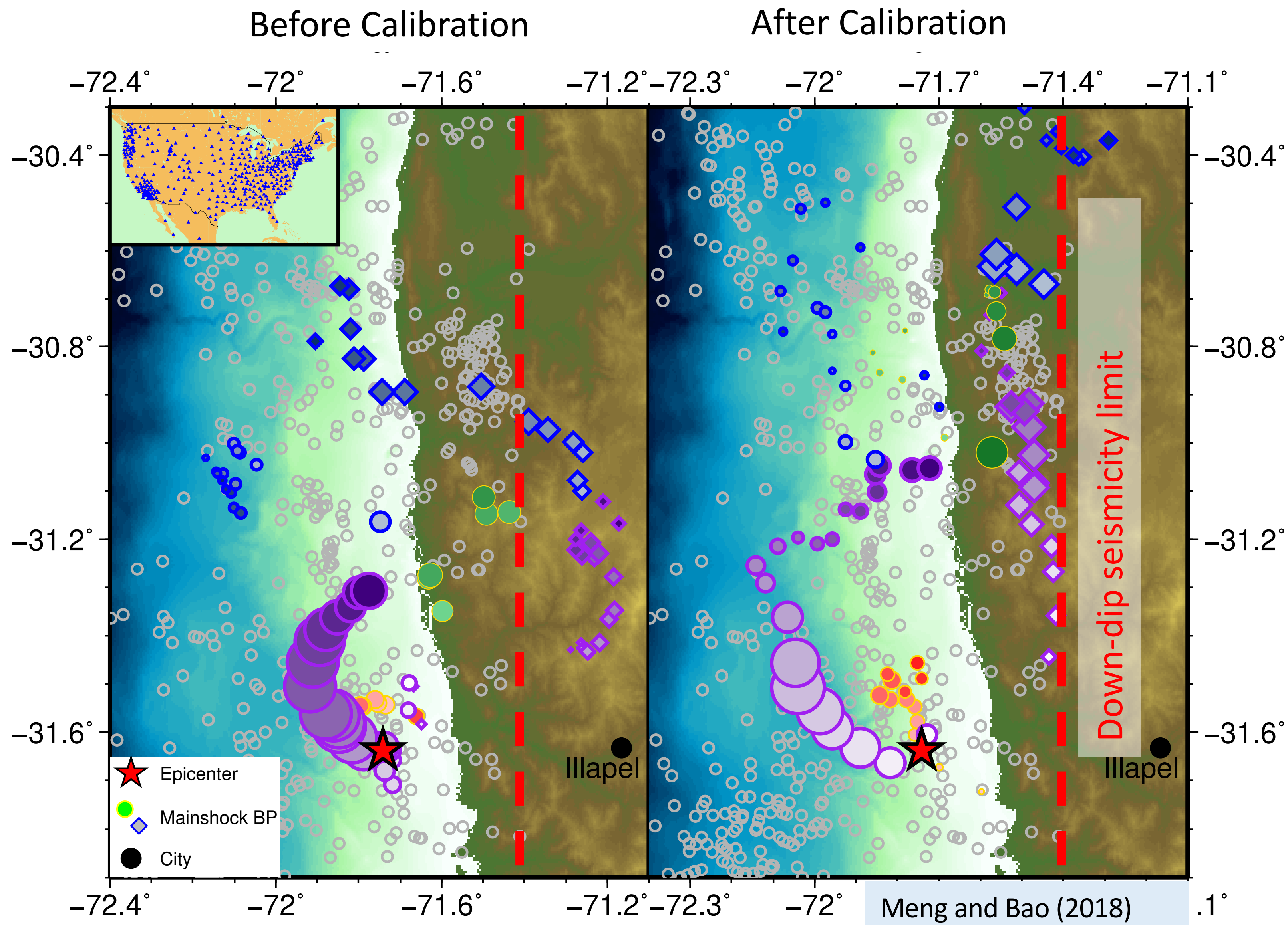
Additional dynamic weakening at high slip-rate promotes deeper rupture penetration

2011 Mw 9.0 Tohoku Earthquake



Bao and Meng (**in prep.** 2019)

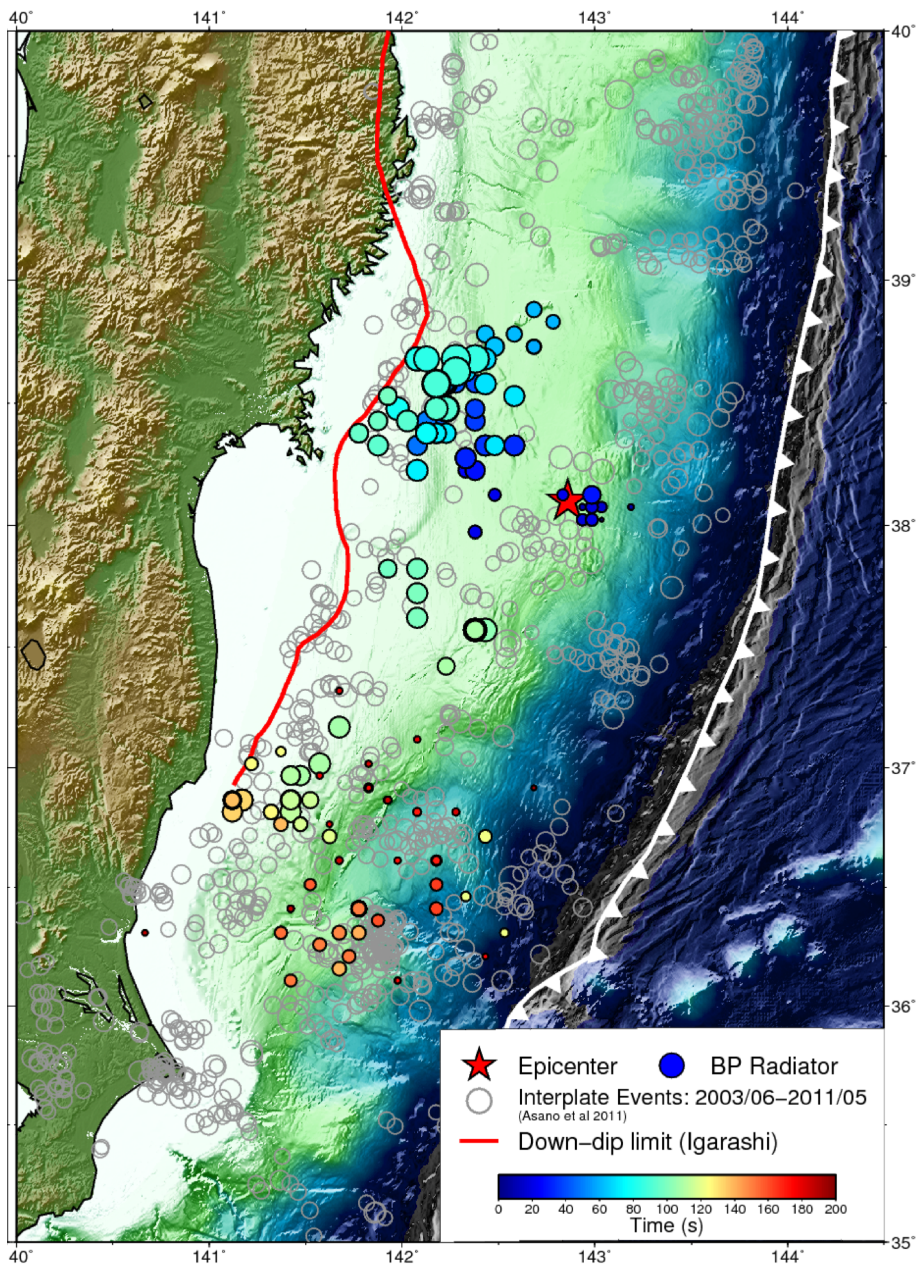
2015 Mw 8.3 Illapel Earthquake



Meng and Bao (2018)

Summary

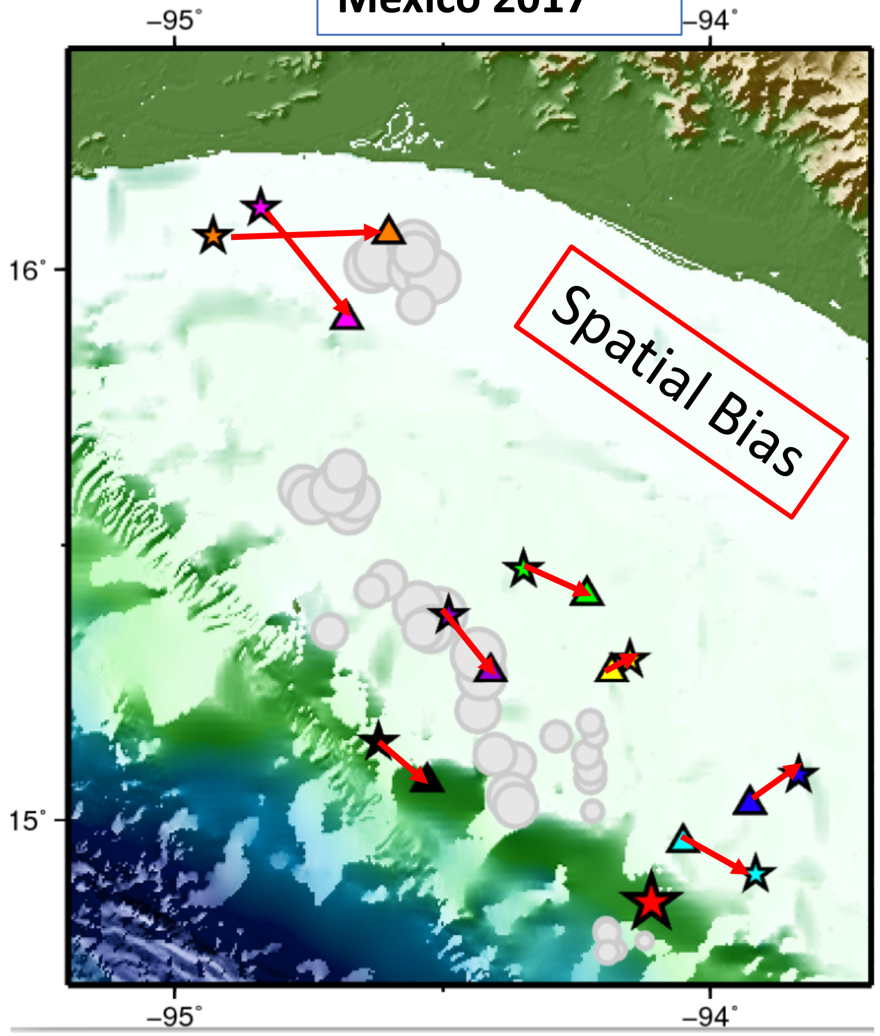
- SEBP effectively reduces the spatial uncertainty of back-projection
- SEBP enables us to resolve earthquake with better accuracy
- ***Network Validation*** *(technical)*



Bao and Meng (**in prep**. 2019)

Extra Slides for question: BP

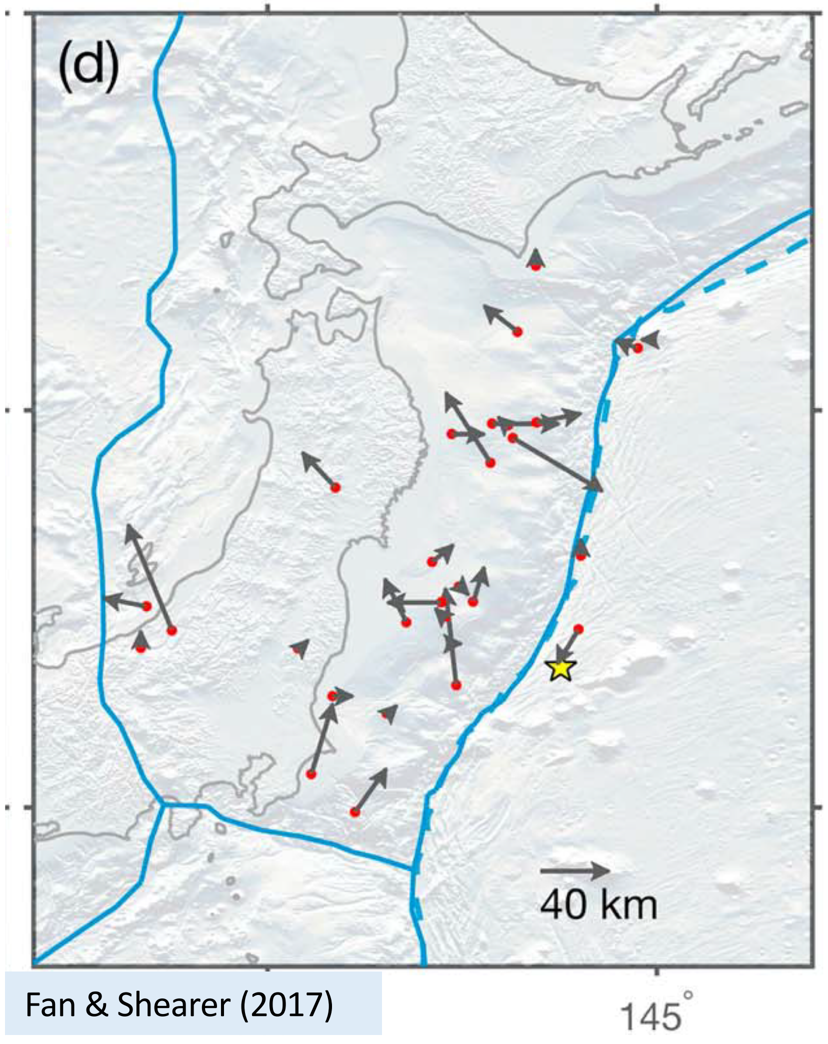
Mexico 2017



Meng and Bao (In review)

Systematic bias

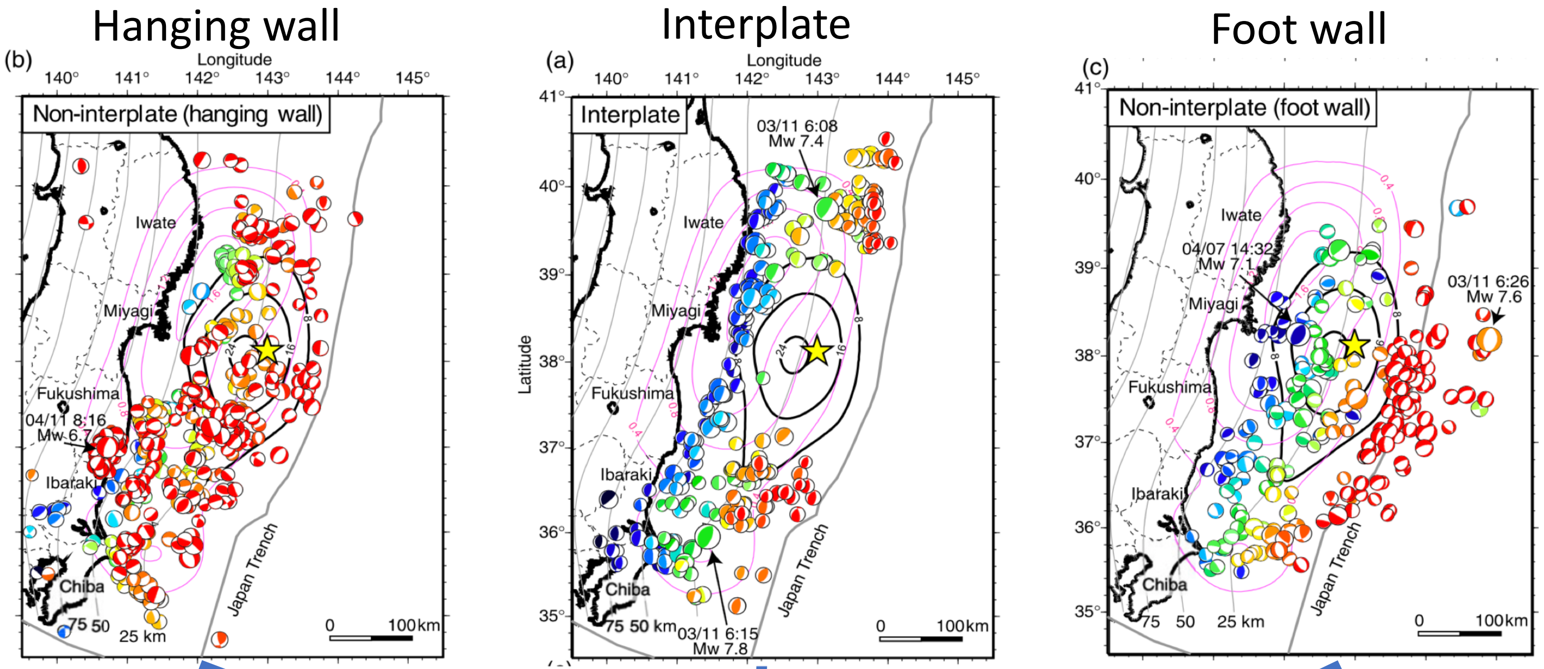
Tohoku 2011



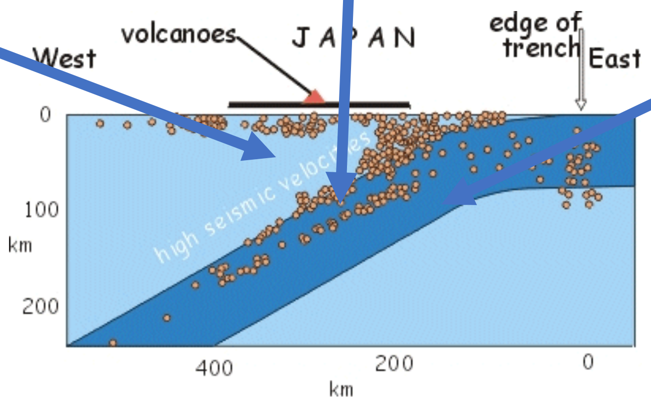
Fan & Shearer (2017)

Unsystematic bias

Tohoku Earthquake Aftershocks

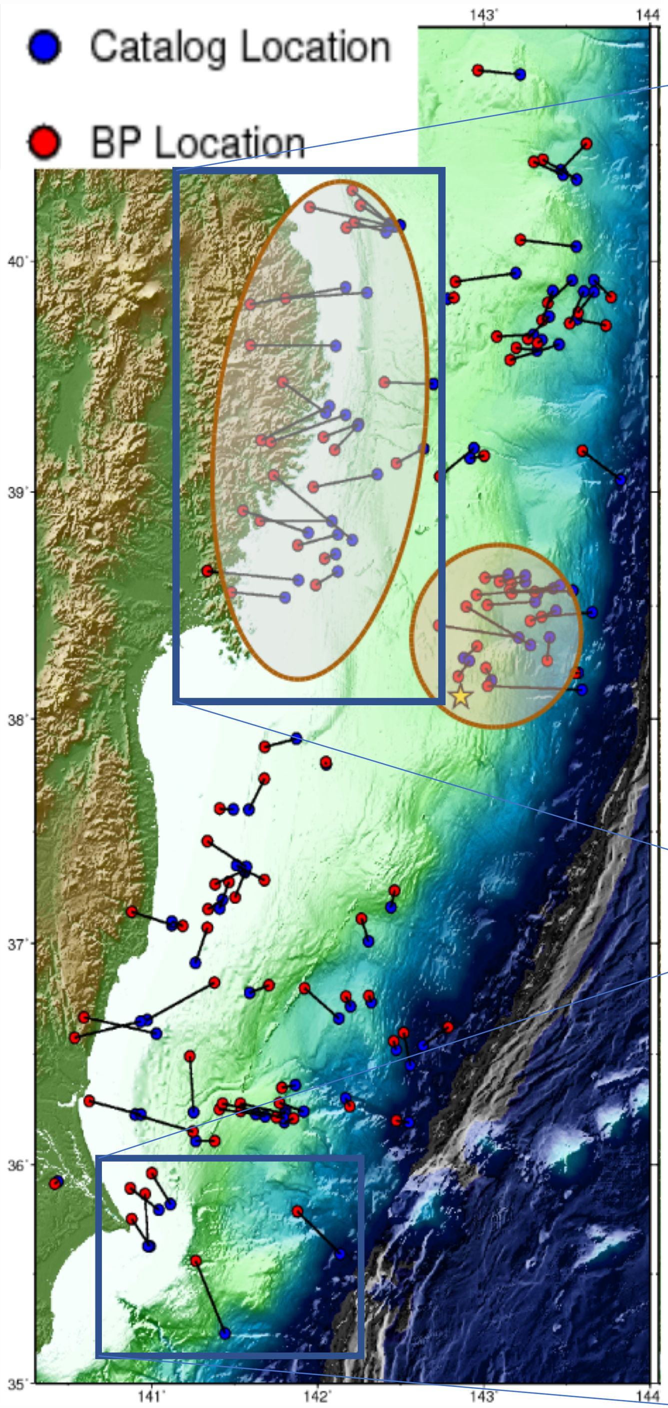


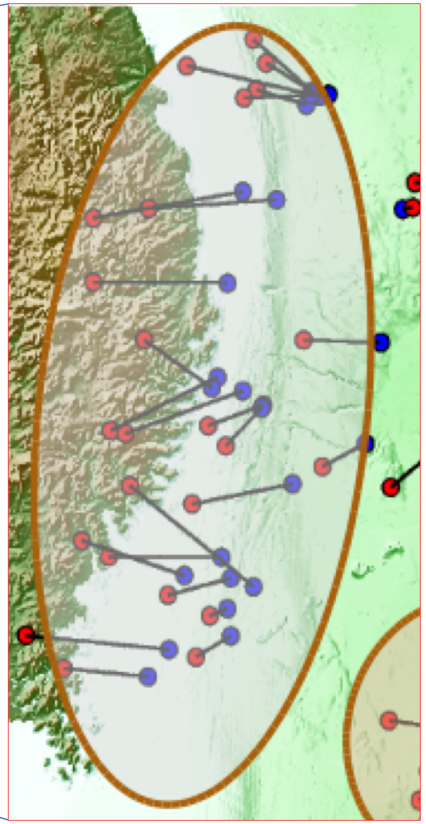
Asano et al., 2011



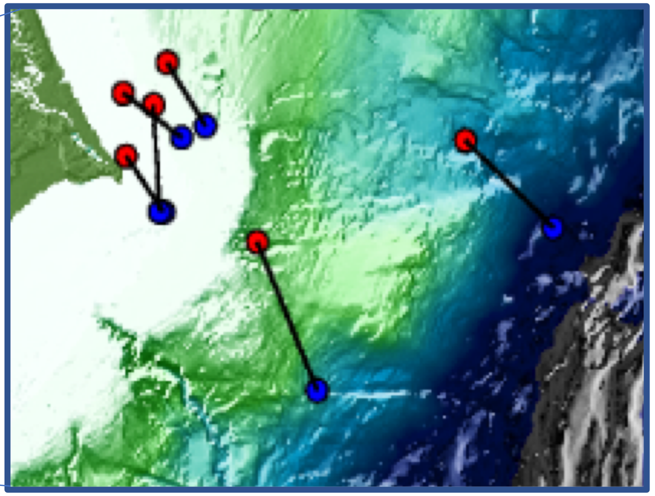
Separating aftershocks based on focal orientation and distance to the slab interface.

Consistent structural effect for interplate earthquakes and the coseismic rupture



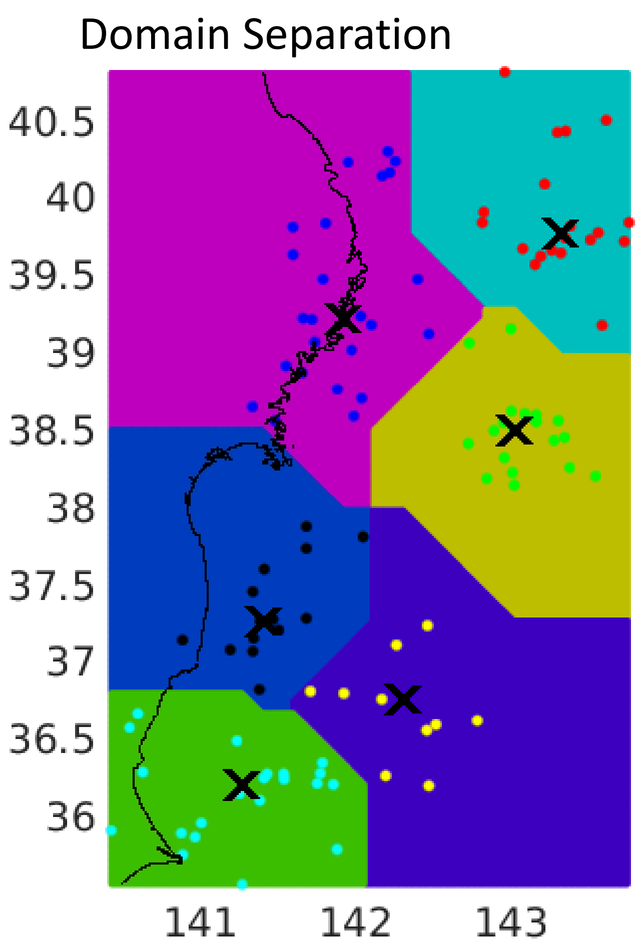


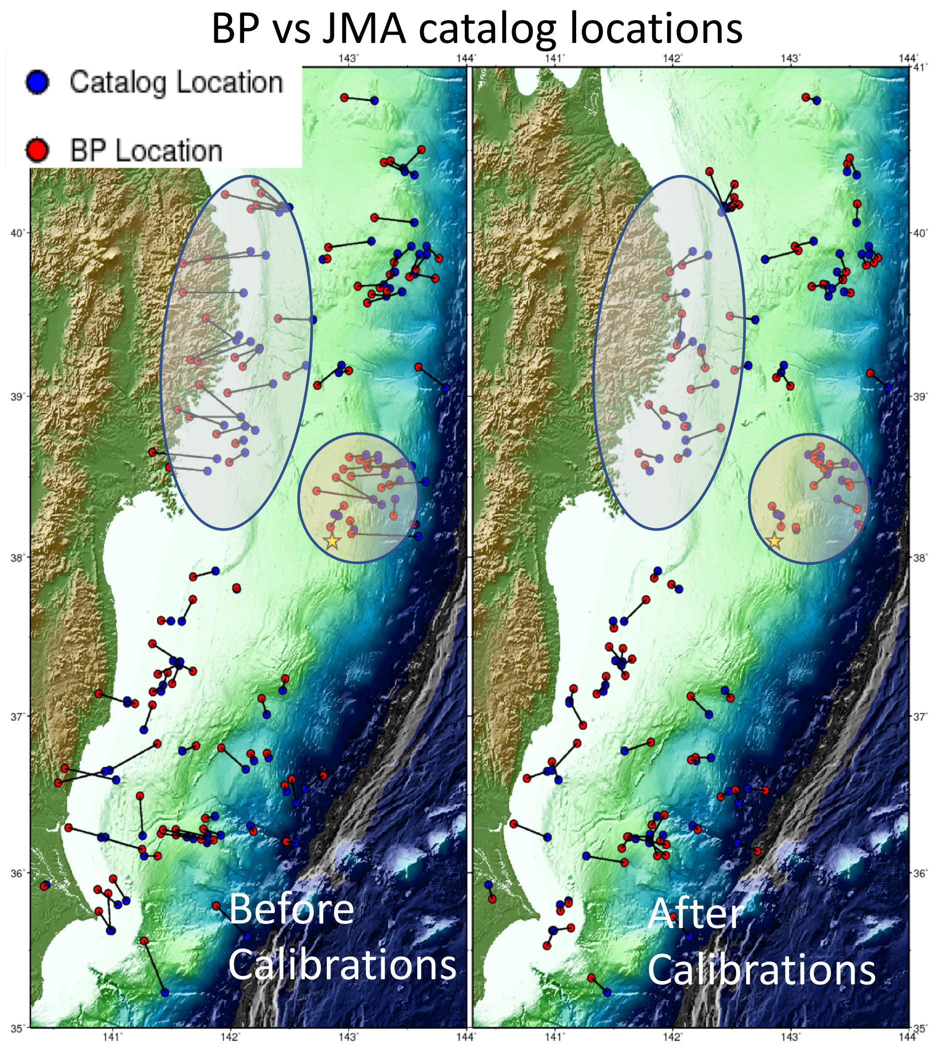
BP locations are biased towards to the west (deeper along-dip)



BP locations are biased towards to the NW

We found a way to qualify aftershocks for calibration


Domain Separation
40.5
40
39.5
39
38.5
38
37.5
37
36.5
36
141
142
143


BP vs JMA catalog locations
Catalog Location
BP Location
Before
Calibrations
After
Calibrations

Confidence intervals of locations of high-frequency radiation