Radiated energy of shallow moderate-to-large earthquakes

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NMEM, Smolenice, 2015

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UC San Diego

Earthquake energy budget

$$\Delta W = E_G + E_R + E_F$$

Fracture Radiated Friction (heat)

Radiated energy is estimated from the kinetic energy carried by seismic waves

$$E_R = \iint_{S_0} \int_{-\infty}^{\infty} \rho c \, \mathrm{v}^2(t) \, dt \, dS$$

Most of the energy is carried by high frequencies (mostly P and S)

S_0 is a sphere in the far-field of the source within which we assume a homogeneous whole space

Need to remove wave propagation effects

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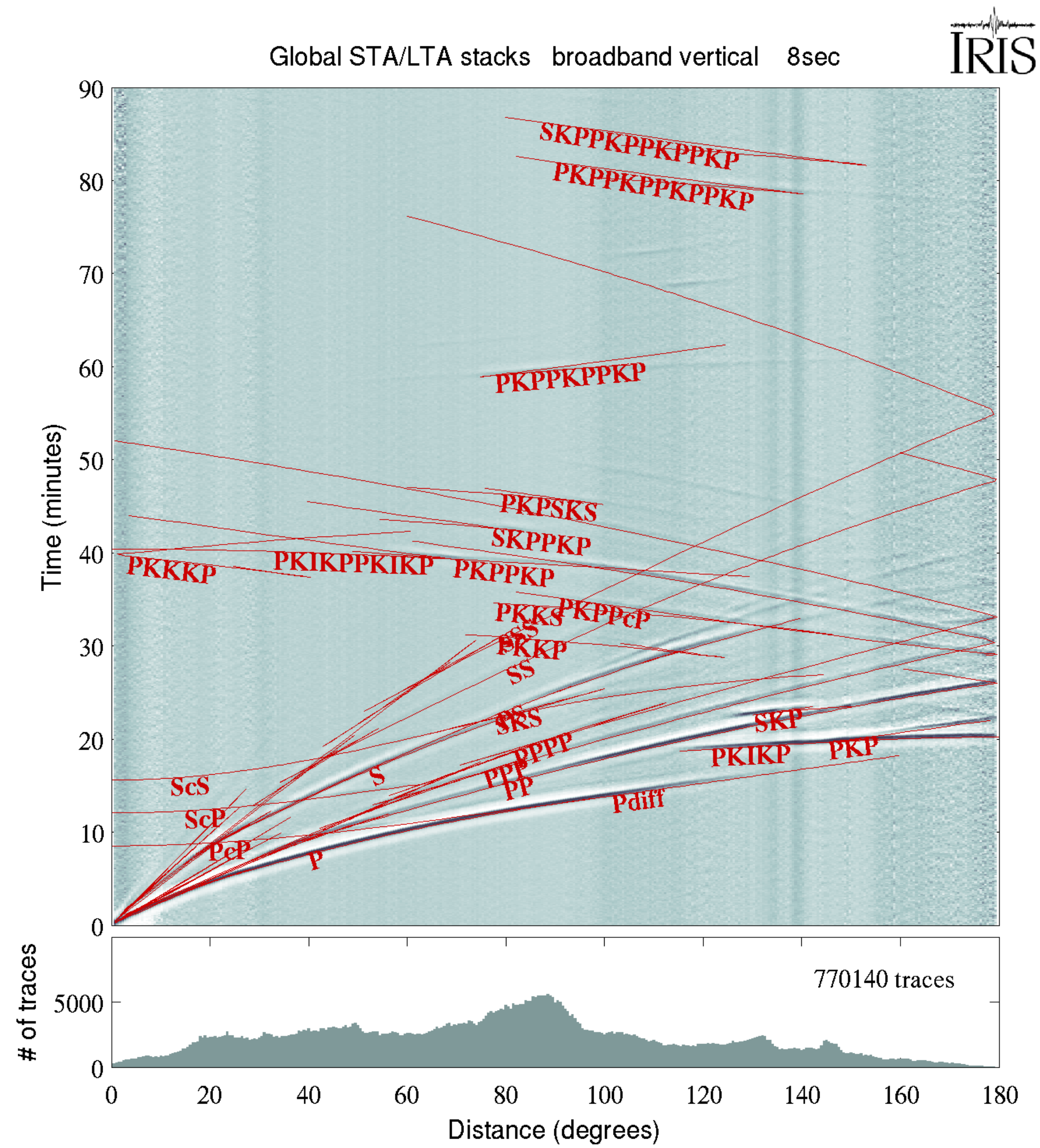
Data: global arrivals of body waves



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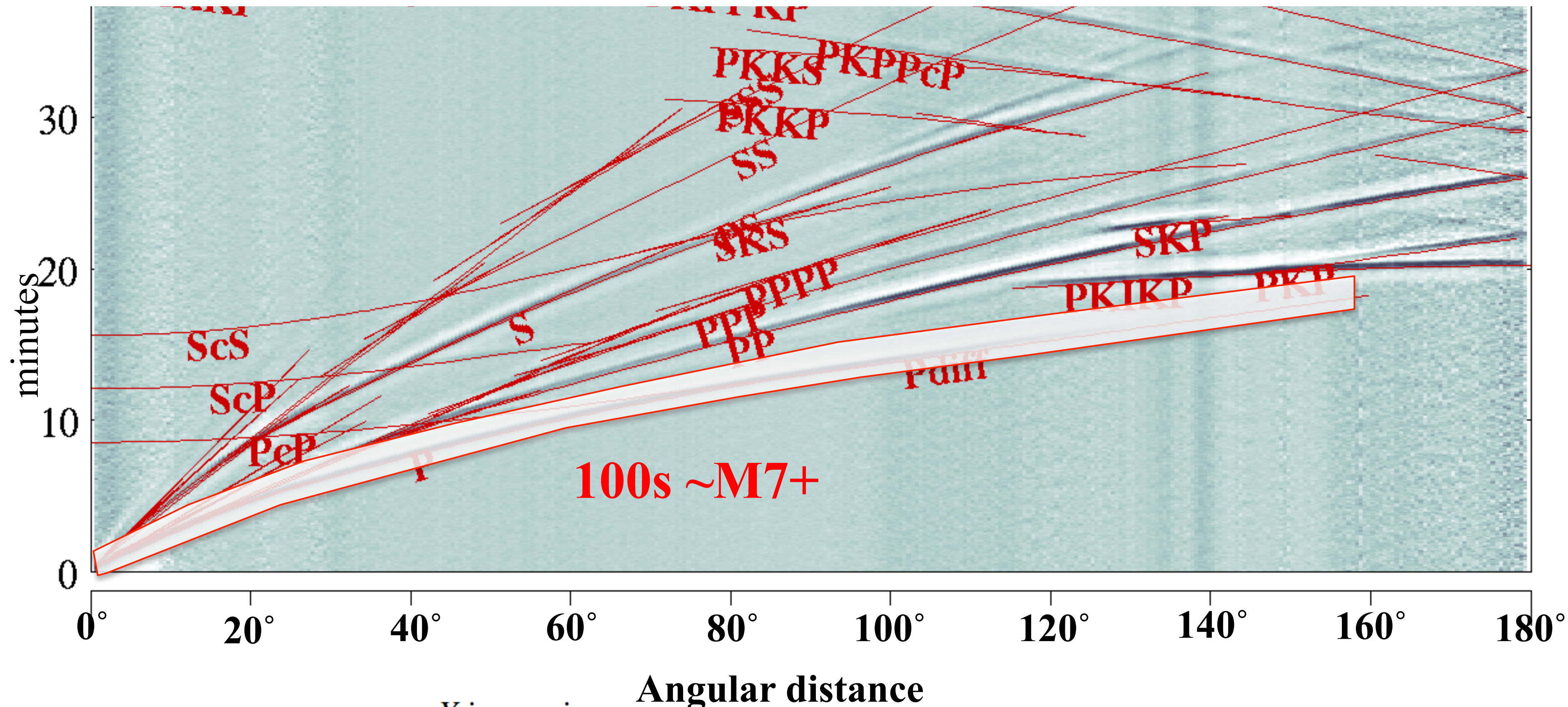

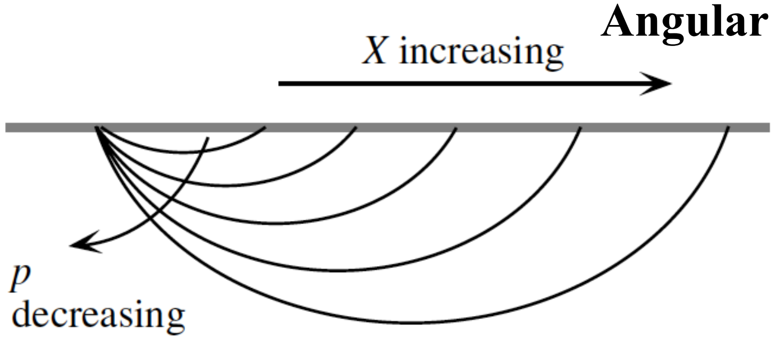

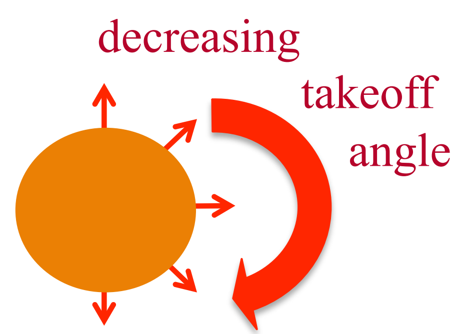

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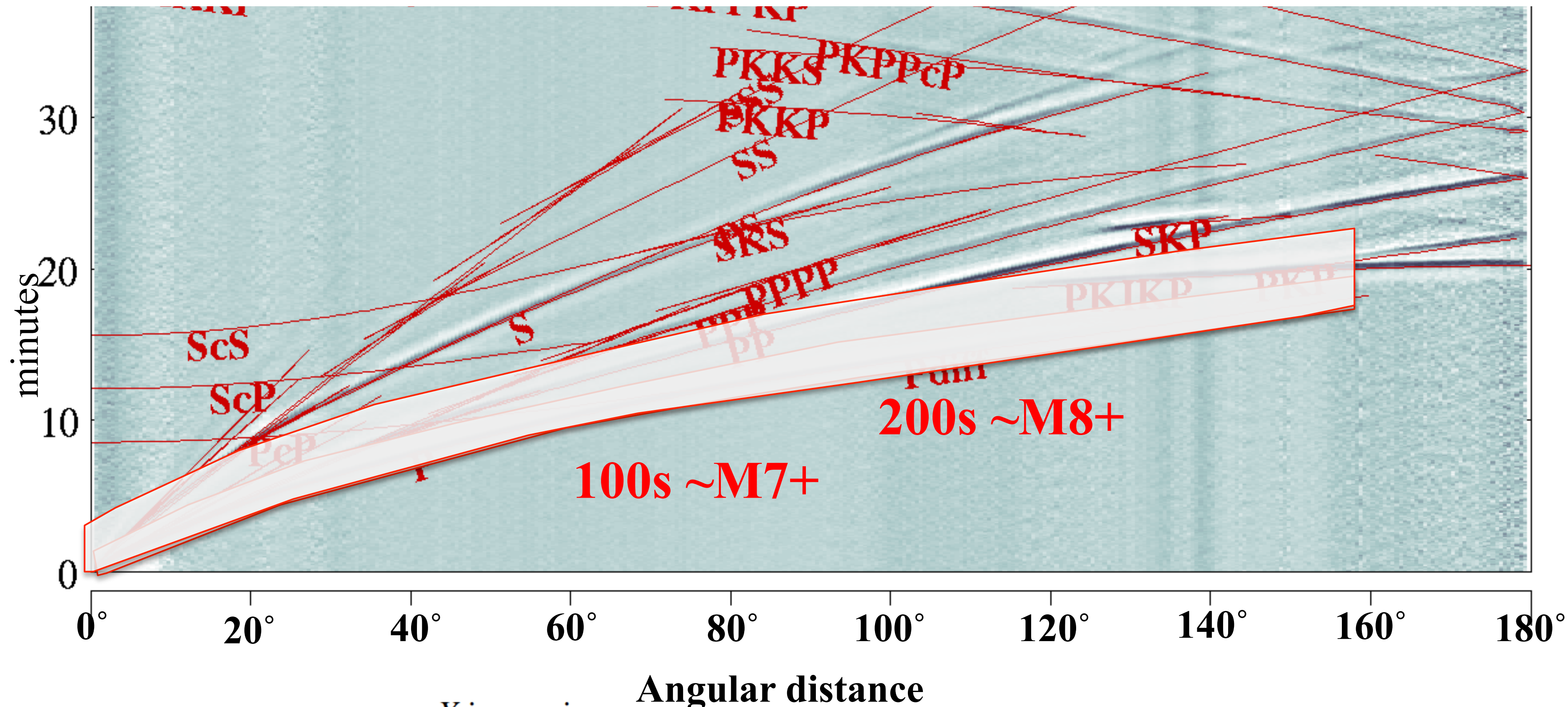

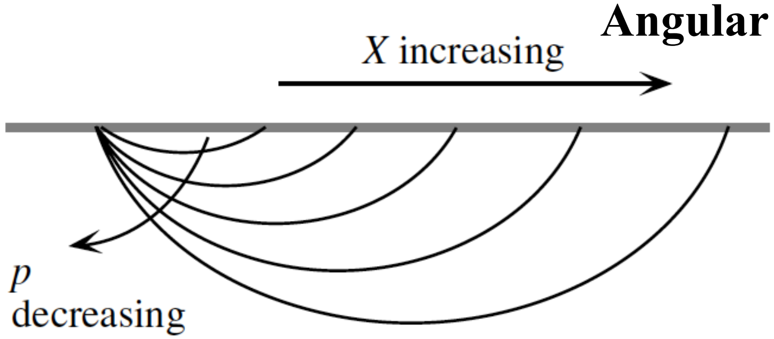

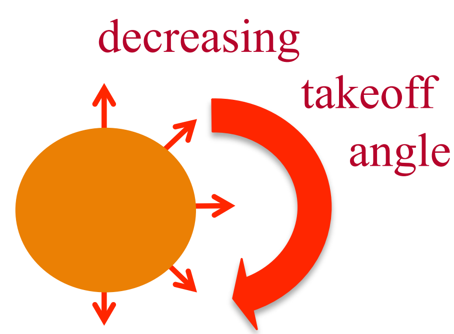

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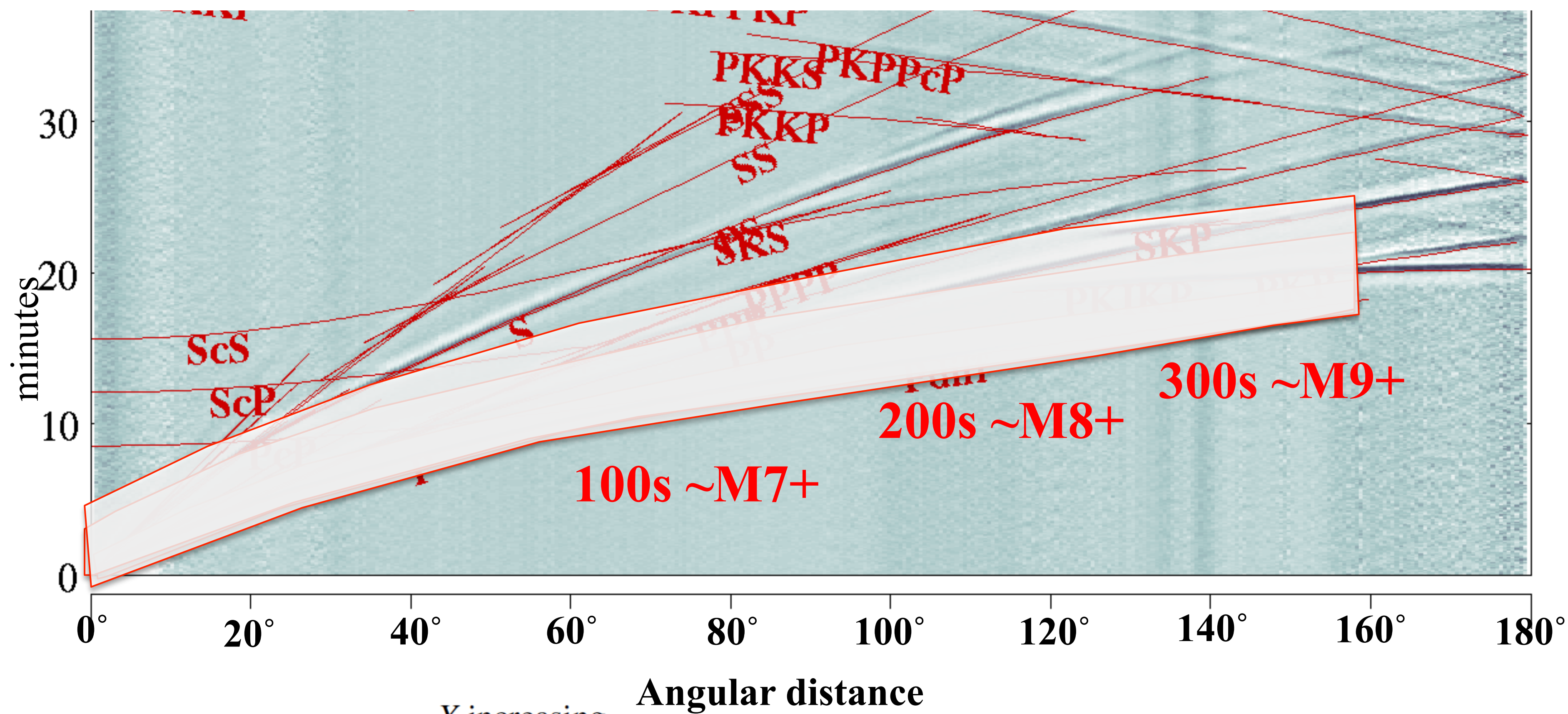

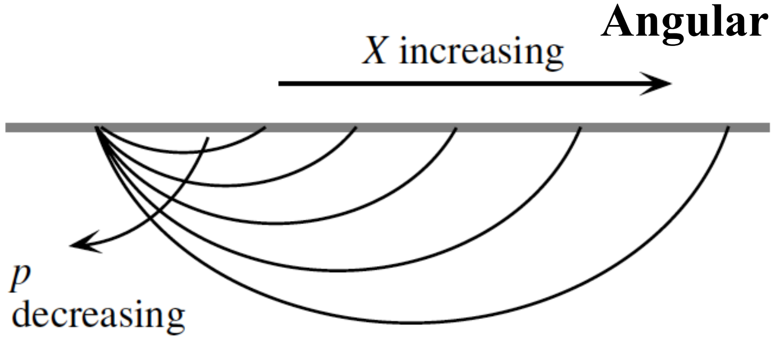

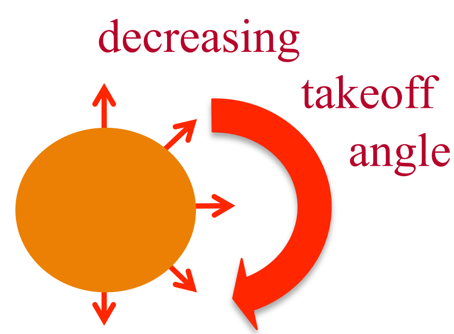

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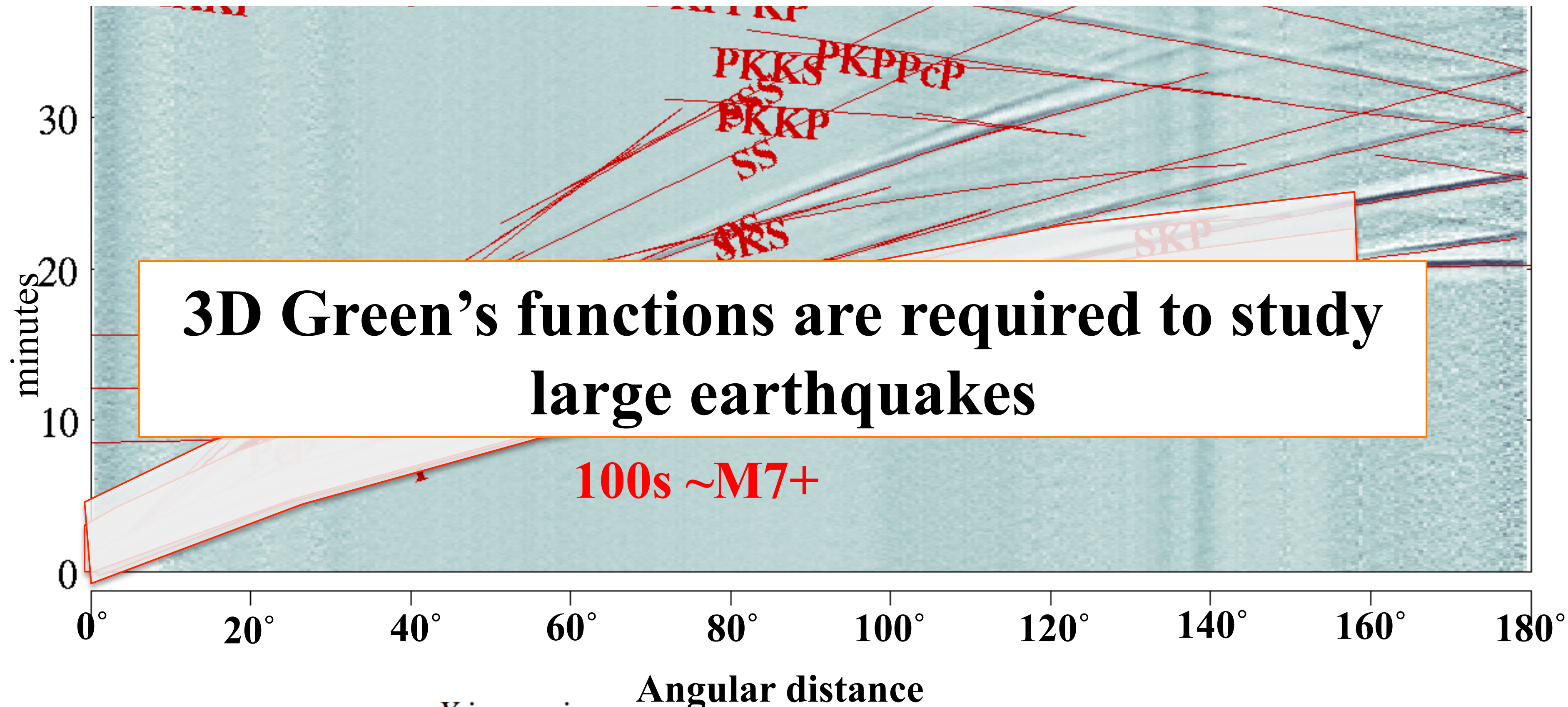
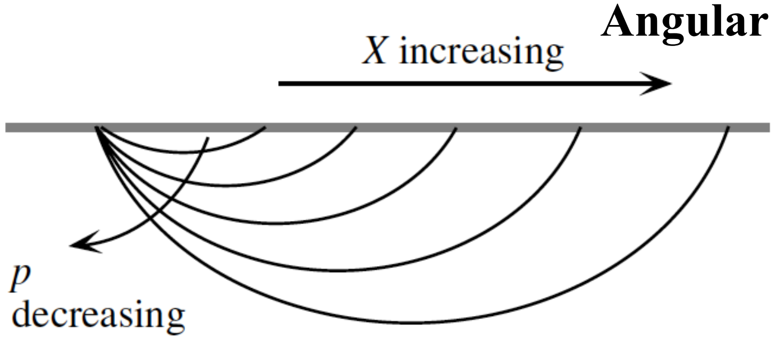
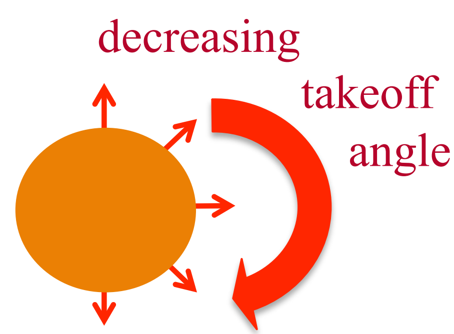


3D Green's functions are required to study large earthquakes

100s ~M7+





Global Green's functions to calibrate path effects

1. Green's function from simulation of wave propagation in 3D Earth

+ would be ideal
+ receivers can be from anywhere
− computationally challenging for high frequency Gfs
− require accurate high resolution global velocity models

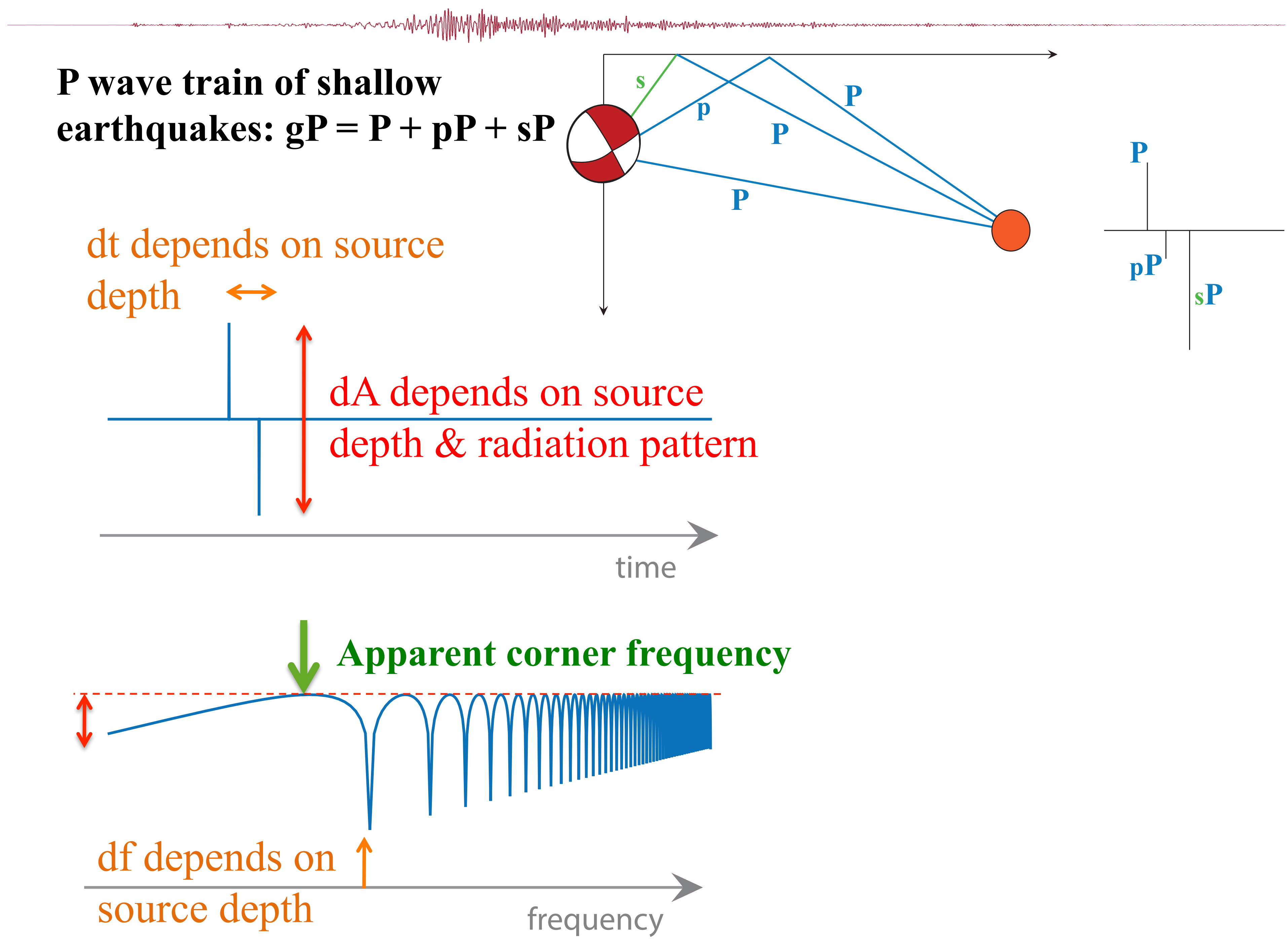
2. Empirical Green's function from small events (eGf)

+ true 3D path
+ aftershocks are great candidates for eGf
+ receivers can be from anywhere
− Small events have lower SNR at long periods
− require knowledge of eGf source spectrum

3. Attenuation Q and ray tracing in simple PREM/IASPEI 3D Earth

+ computationally inexpensive
+ good approximation at long period
− only valid for direct waves such that receivers are restricted to 30-90˚ angular distance
− does not include lateral path effects (often called 1D Green's function)

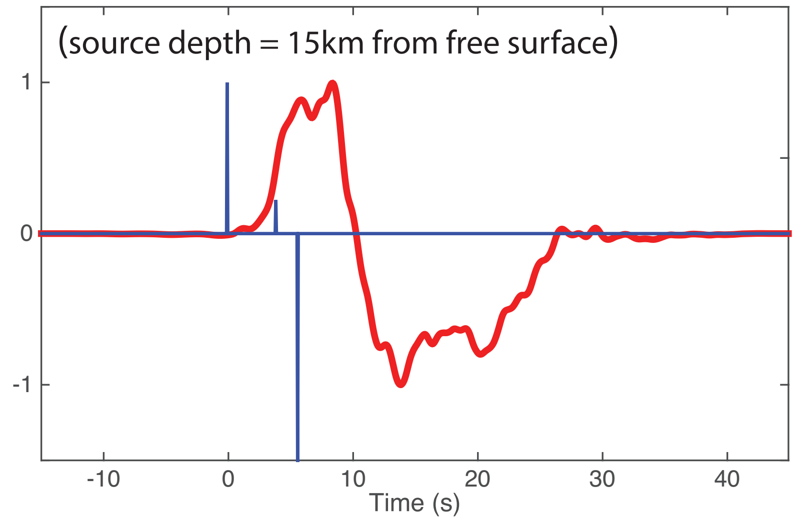
Free surface affects the body-wave GF


P wave train of shallow earthquakes: gP = P + pP + sP
s
p
P
P
P
P
pP
sP
dt depends on source depth
dA depends on source depth & radiation pattern
time
Apparent corner frequency
df depends on source depth
frequency

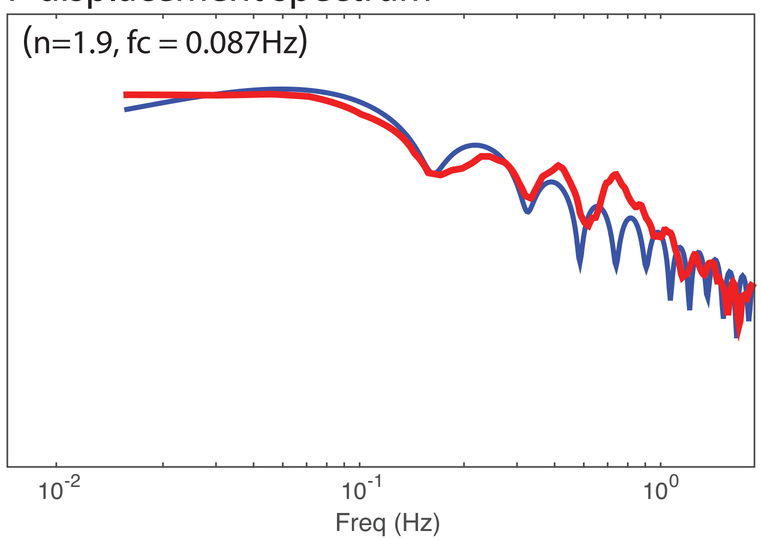
P wave train of shallow earthquakes: gP = P + pP + sP

M7.3 05/12/15 IU.INCN

P displacement time series



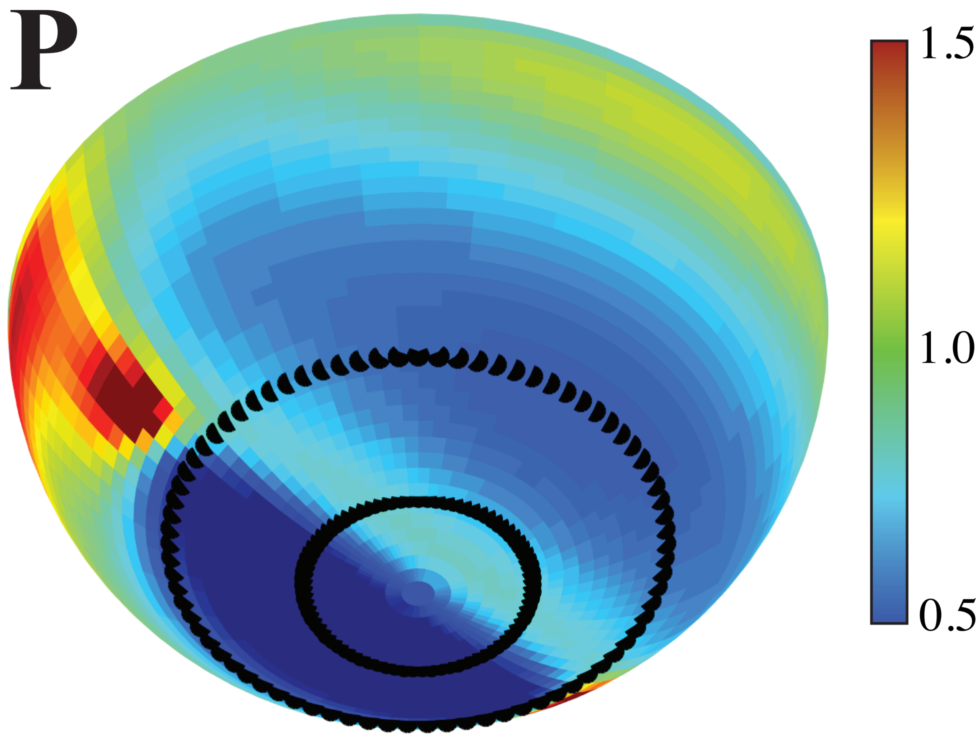
P displacement spectrum



Depth-phase interference

Boatwright and Choy (1986) propose a depth-phase correction and assume that we can sum the energies: $$E_{gP} = E_P + E_{sP} + E_{pP}$$

15˚ dipping pure thrust



$$\frac{E_{gP}}{E_P + E_{sP} + E_{pP}}$$

Two approaches to estimating radiated energy

1. Energy flux from Boatwright's work

$$E_B = 32\pi^3 \rho\alpha \underbrace{\int_0^\infty \left| f\, S(f) \right|^2 df}_{\text{velocity}^2}$$

Respect use of Parseval's theorem

impedance

2. Energy from spectral shape (single-station)

$$E_S = \frac{2\pi M_0^2 \langle R_P \rangle^2}{\rho\alpha^5} \int_0^\infty \left| f\, \bar{S}(f) \right|^2 df$$

Independent measure of seismic moment

Radiation pattern squared averaged over the focal sphere

Velocity^2: S(f) is normalized to low frequency asymptote

Two approaches to estimating radiated energy

1. Energy flux from Boatwright's work

$$E_B = 32\pi^3 \rho\alpha \int_0^\infty \left| f\,S(f) \right|^2 df$$

+ true measure of energy flux

− individual measurements are sensitive to:

- radiation pattern
- geometrical spreading

− require well distributed and dense receivers to capture the entire focal sphere

Often used with "1D" Green's function

$$\left|G(f)\right| = \frac{1}{\Re_P}\exp(-\pi f\, t^*(f))$$

Depth-phase correction

$$E_B = E_B / \left(1 + E_{sP}/E_P + E_{pP}/E_P\right)$$

2. Energy from spectral shape (single-station)

$$E_S = \frac{2\pi M_0^2 \left\langle R_P \right\rangle^2}{\rho\alpha^5} \int_0^\infty \left| f\,\bar{S}(f) \right|^2 df$$

+only relies on spectral shape

+one station is sufficient to estimate energy

− assumes that the spectral shape is constant at all azimuth and takeoff angles

− normalization to low frequency asymptote sensitive to SNR and data processing

− assumes a whole space around the source (not valid for "very" shallow earthquakes)

Often used with empirical Green's function

Two approaches sensitive to depth phases

1. Energy flux from Boatwright's work

Tendency to underestimate energy

Destructive interferences

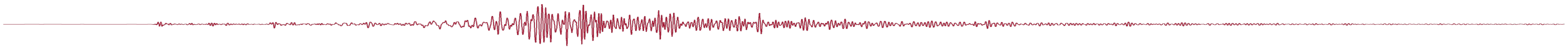
2. Energy from spectral shape (single-station)

Tendency to overestimate energy

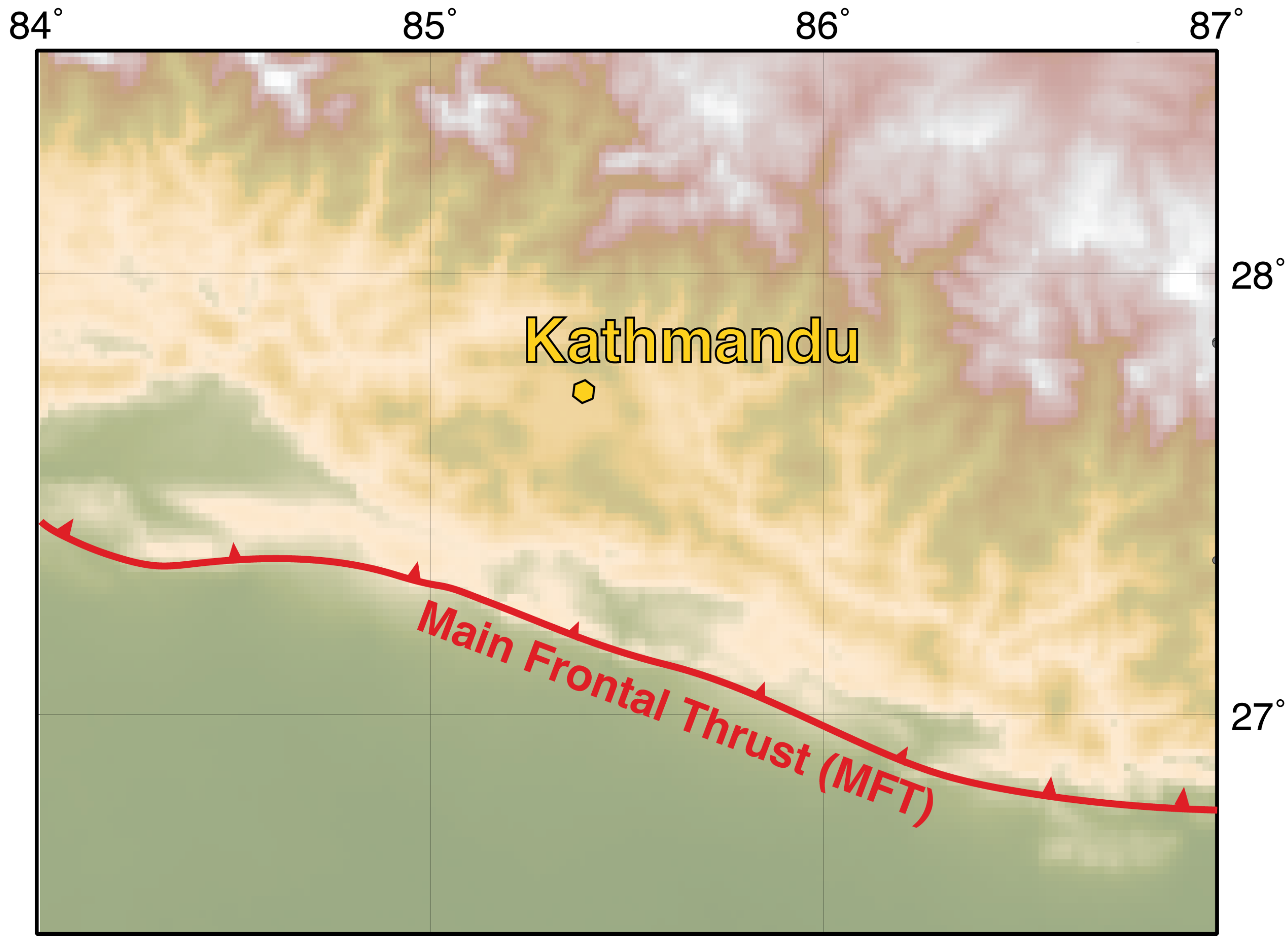
High apparent corner frequency *if normalization is performed on the low frequency asymptote*

➔ Correction for both approaches when we use 1D Green's functions

➔ Characterize uncertainties when we use empirical Green's functions



Example : Nepal 2015 earthquake sequence



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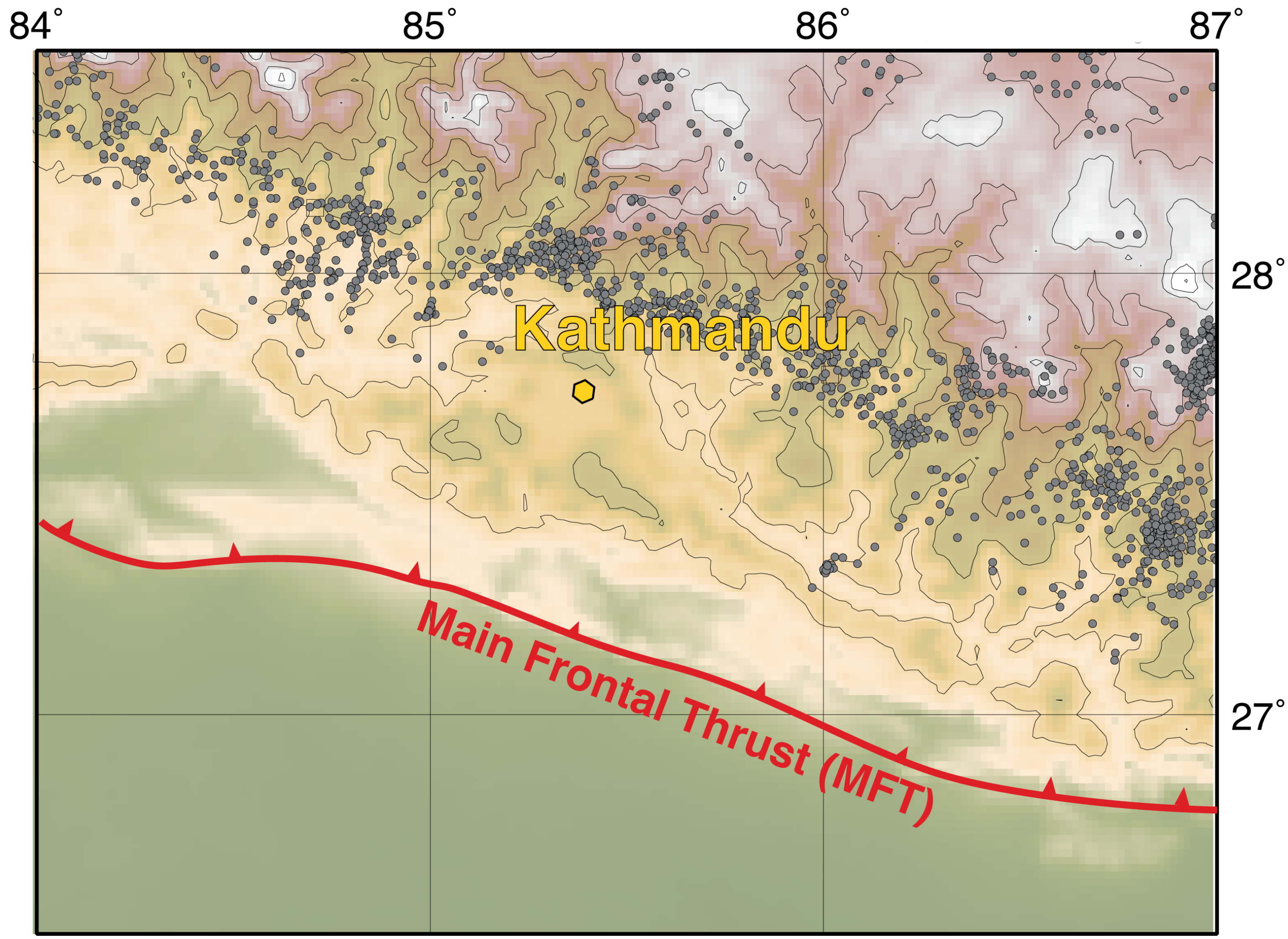

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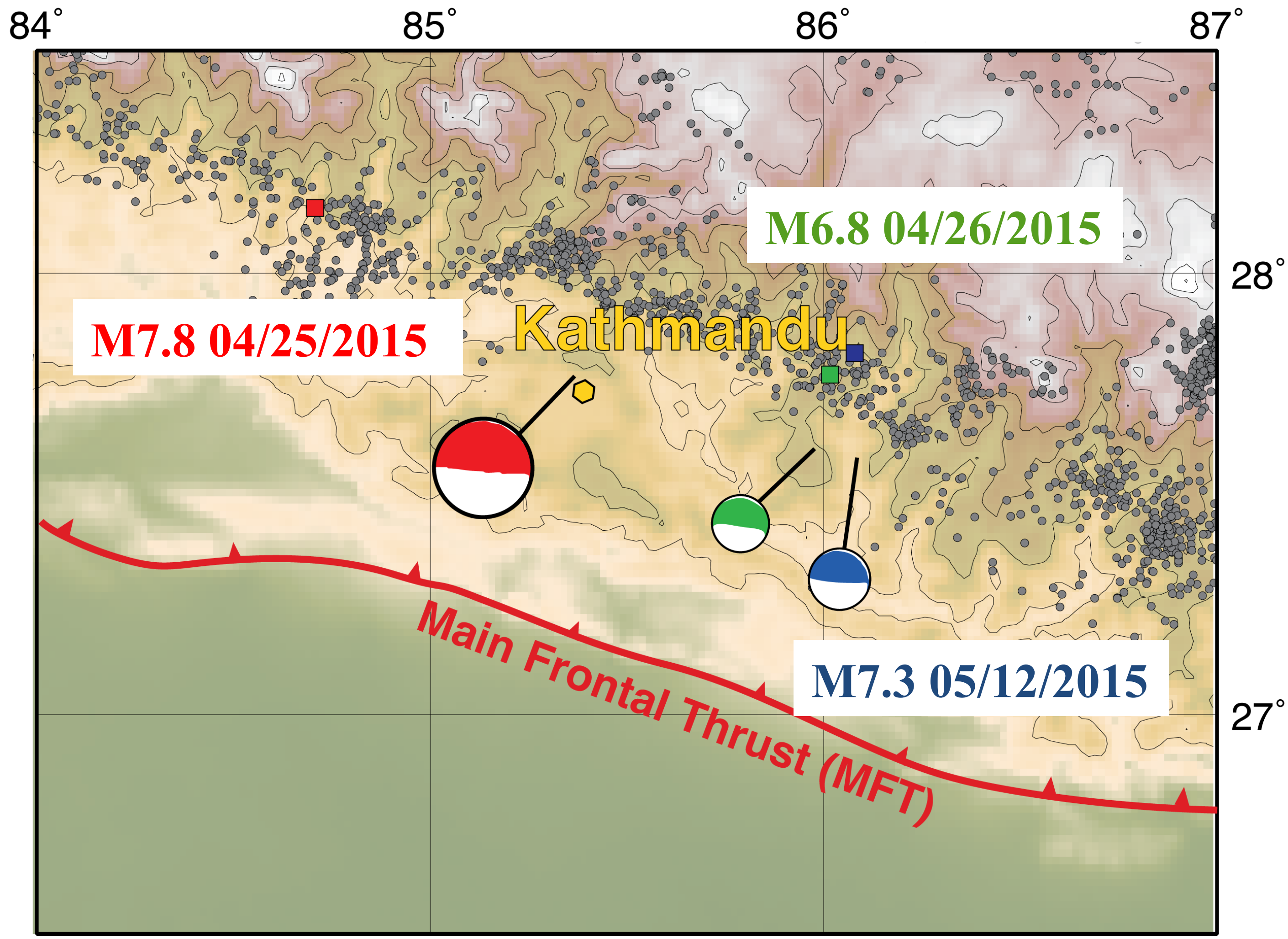
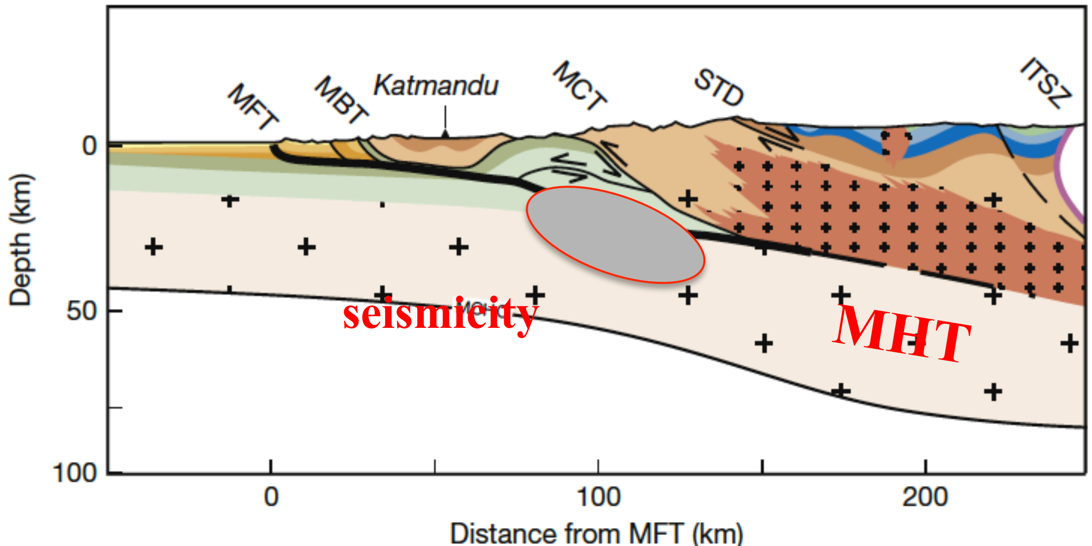
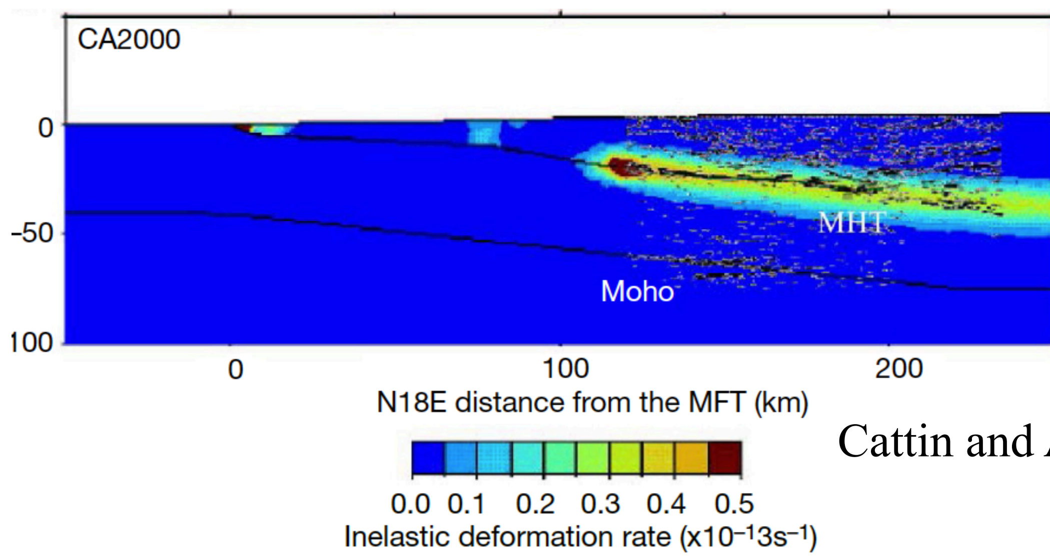


Along-dip Main Himalayan Thrust (MHT) geometry

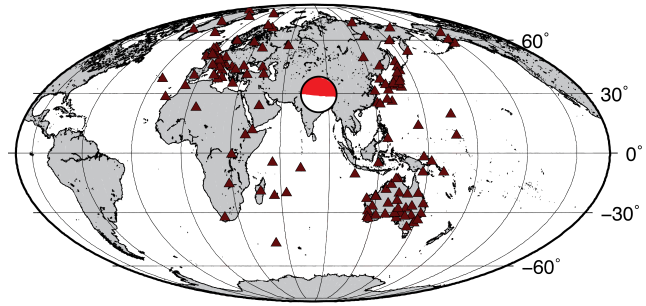


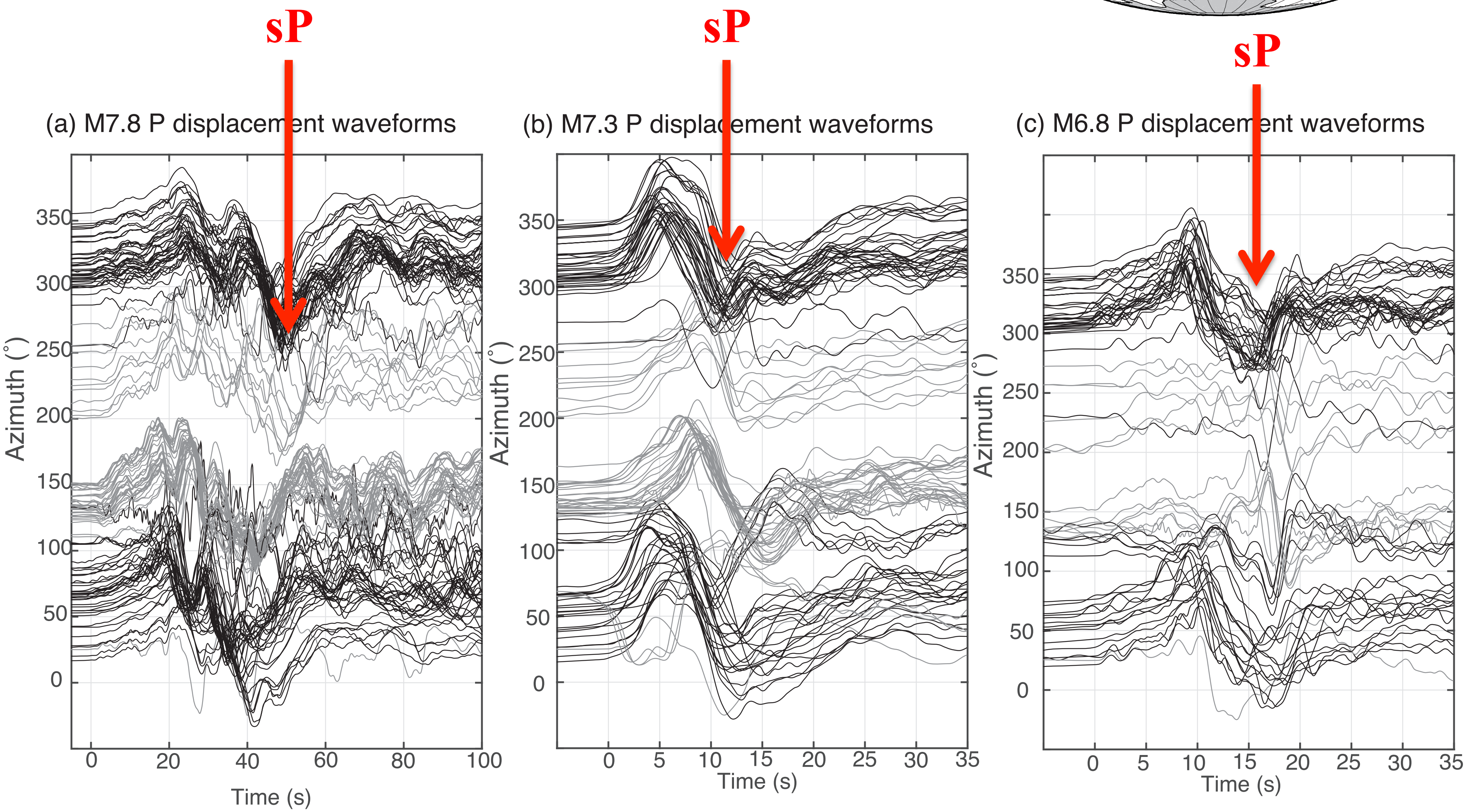
J.P. Avouac (2015)



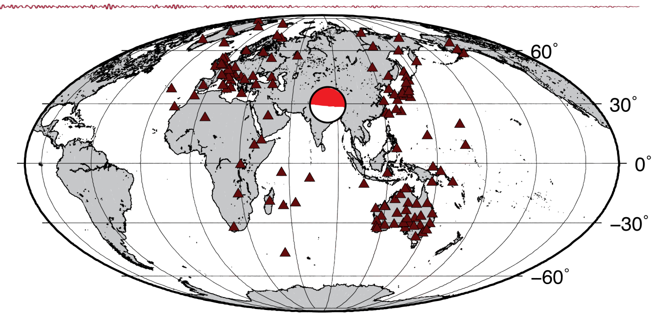
Cattin and Avouac (2000)

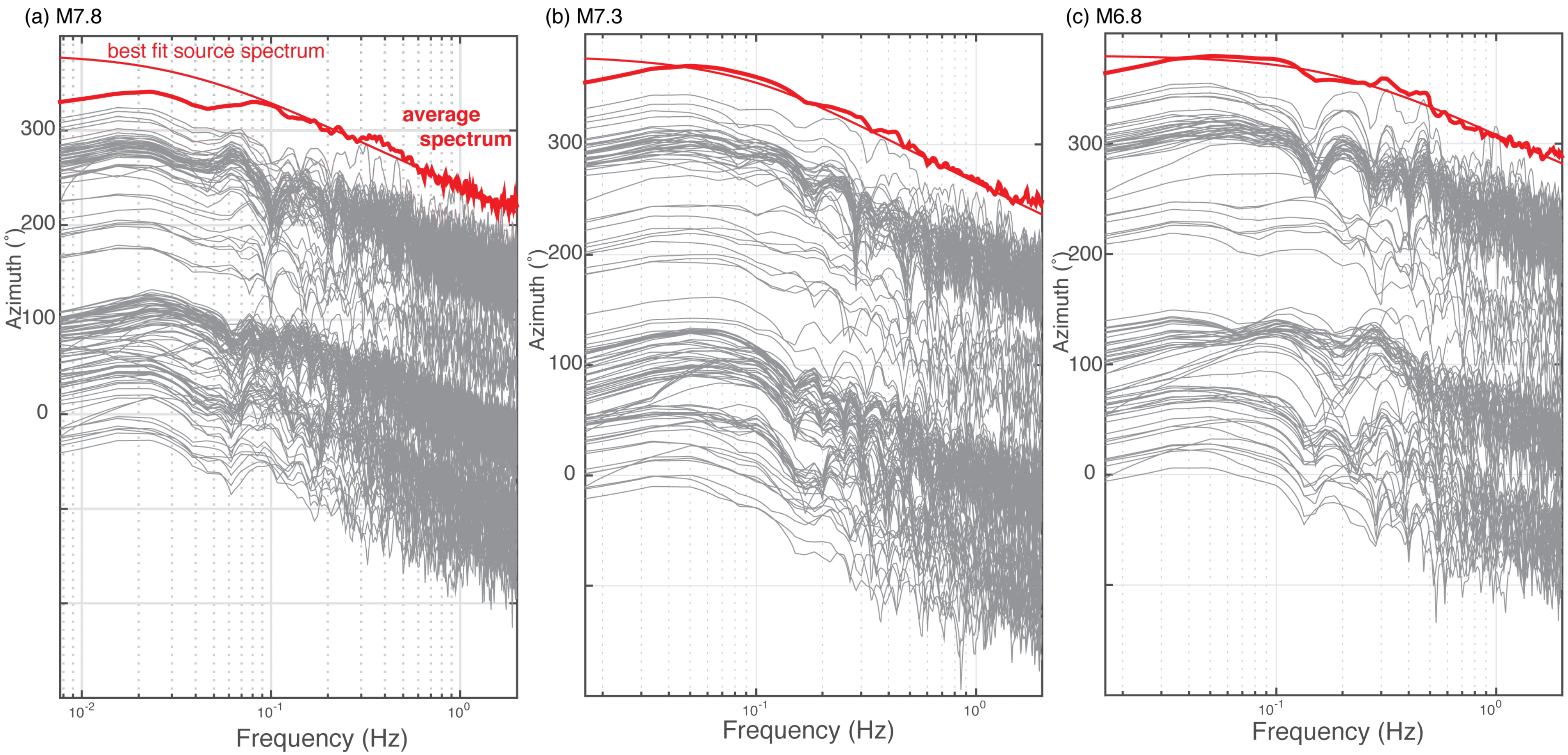
P displacement waveforms (GSN stations)



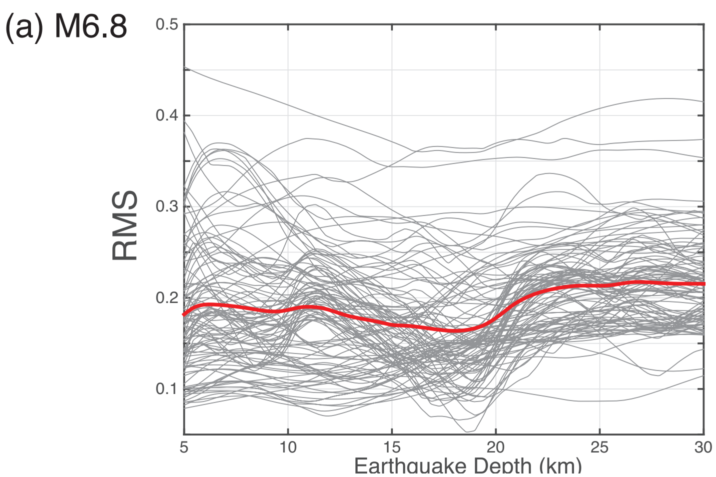


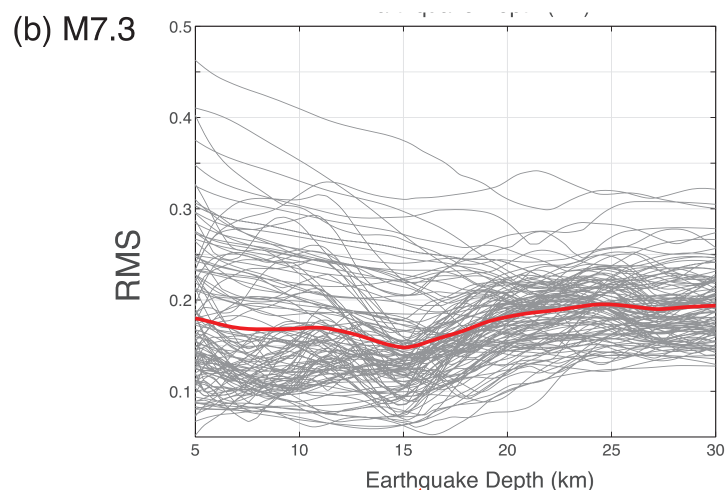
P displacement spectra (GSN stations)





Fit source depth





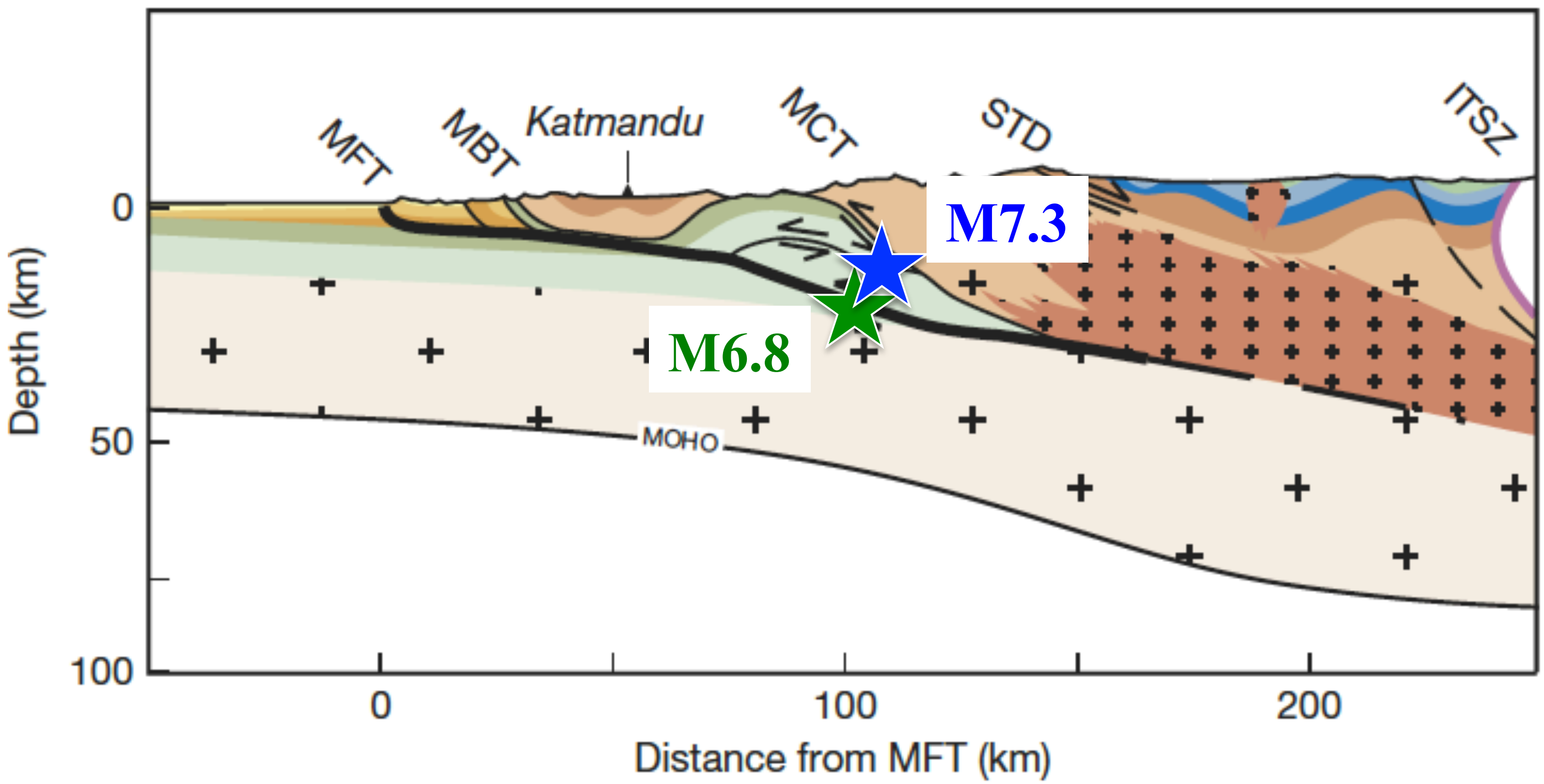
18 km

15 km

CMT depth: 17.4 km
PDE/NEIC depth: 24.8 km

CMT depth: 15 km
PDE/NEIC depth: 12 km

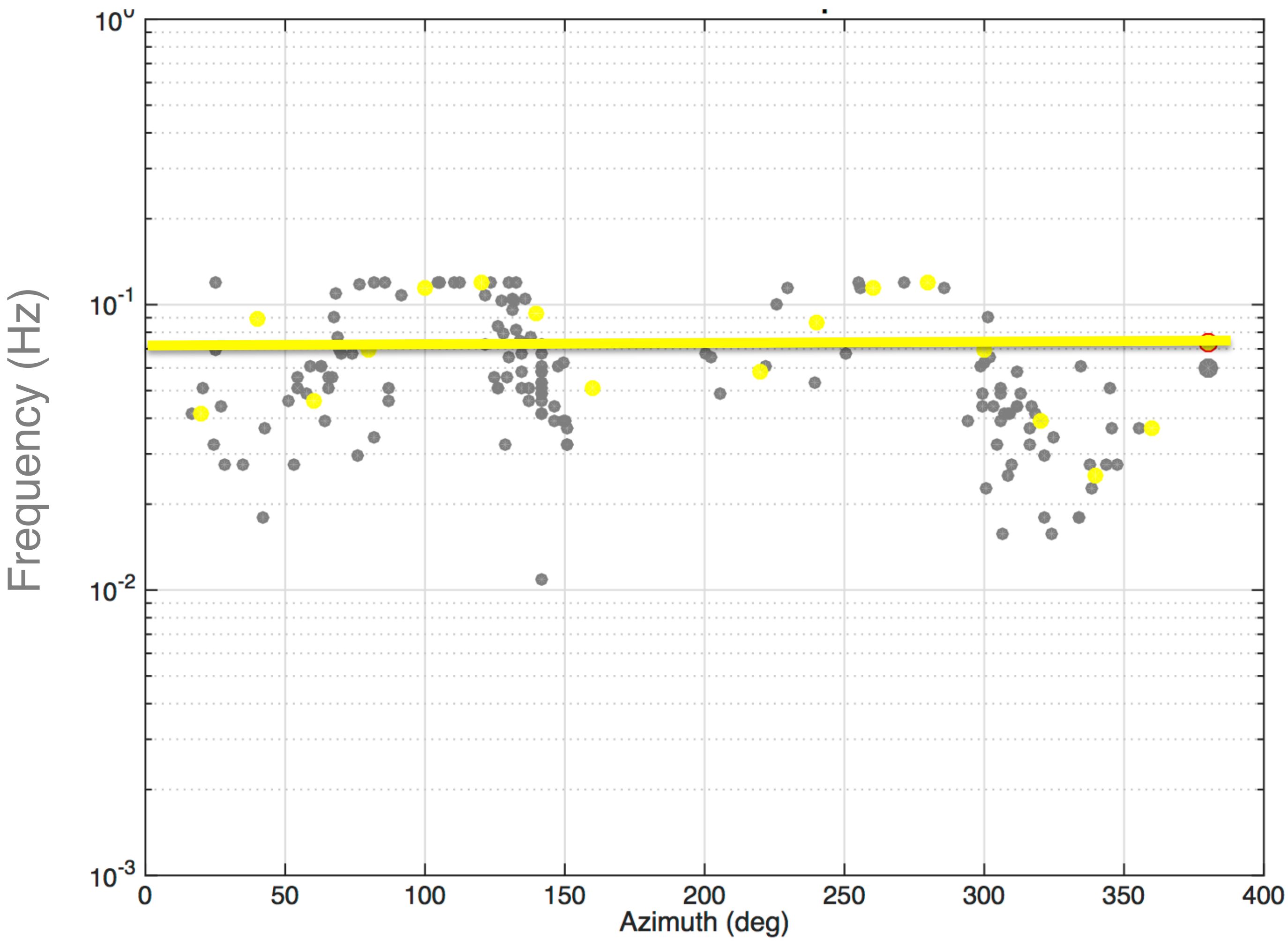
Fit source depth



Fit source spectrum: corner frequency (ignore depth phase)

$$\Delta\sigma = M_0\left(\frac{f_c}{0.42\beta}\right)^3$$

Madariaga (1976)

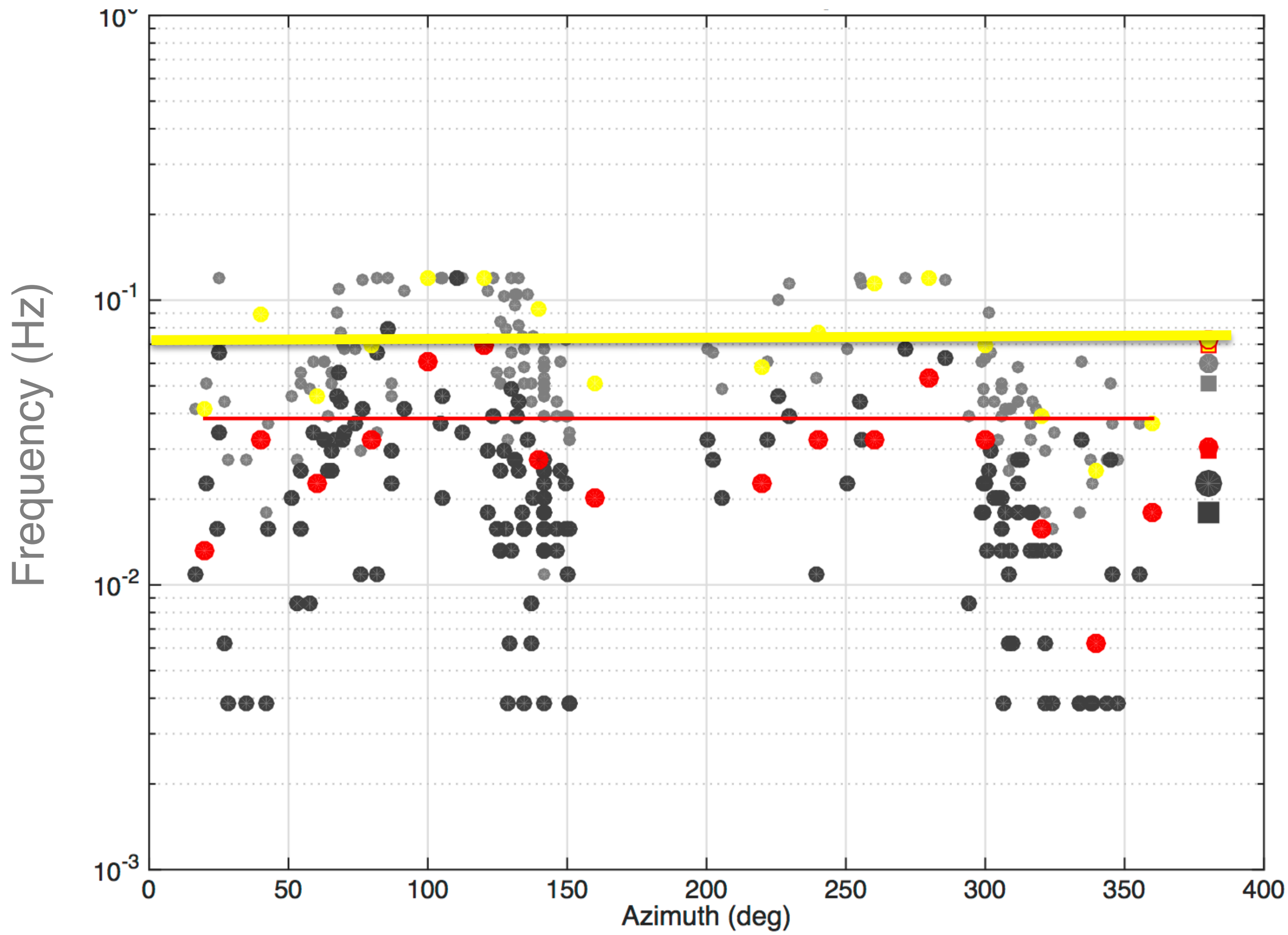


Δσ = 137 MPa

Fit source spectrum: corner frequency (account for depth phases)

$$\Delta\sigma = M_0\left(\frac{f_c}{0.42\beta}\right)^3$$

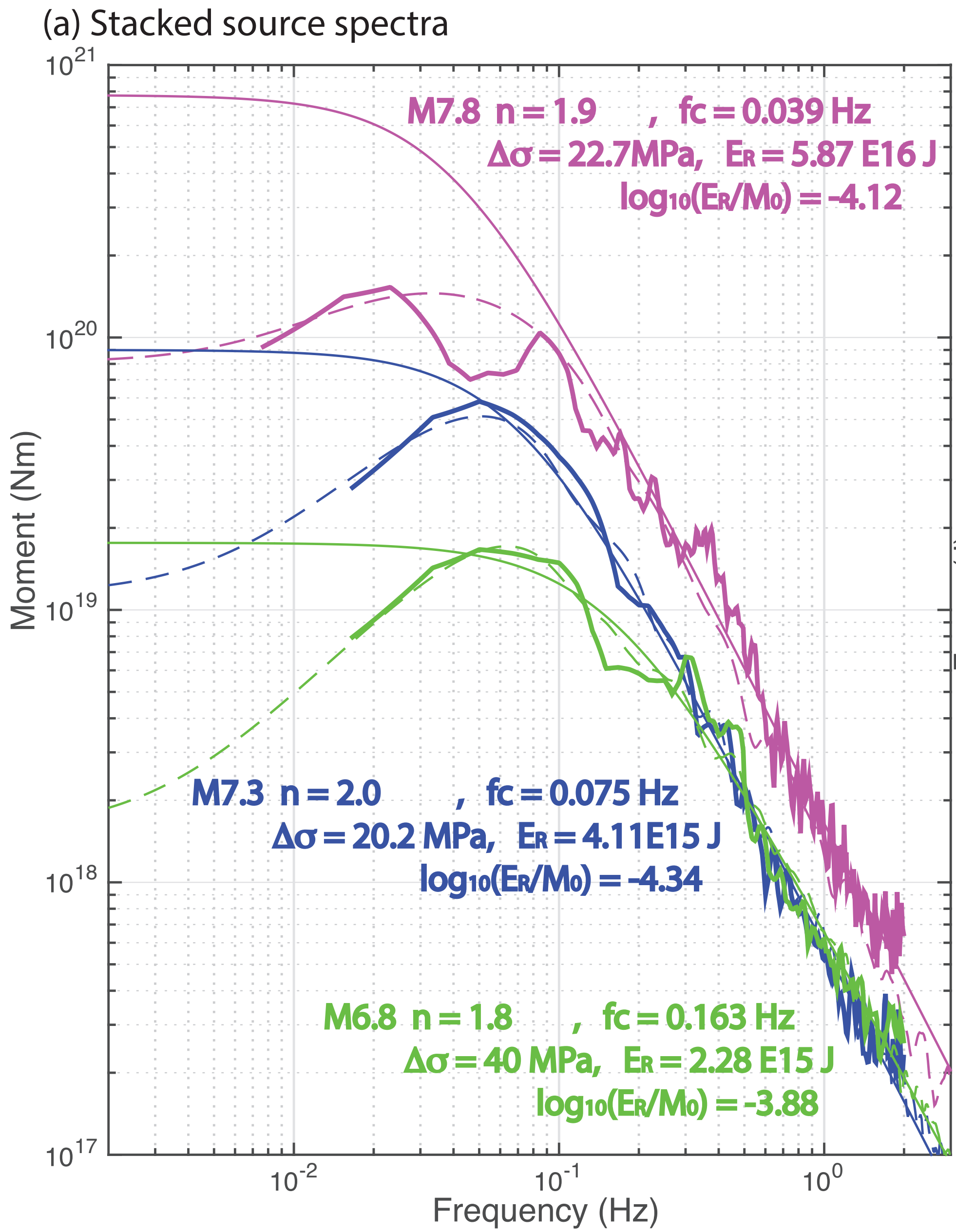
Madariaga (1976)



Δσ = 137 MPa

Δσ = 22 MPa

Best fit source stack



Radiated Energy Correction for depth phase interference

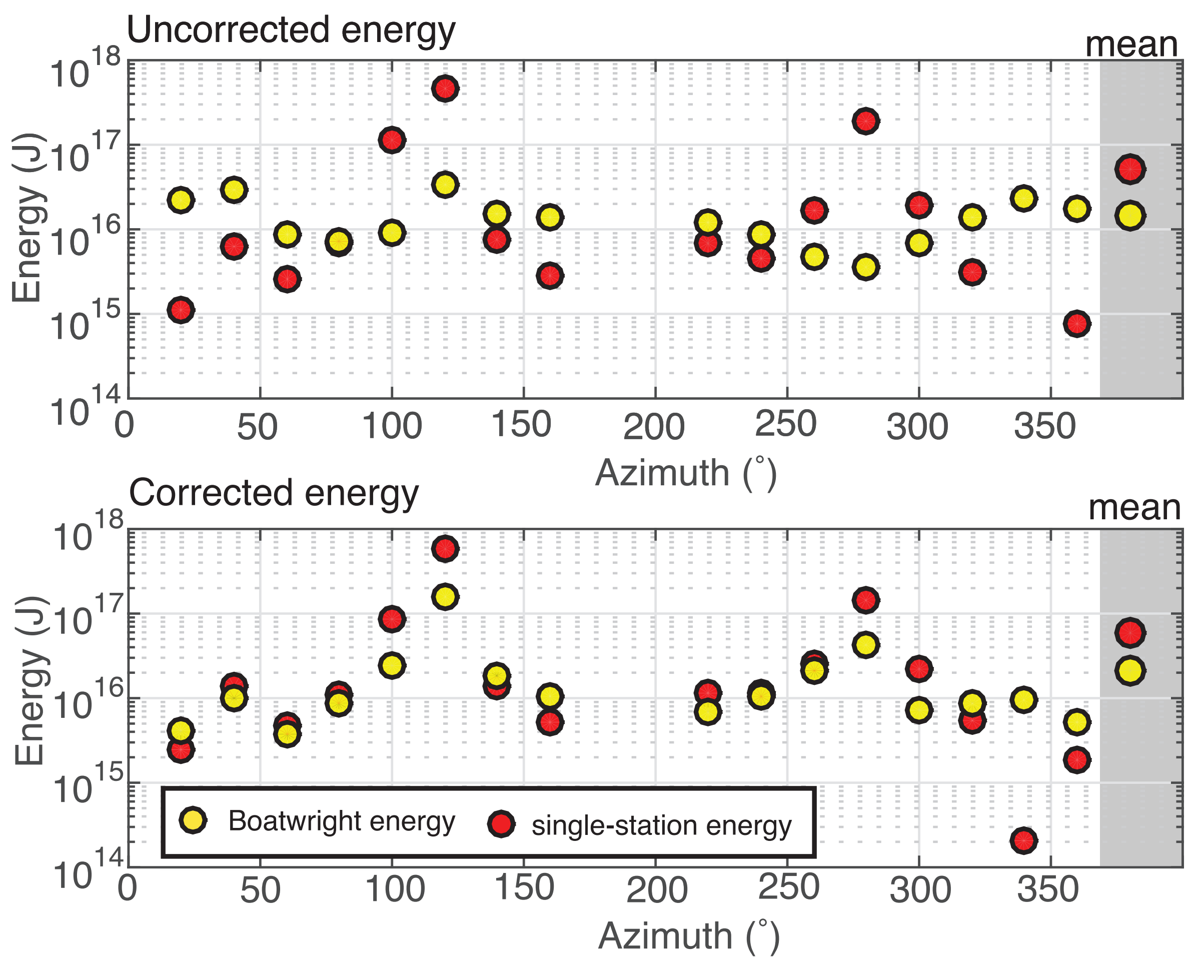
1) Measure apparent energy from synthetics at each station i between f_1 and f_2 :

$$E_{syn}(i,[f_1\ ,f_2])$$

2) Measure total synthetic energy between 0 and ∞ :

$$E_{true}([0\ ,\ \infty])$$

3) Multiply individual apparent energy measurements with the ratio (2) by (1).



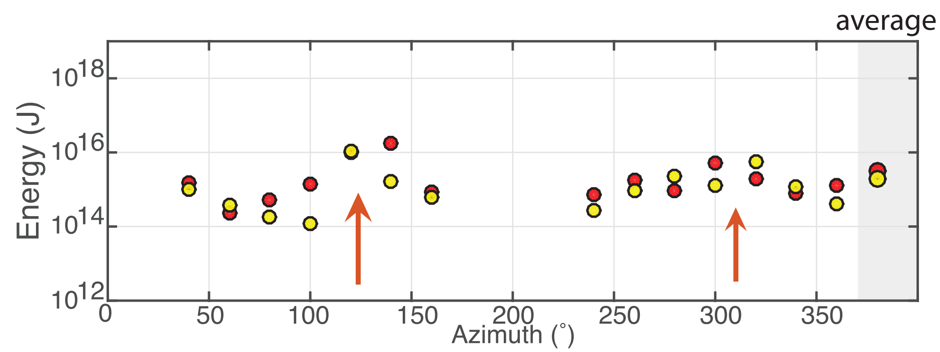
Estimates from point sources

- P wave trains at teleseismic distances from M6+ in the upper 35 km will show interferences of direct and depth phases.

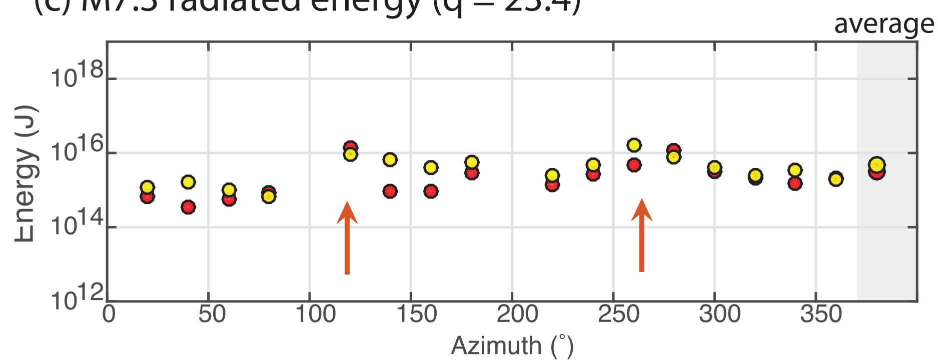
- Interferences significantly bias estimates of corner frequencies and low frequency asymptote.

- Bias in radiated energy estimates is controlled by source depth and source size (~ corner frequency).

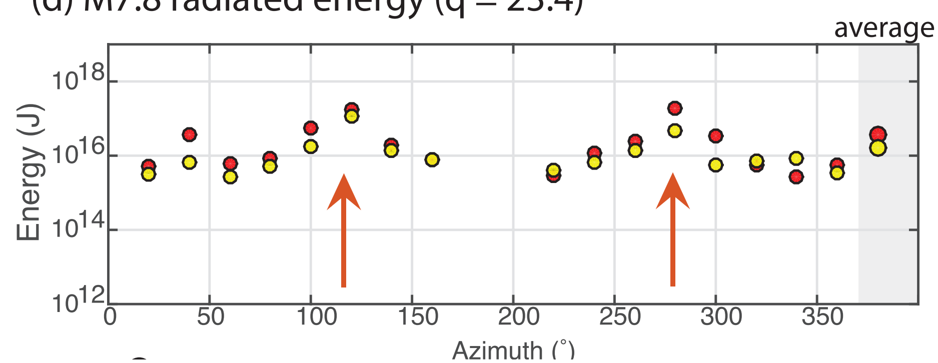
(b) M6.7 radiated energy (q = 23.4)



(c) M7.3 radiated energy (q = 23.4)

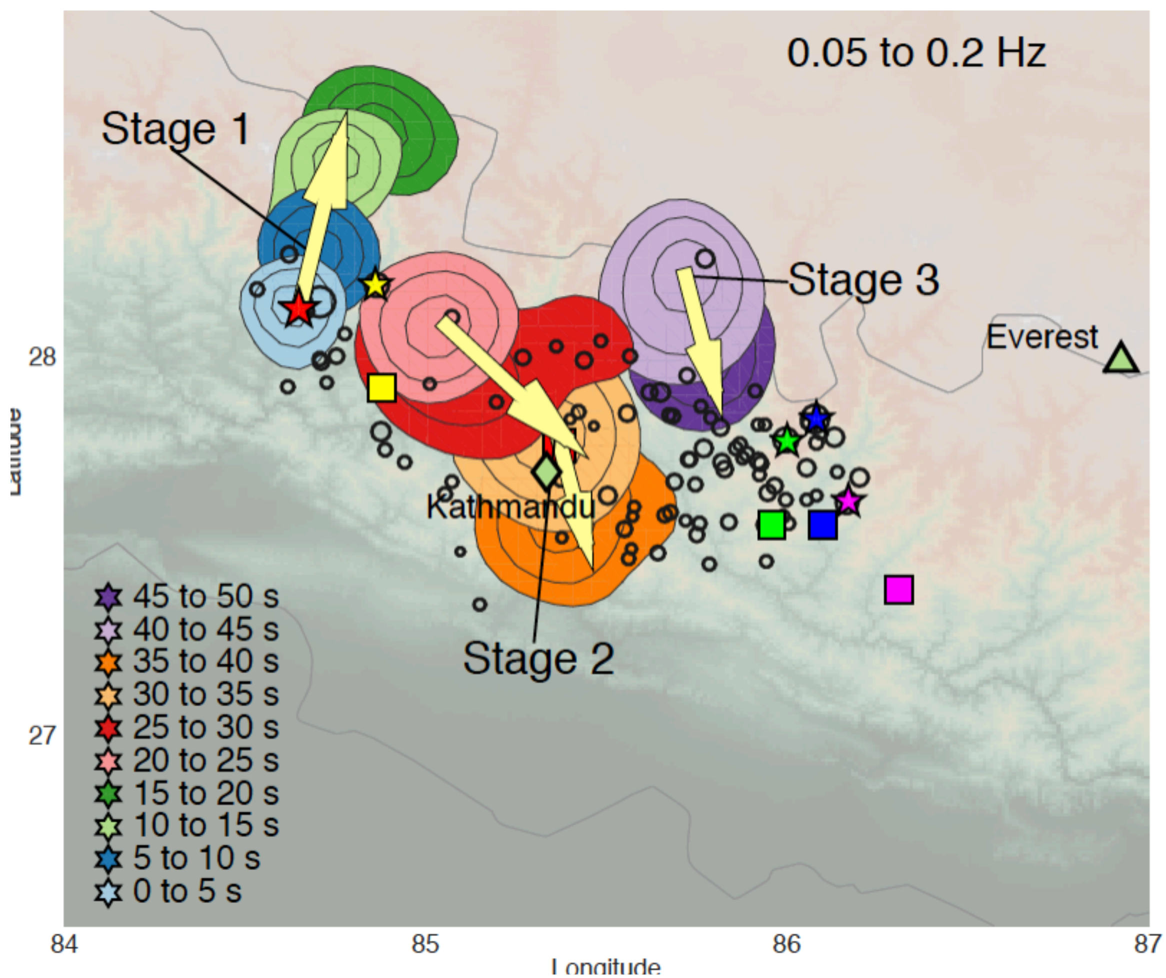


(d) M7.8 radiated energy (q = 23.4)

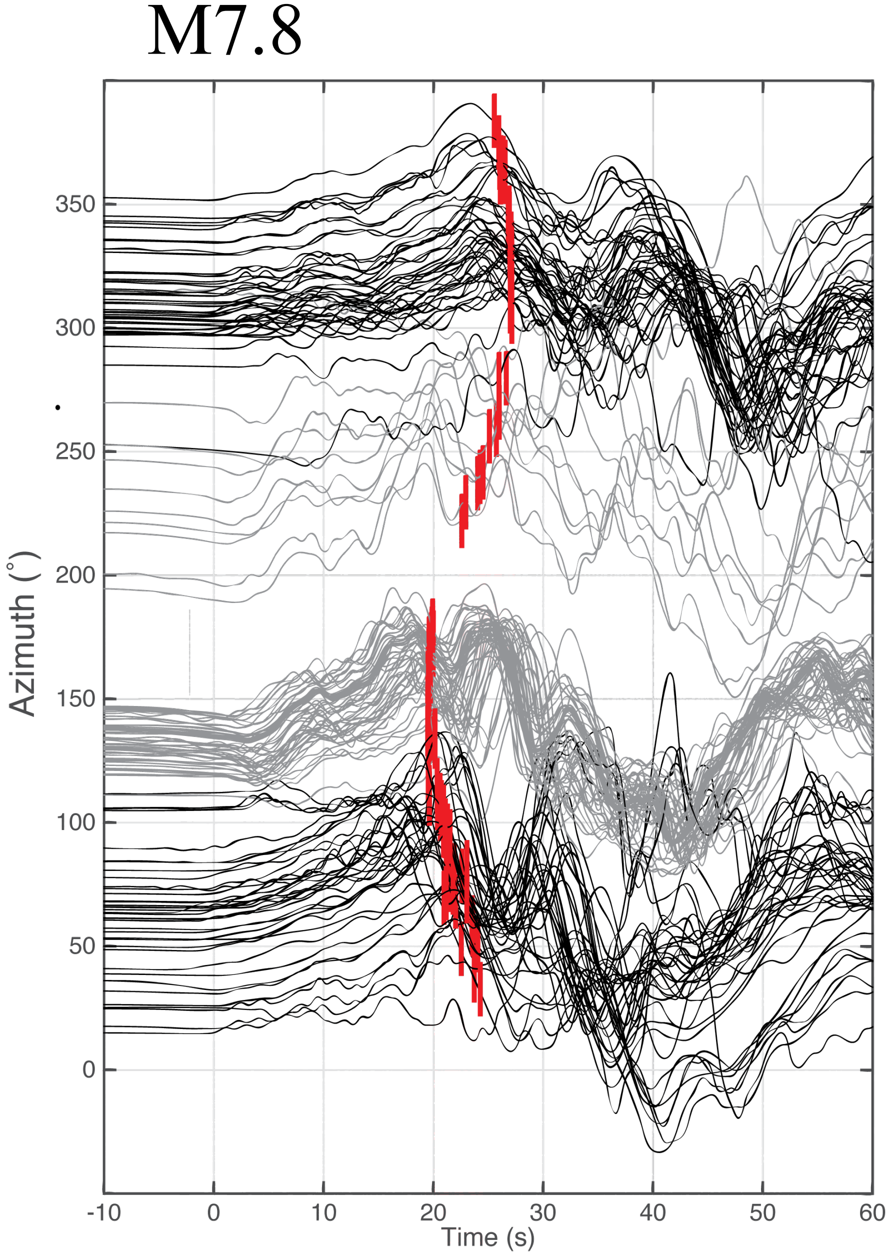


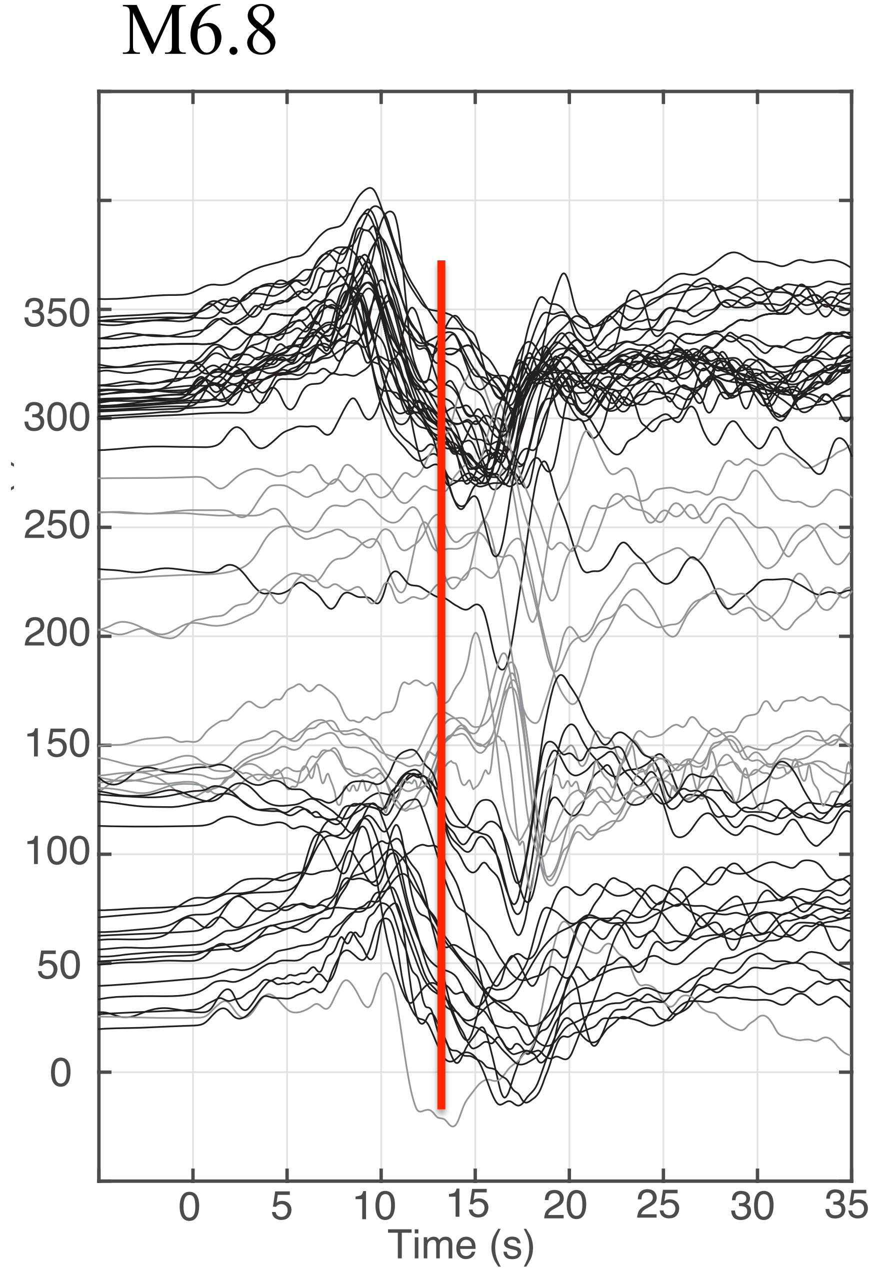
Estimates from finite sources: low and high frequency backprojection

From Wenyuan Fan and Peter Shearer (Fan and Shearer, accepted in GRL)

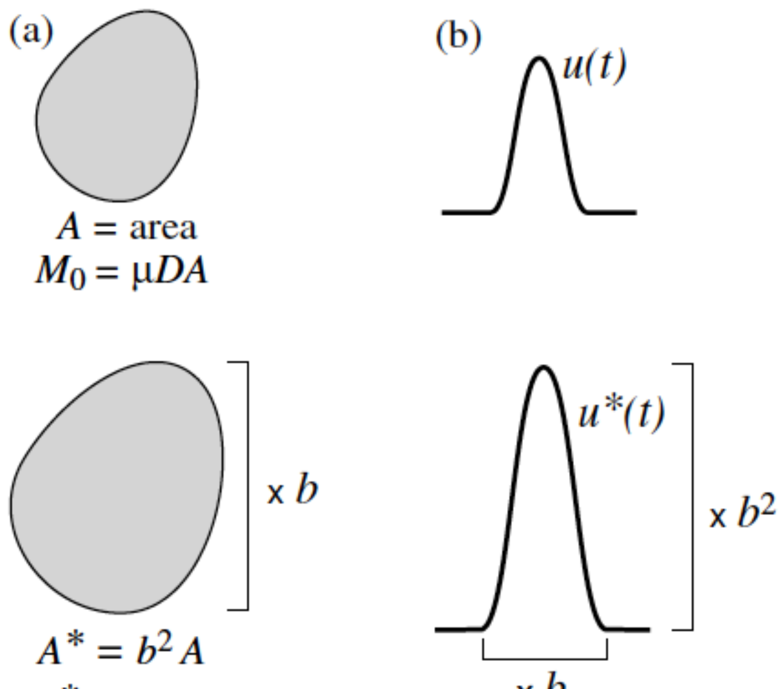


Estimates from finite sources: Stage #1





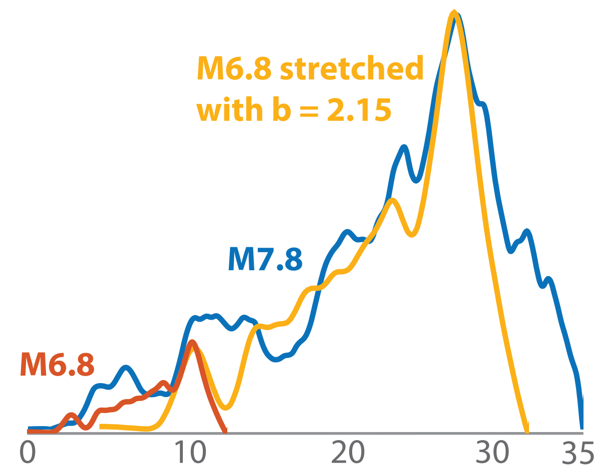
Estimates from finite sources: Stage #1



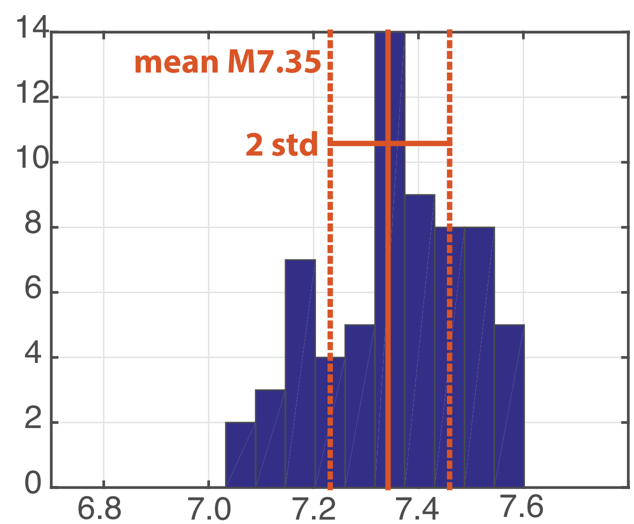
Prieto *et al.* (2004)

$$\frac{M_0^A}{T_A^3} = \frac{M_0^B}{T_B^3}$$

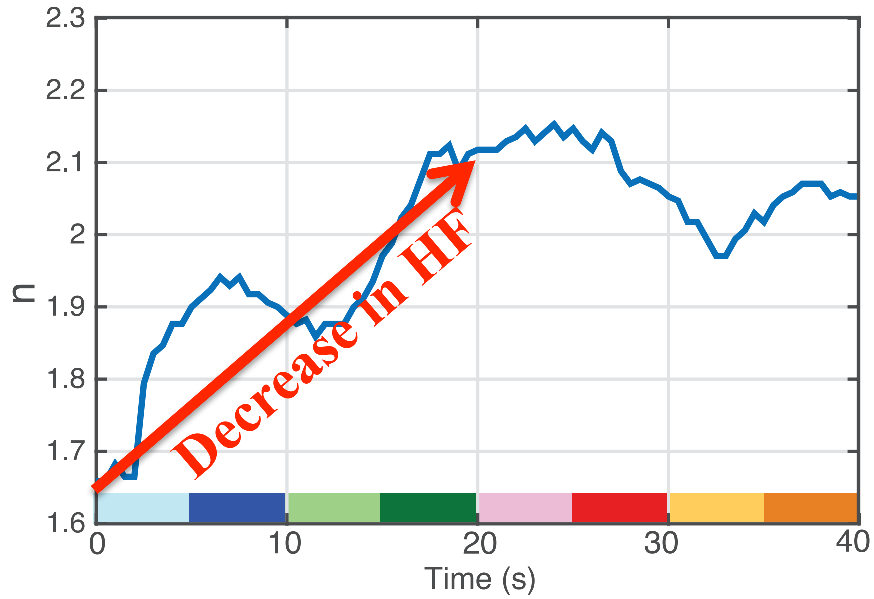
(a) II.KIV displacement P pulse

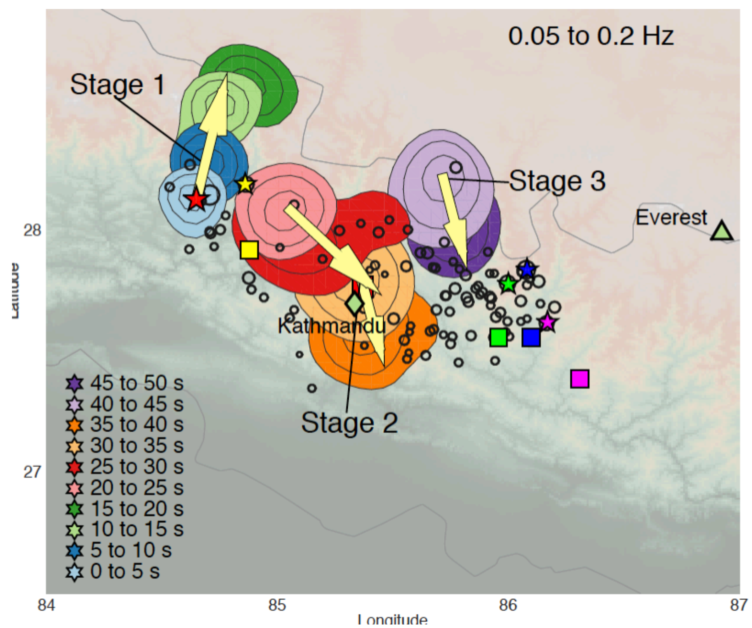


(b) Moment magnitude estimates

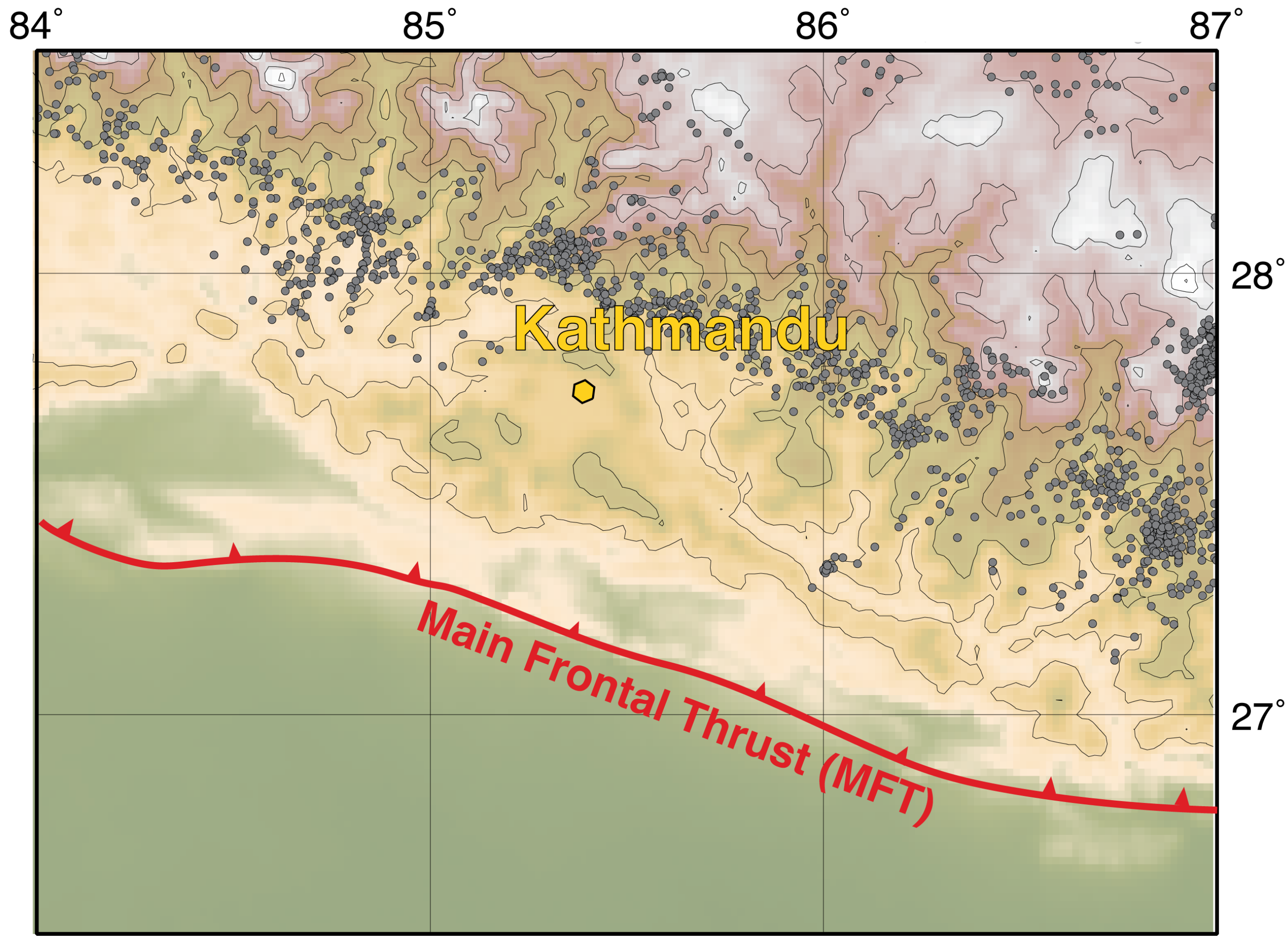


Estimates from finite sources: Stage #1





From stage #1 to stage #2: passage through a lateral ramp



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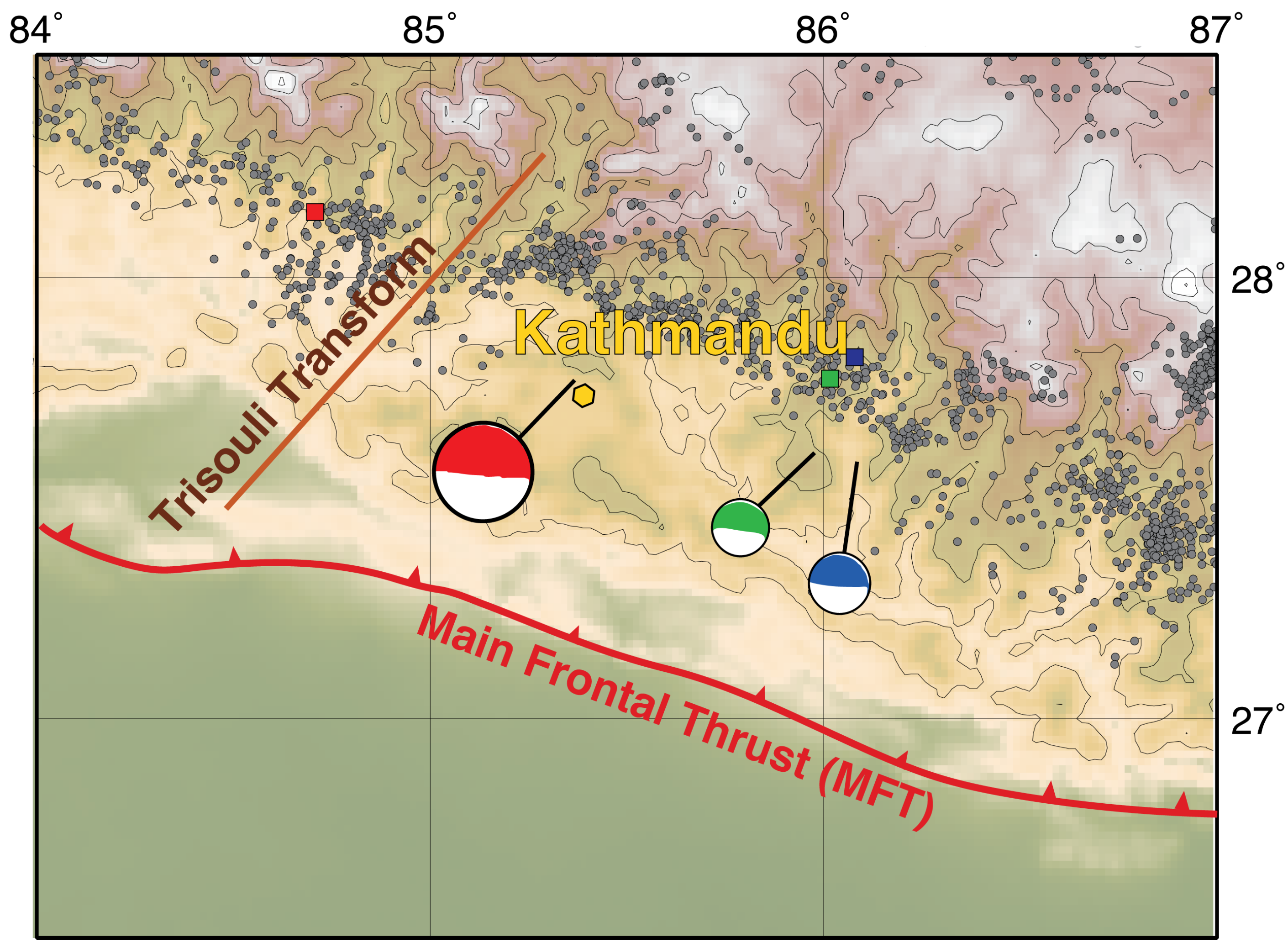
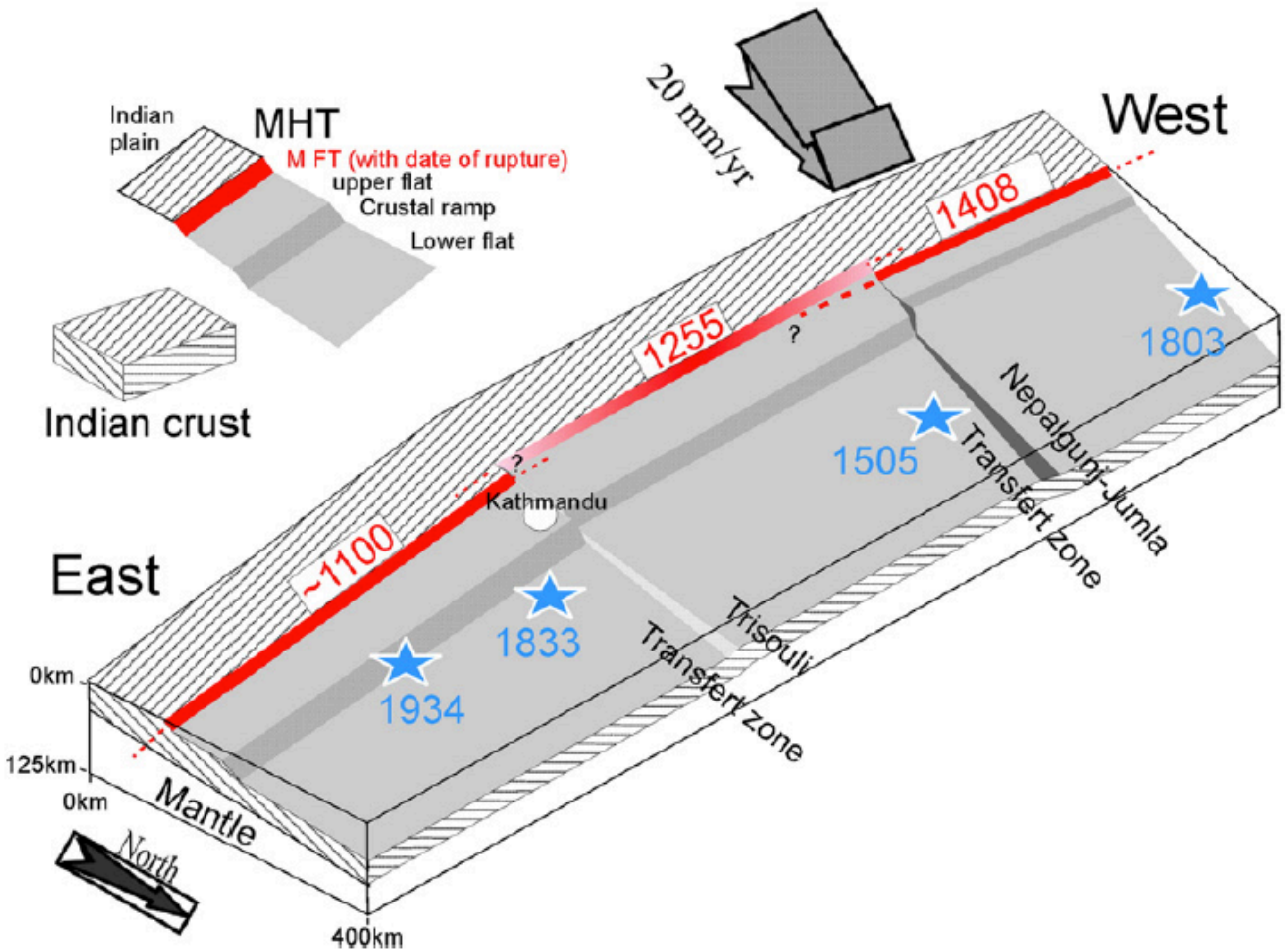


From stage #1 to stage #2: passage through a lateral ramp

J.L. Mugnier et al. / Tectonophysics 509 (2011) 33–49



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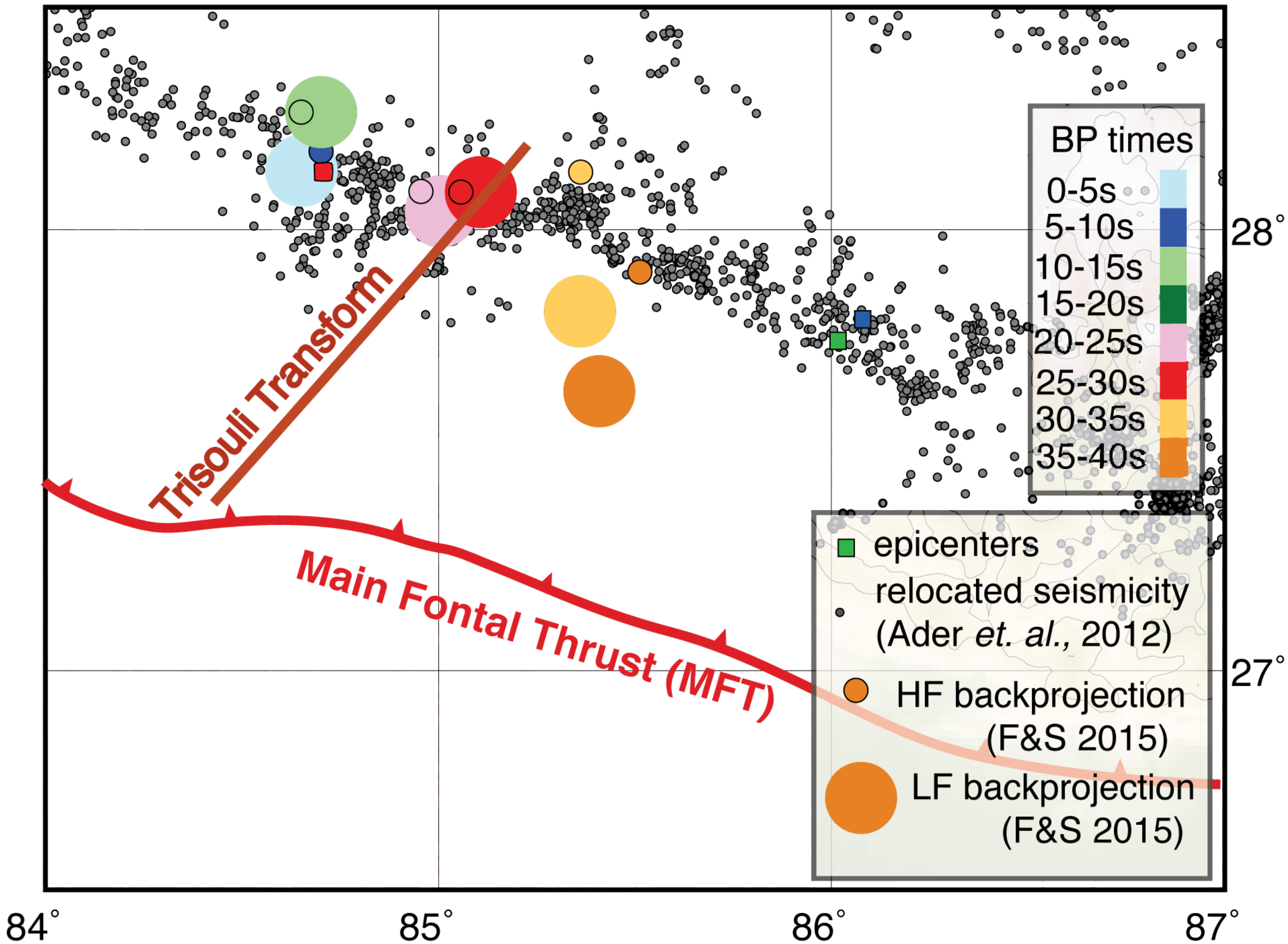
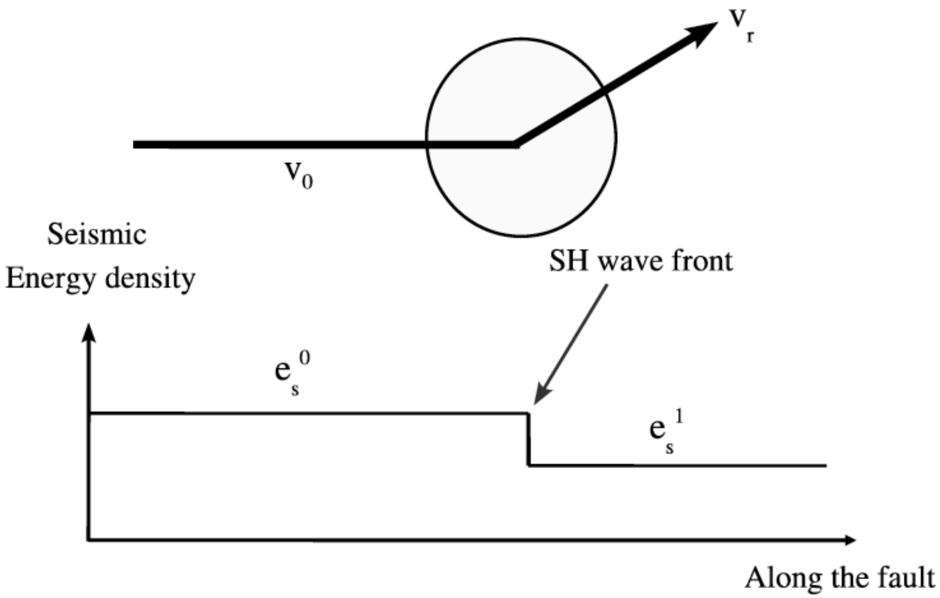


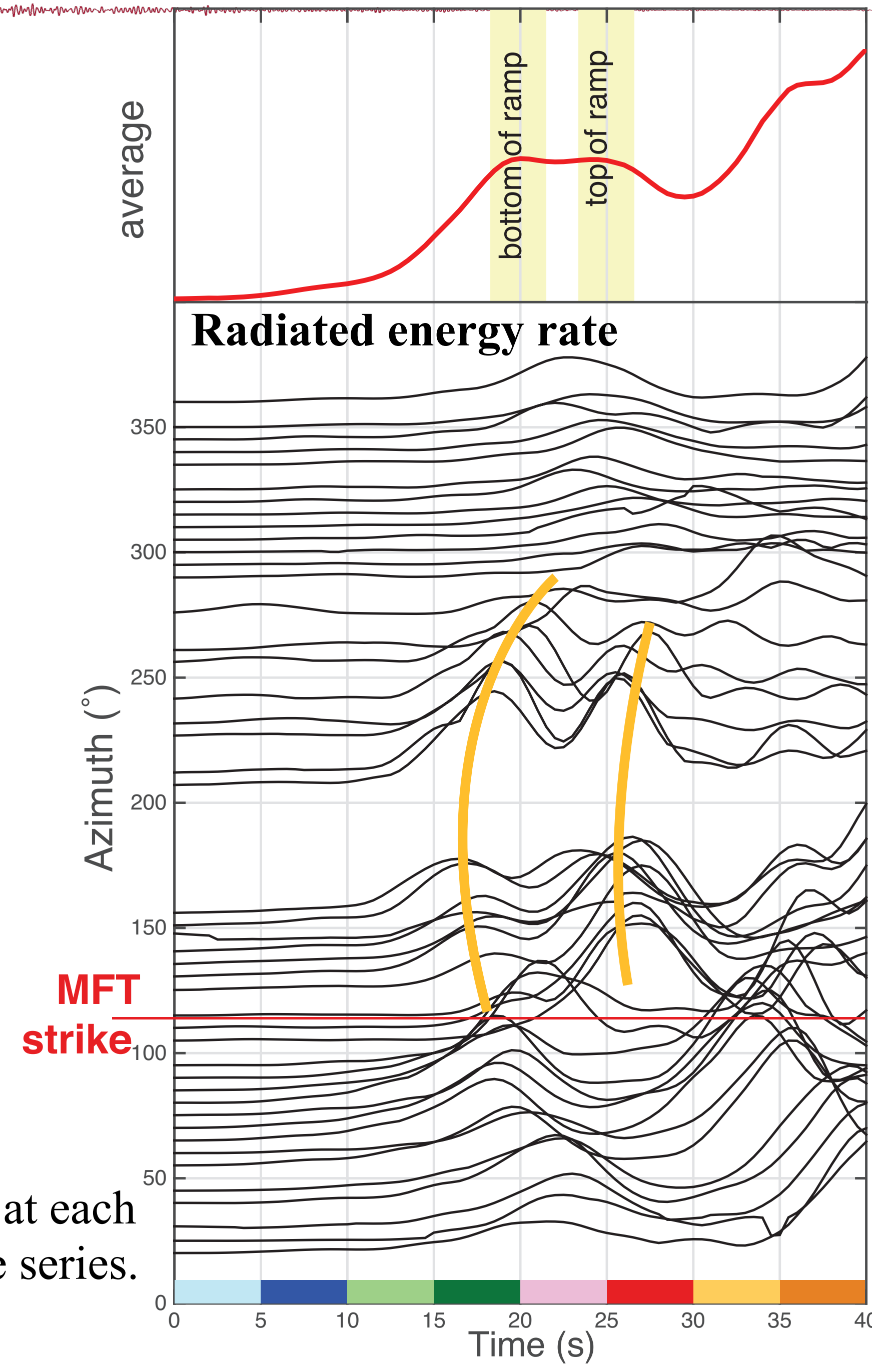
From stage #1 to stage #2: passage through a lateral ramp

Rupture through kinks:
The antiplane-shear S_H case



Adda-Bedia and Madariaga (2008)

Radiated energy rate is calculated using the Boatwright estimate (corrected for depth phases at each station), and normalized to its peak value in time series.



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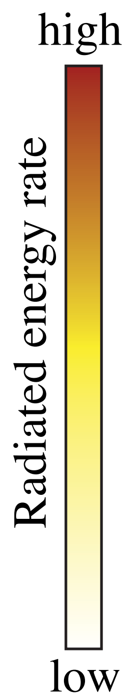
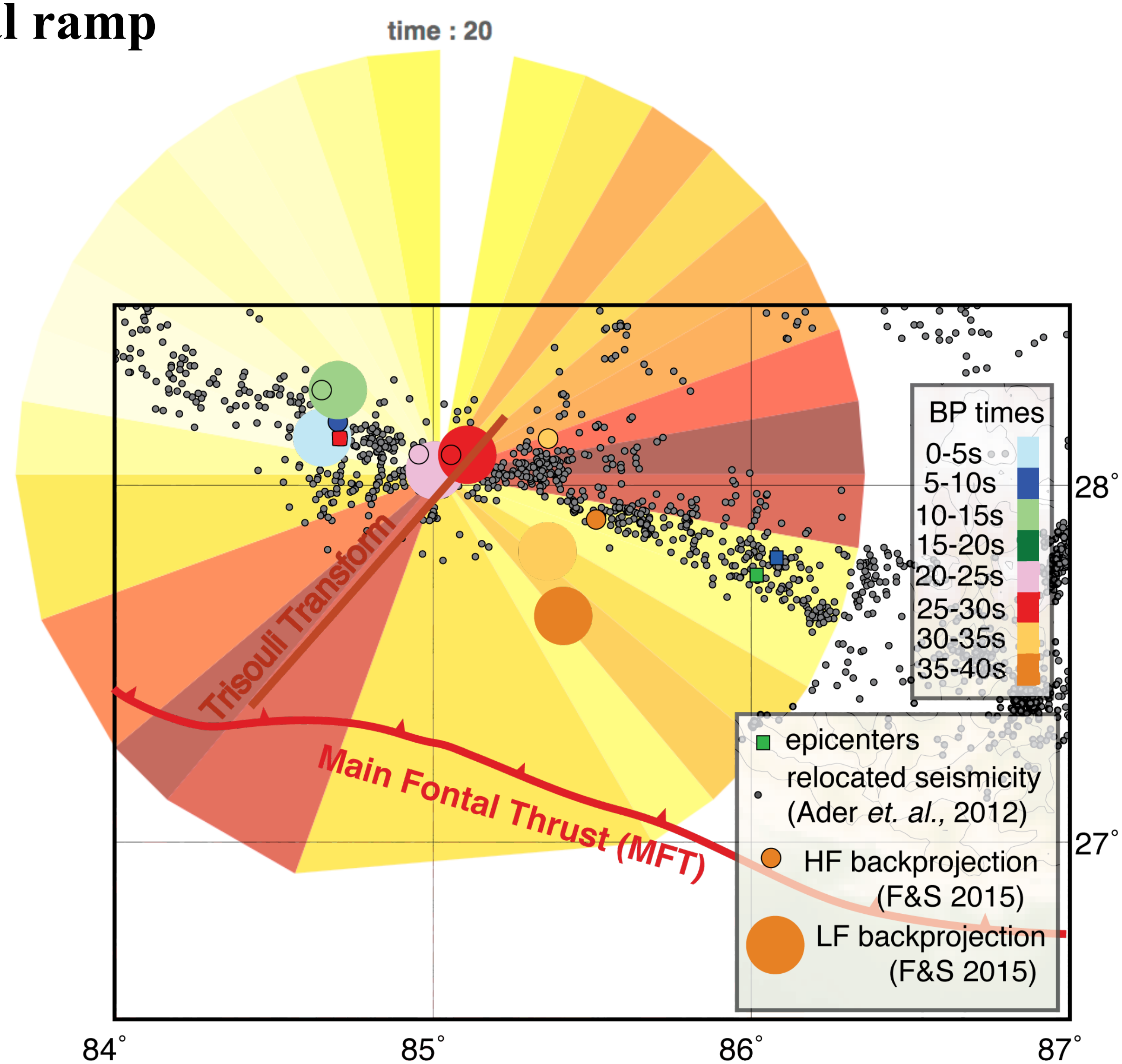
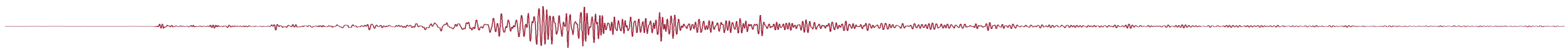
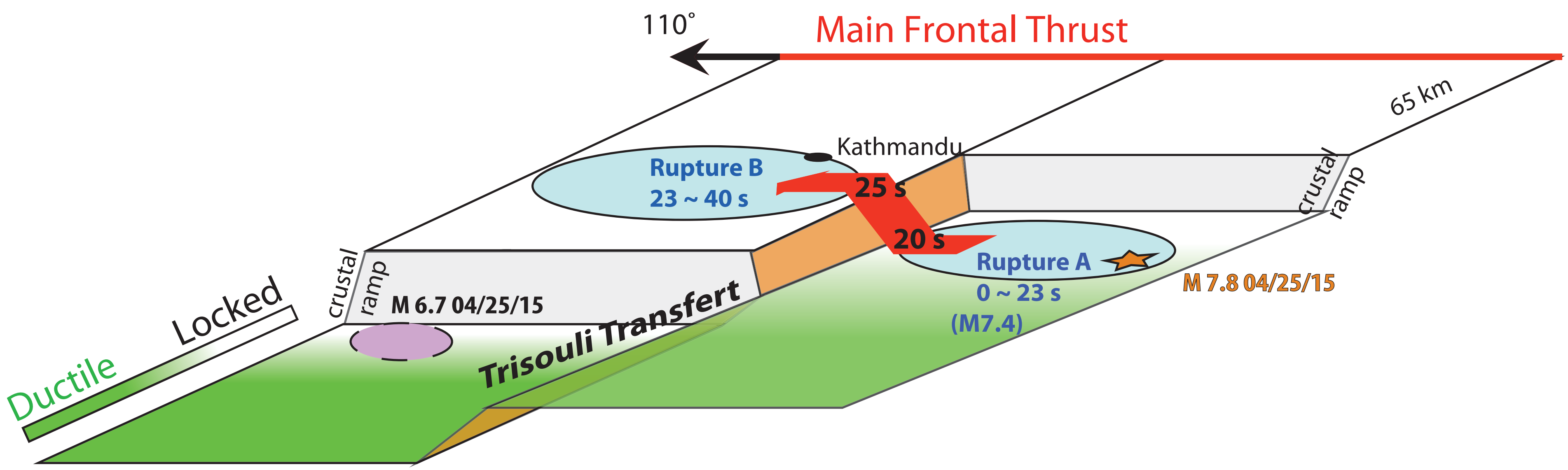






Conclusion on the beginning of the Nepal M7.8 earthquake



Concluding remarks

• If not properly removed from path effects, direct and depth phases interference greatly affects the P spectral shape.

• Interferences introduce large biases in corner frequency and low-frequency asymptote.

• We can properly estimate the source depth, spectra, and radiated energy by best fitting the predicted P wave train spectral shape.

• We applied these methods to the Nepal earthquake sequence.

• We expanded the point source approximation to look into finite source effects on high frequency radiated energy.

Questions

• Are depth-phase interference responsible to the apparent scaling in scaled energy E_R / M_0 (in cases of shallow large seismicity)?

• With refined depth and radiated energy estimates, do we see trends radiated energy with depth?

• When earthquake size > earthquake depth, the homogeneous whole space assumption fails. What do we do?