Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations
ICTP, Trieste, Sept 11 2019

Lecture 2: The Slowness-Enhanced Back-Projection

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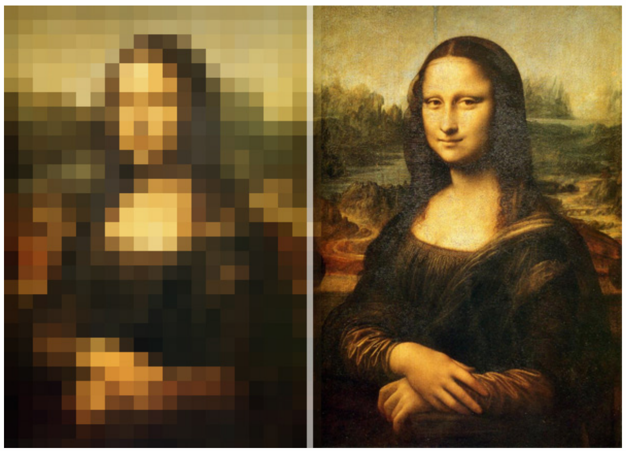
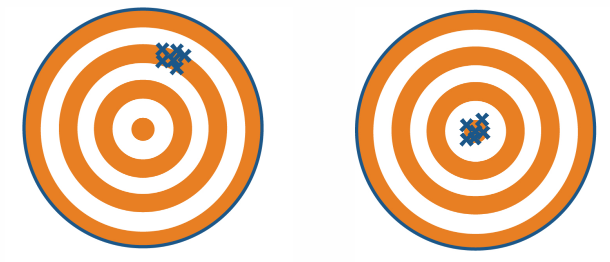
Improving Imaging Quality

Low Resolution High Resolution



Low Accuracy High Accuracy



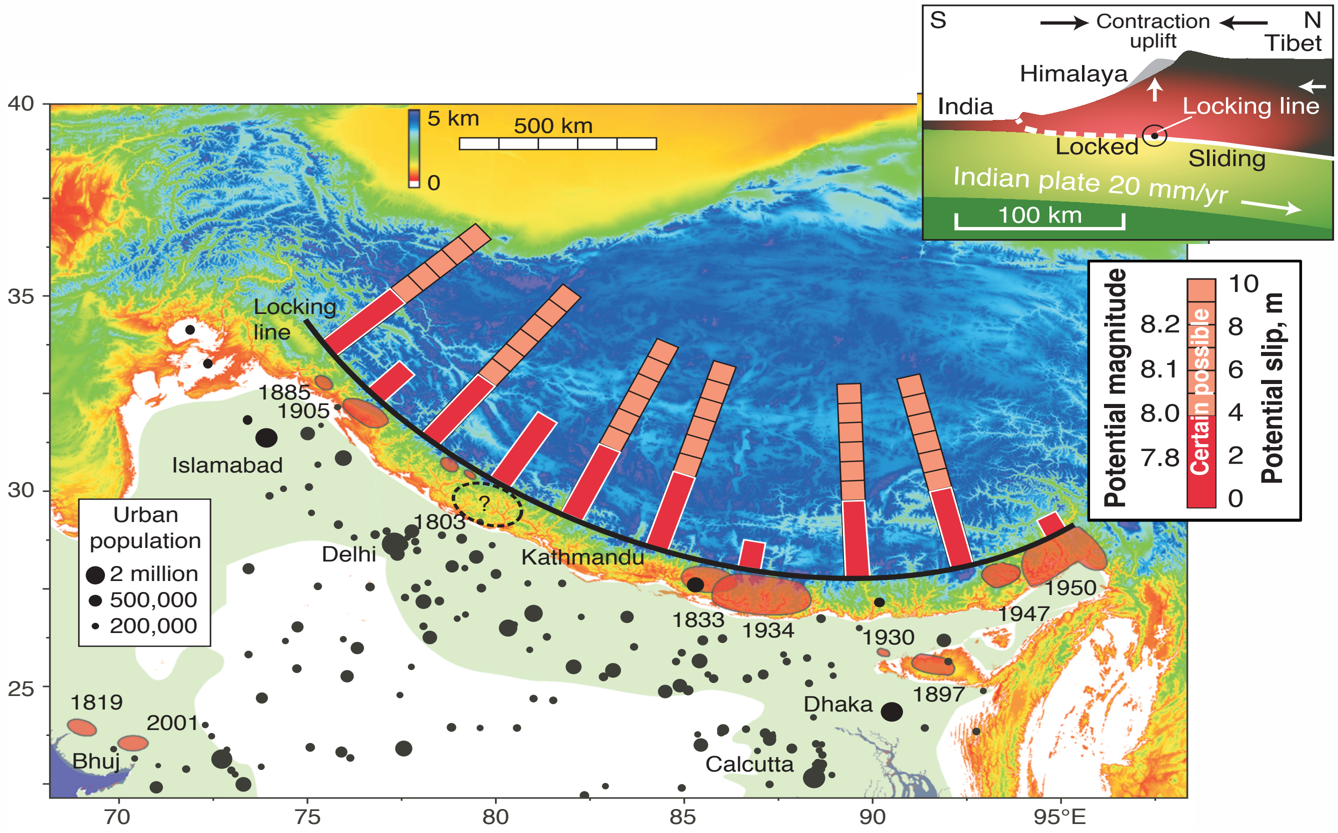
Objective: Improving Resolution
Solution**: MUSIC method**

Objective: Reduce Spatial Biases
Solution: **Slowness Calibration**

Outlines

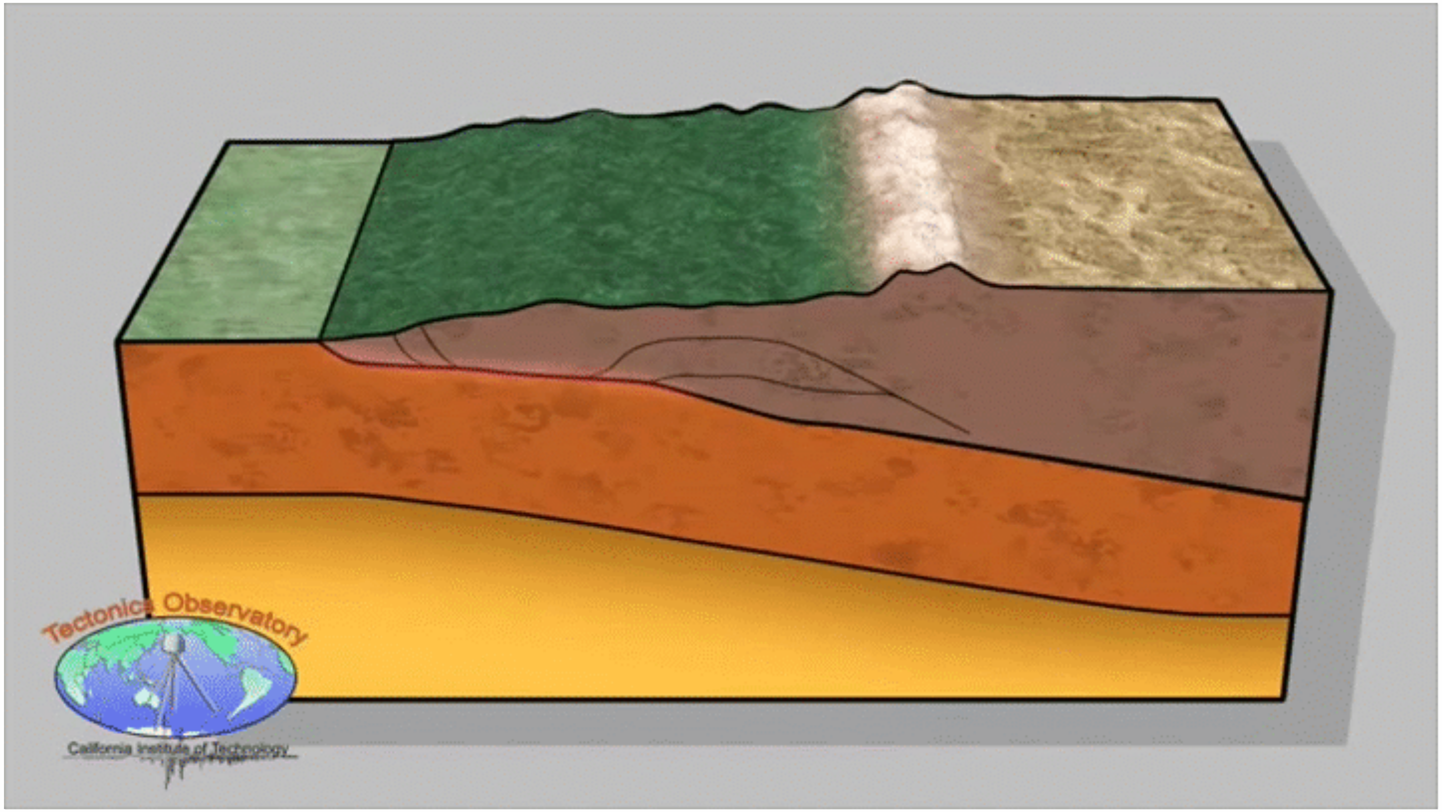
- Travel-time correction in back-projections
- Hypocenter alignment
- Slowness Enhanced back-projection
- Unzipping of bottom of seismogenic zone in the Gorkha Earthquake
- Absence of deep penetration in the Tohoku earthquake
- Early and Persistent supershear rupture of the 2018 Palu earthquake
- Wide step-over of the 2017 Chiapas earthquake

Tectonic View of the Indo-Asian Collision Zone



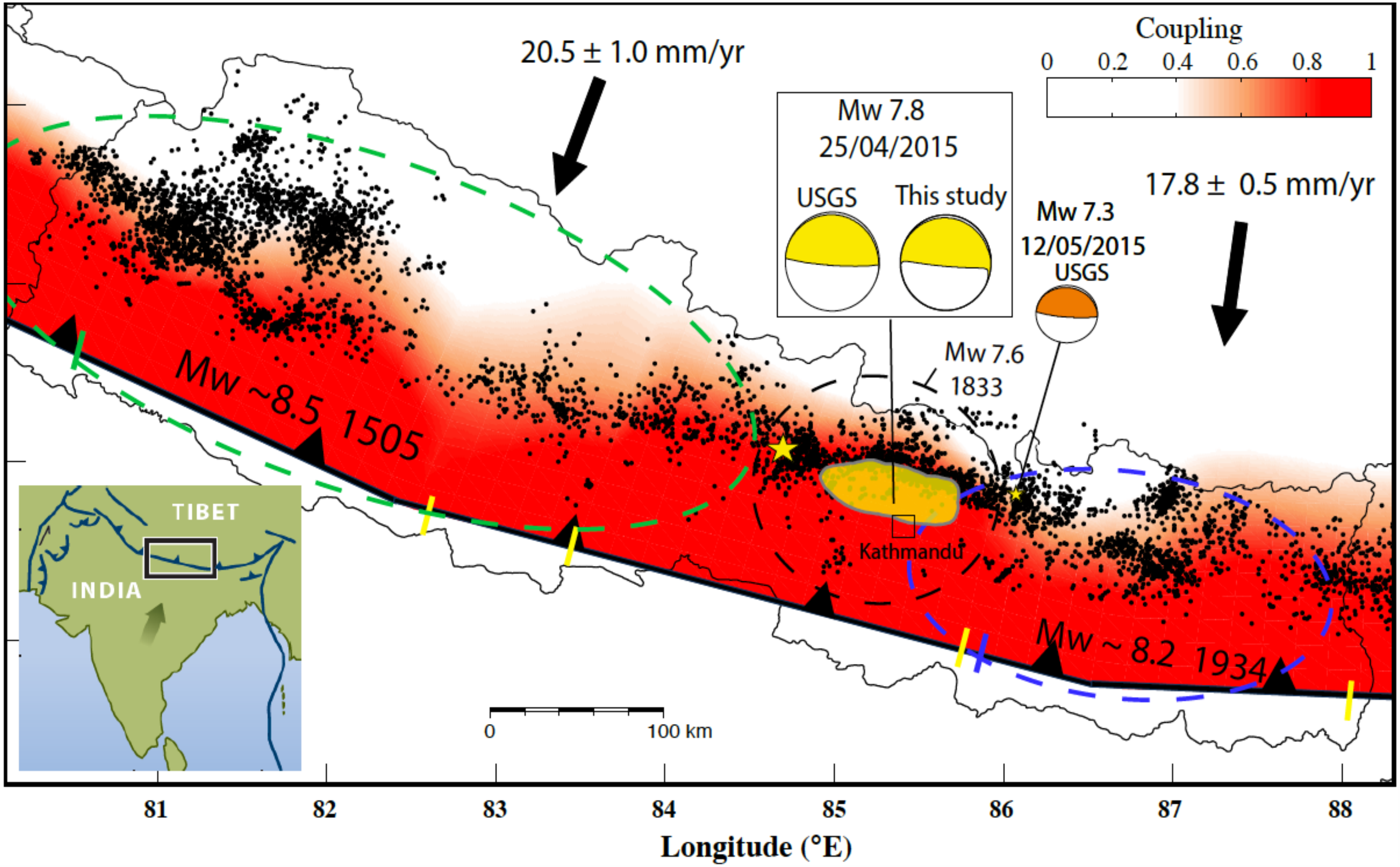
Bilham et al., Science, 2001

Mountain Building and Megathrust Earthquakes



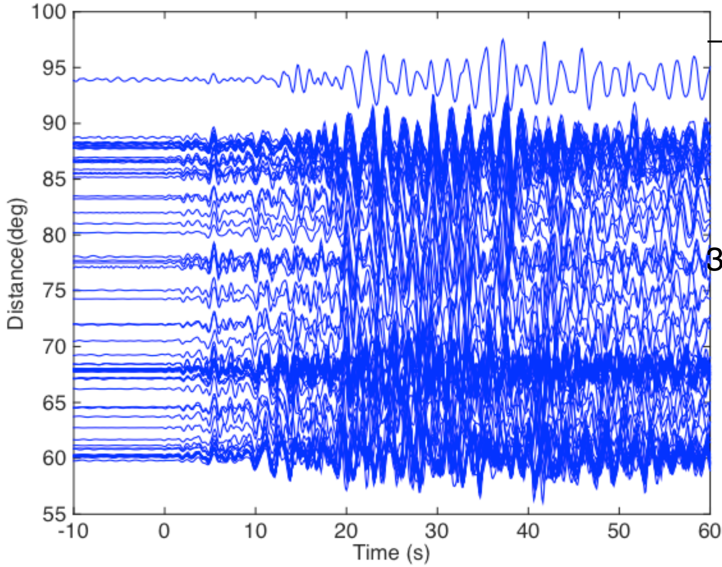
Credit: Seismo Lab, Caltech

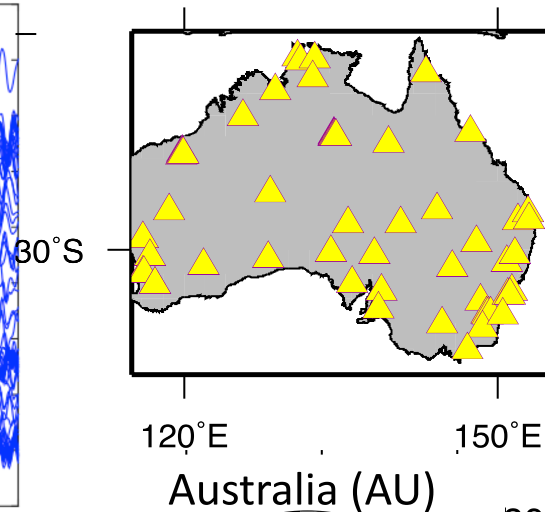
Tectonic Background

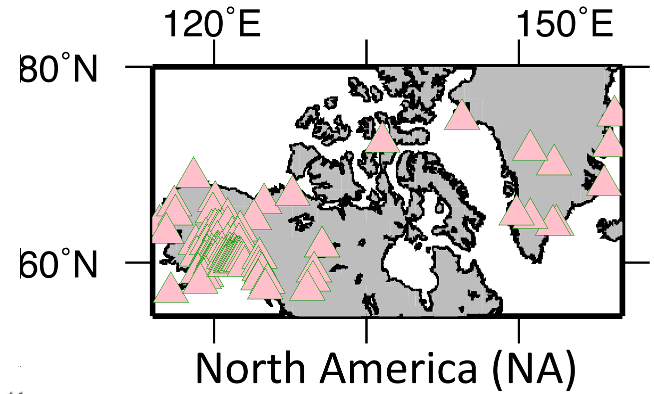


Avouac et al., 2015

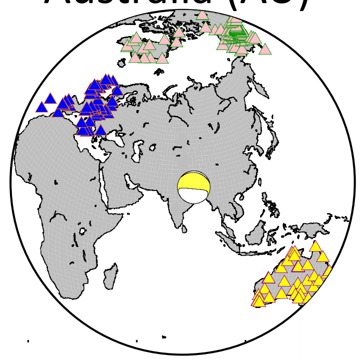
Data and Processing

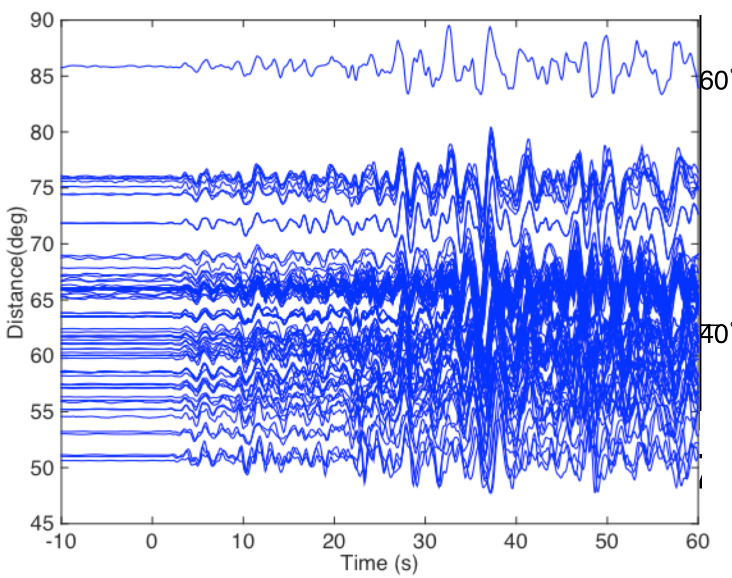


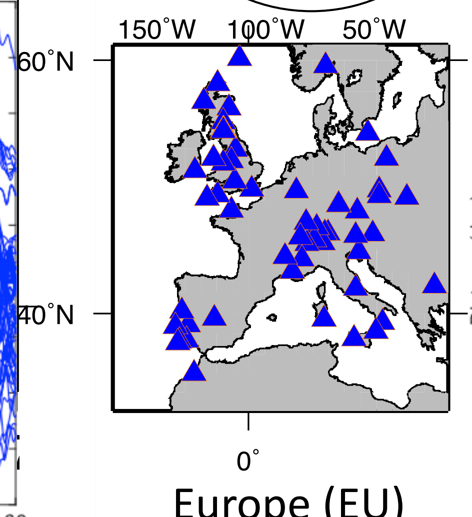


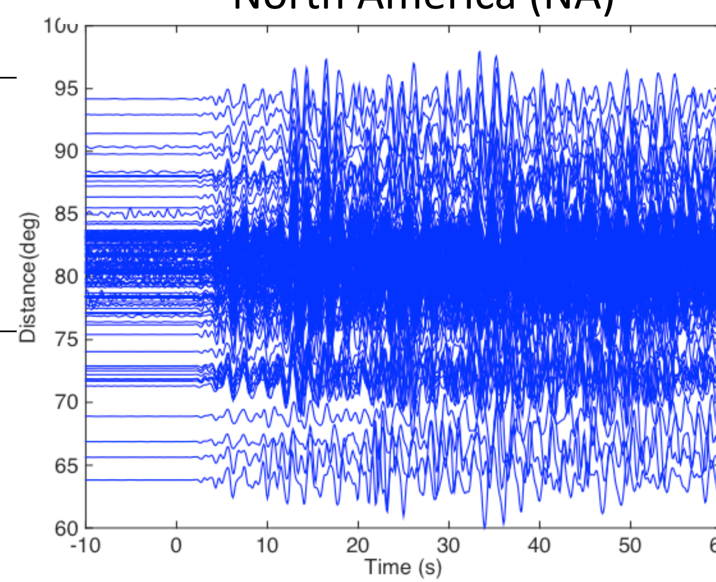


Broad-band seismograms filtered between 0.5 -2 Hz;
Epicentral distance between 50 and 95 degrees;
MUSIC back-projection technique;
Reference window strategy;

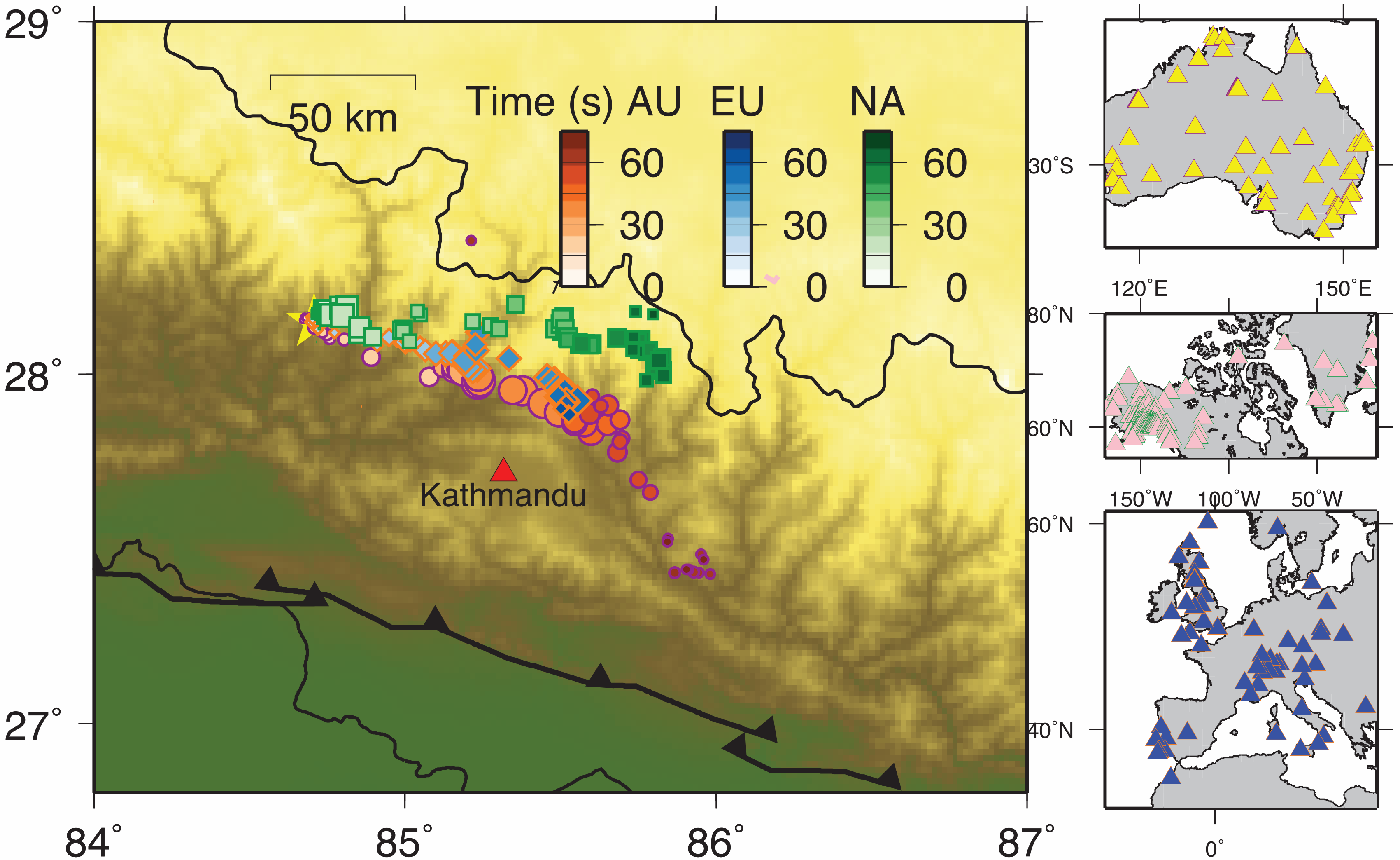




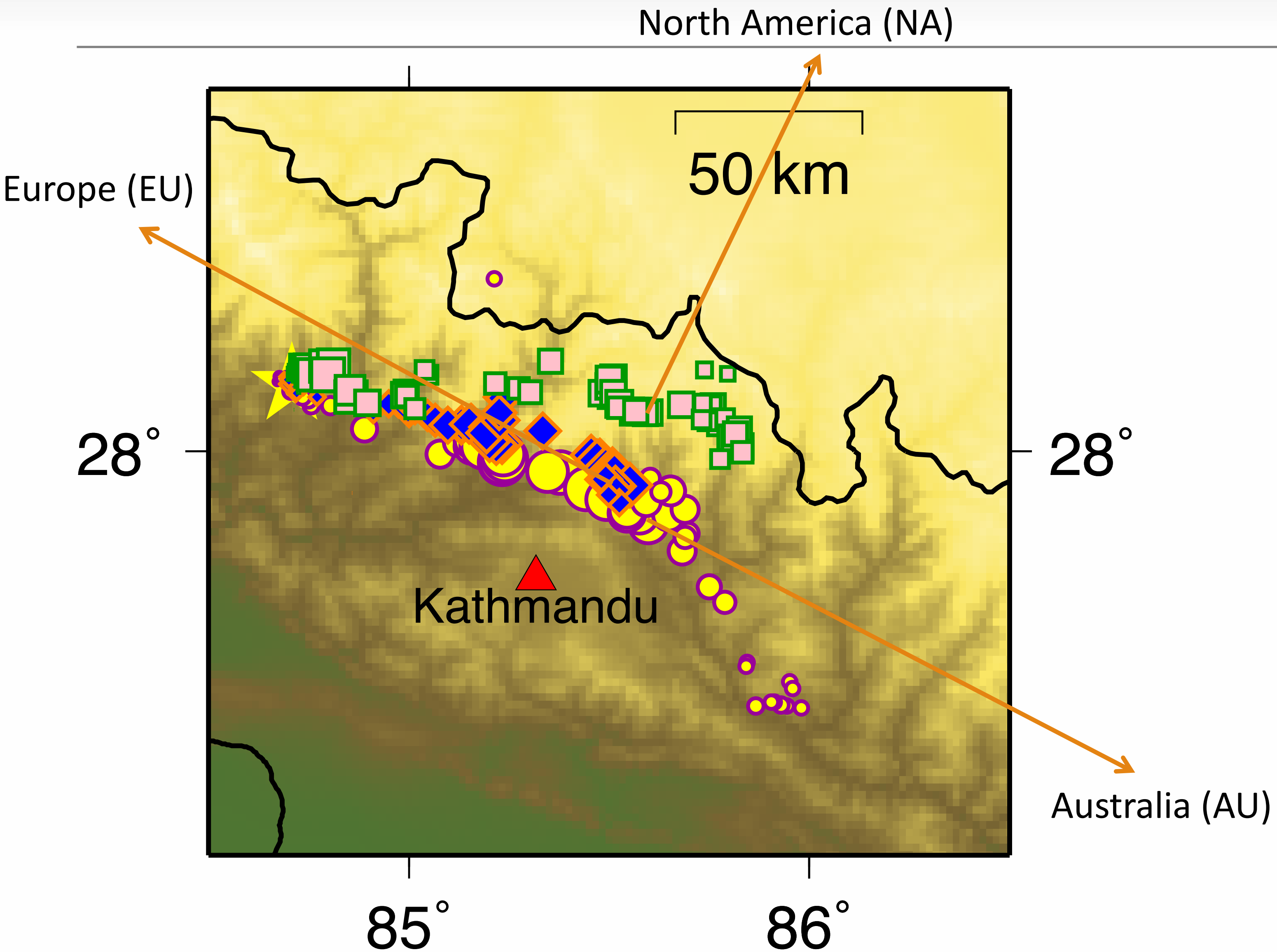




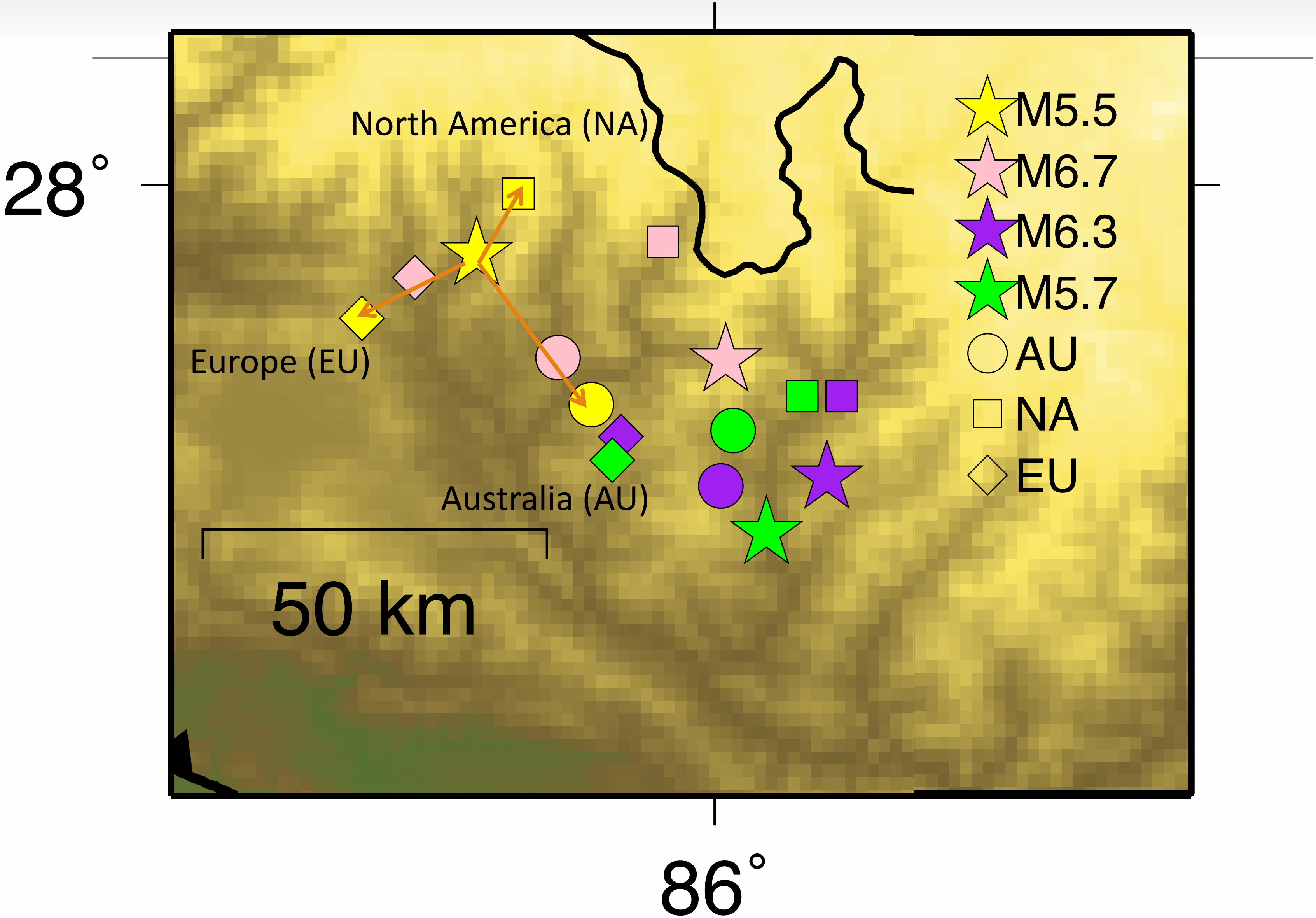
Back-projections of Three Large Continental Arrays



Back-projections of Three Large Continental Arrays



Aftershock Test

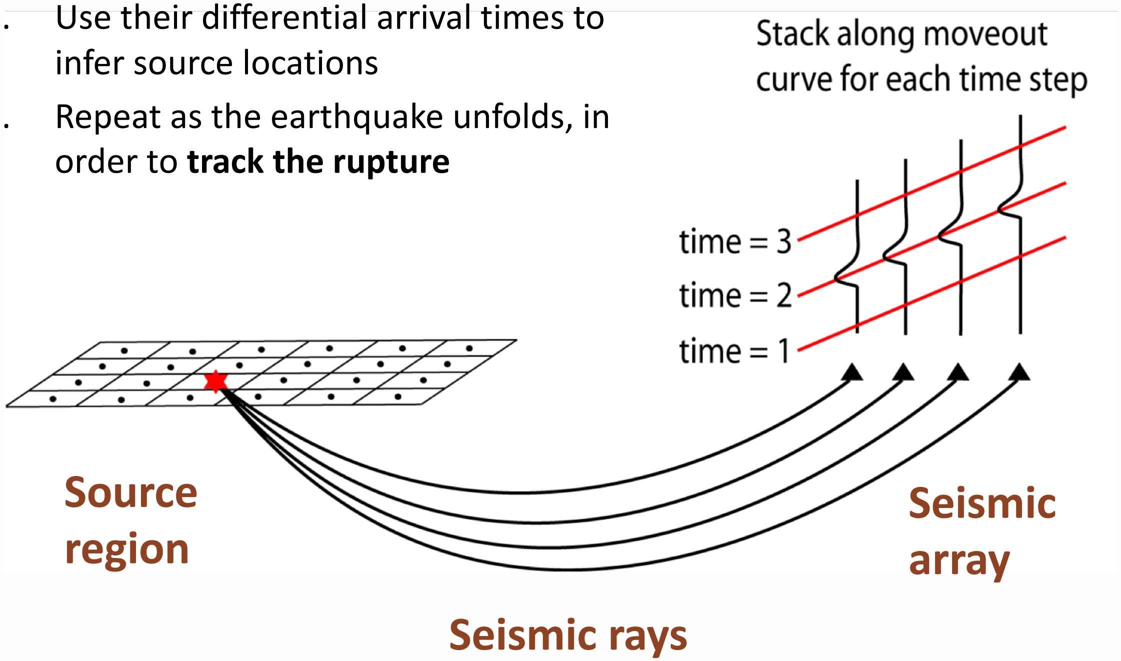


Back-projection

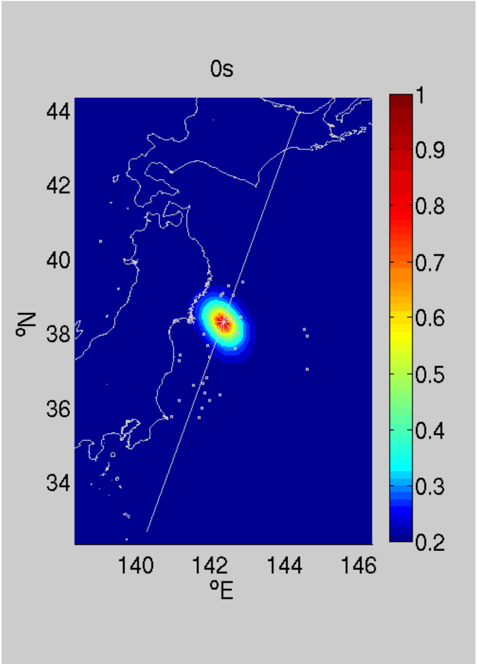
Introduced by Ishii, Shearer et al (2005)

Principle:

1. Identify coherent wave arrivals across a dense tele-seismic array
2. Use their differential arrival times to infer source locations
3. Repeat as the earthquake unfolds, in order to **track the rupture**



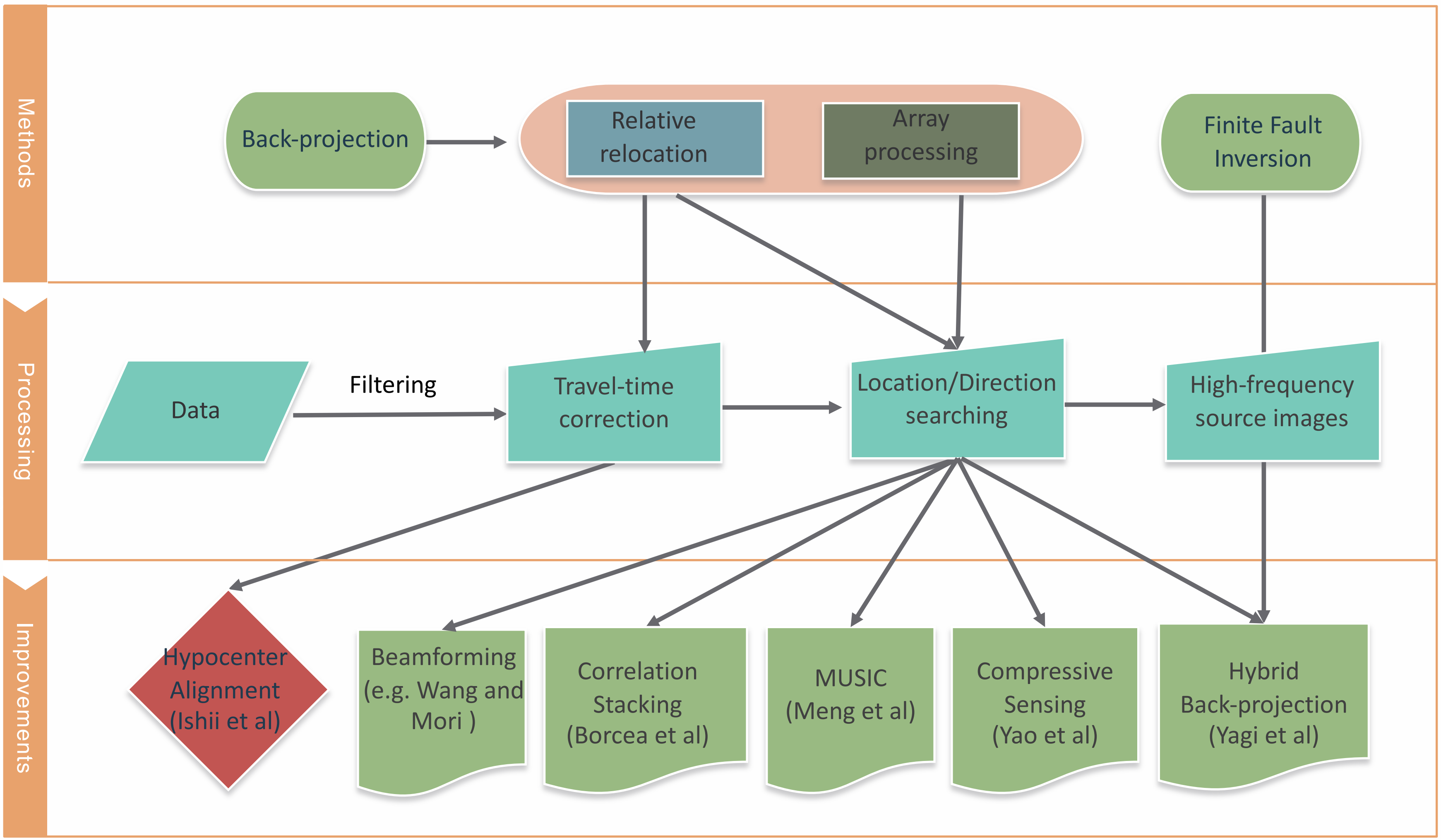
Tohoku Earthquake



Meng et al., GRL (2011)

High-resolution is obtained by exploiting high-frequency waves (~1Hz)

Anatomy of the Back-projection Method



Principles of Back-projection

Source location — Seismogram — Travel time

BP equation: $$BP(\xi,t)=\sum_j u_j\left(t+T_j^0(\xi)\right)$$

Time — Station index

Introducing Uncertainty of Travel time

$$T_j^0(\xi)=T_j^{cal}(\xi)+\delta T_j(\xi)$$

Theoretic travel time — Travel time error

Hypocenter Alignment

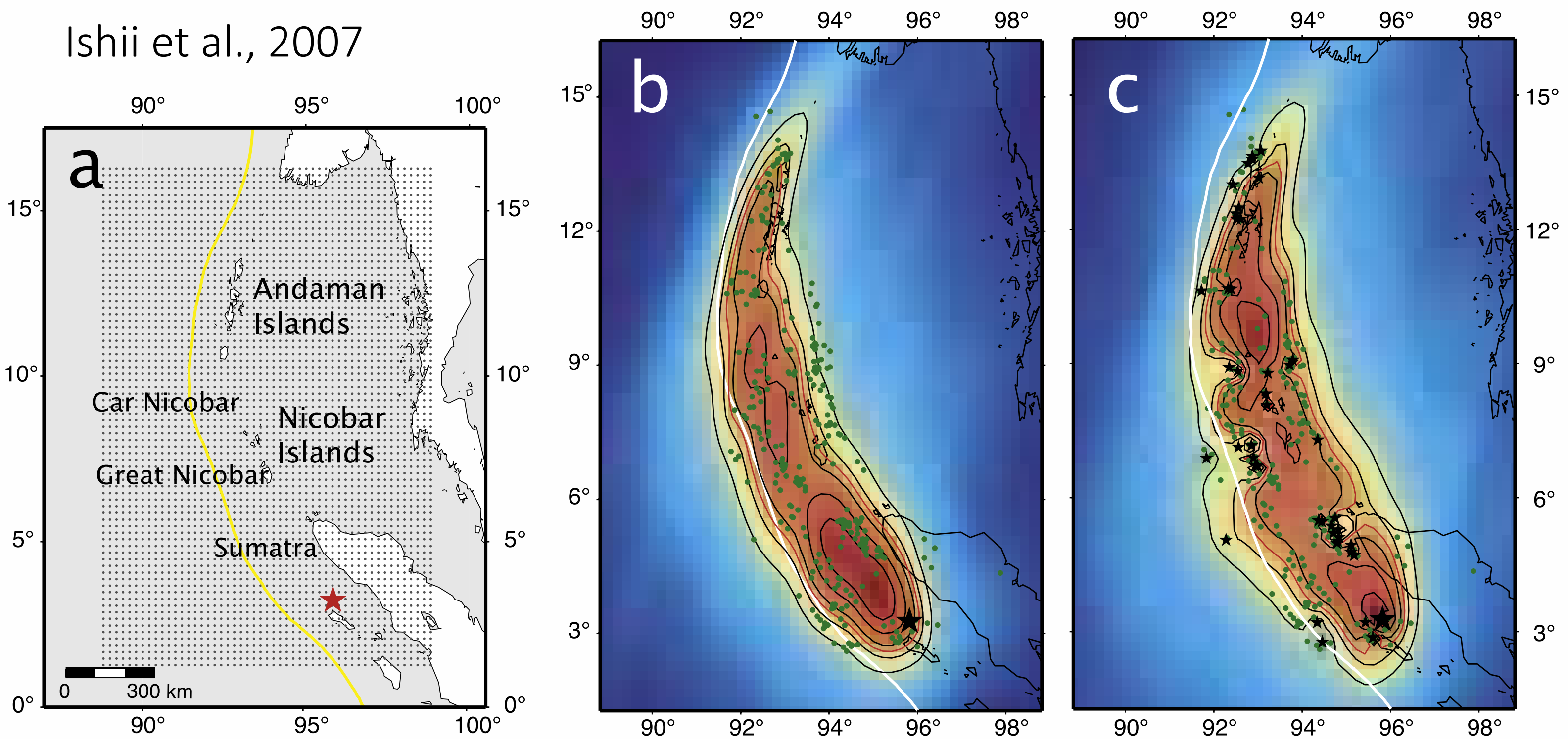
$$\boxed{\delta T_j(\xi)\simeq\delta T_j(\xi_h)}=T_j^0(\xi_h)-T_j^{cal}(\xi_h)$$

Not always true !

Hypocenter

Empirical aftershock calibrations of Back-projection

Ishii et al., 2007

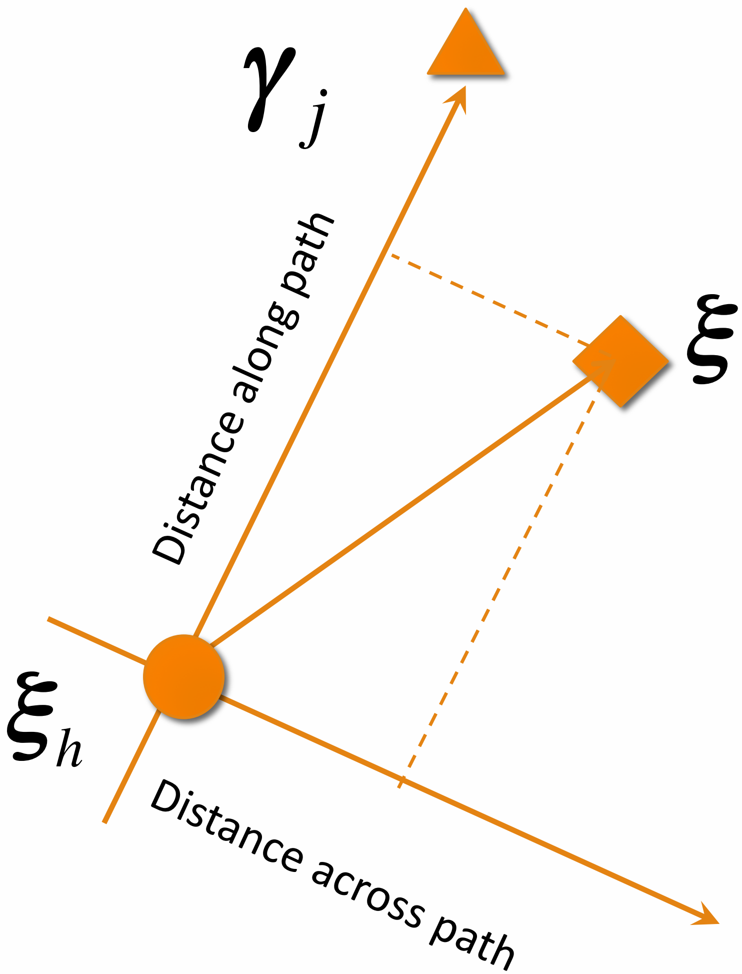


Interpolation by weighted sum of aftershock travel-time errors!

Challenges:

1. Sparseness of large aftershocks.
2. Aftershocks are mostly distributed away from large co-seismic slip

Introducing slowness correction



Far-field travel-time approximation

$$T_j^{cal}(\xi) = T_j(\xi_h) + s_j \gamma_j \cdot (\xi - \xi_h)$$

Introducing the slowness correction term

$$\delta T_j(\xi) \simeq \delta T_j(\xi_h) + \boxed{\delta s_j \gamma_j \cdot (\xi - \xi_h)}$$

Accounting for travel time errors away from hypocenter!

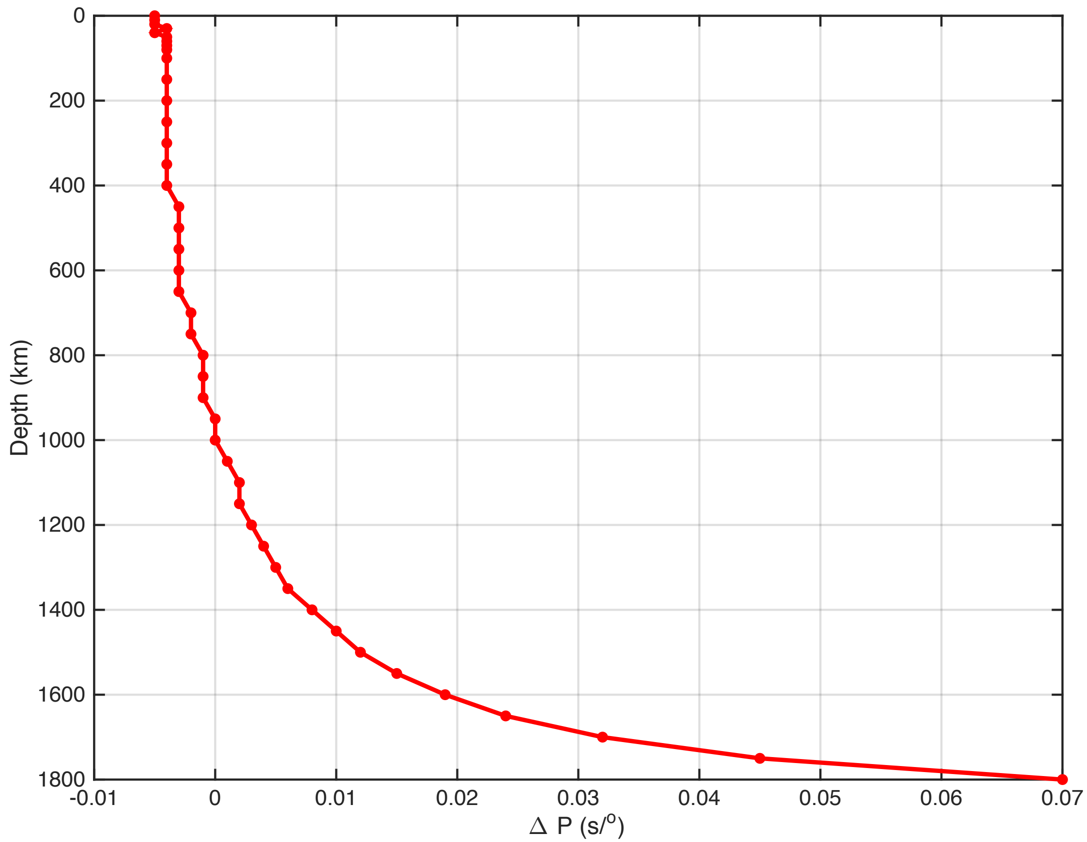
Revised Back-projection Formula

$$BP(\xi, t) = \sum_j u_j\left(t + T_j^0(\xi)\right)$$

$$= \sum_j u_j\left(t + T_j^{cal}(\xi) + \delta T_j(\xi_h) + \delta s_j \gamma_j \cdot (\xi - \xi_h)\right)$$

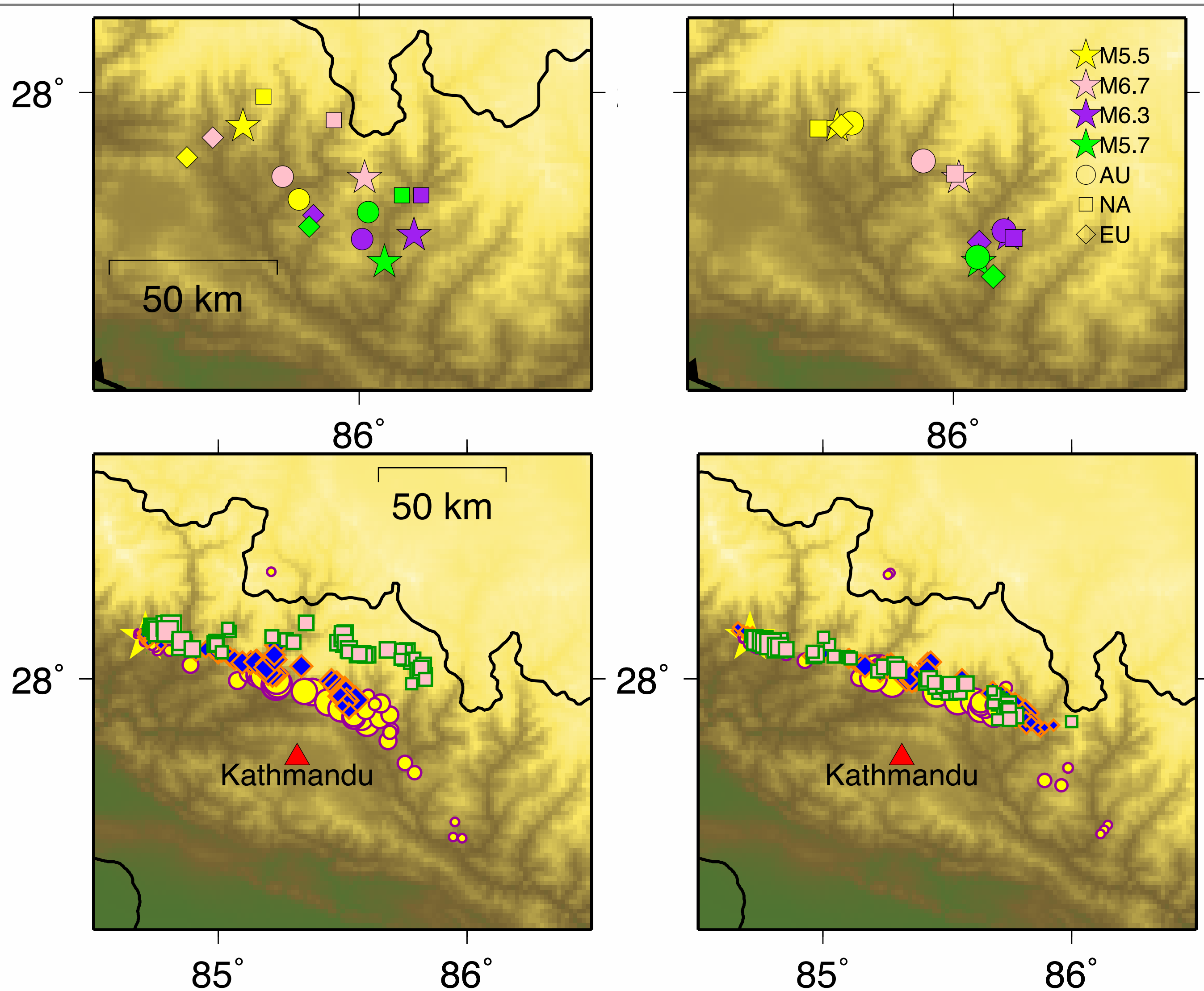
$$= \sum_j u_j\left(t + T_j^0(\xi_h) + (s_j + \delta s_j)\gamma_j \cdot (\xi - \xi_h)\right)$$

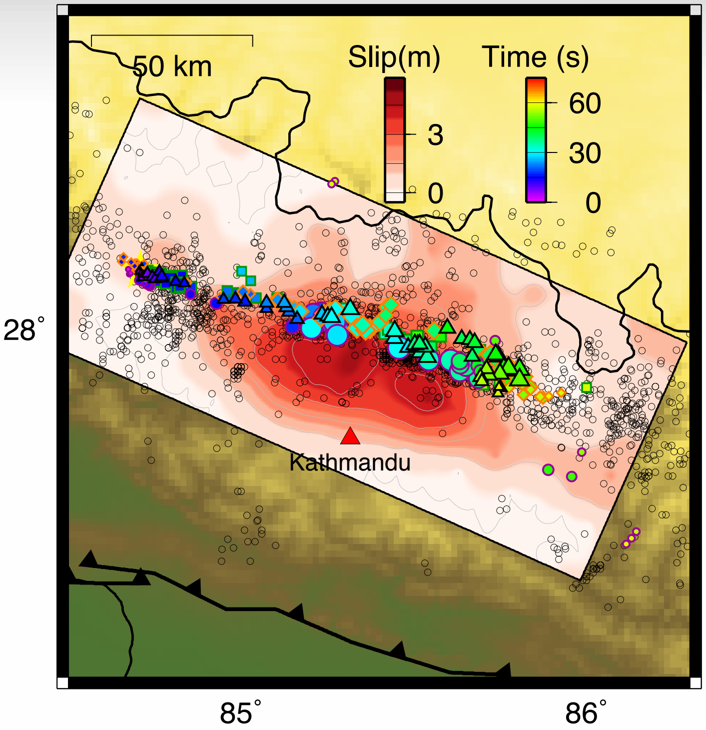
Source of Slowness Error

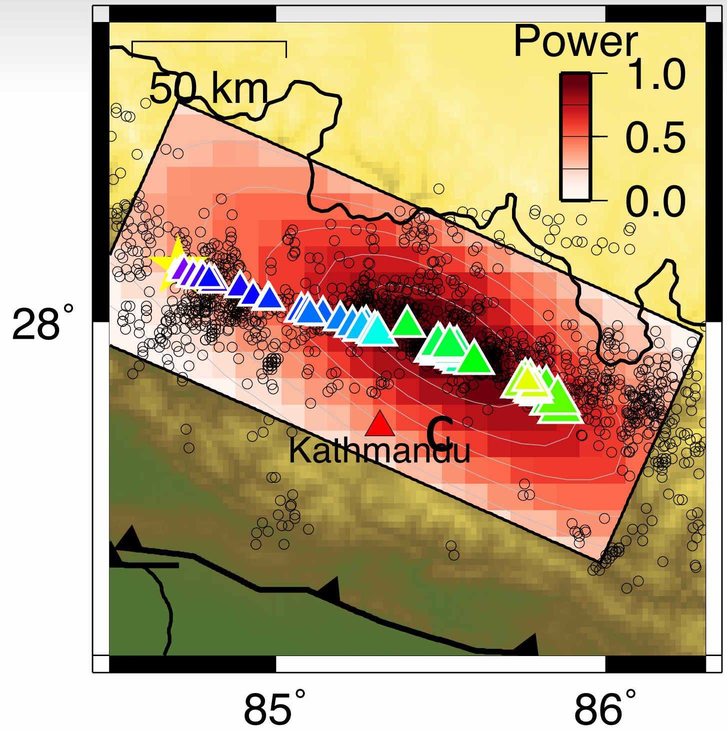


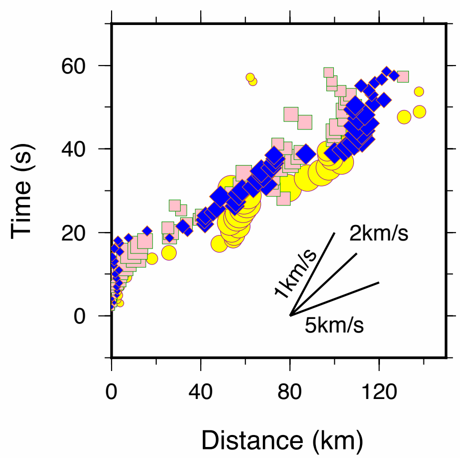
Slowness (ray parameter) error as a function of velocity change at different depths

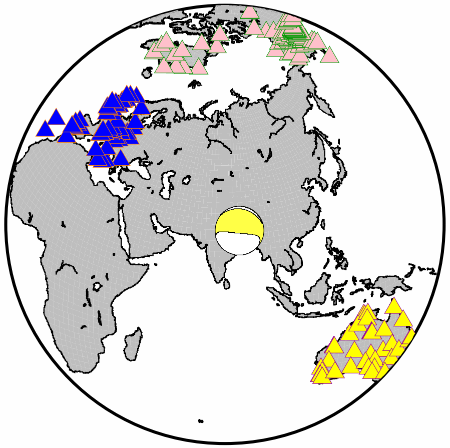
Back-projections with Slowness Calibration



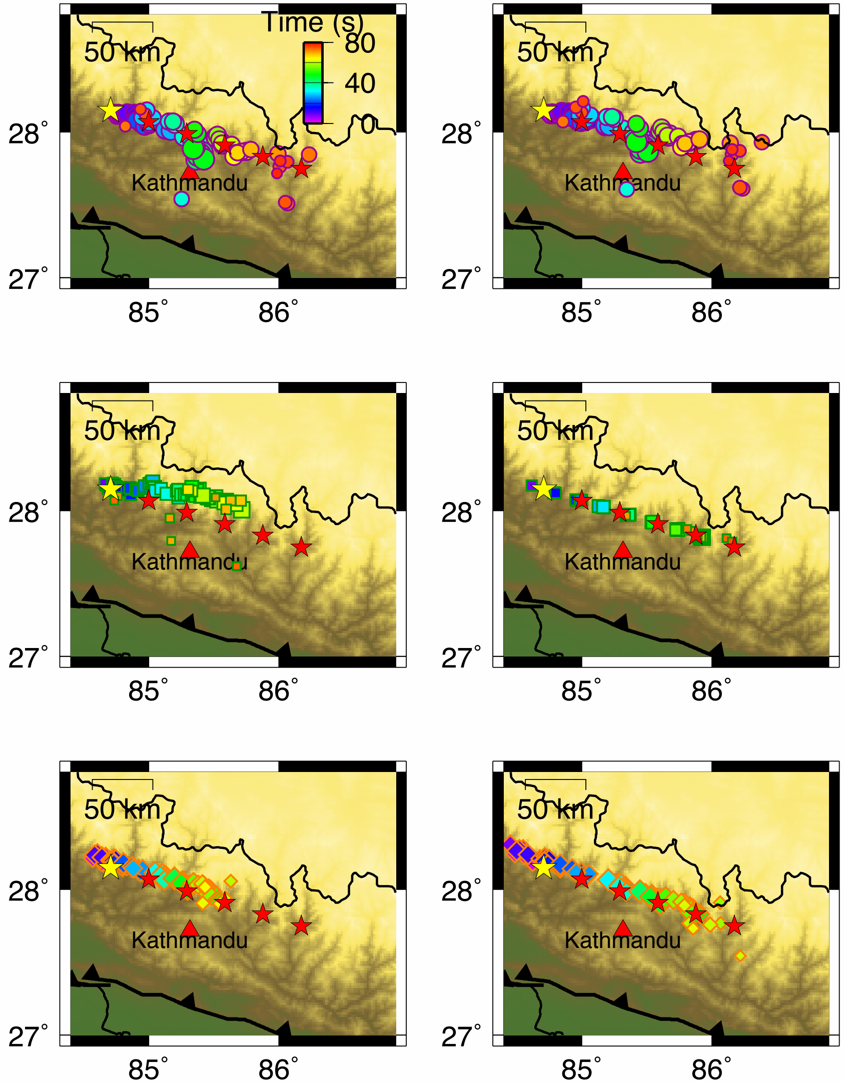

50 km
Slip(m)
3
0
Time (s)
60
30
0
28°
Kathmandu
85°
86°


50 km
Power
1.0
0.5
0.0
28°
Kathmandu
85°
86°

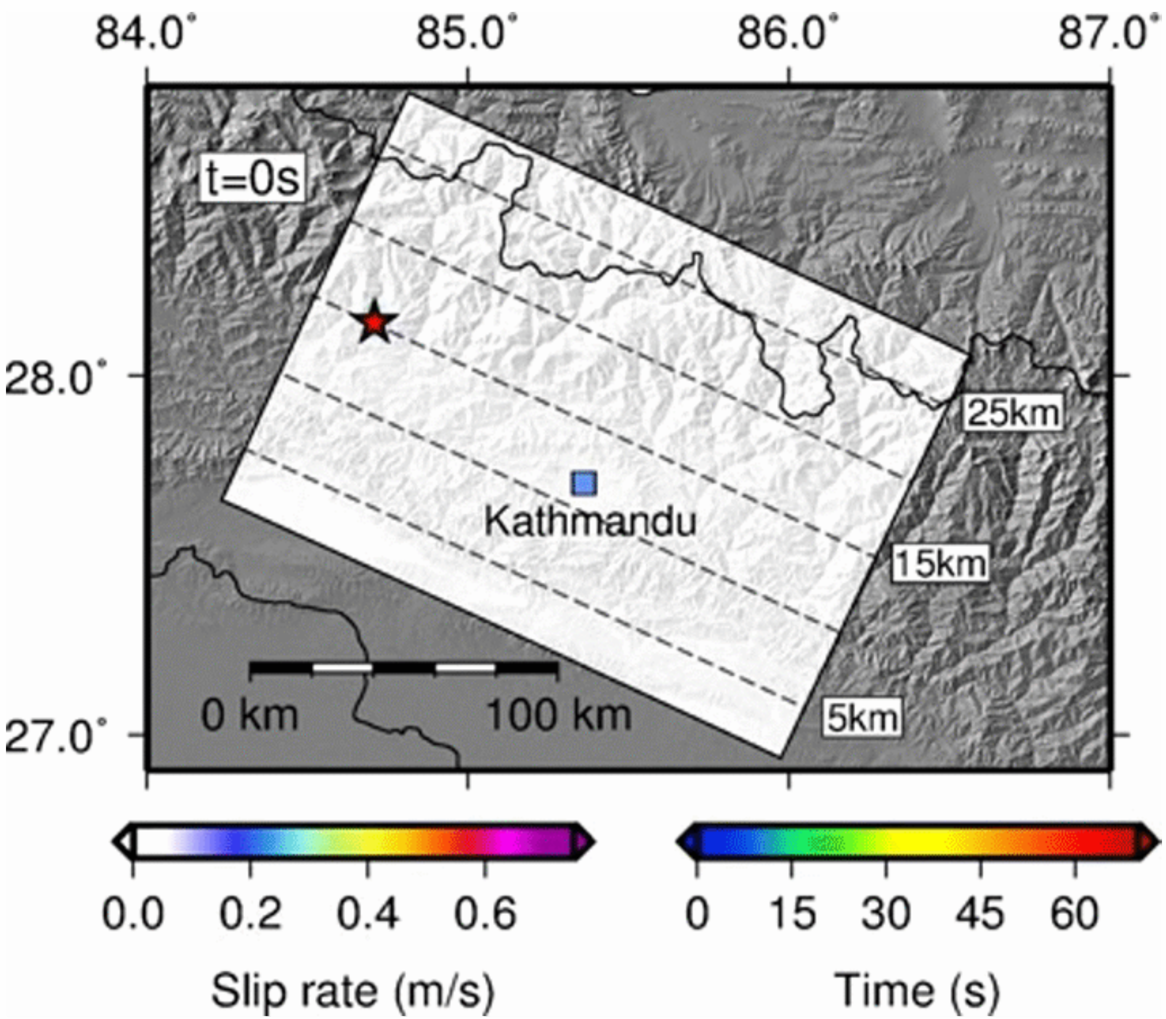

Time (s)
60
40
20
0
2km/s
1km/s
5km/s
0
40
80
120
Distance (km)



Synthetic tests of kinematic rupture scenarios

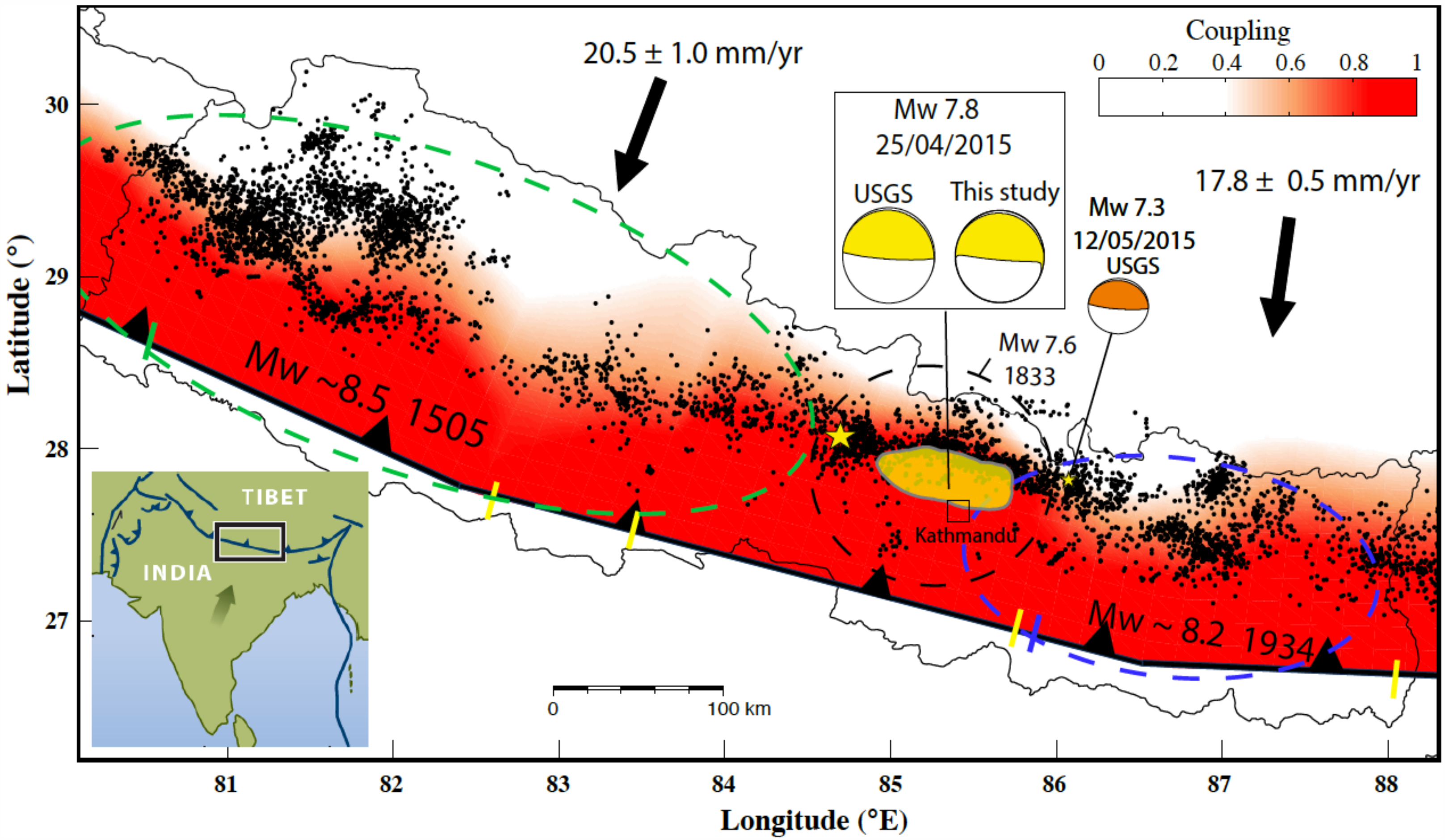


Consistency Between BP and Finite Fault Models



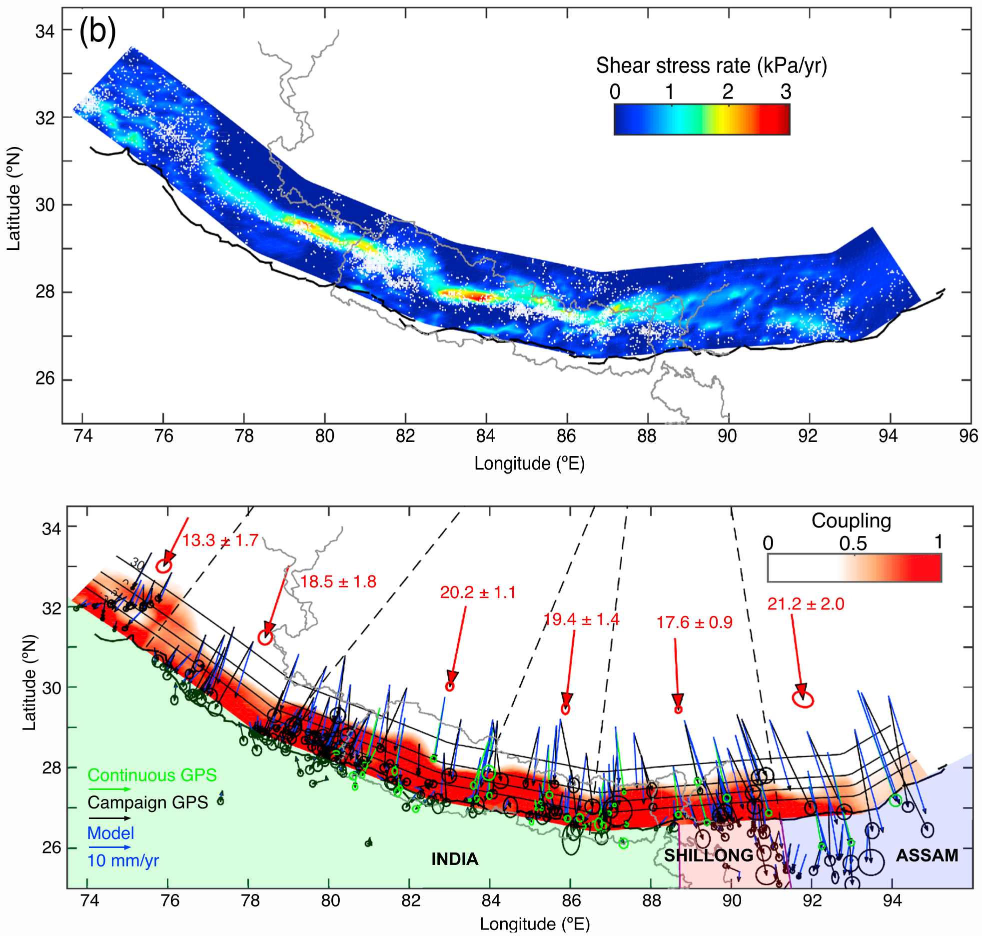
Credit: Diego Melgar and Lingsen Meng

Unzipping of the Lower Edge of the Locked Megathrust



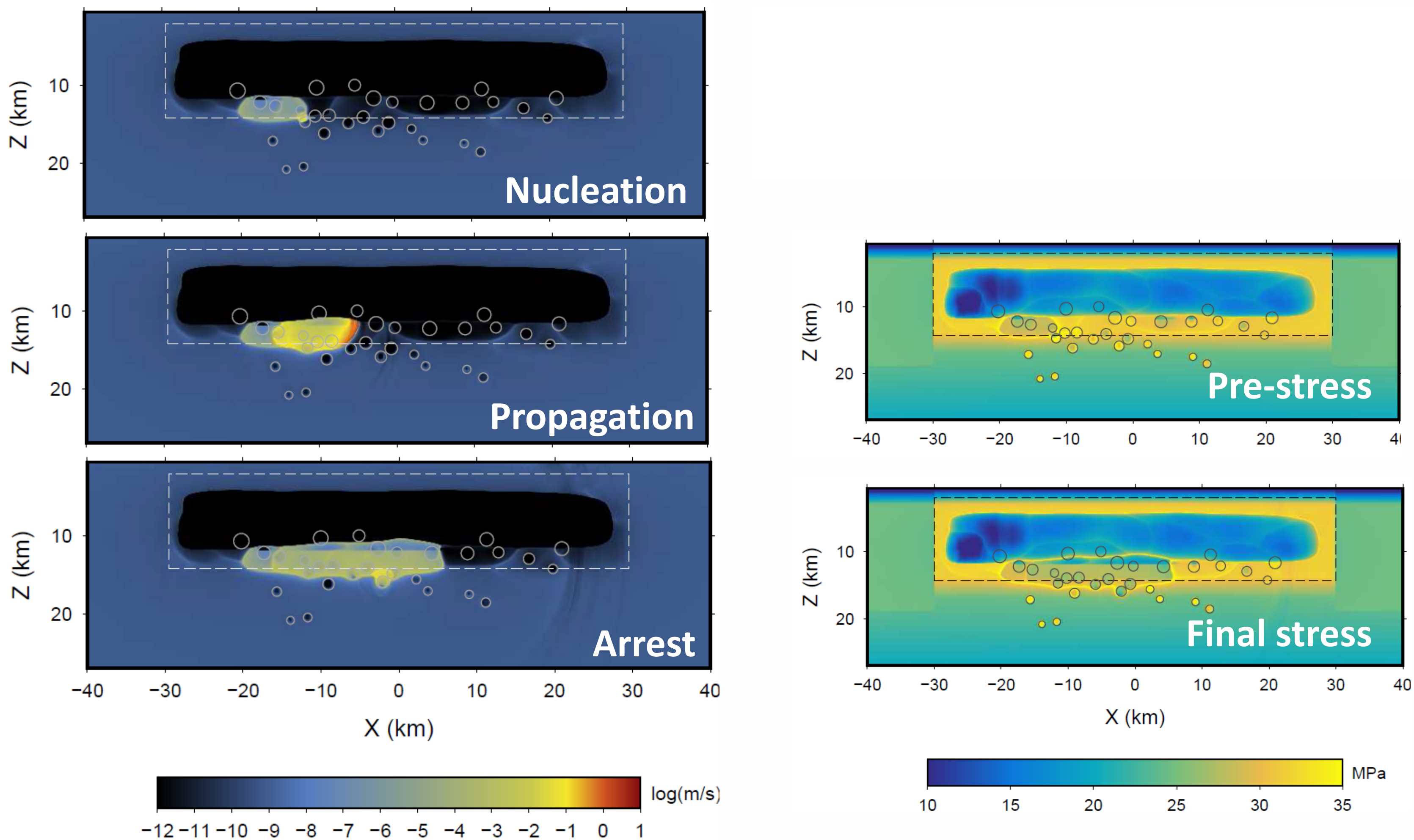
Avouac et al., 2015

Stress Loading at the Bottom of the Coupling Zone



Stevens and Avouac, 2015

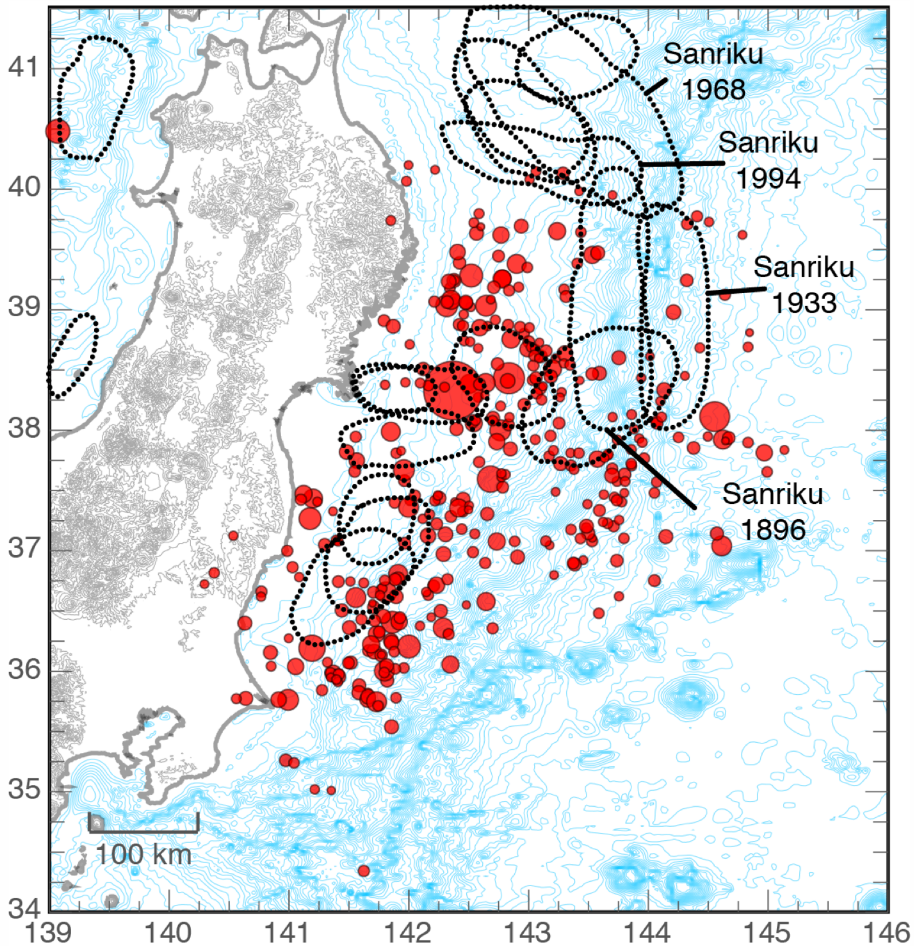
Unzipping of the Lower Edge of the Locked Megathrust



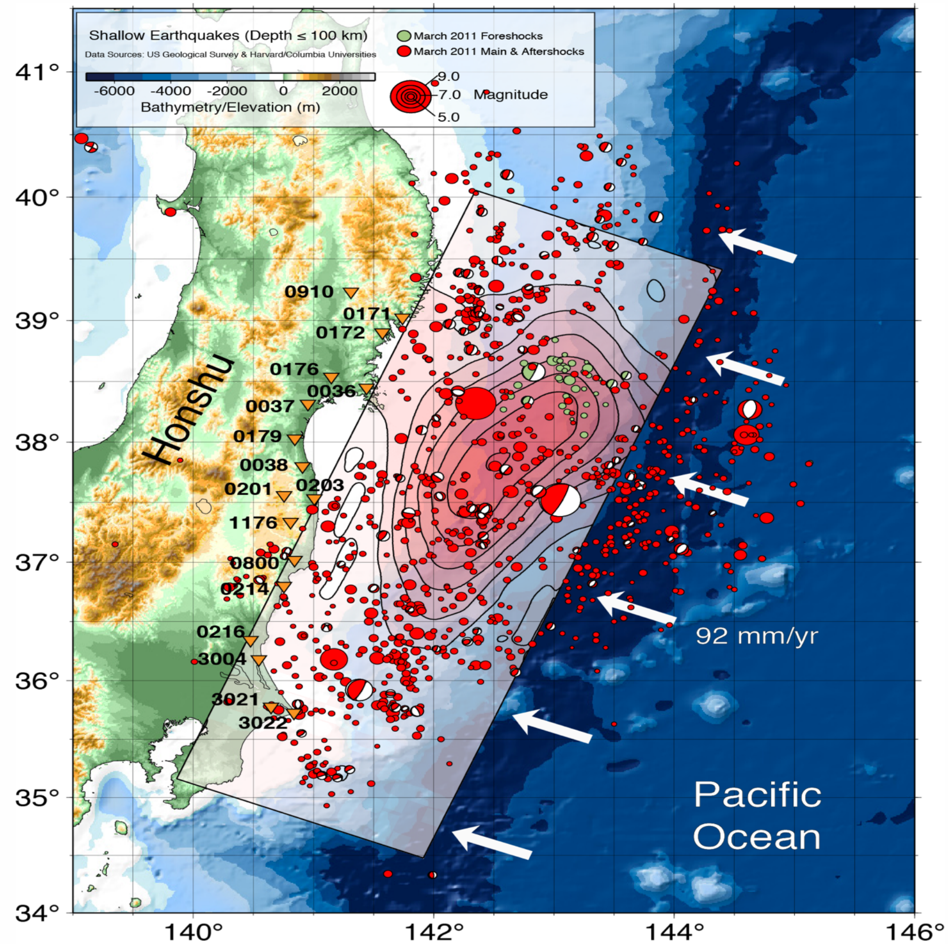
Credit: Junle Jiang and Nadia Lapusta

Earthquake Cycles in Tohoku Region

Historical earthquakes



2011 Tohoku Earthquake



Allmon et al., 2011

Summary

- Multi-Array back-projections of the Gorkha earthquake provides a unique opportunity to understand the spatial uncertainties of BP imaging.
- A slowness error term calibrated by aftershocks needs to be introduced to achieve consistency between BPs of different arrays.
- Refined source imaging reveals a narrow unilateral eastward rupture unzipping the lower bottom of the locked portion of the MHT.
- The Gorkha earthquake is possibly a intermediate event during the interseismic period of larger earthquakes.