Great Earthquakes: Observations and modeling

COLLÈGE DE FRANCE 1530

Rupture Complexity of Great Earthquakes and its Effects on Seismic Radiation

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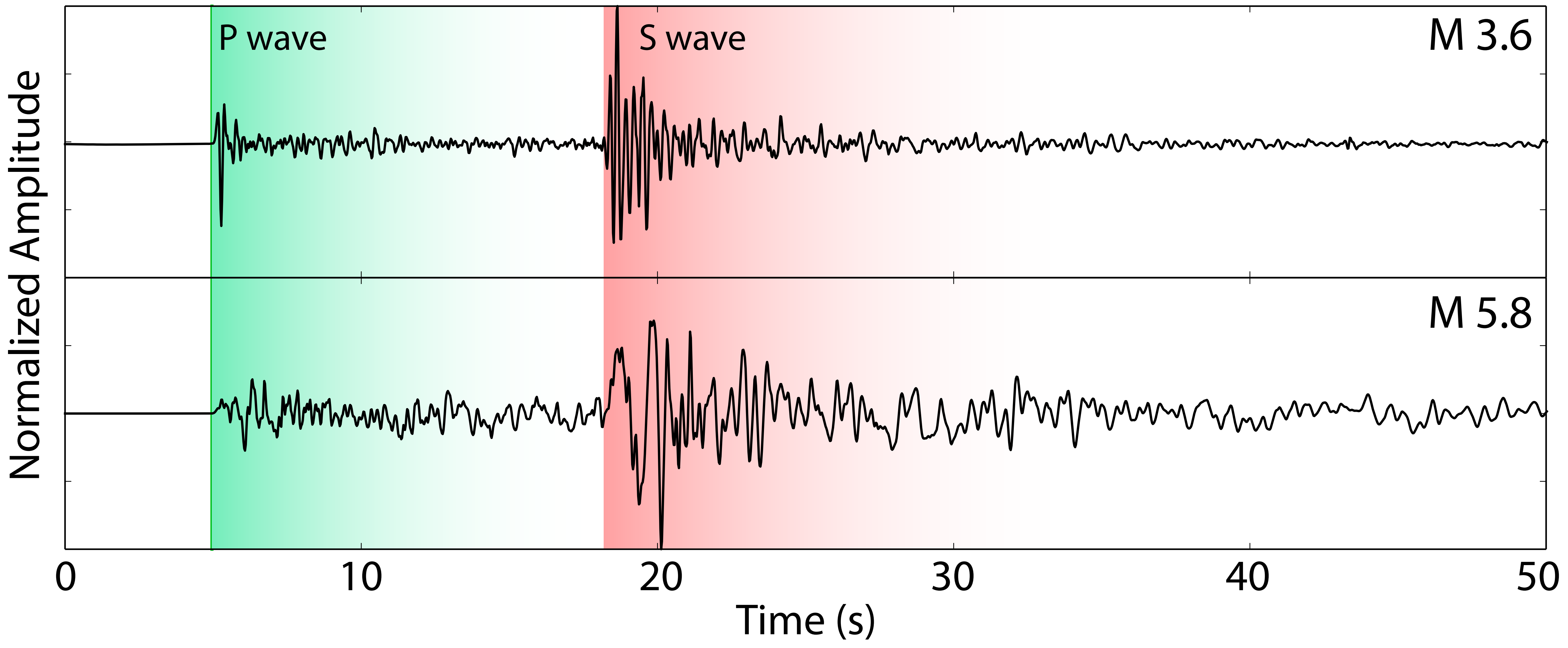
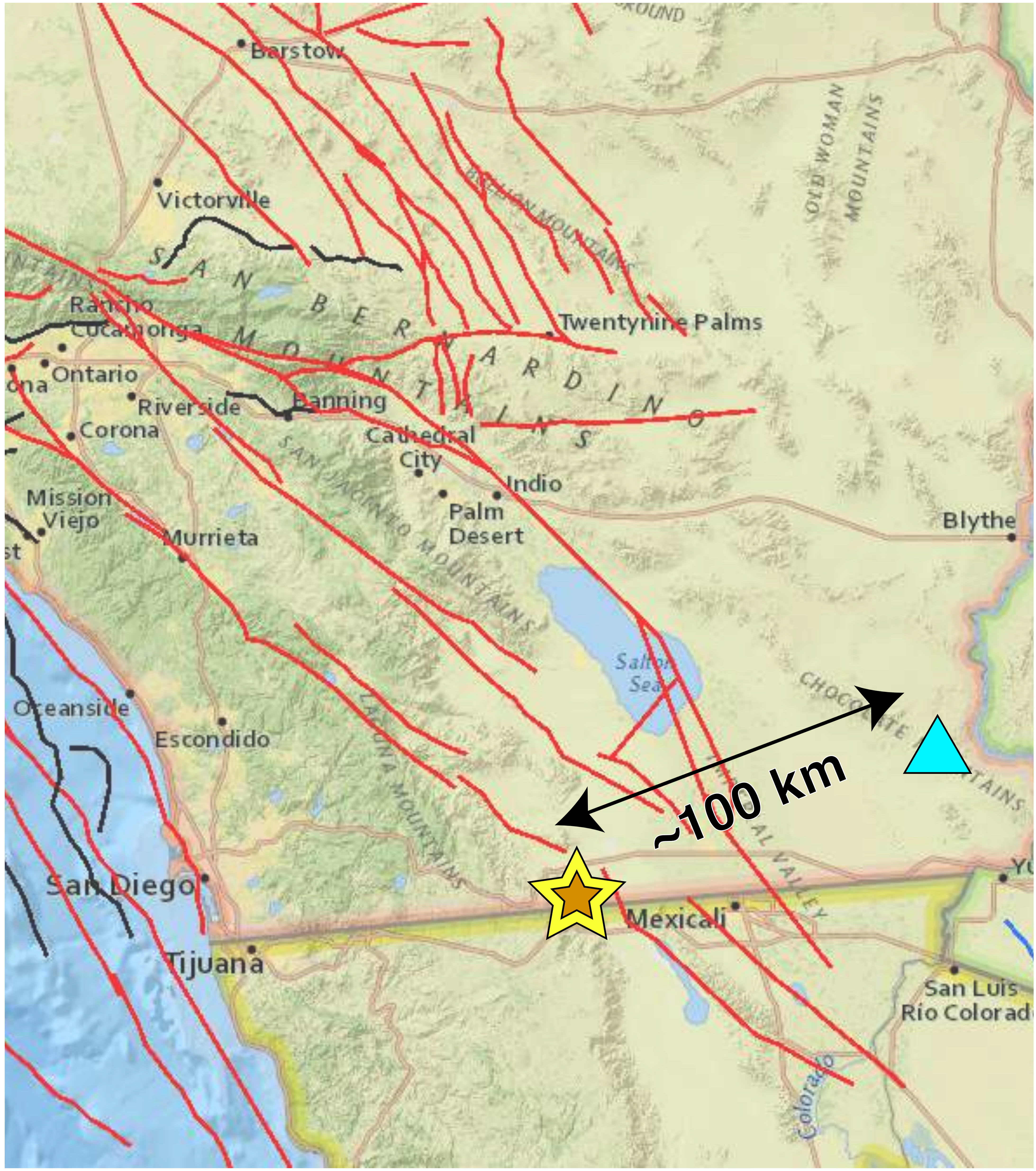
Collège de France, November 30th 2017

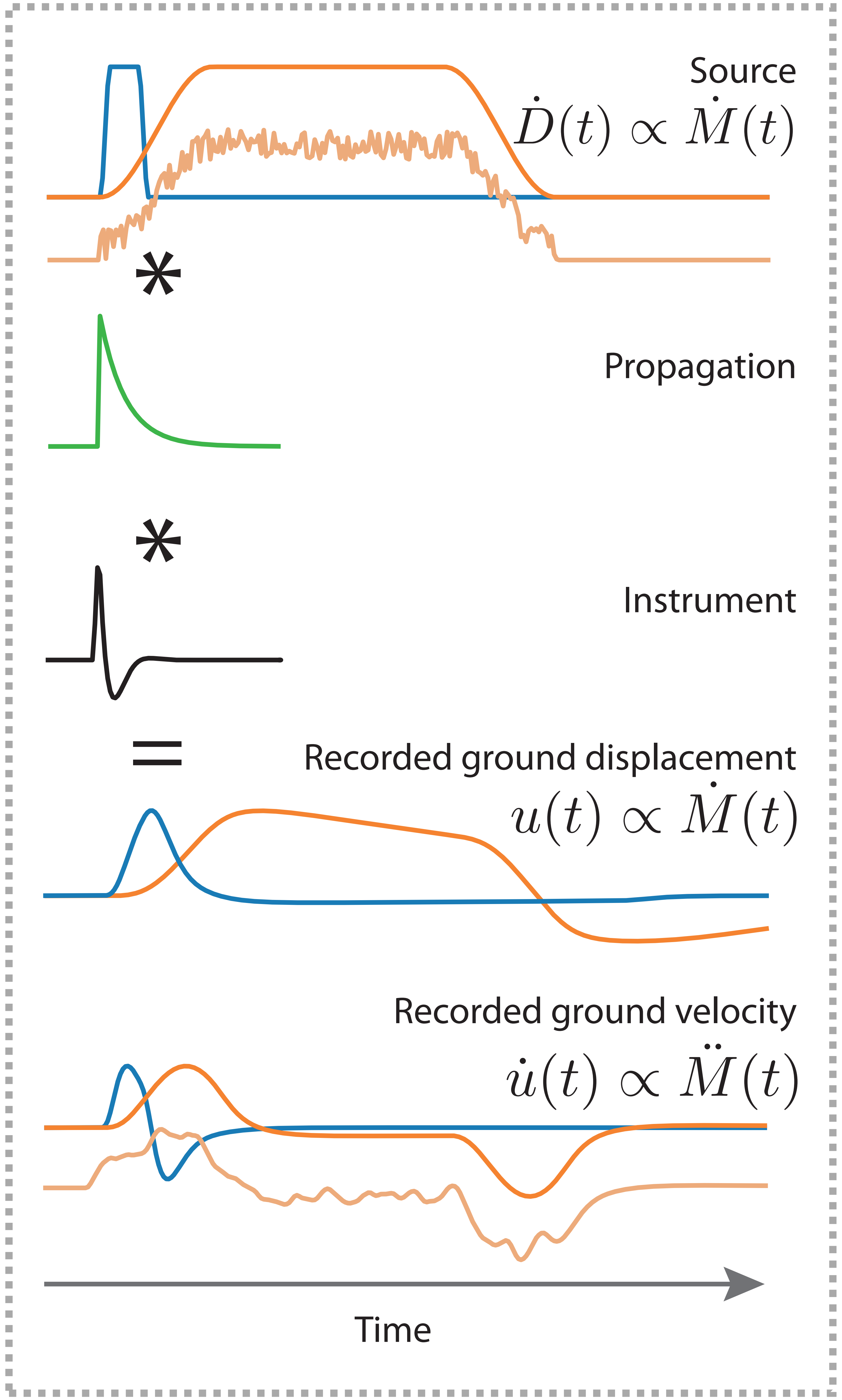
Seismic radiation and earthquake size

Since the early days of Seismology (1930-1940), it has been well known that **the greater the size of an earthquake, the more efficiently longer-period waves are generated**.

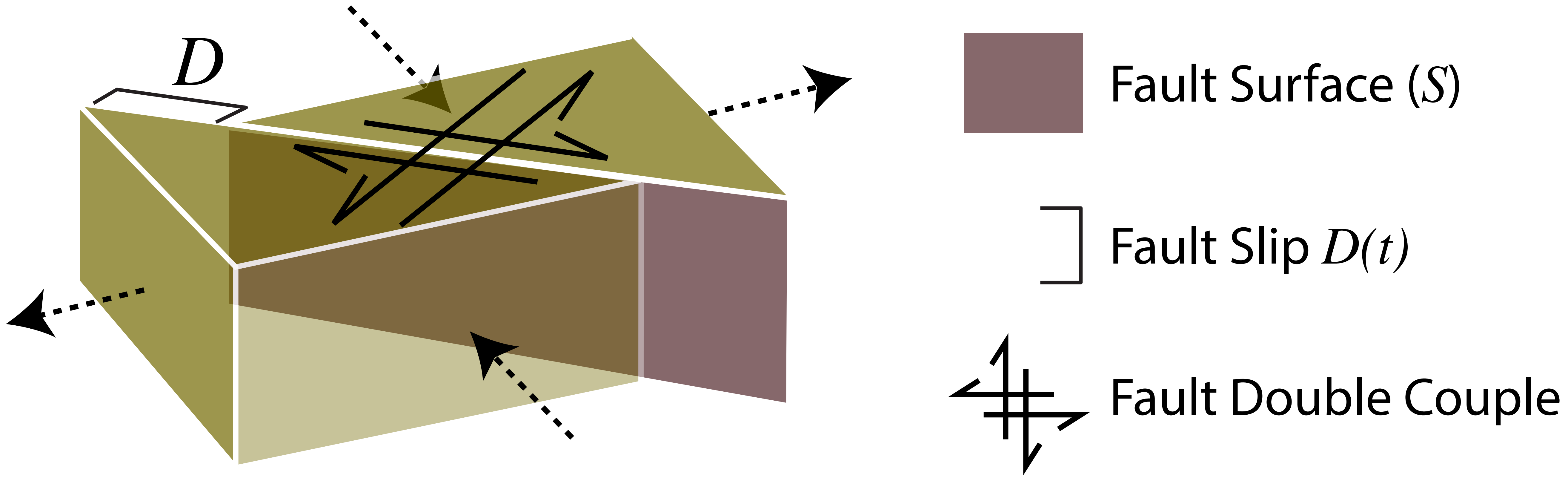




Far field radiation from a dislocation source



Far field ground displacement is proportional to slip (moment) rate on the fault



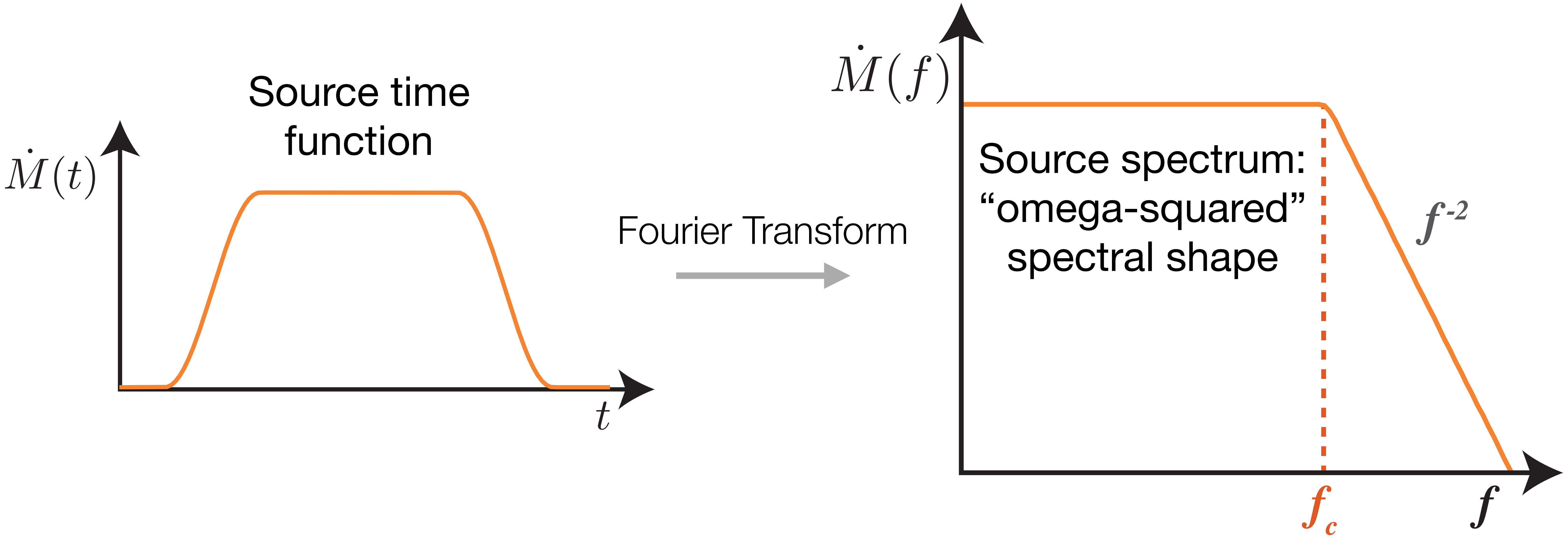
Seismic moment (Aki, 1966)

$M_0 = \mu S D(t \rightarrow \infty)$ (μ : rigidity)

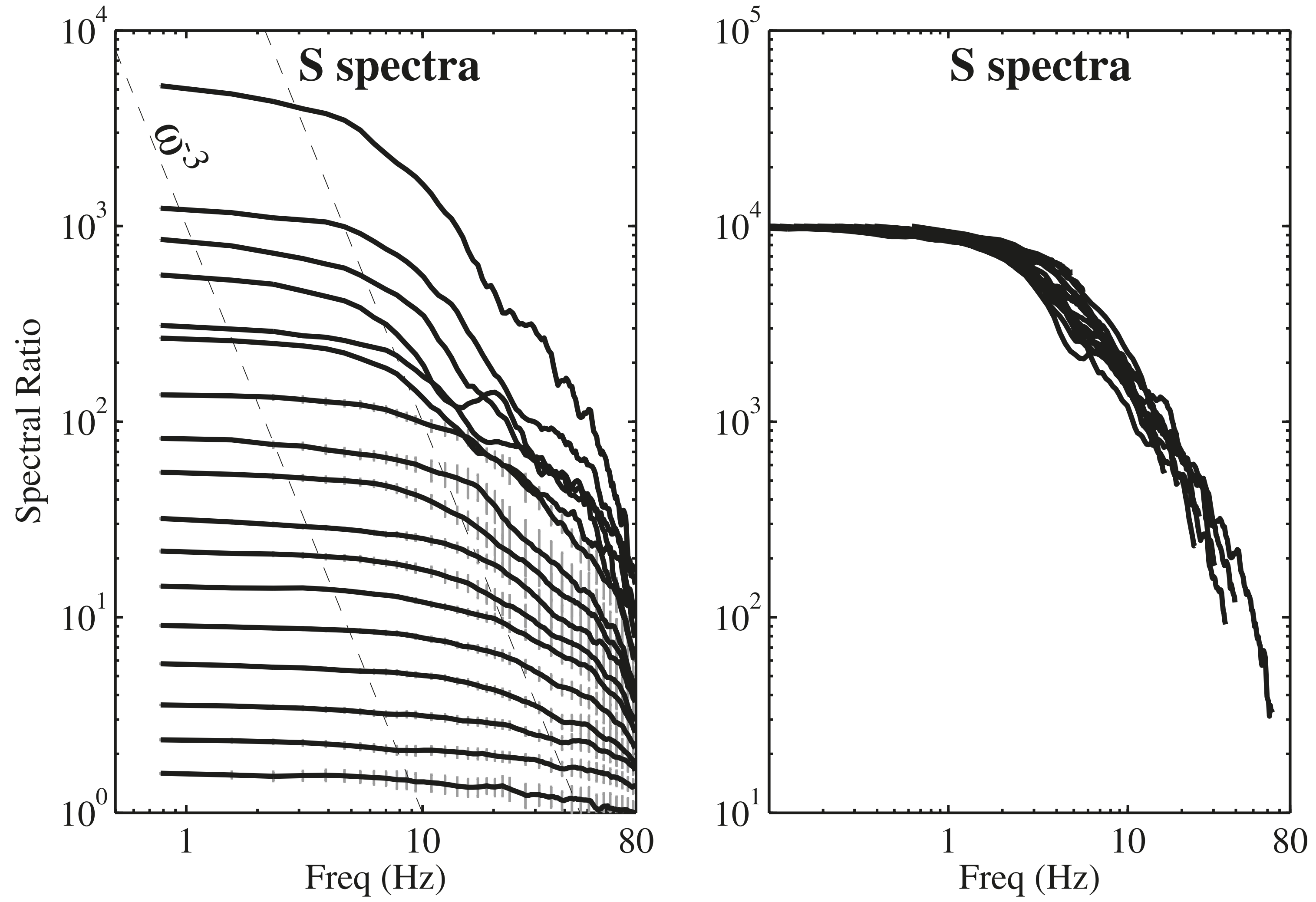
e.g.,
Knopoff and Gilbert (1960)
Haskell (1964, 1966)
Aki (1967)

Scaling law of seismic spectrum (Aki, 1967)

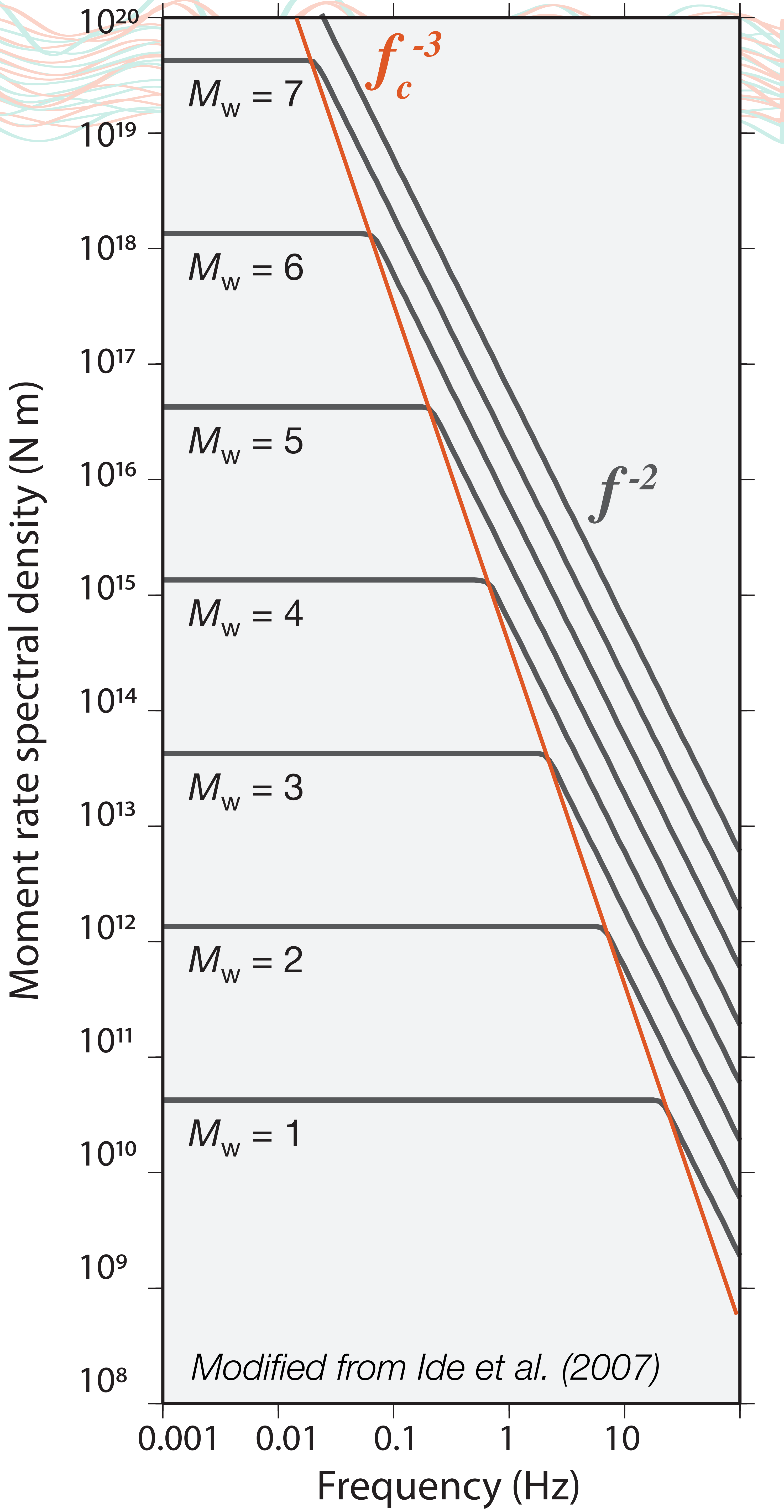
1. The seismic spectrum has a characteristic **“omega-squared”** shape: $\omega := 2\pi f$



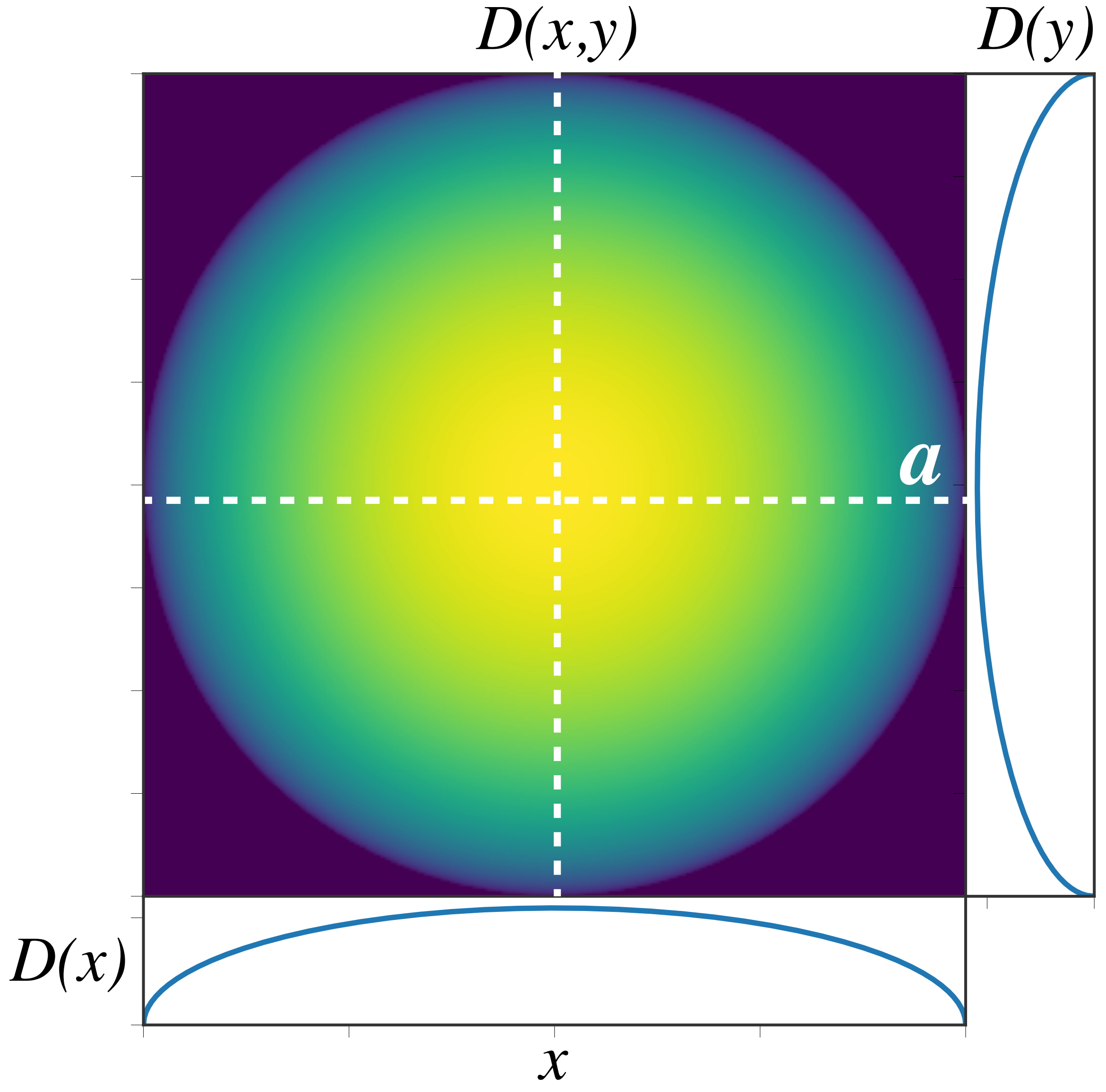
2. The seismic spectrum is **self-similar:** $M_0 \propto f_c^{-3}$



e.g., Prieto et al, 2004



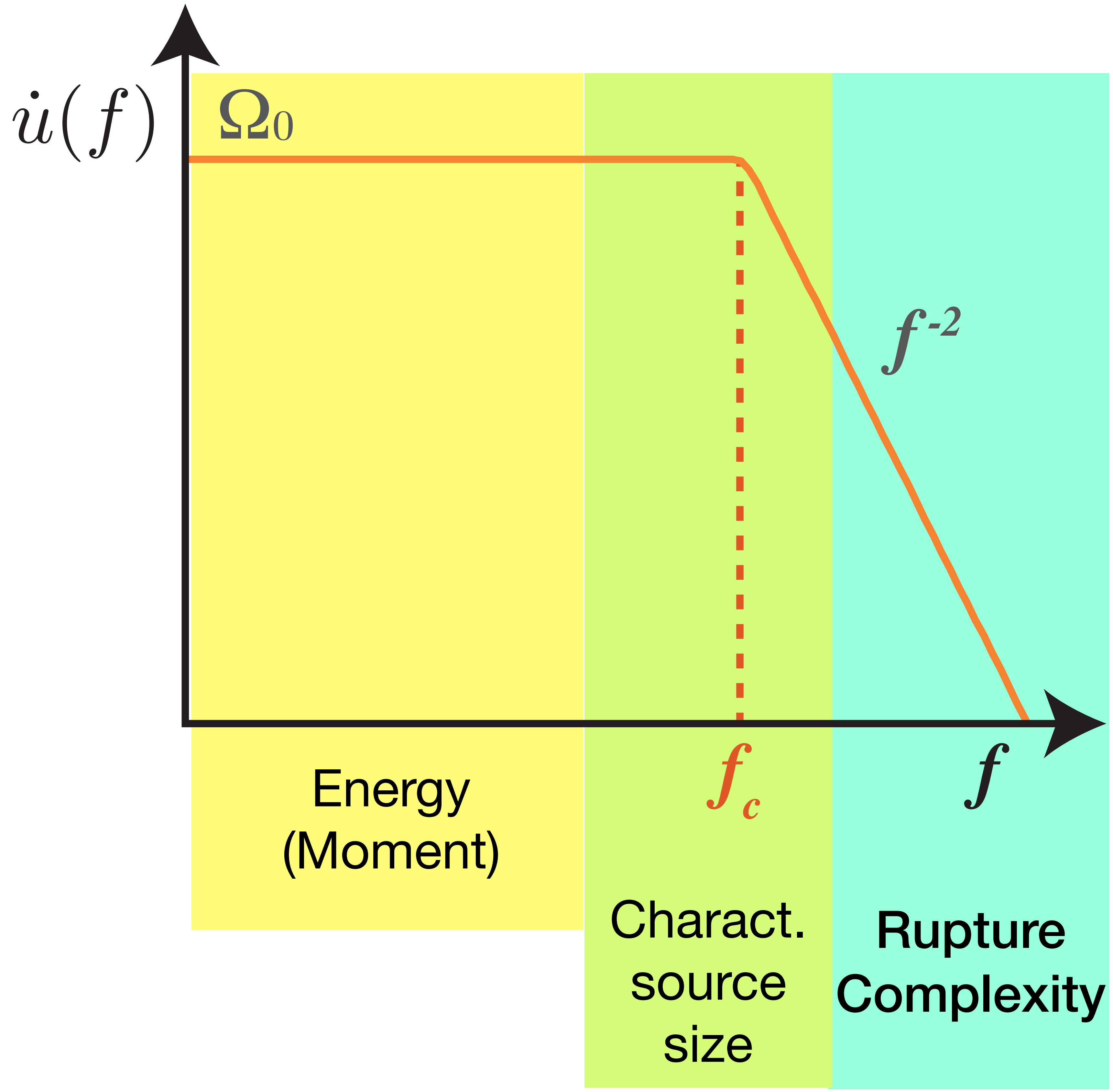
Source spectrum and rupture complexity

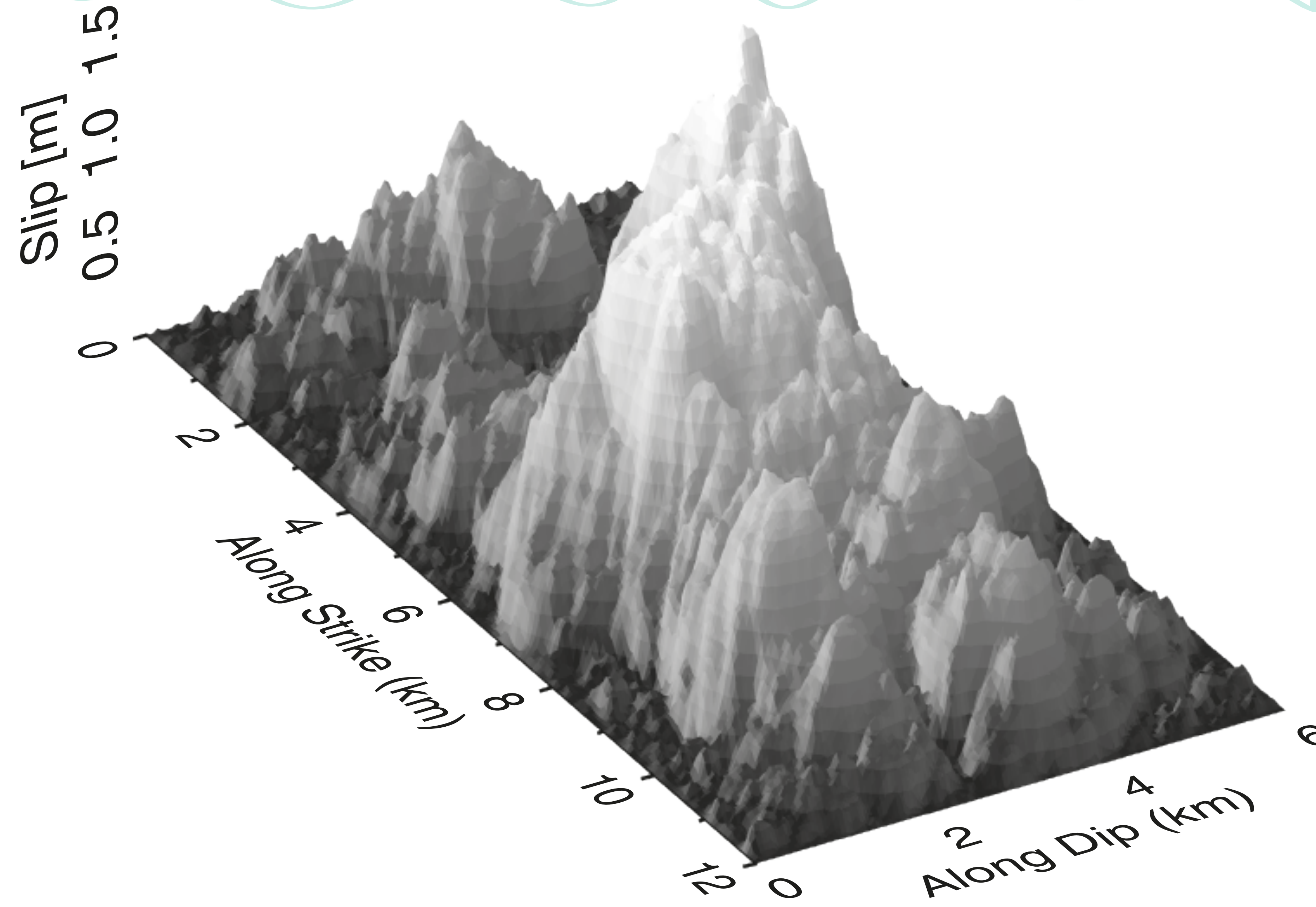


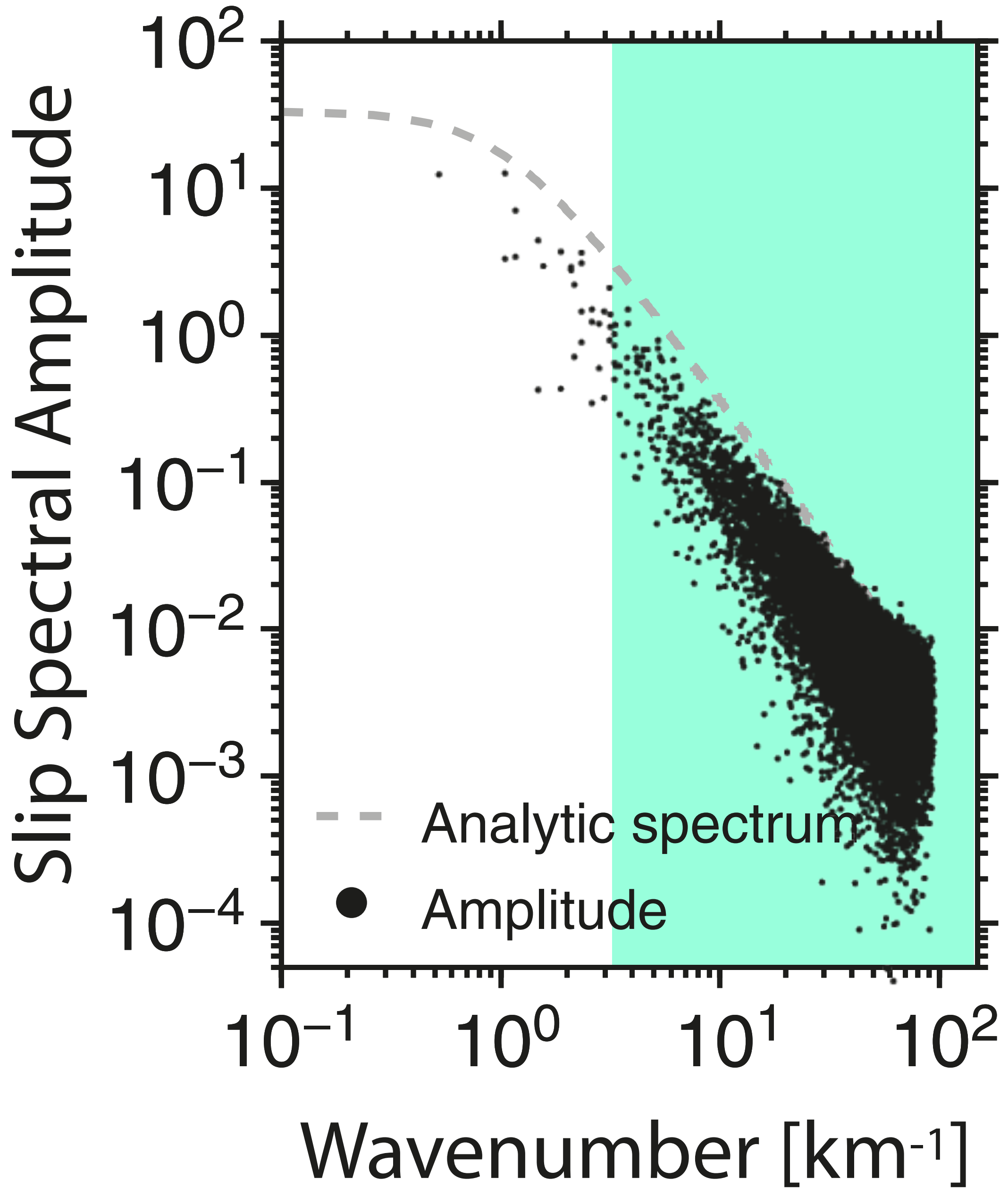
Circular crack model
(Brune, 1970; Madariaga, 1976)

$$u(f) \propto \frac{\Omega_0}{1 + \left(\frac{f}{f_c}\right)^2}$$

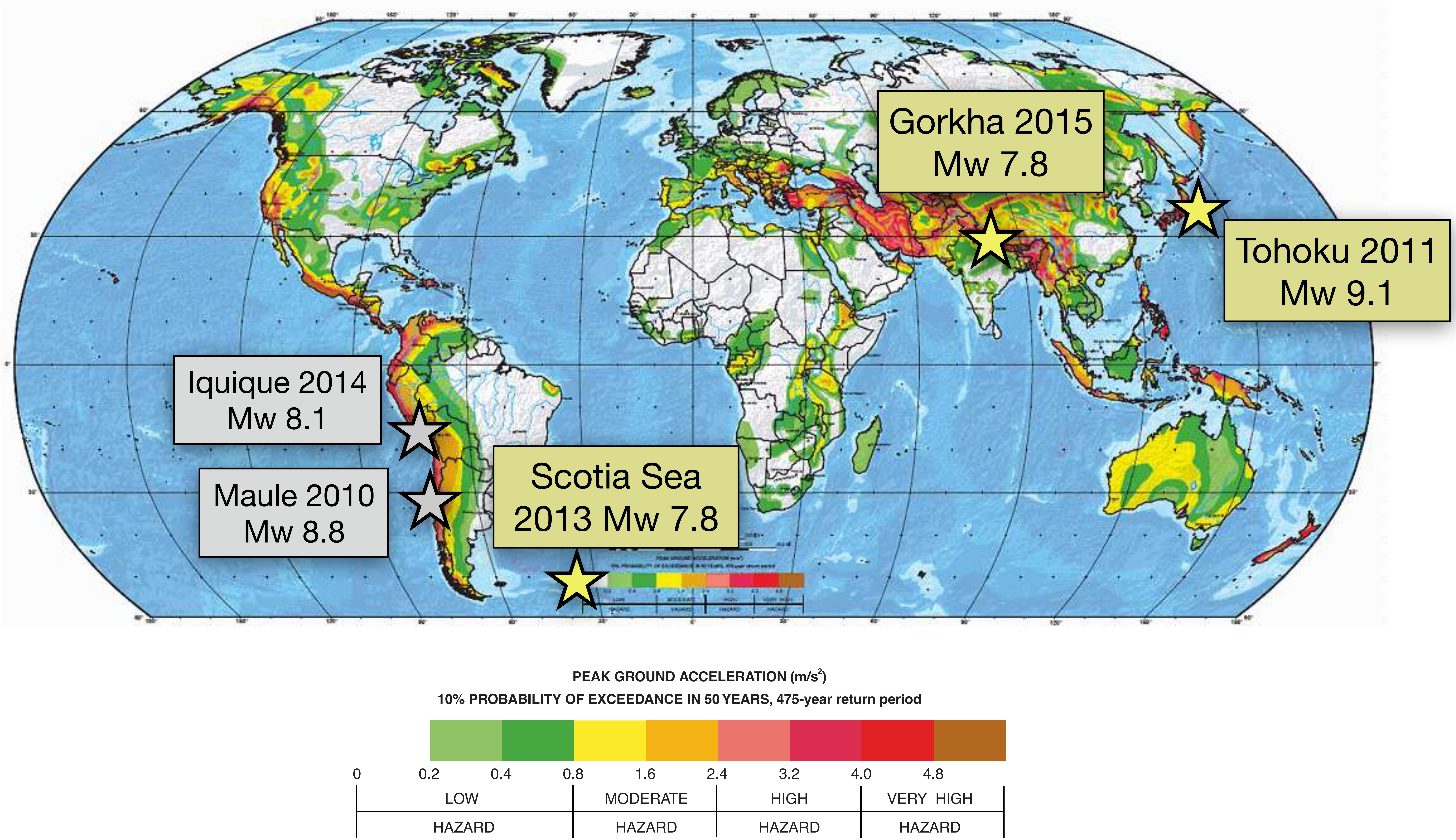
$$f_c = 0.3724\frac{\beta}{a} \qquad \beta = \text{S-wave speed} \quad a = \text{source radius}$$



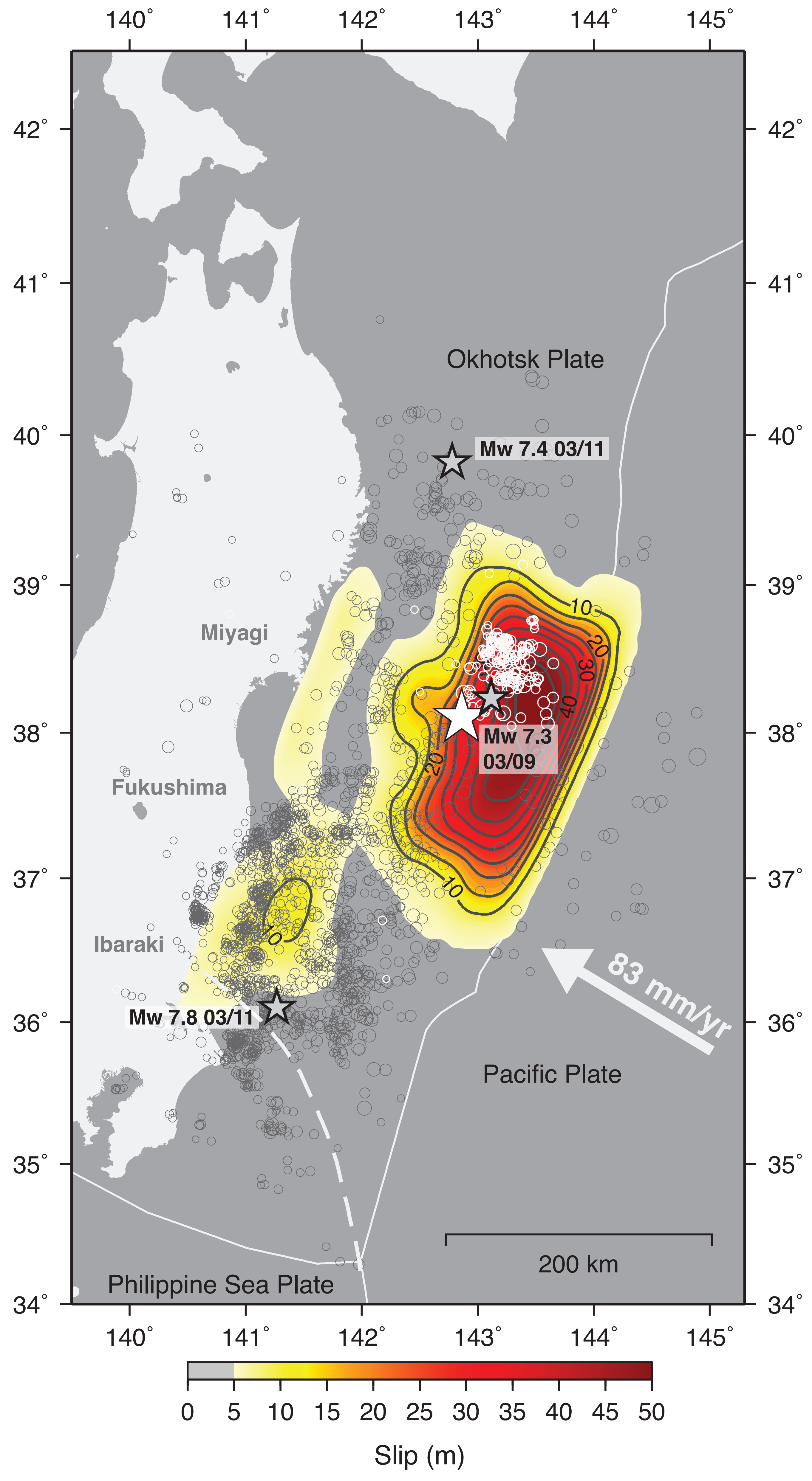


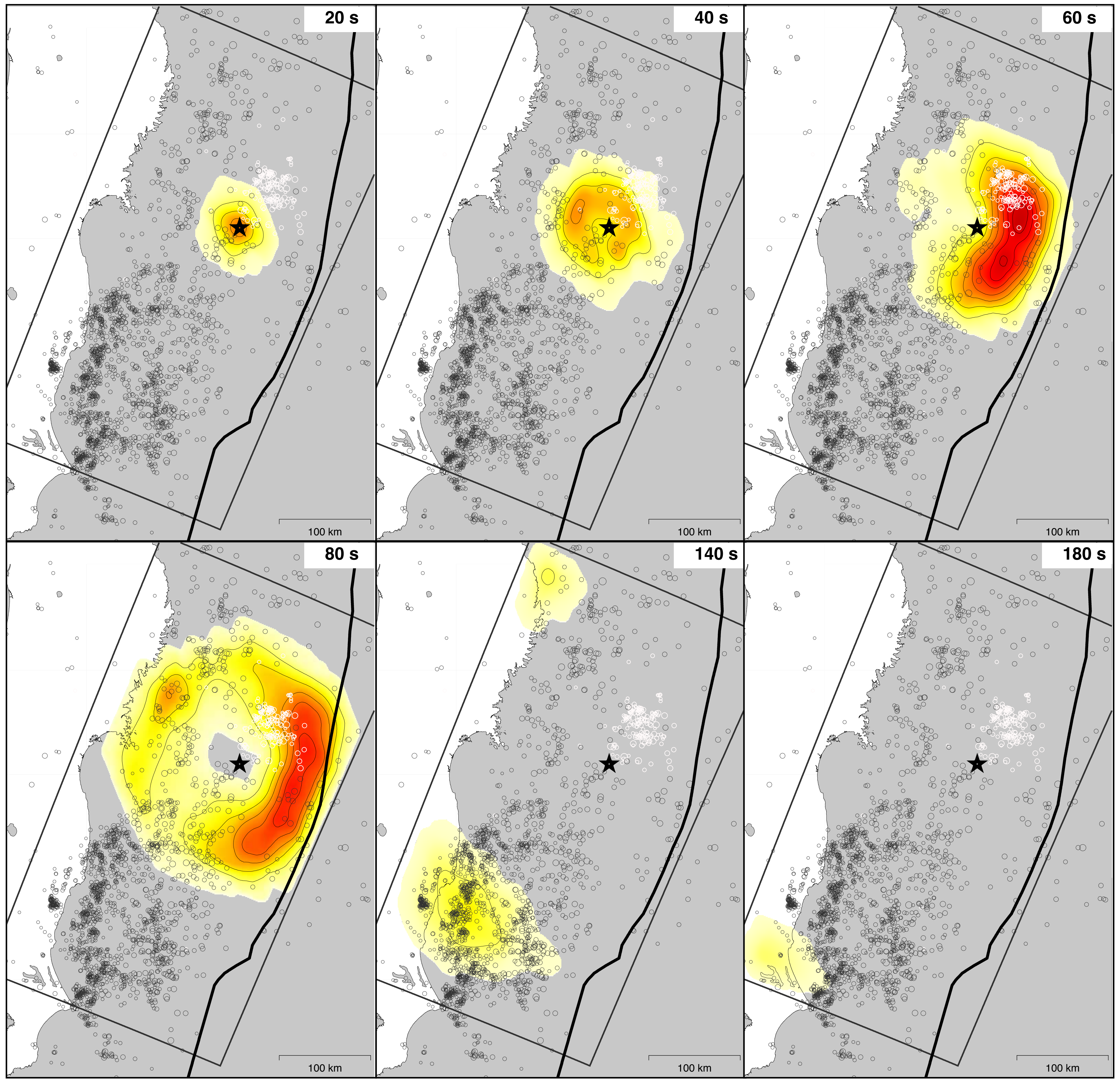


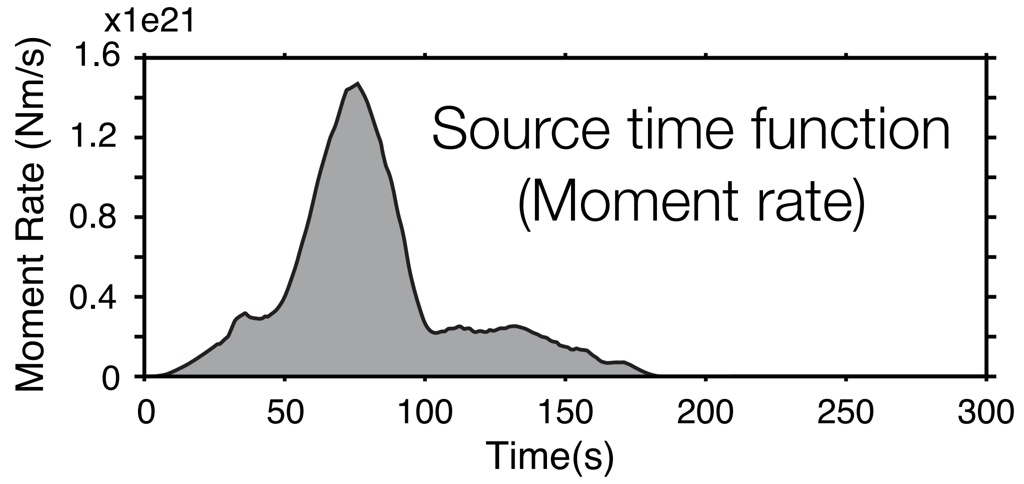
"k-squared" models:
self-similar slip on the fault
at high wavenumbers *k*.
(Herrero and Bernard, 1994;
Causse et al., 2010;
Ruiz et al., 2011;)


Gorkha 2015
Mw 7.8
Tohoku 2011
Mw 9.1
Iquique 2014
Mw 8.1
Maule 2010
Mw 8.8
Scotia Sea
2013 Mw 7.8
PEAK GROUND ACCELERATION (m/s²)
10% PROBABILITY OF EXCEEDANCE IN 50 YEARS, 475-year return period
0
0.2
0.4
0.8
1.6
2.4
3.2
4.0
4.8
LOW HAZARD
MODERATE HAZARD
HIGH HAZARD
VERY HIGH HAZARD

The 2011 Tohoku earthquake (Mw 9.1): slip from kinematic modeling

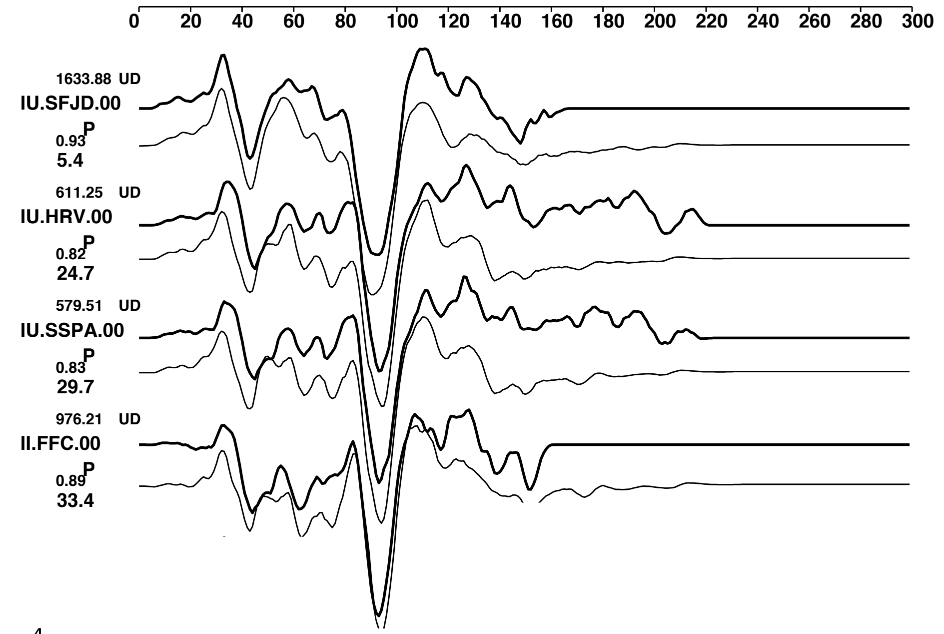


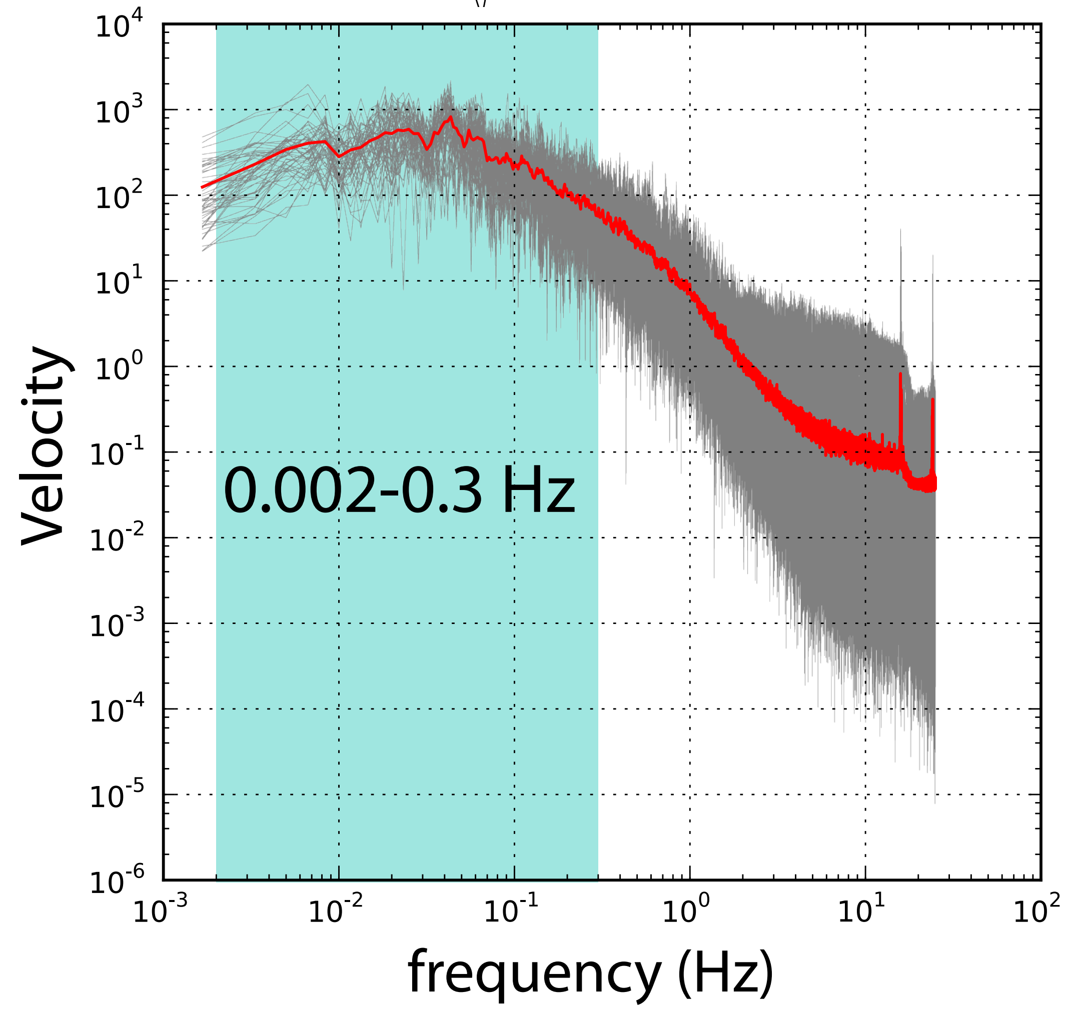




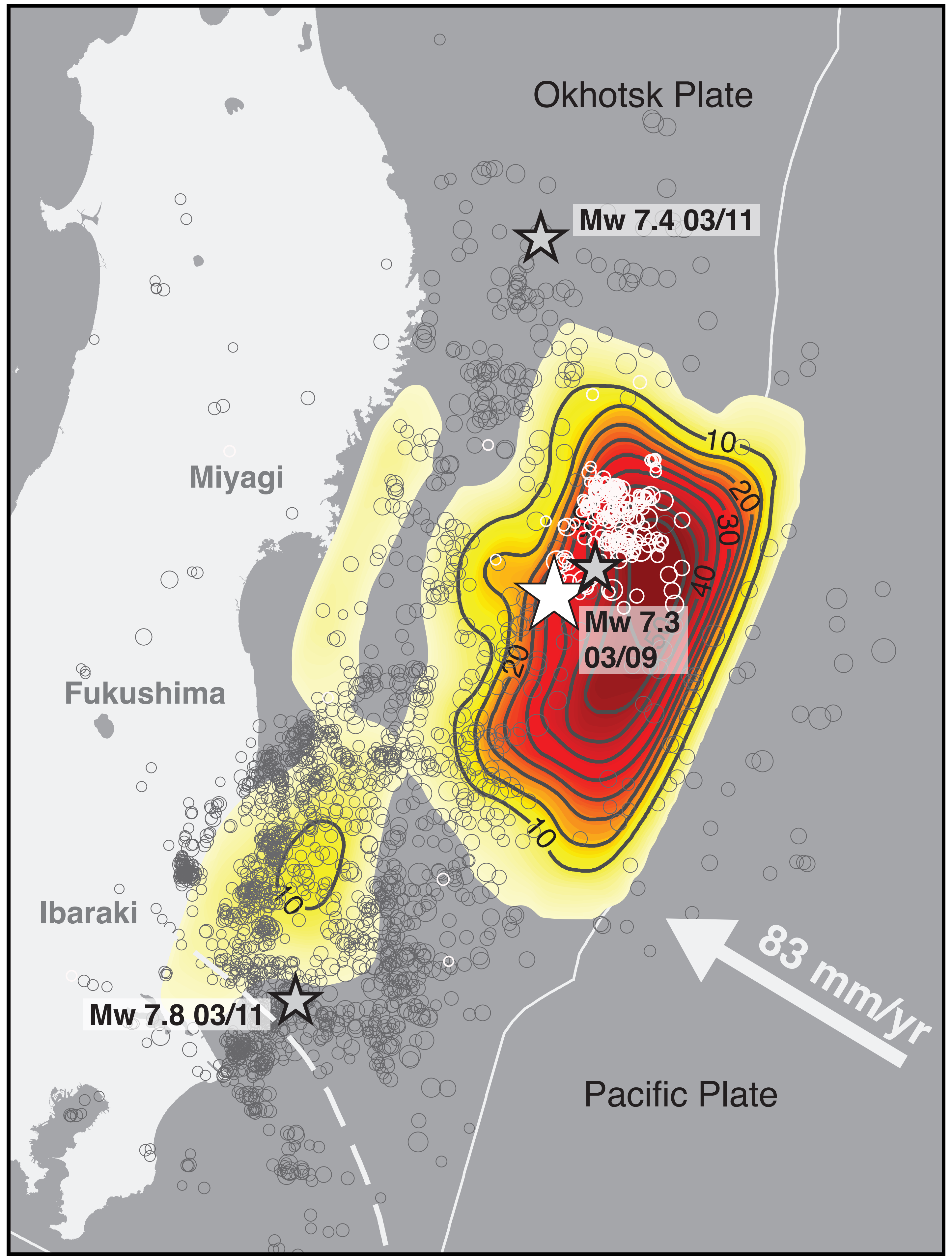
Satriano et al., EPSL (2014)

Data

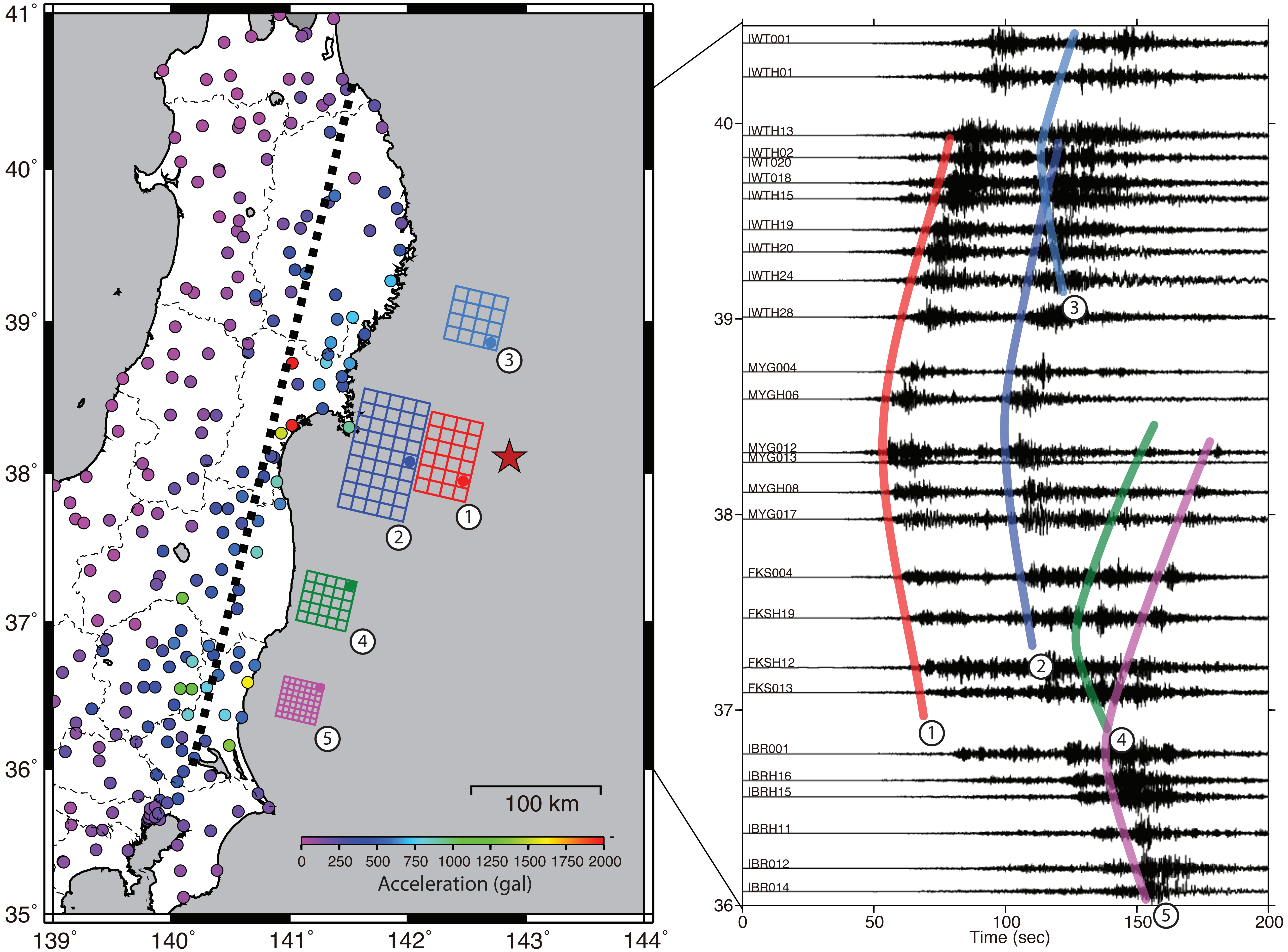




Tohoku: a complex rupture when seen through strong motion



Fault slip imaged by teleseismic data
A compact rupture, close to the trench.

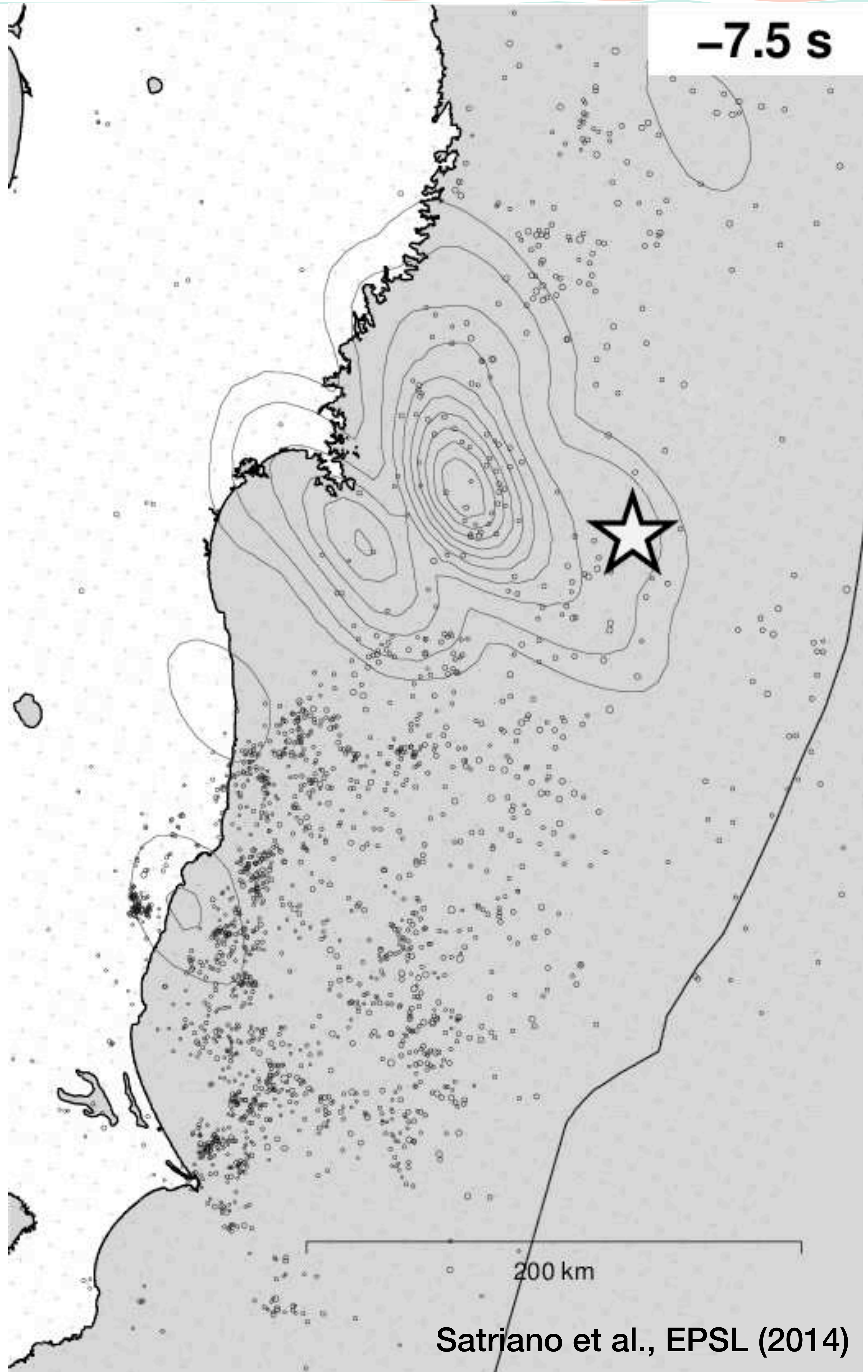


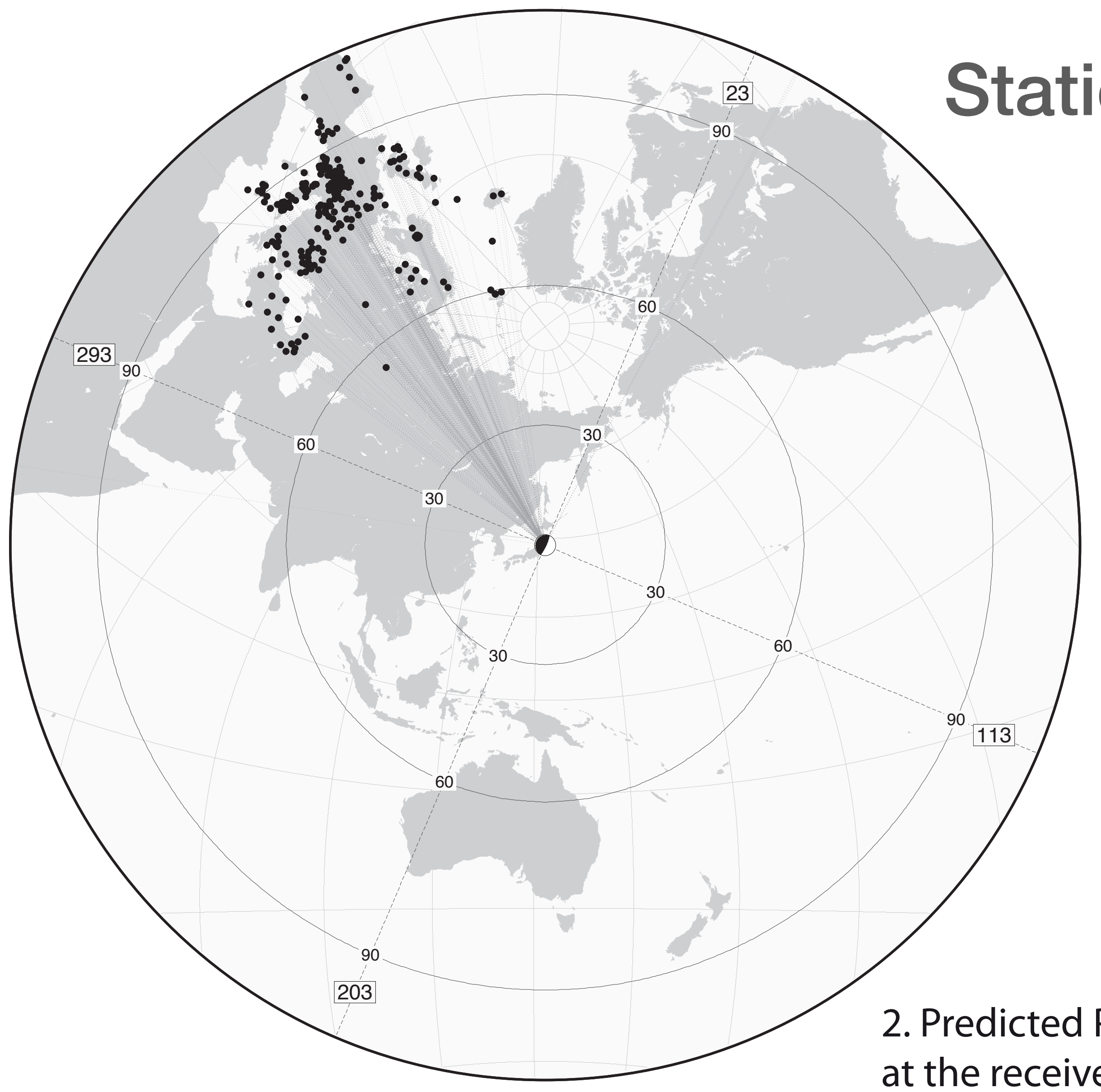
Ground acceleration at regional scale
A complex rupture: at least 5 sub-events,
close to the coast.

Satriano et al., EPSL (2014)

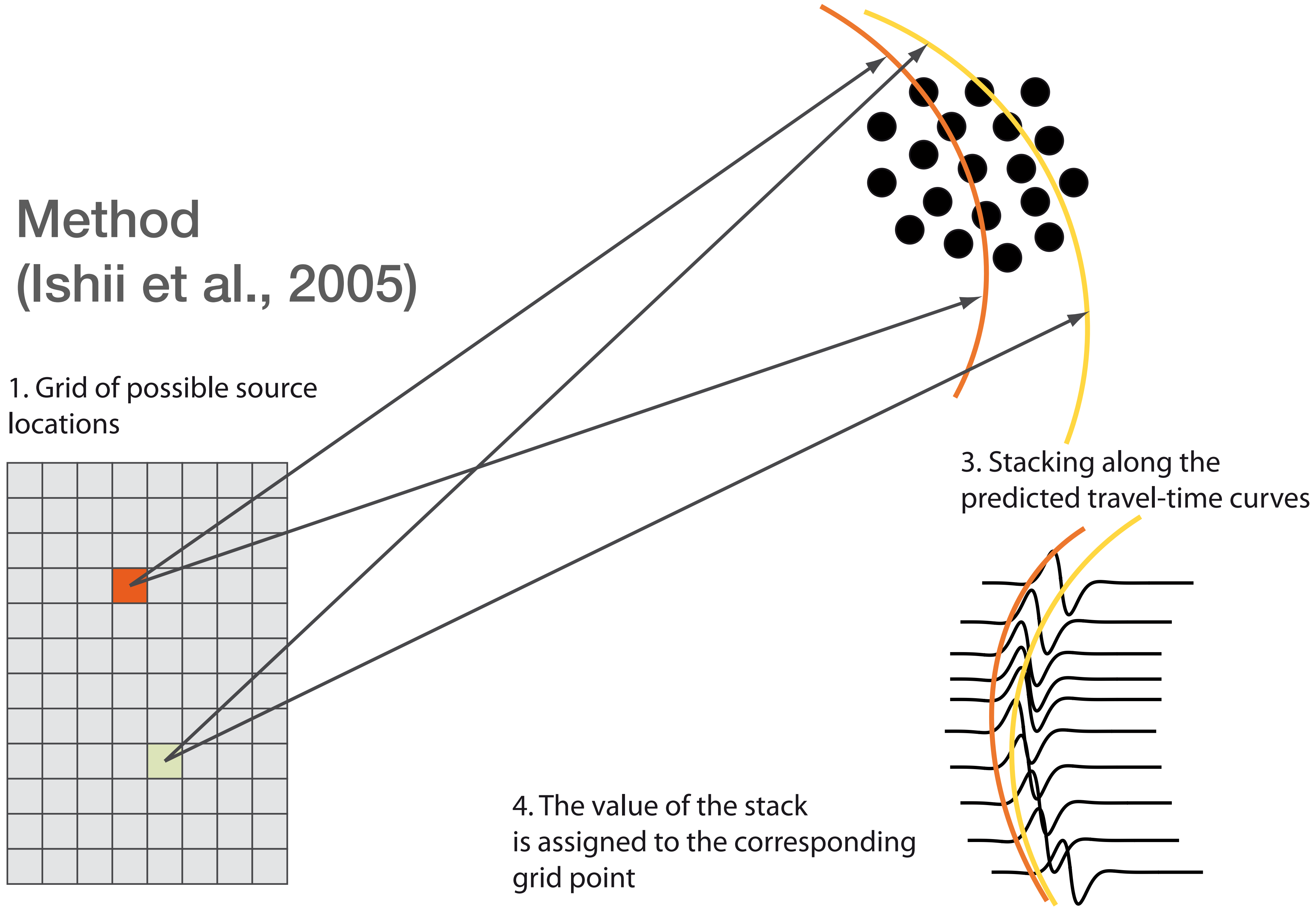
Lee et al., 2011 (redrawn)

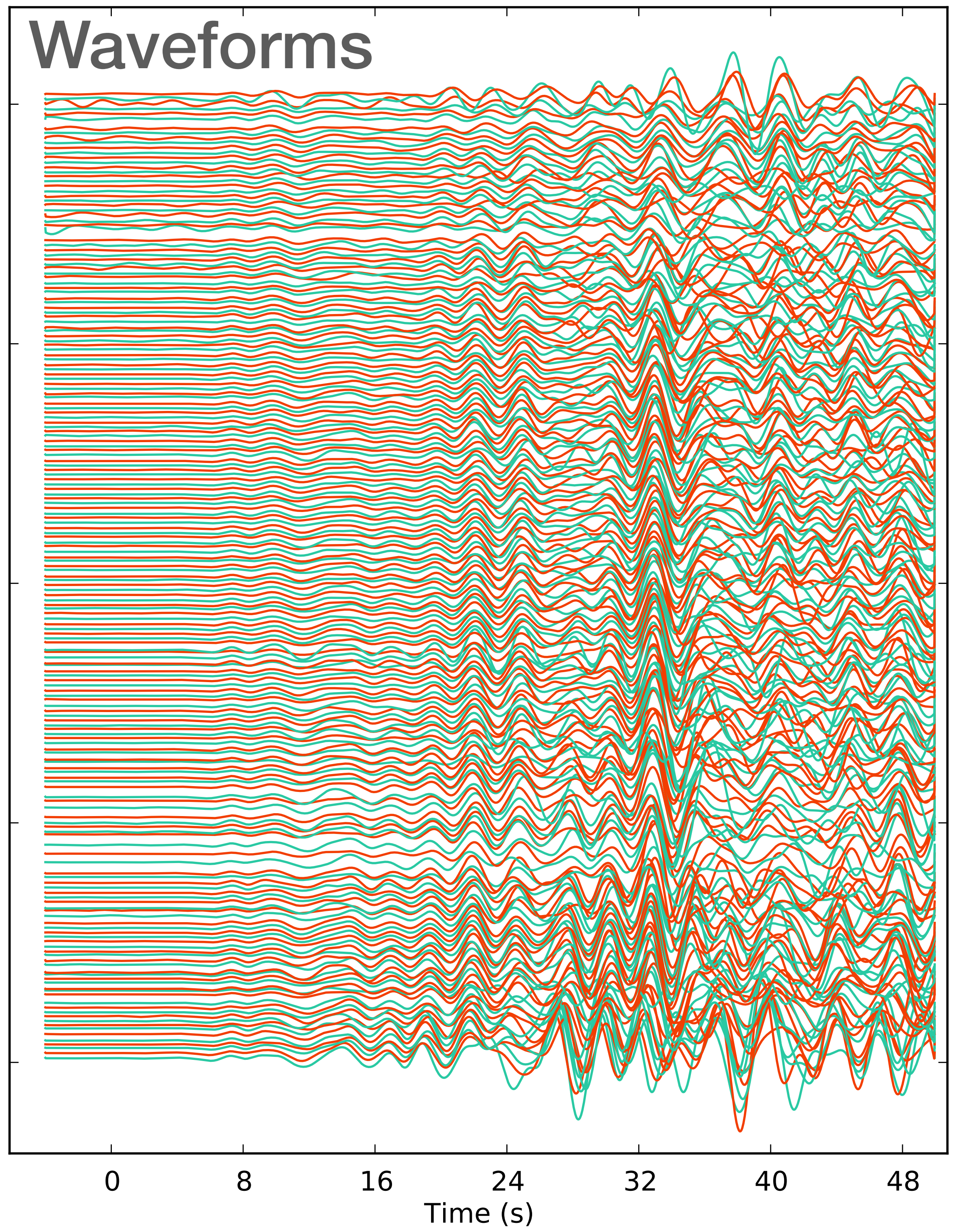
Teleseismic imaging of high-frequency radiation: back projection

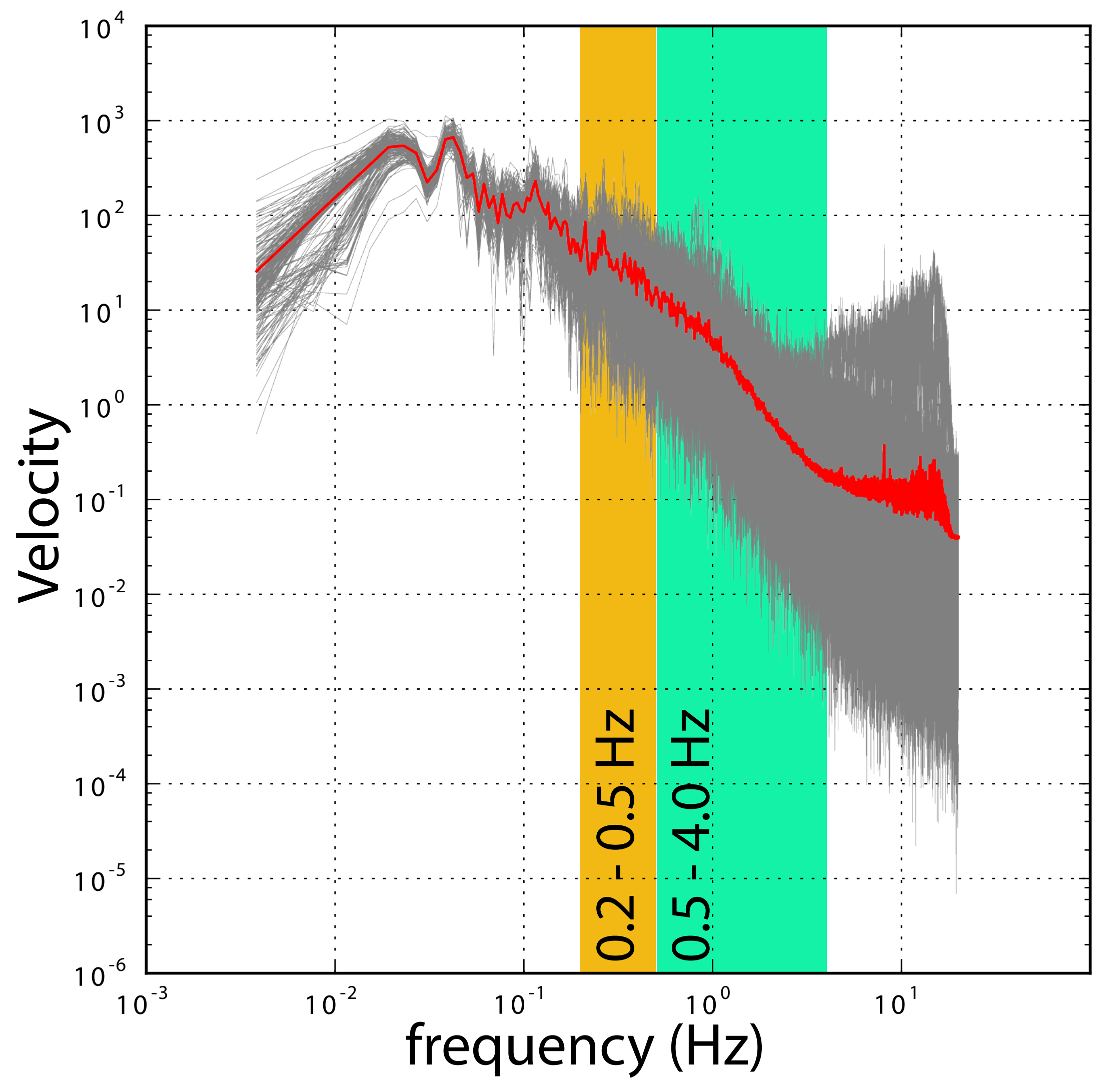




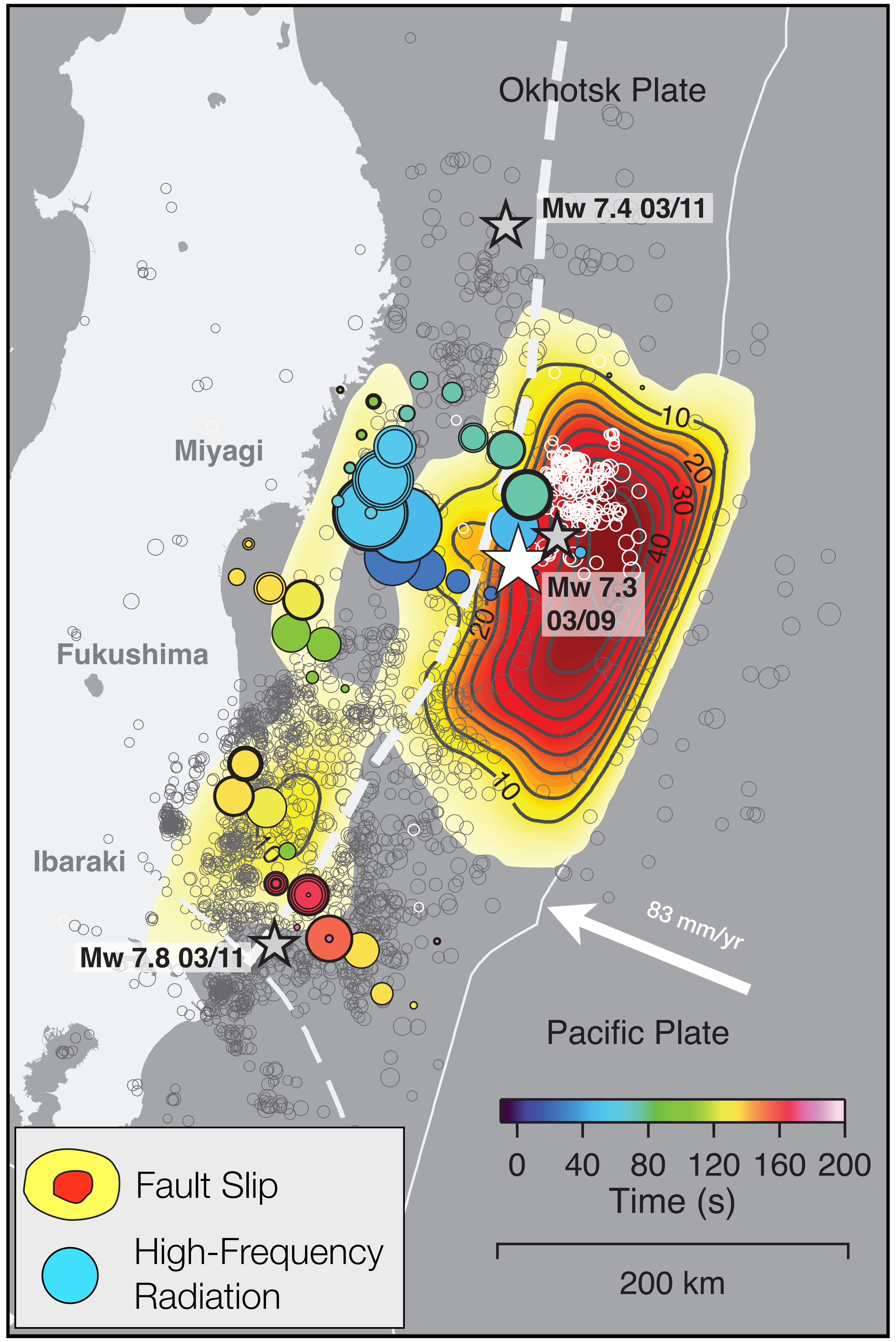
Method
(Ishii et al., 2005)





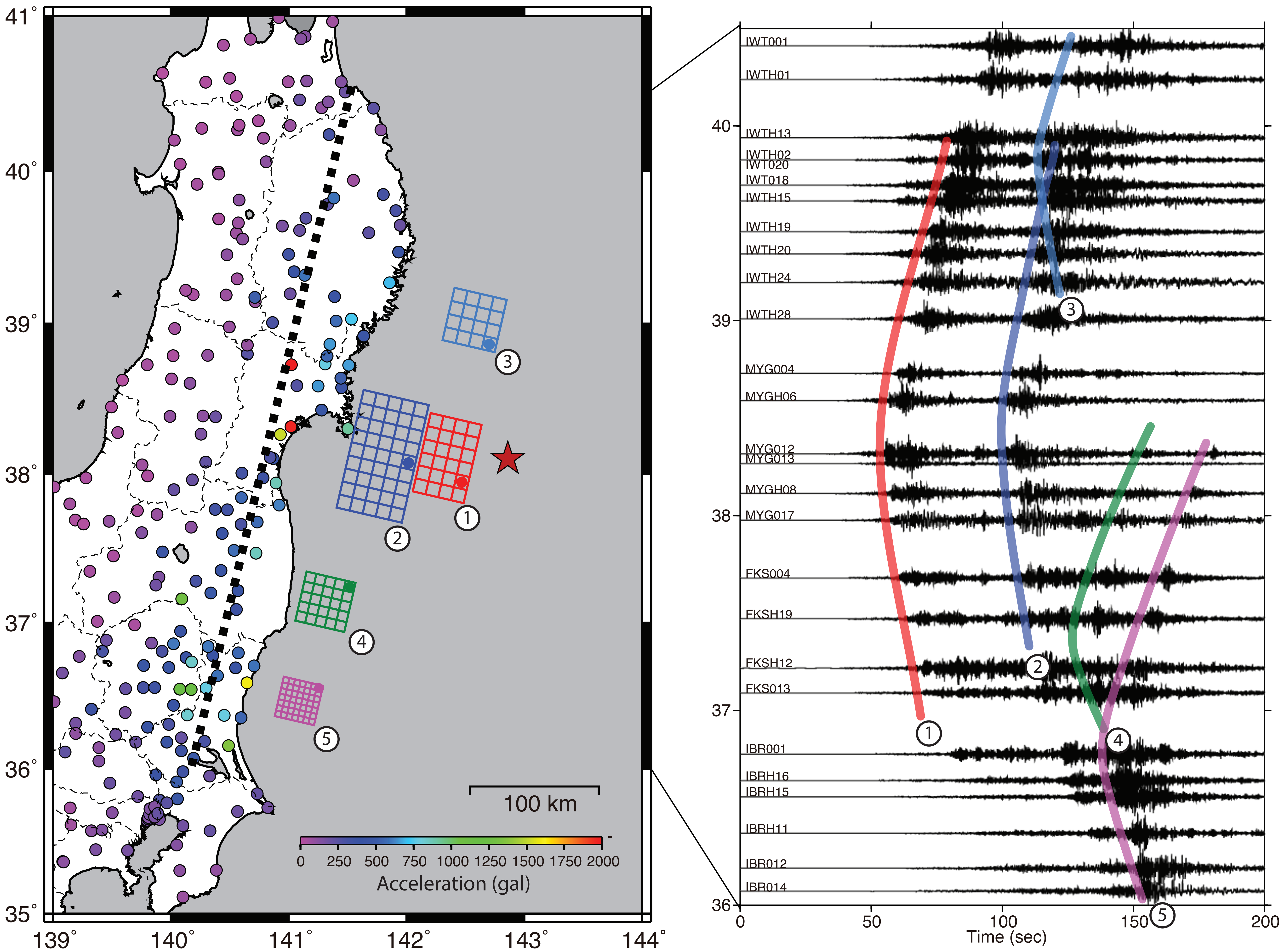


High-frequency sources and strong ground motion



Fault slip hand high-frequency sources imaged by teleseismic data

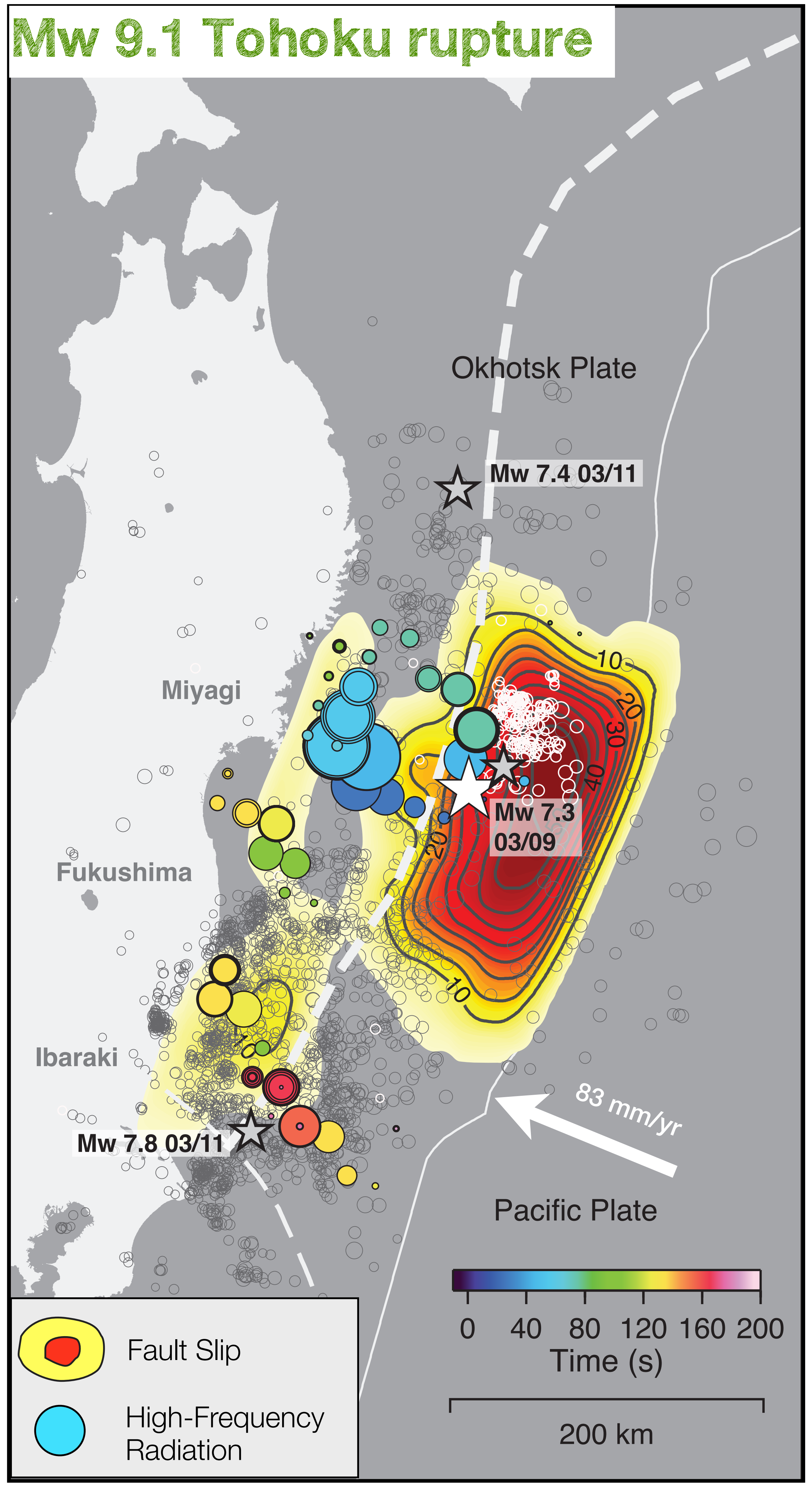
Satriano et al., EPSL (2014)

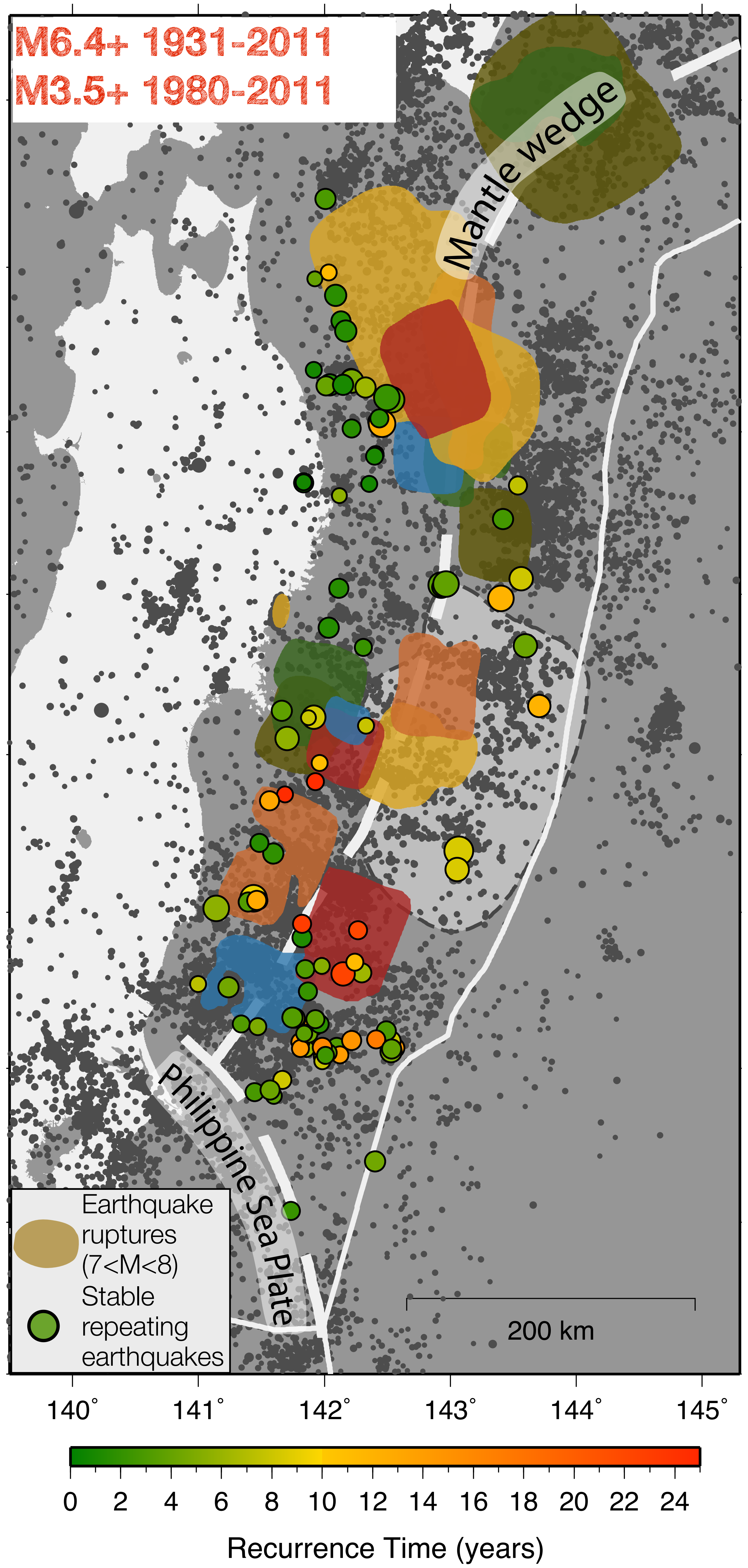


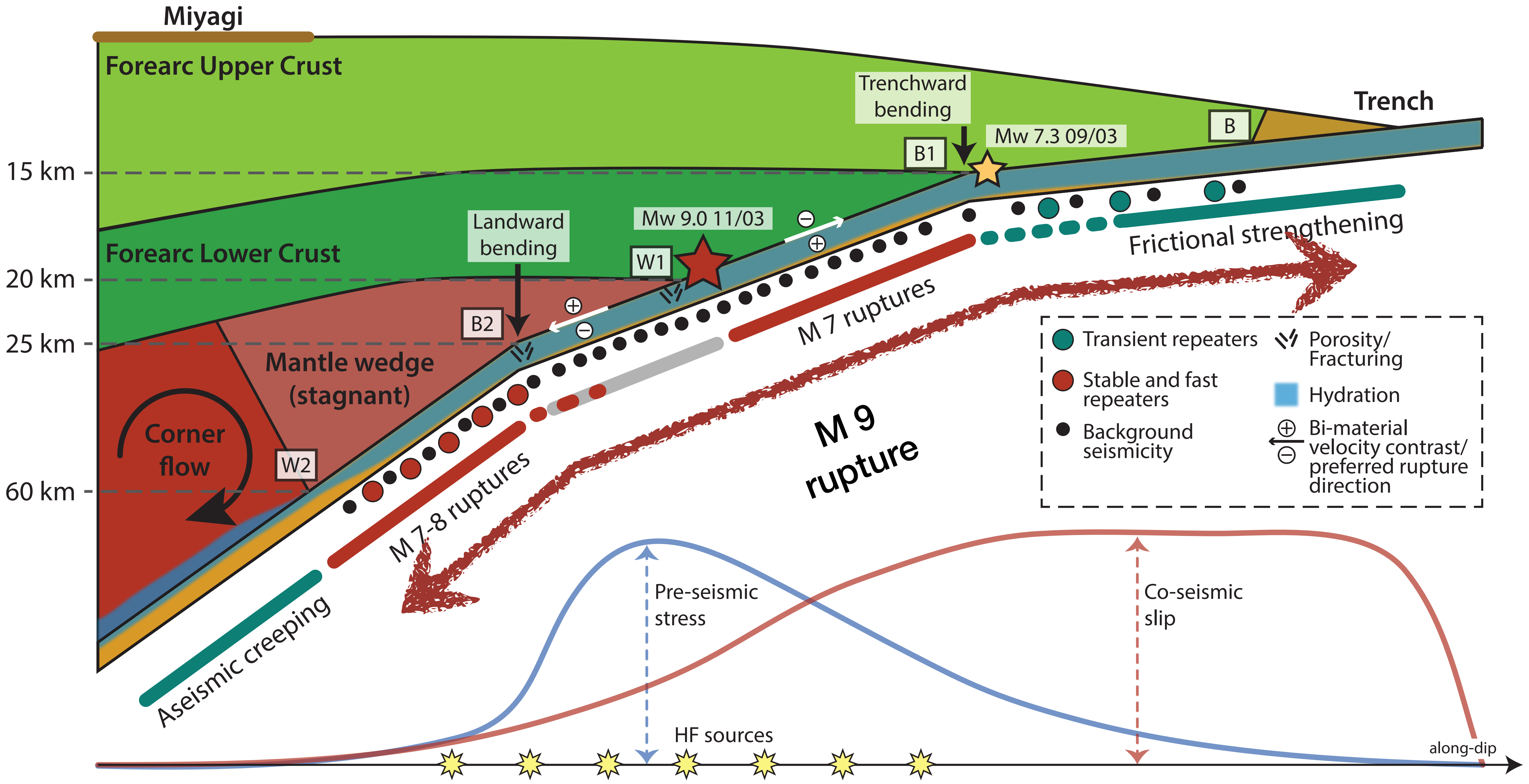
Ground acceleration at regional scale

Lee et al., 2011 (redrawn)

Northwest Japan: Structural heterogeneity and seismic asperities







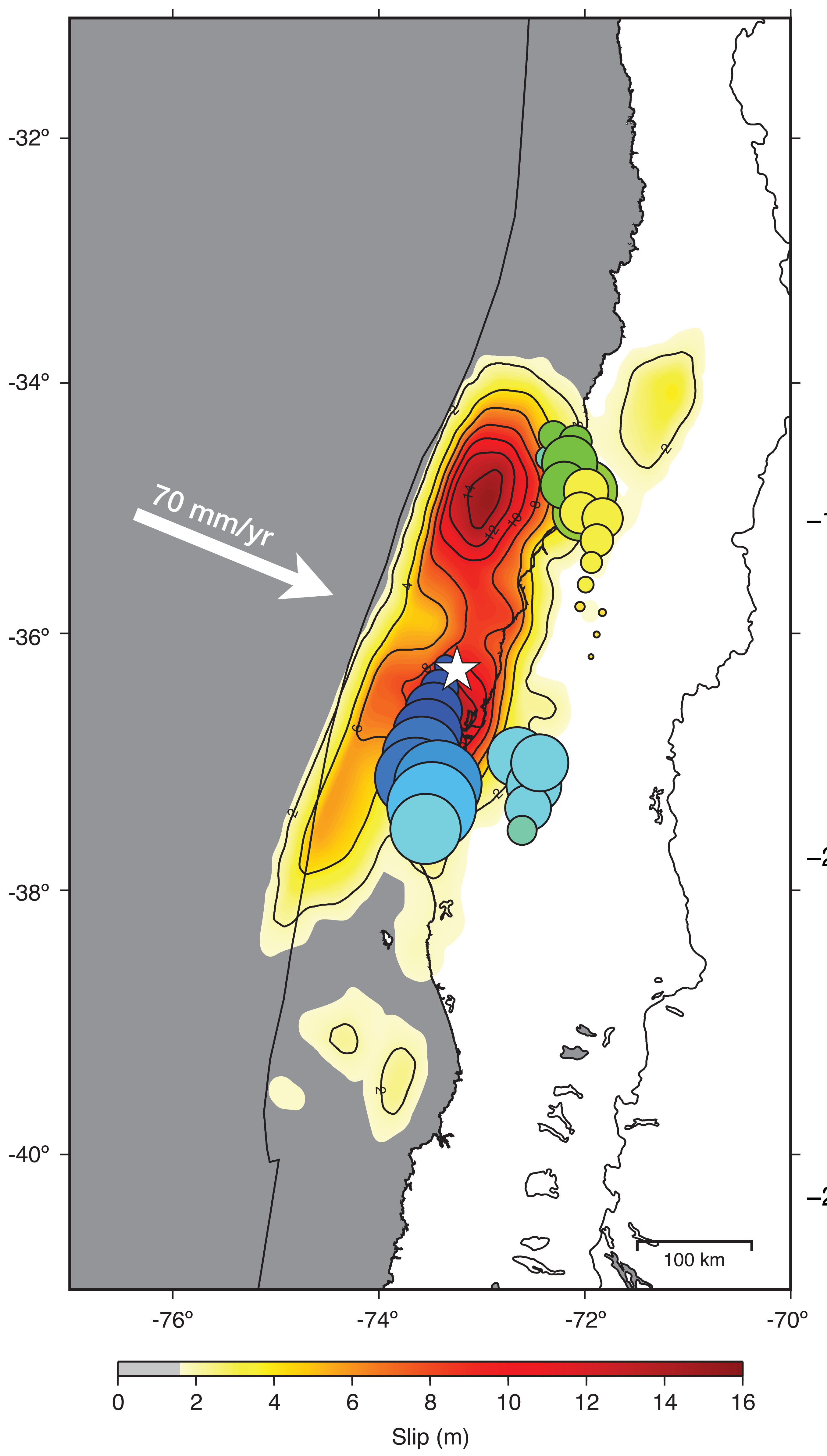
Background seismicity and large earthquake ruptures (M 7-8) inform us on the mechanical state of the plate interface.

This information is useful to forecast the rupture and radiation properties of future large earthquakes.

Satriano et al., EPSL (2014)

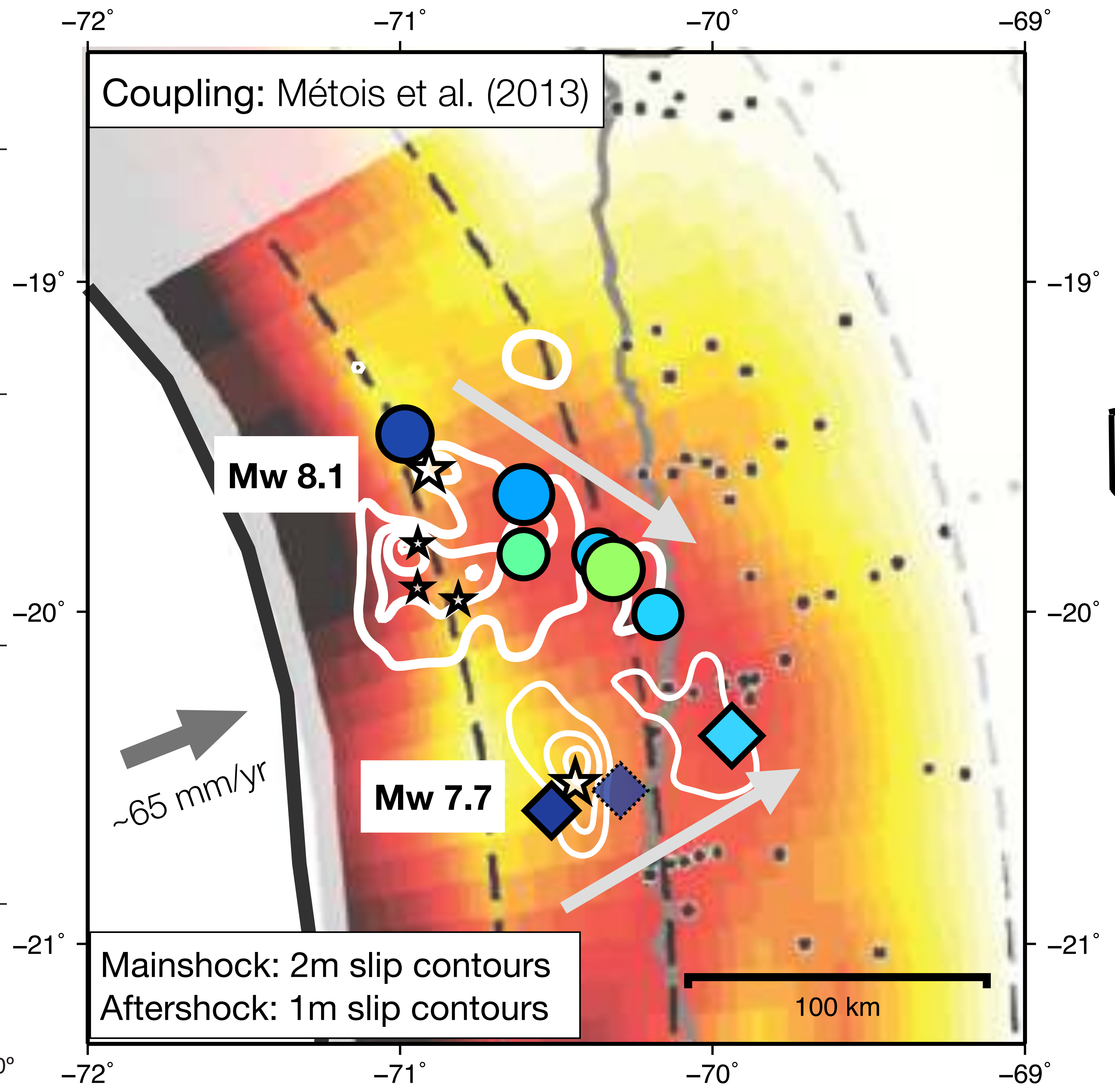
Other examples: downdip HF emission for large subduction earthquakes

Maule (Chile) 2010 Mw 8.8



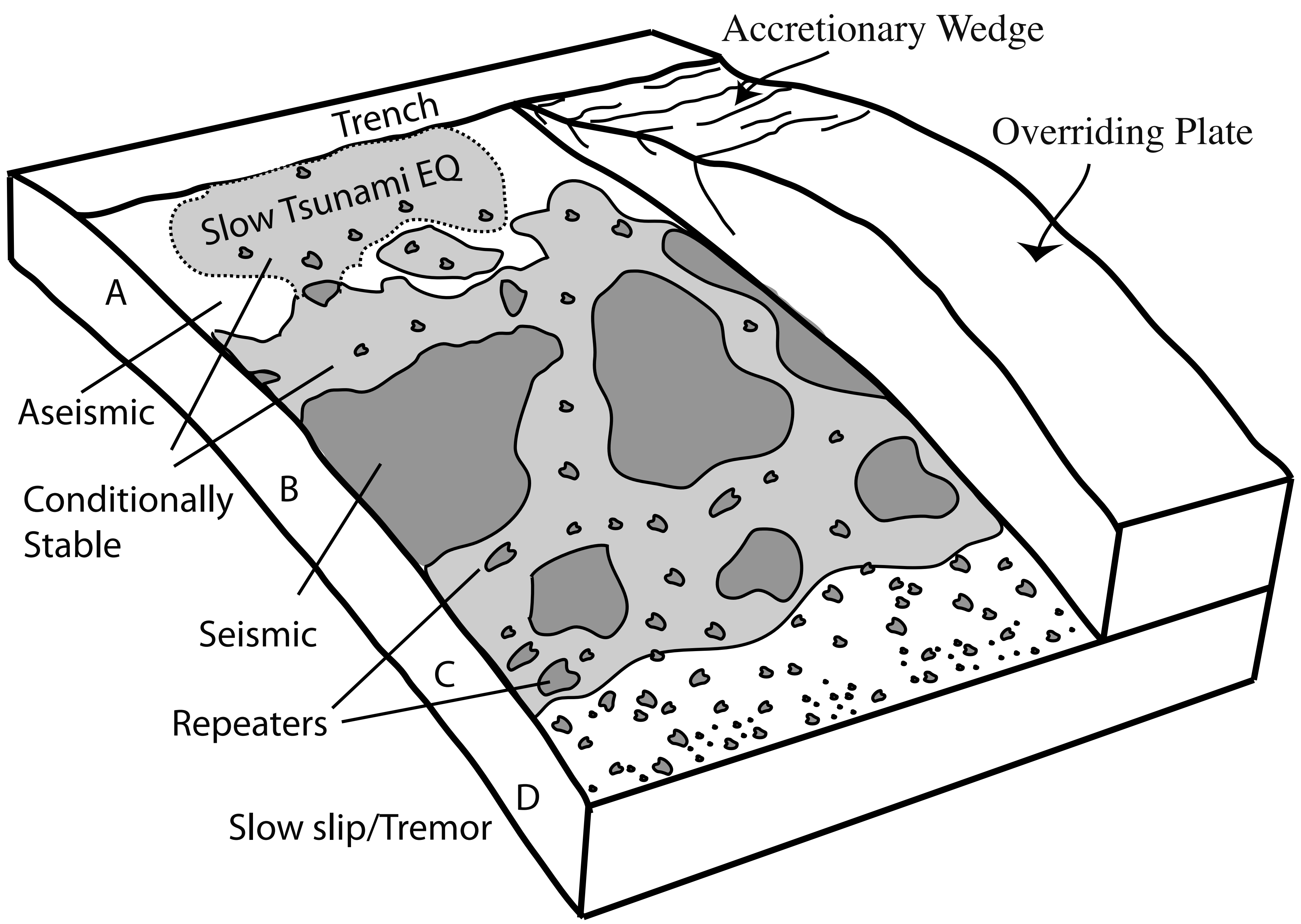
Satriano et al., AGU (2010)

Iquique (Chile) 2014 Mw 8.1

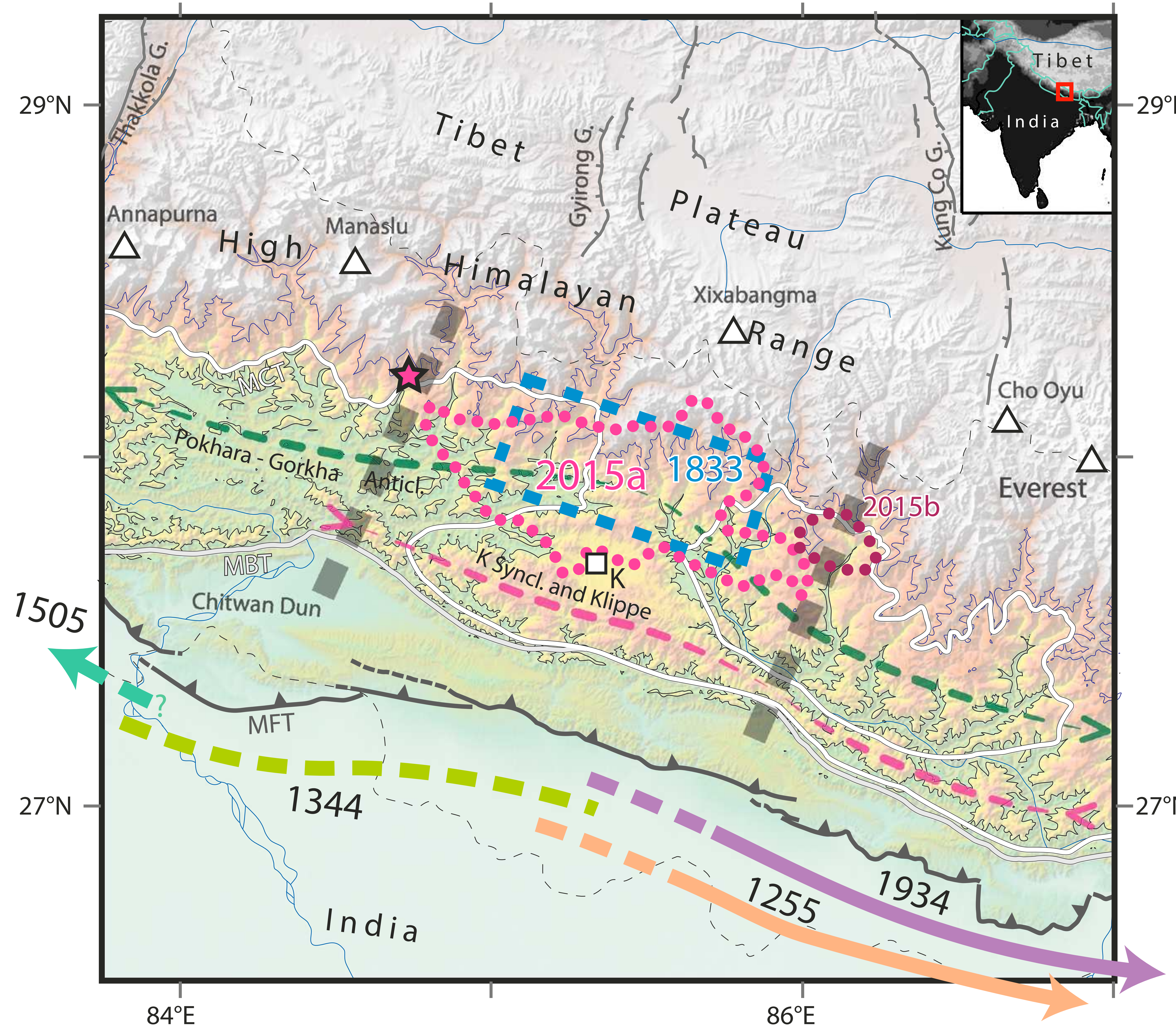


Satriano et al., AGU (2014)

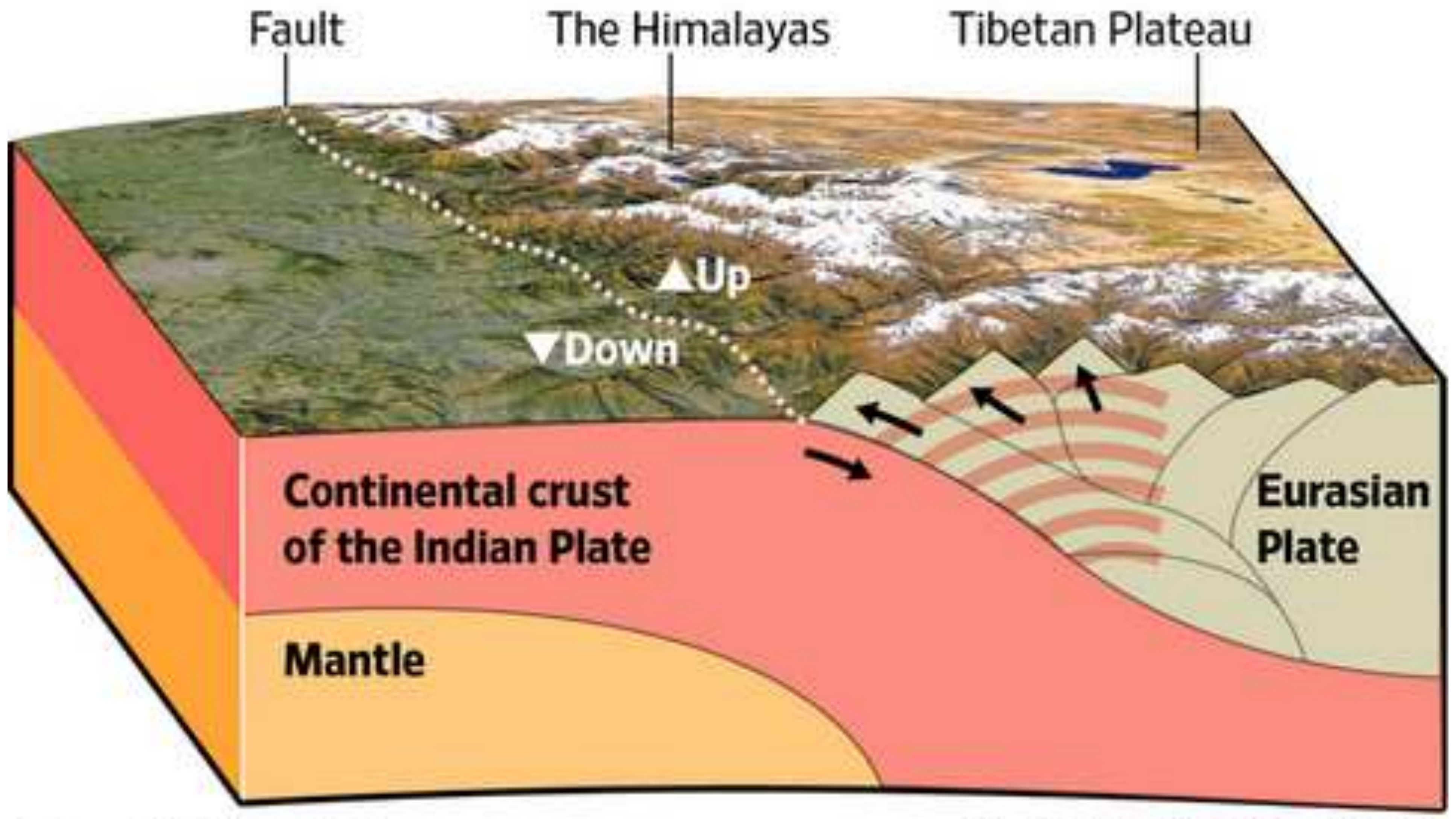
Lay et al., JGR (2012)



The 2015 Mw 7.8 Gorkha earthquake



Grandin, Vallée, Satriano et al., GRL (2015)

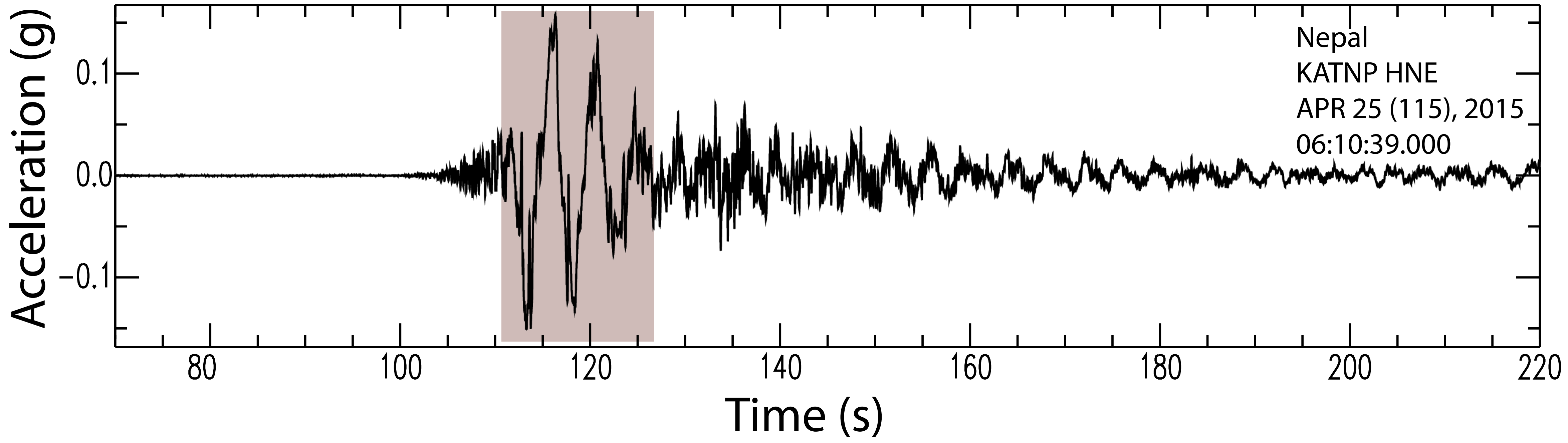


Death toll of ~9000 people :

- About 1700 in Kathmandu and its valley
- 600-1000 by landslides

Maximum acceleration in Kathmandu (PGA) ~0.15 g:

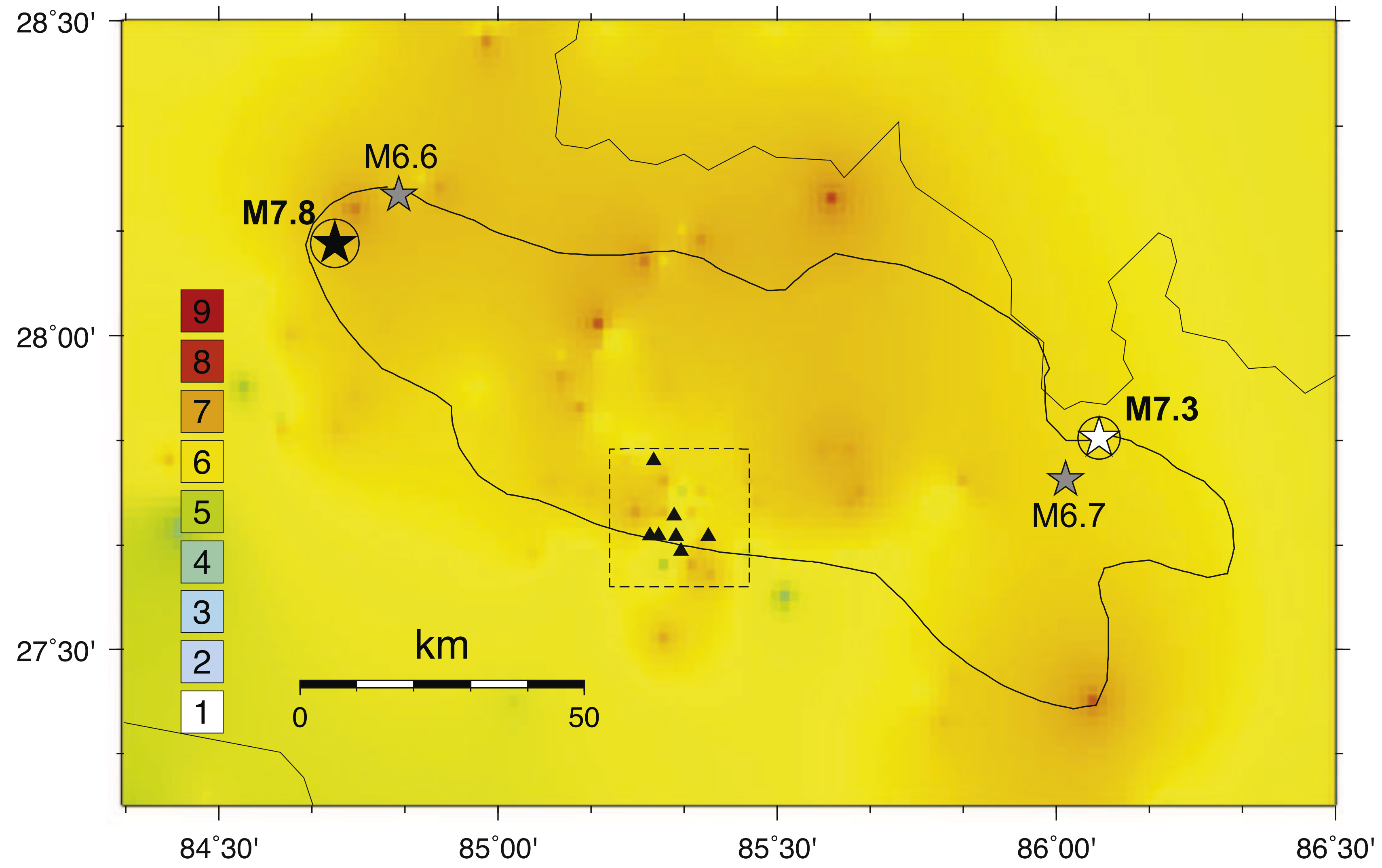
- lower than expected
- in agreement with large damages but not full destruction

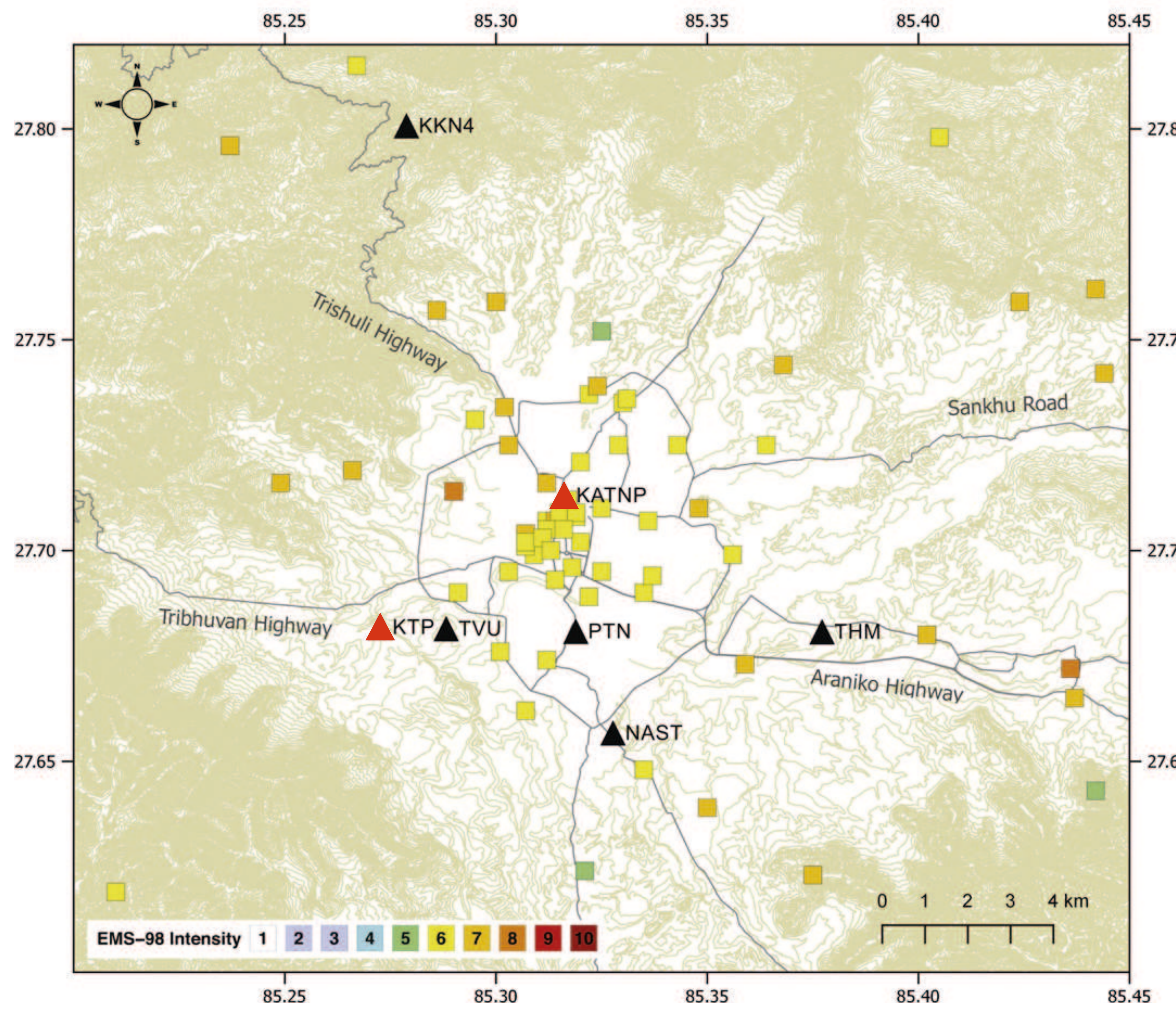


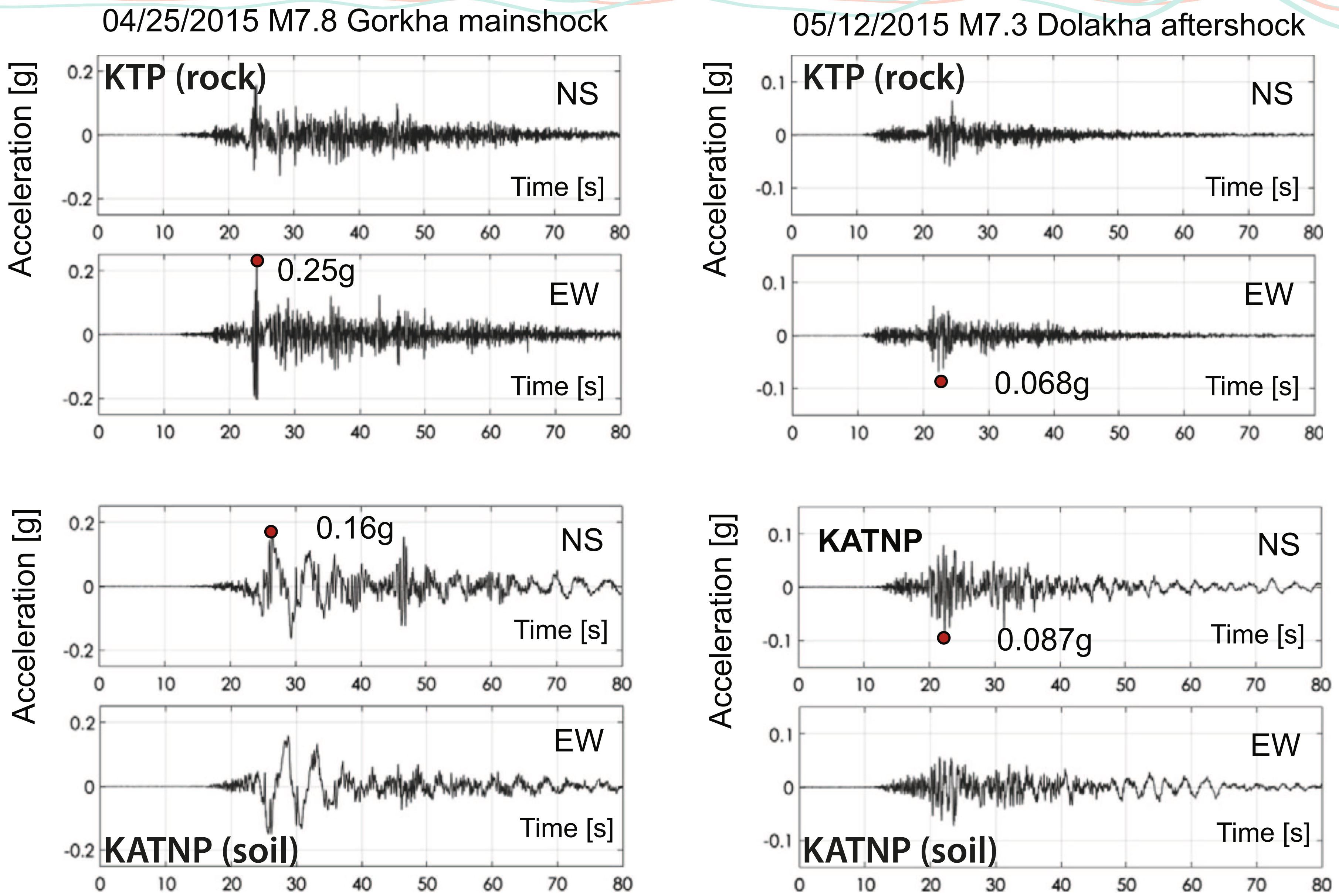

04-25-2015 Sat 11:56:28
Acceleration (g)
0.1
0.0
-0.1
Nepal
KATNP HNE
APR 25 (115), 2015
06:10:39.000
80
100
120
140
160
180
200
220
Time (s)
DABALI

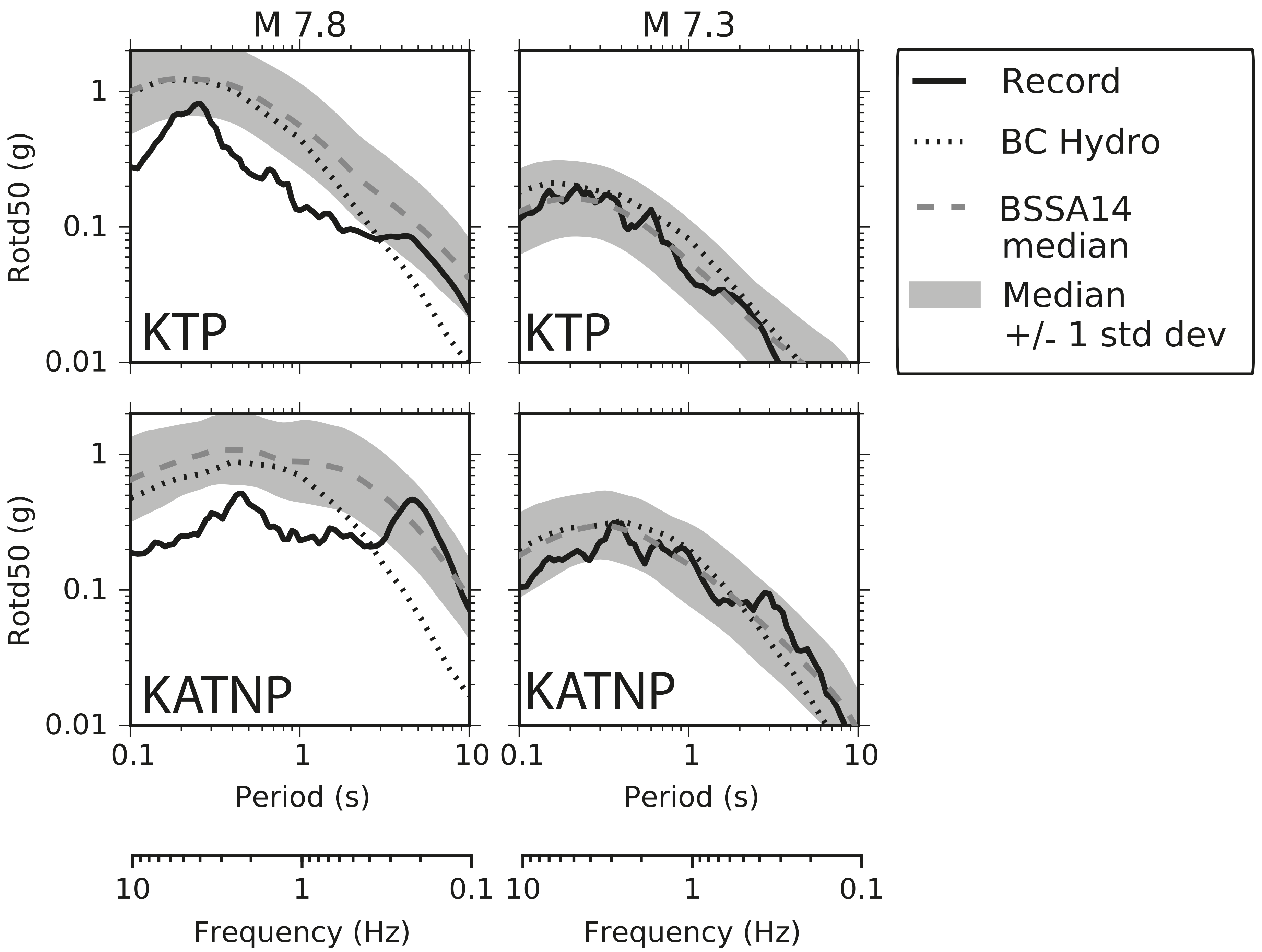
Gorkha earthquake: intensity and ground acceleration above the rupture

Modified from
Rajaure et al., Tectonophysics (2016)









Model

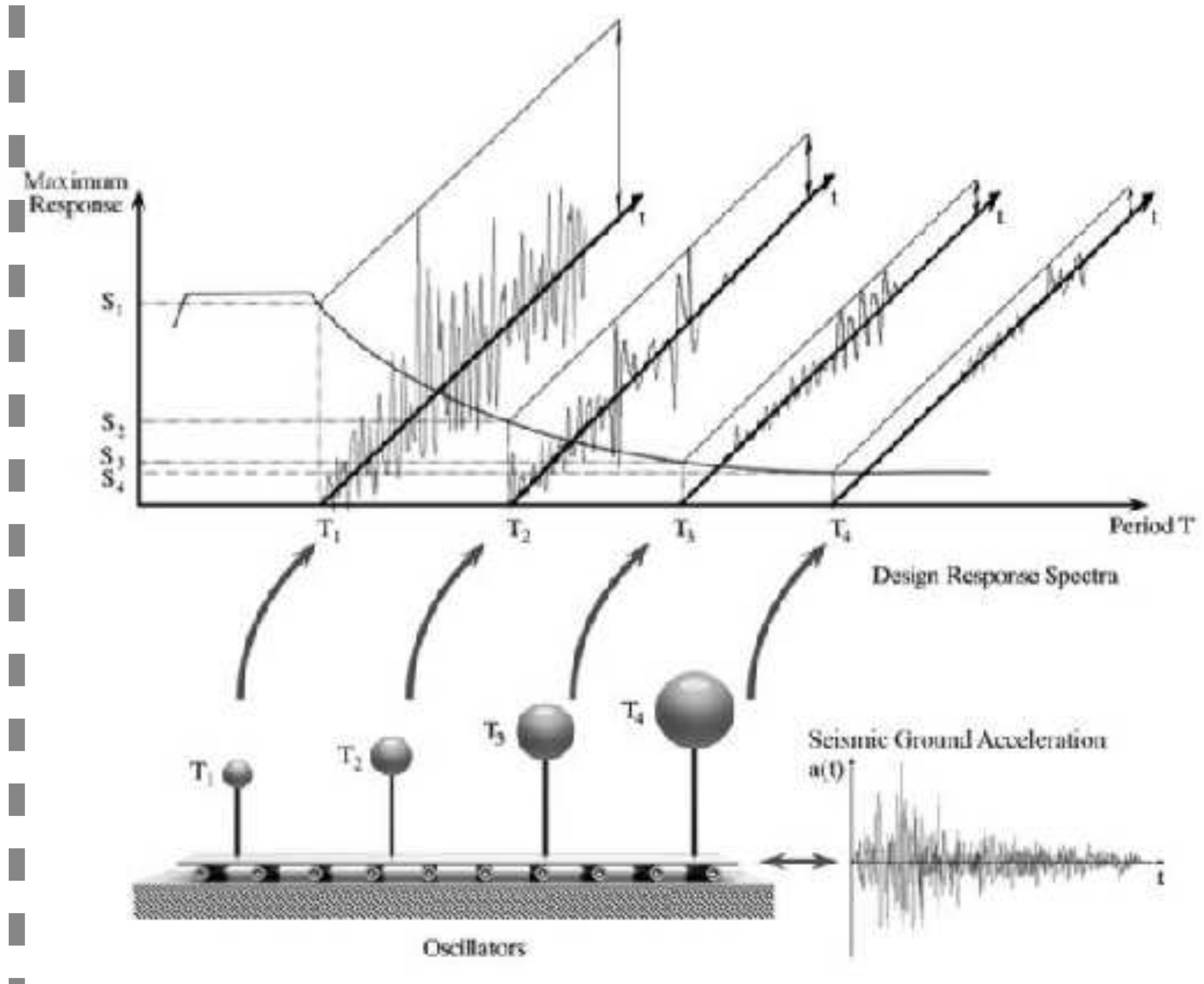
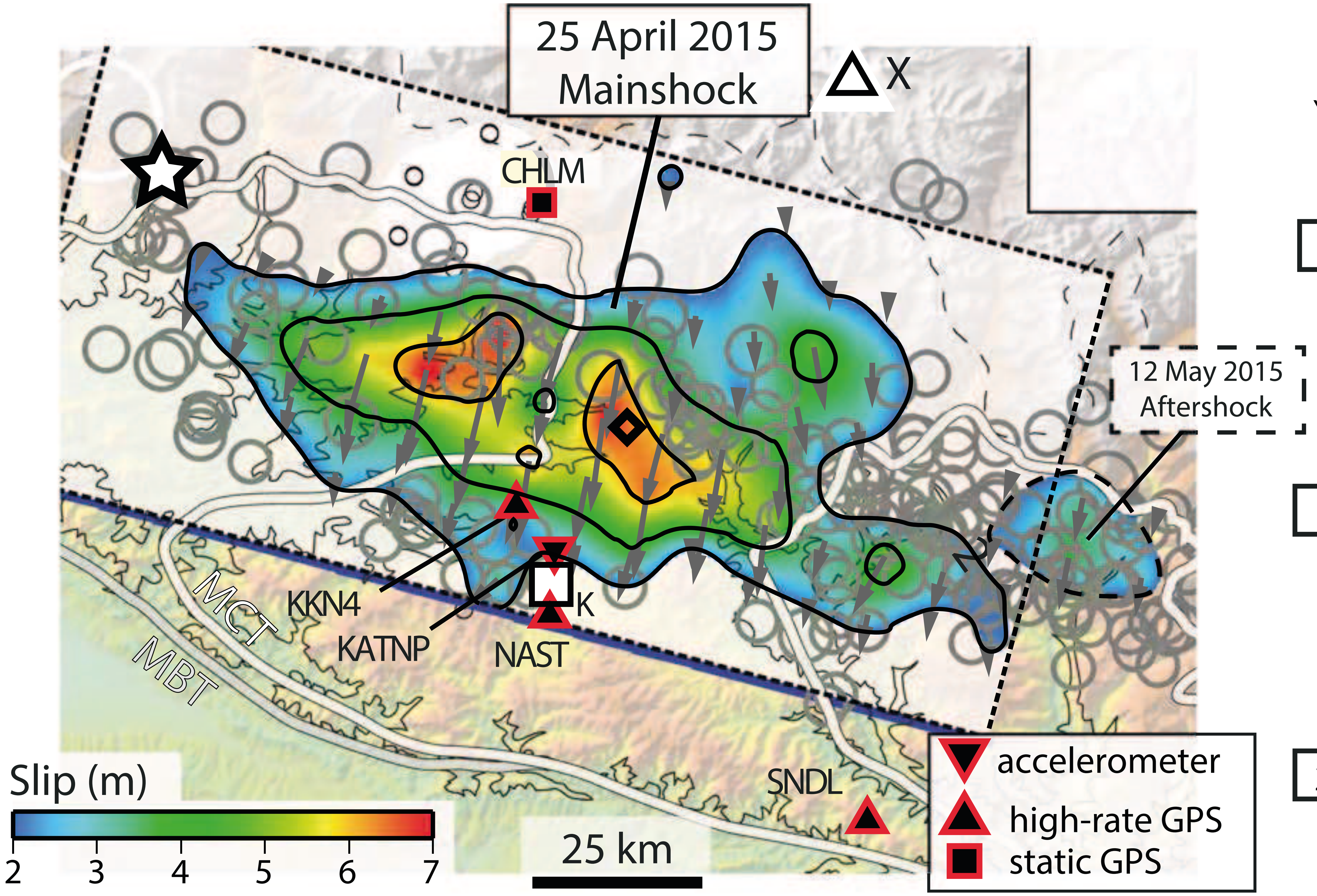
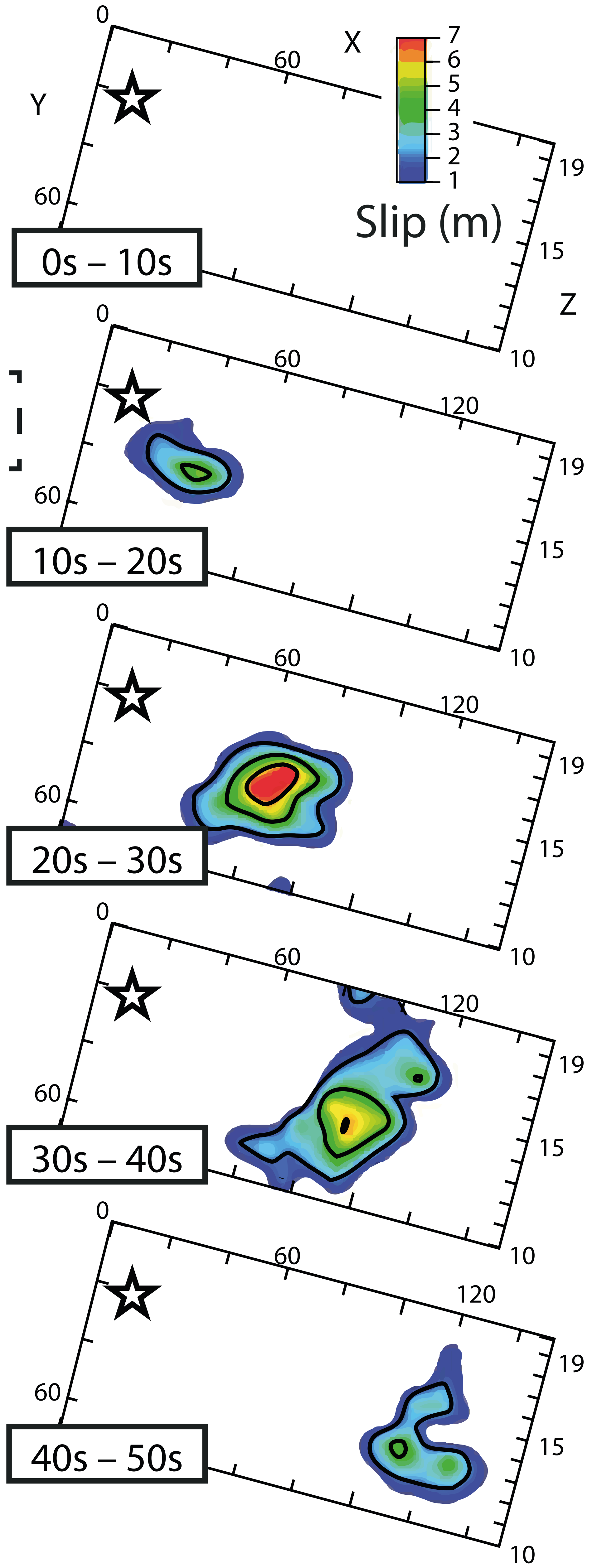


Figure 1. Concept of earthquake response spectrum.

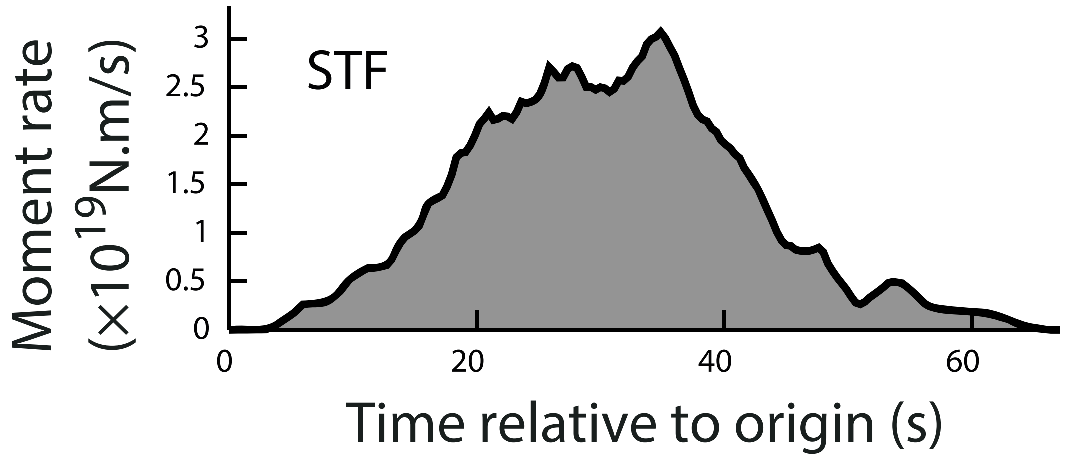
e.g., Vrochidou et al. (2014)

Gorkha earthquake: kinematic slip model



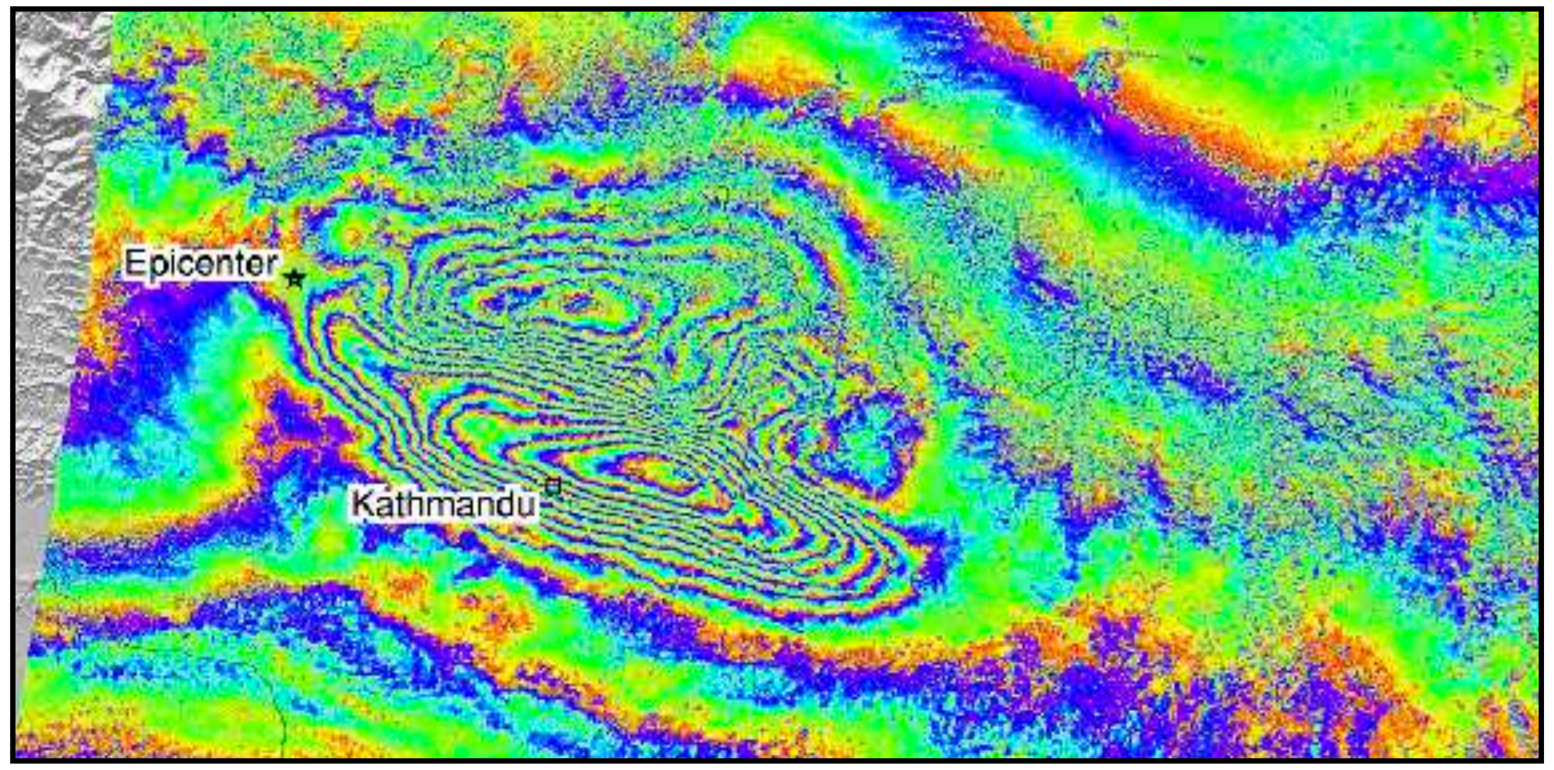


Grandin, Vallée, Satriano et al., GRL (2015)

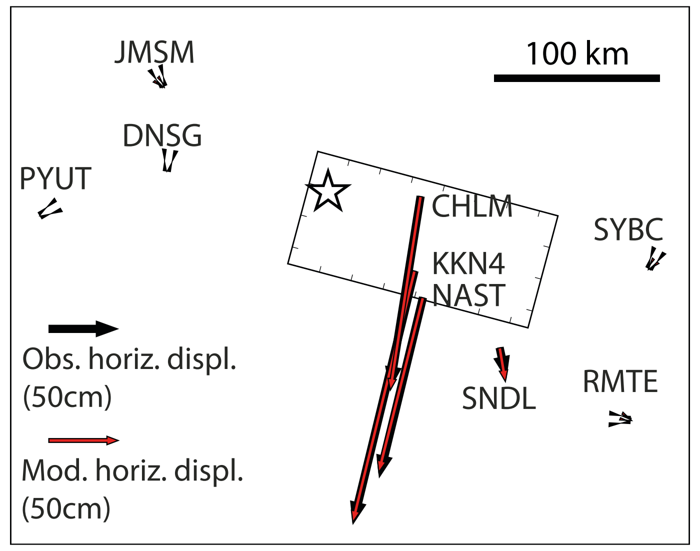


Data

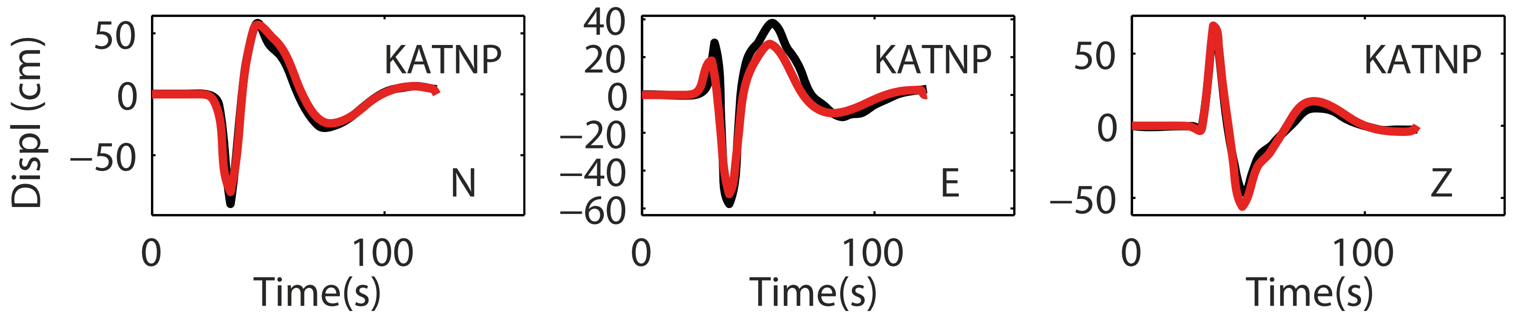
1. Interferometric synthetic aperture radar



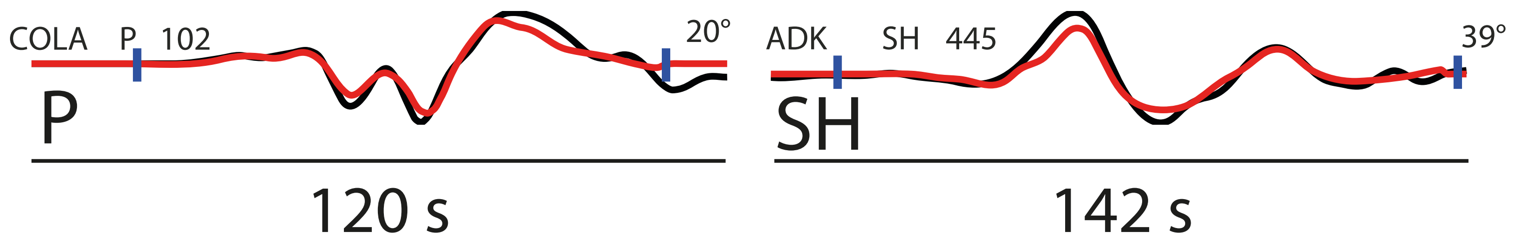
2. Static GPS displacement



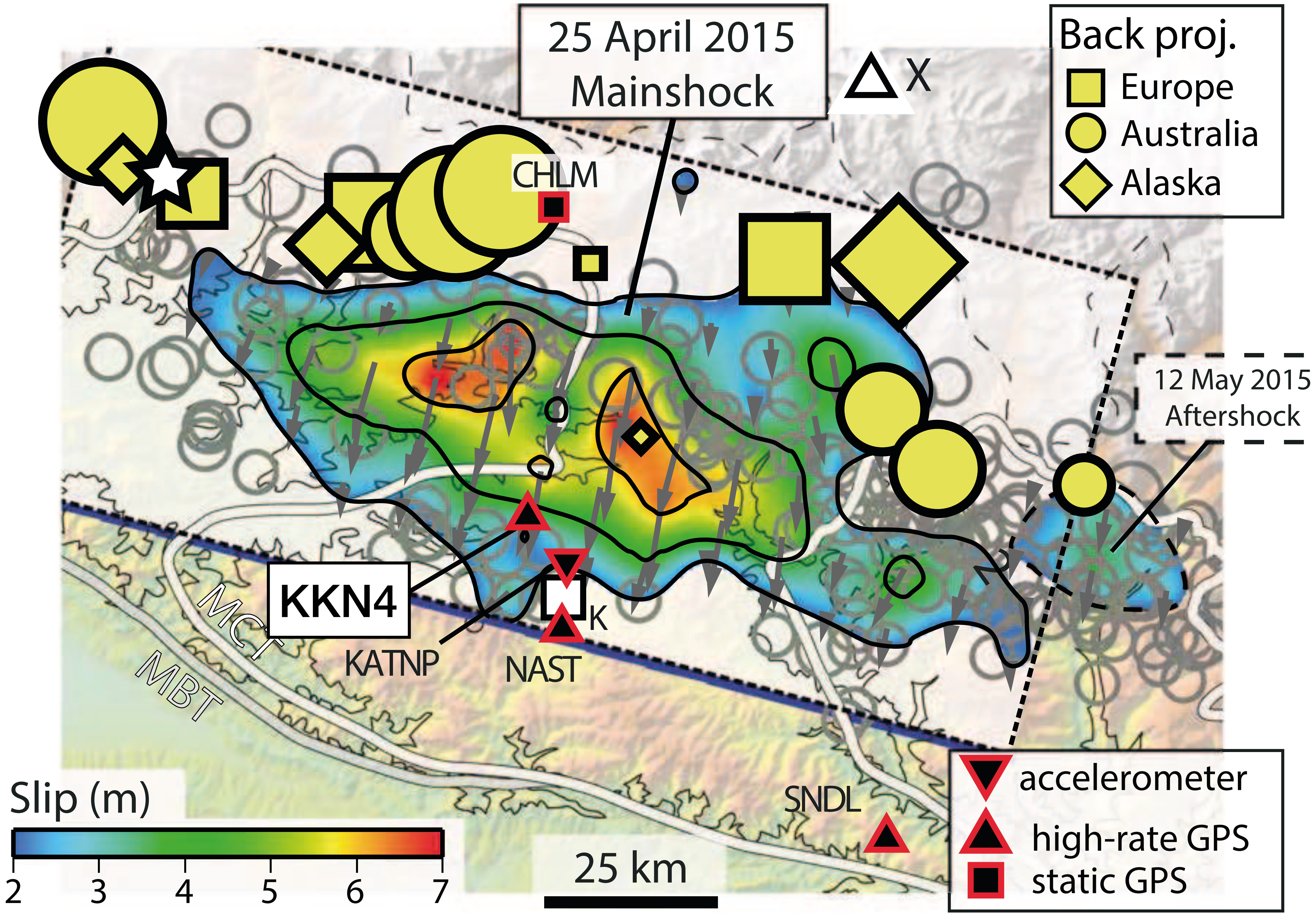
2. Local ground motion (up to 0.1 Hz)

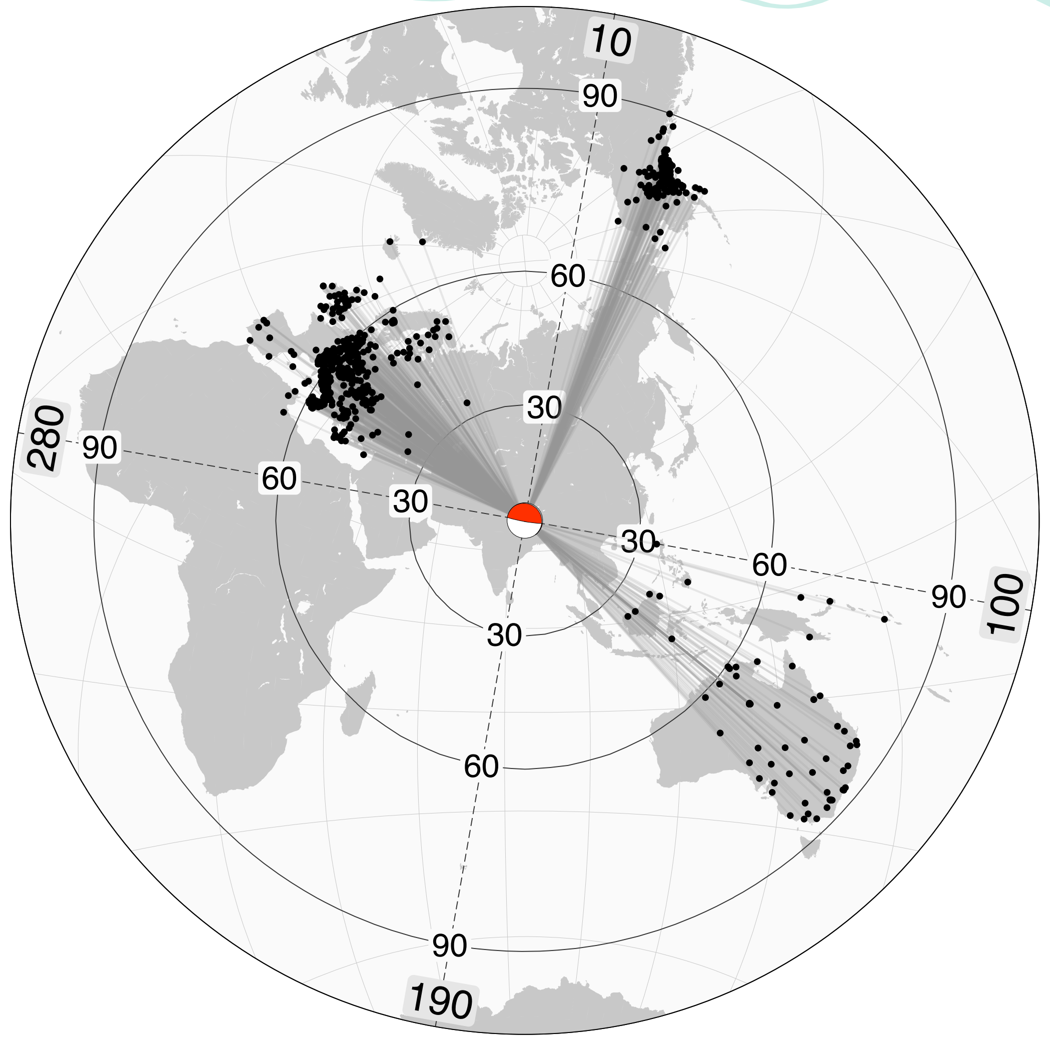


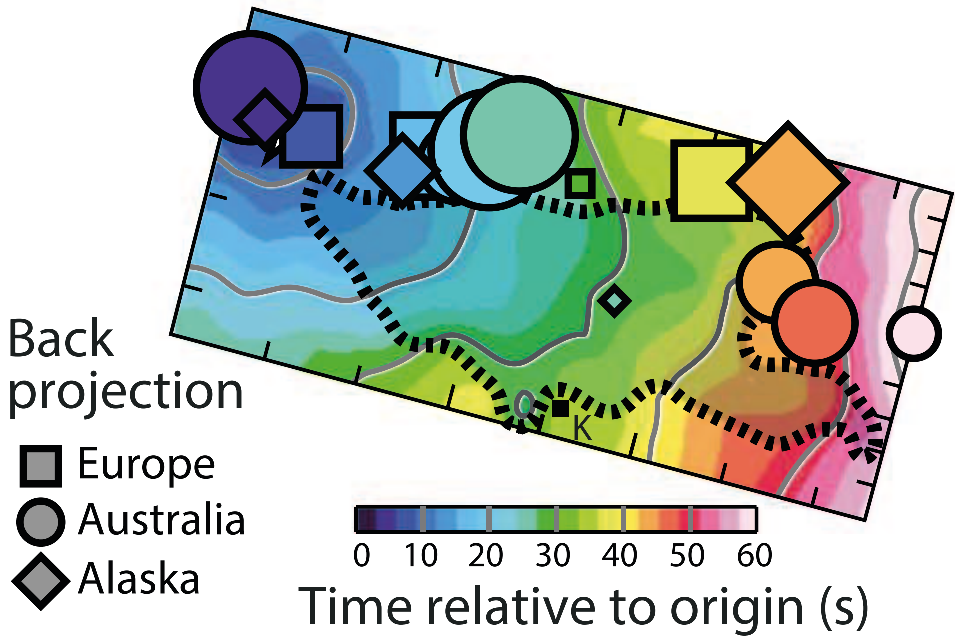
3. Teleseismic waveforms (up to 0.125 Hz)



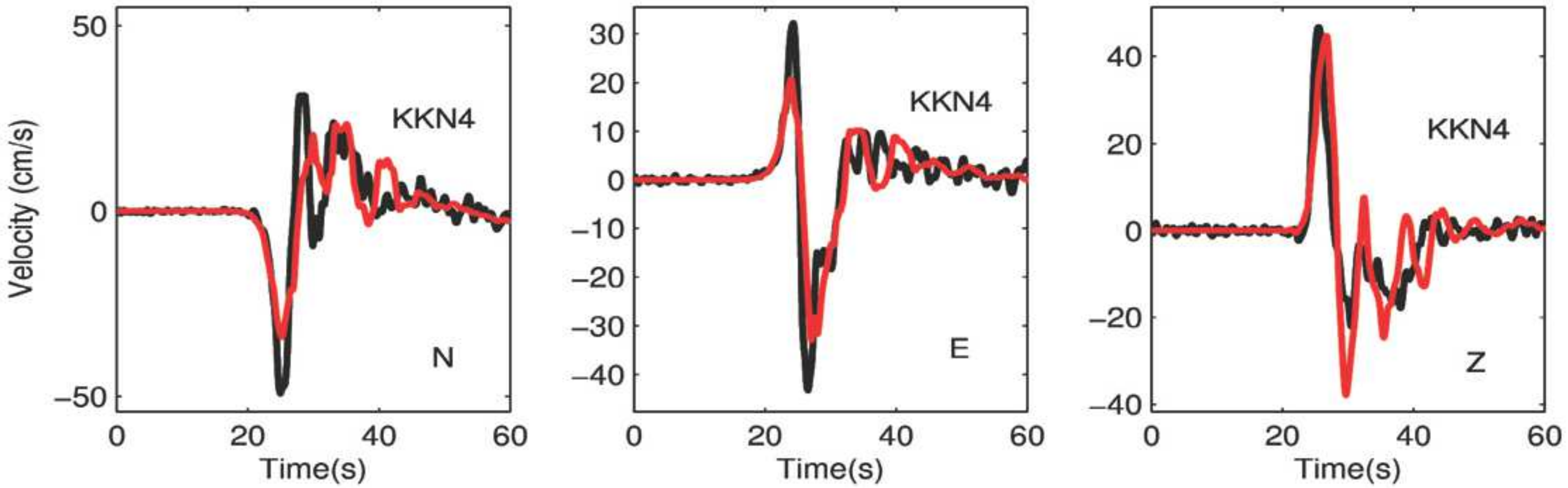
LF earthquake in Kathmandu, HF at the base of the rupture







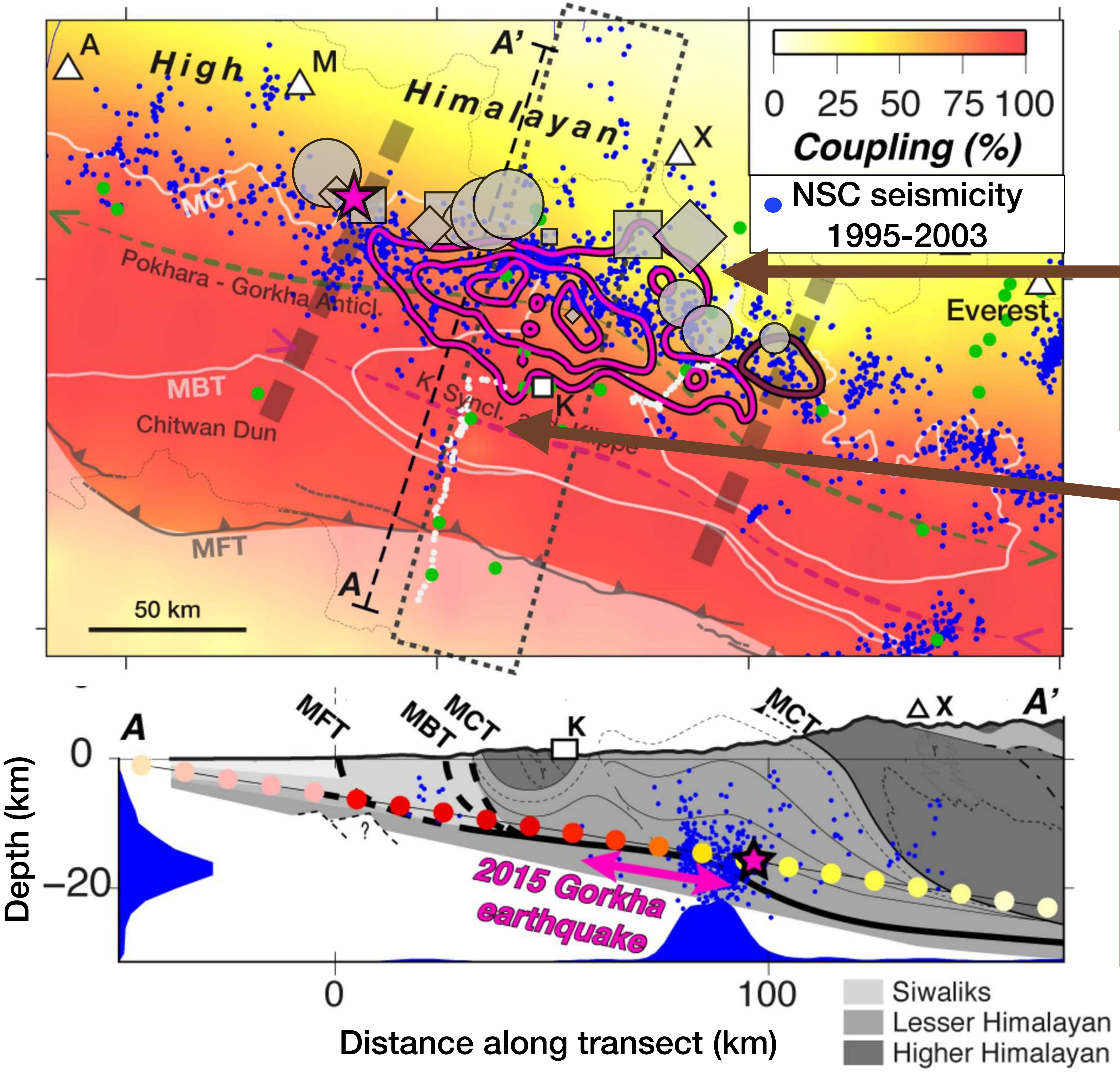
High-Frequency peaks (1-4 Hz) from back projection are at the down dip edge of the rupture



The kinematic model (inversion of data up to 0.1Hz), well explains near-field data at frequencies up to 1Hz

Grandin, Vallée, Satriano et al., GRL (2015)

Rupture properties and fault zone heterogeneity



Rupture abruptly stops down-dip, with high-frequency radiation, where the plate interface strongly decouples.

Almost all the seismicity before 2015 Gorkha earthquake is in this zone: stress concentration?

Rupture gradually slows down up-dip, with no high-frequency radiation.

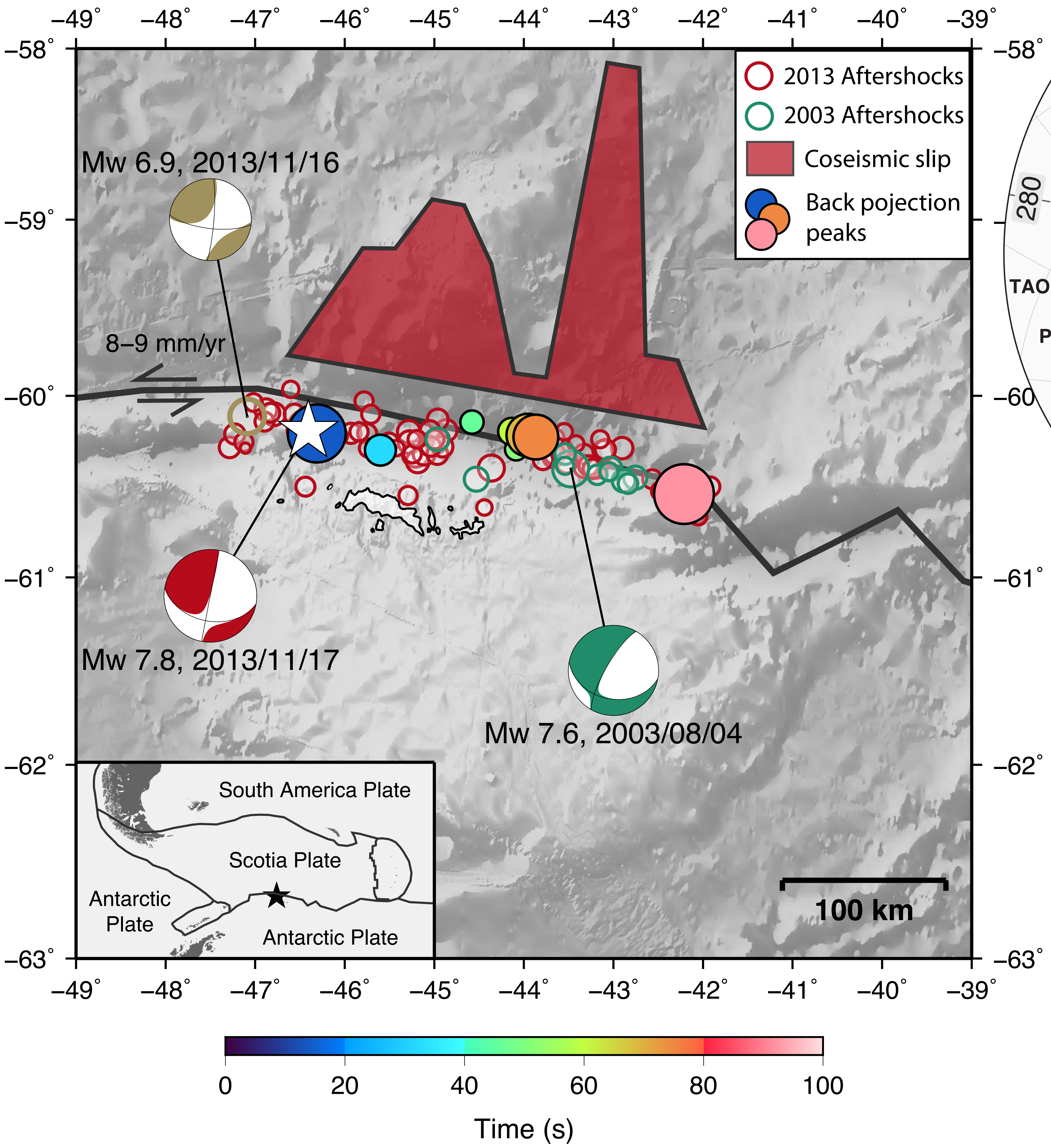
No seismicity in this zone before 2015: fully locked and/or strengthening friction?

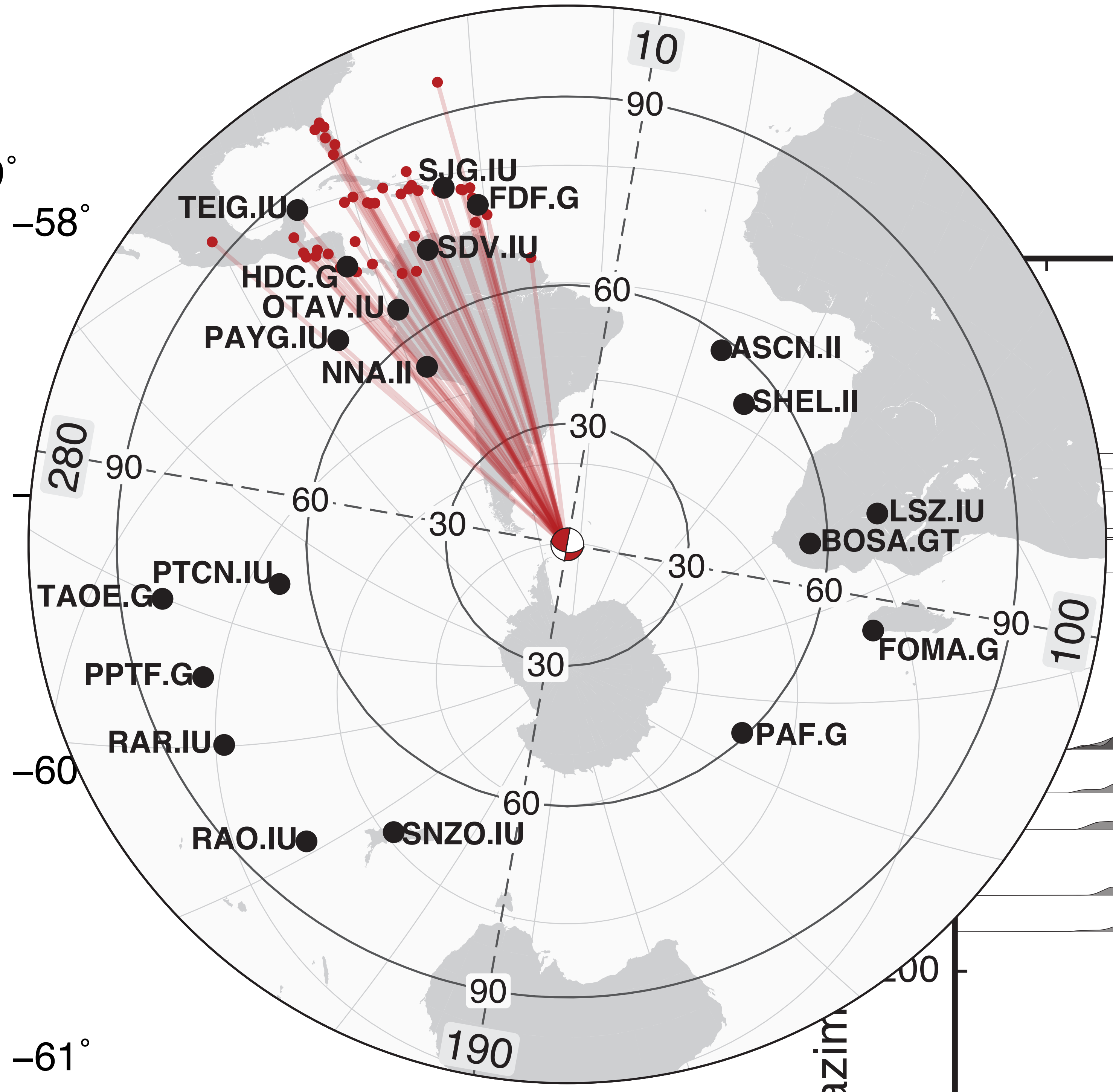
Larger ruptures (M 8+) coud reach the surface but only with low-frequency radiation?

Grandin, Vallée, Satriano et al., GRL (2015)

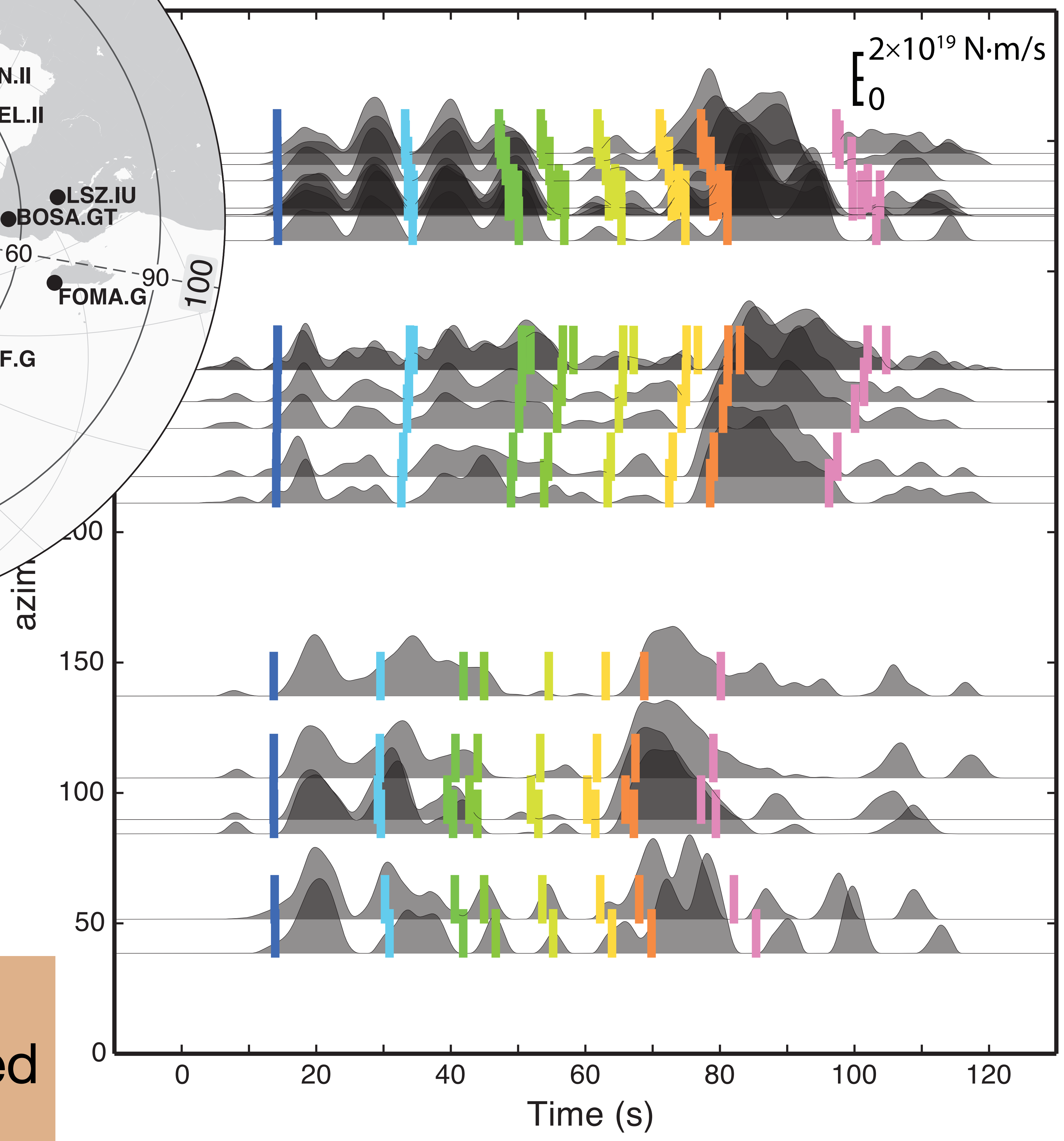
The 2013 Mw 7.8 Scotia Sea earthquake: fault segmentation and HF

Coseismic slip and back projection





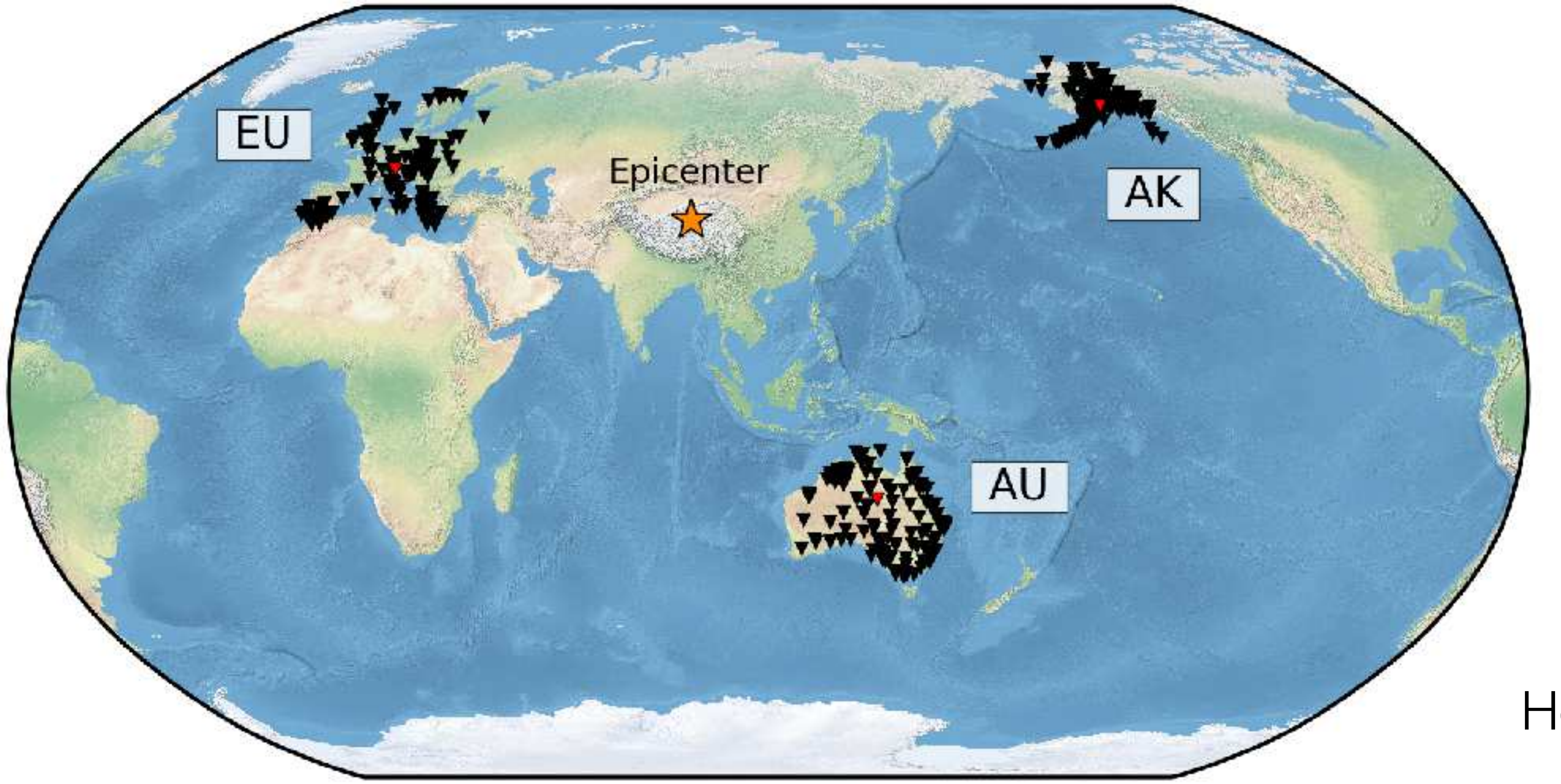
Apparent source time functions + BP peak times (0.5 - 1.0 Hz)



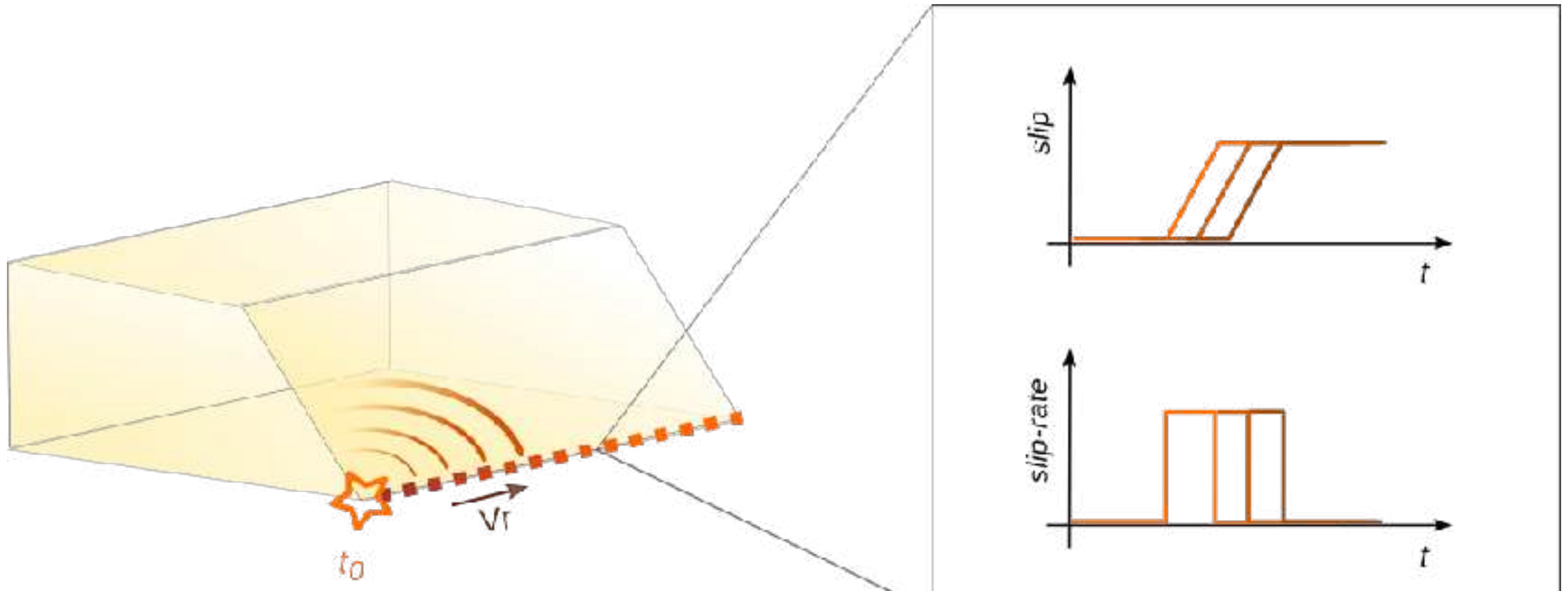
High-frequency radiation associated with slip acceleration

Vallée and Satriano, GRL, 2014

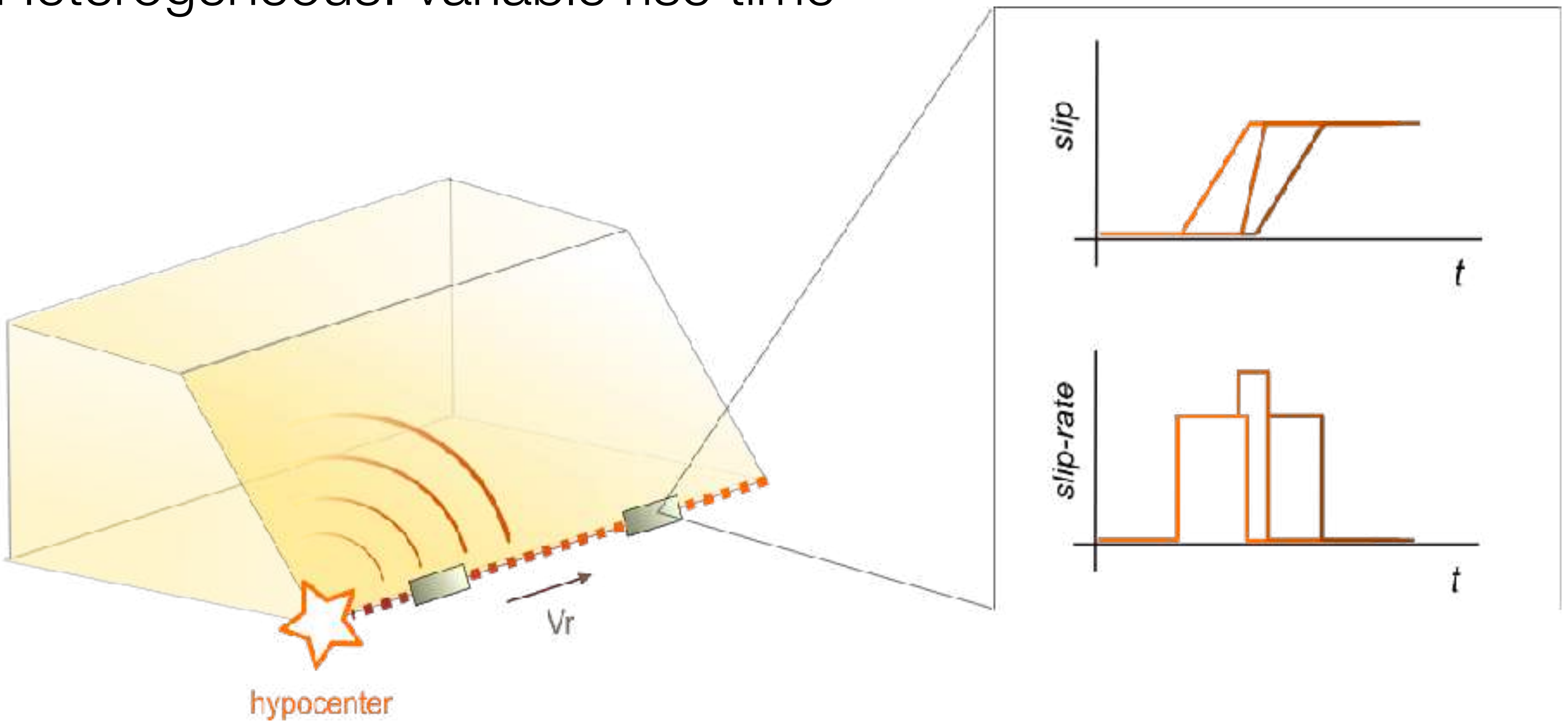
Fault heterogeneity and high-frequency radiation: synthetic tests



Homogenous: “Haskell" fault

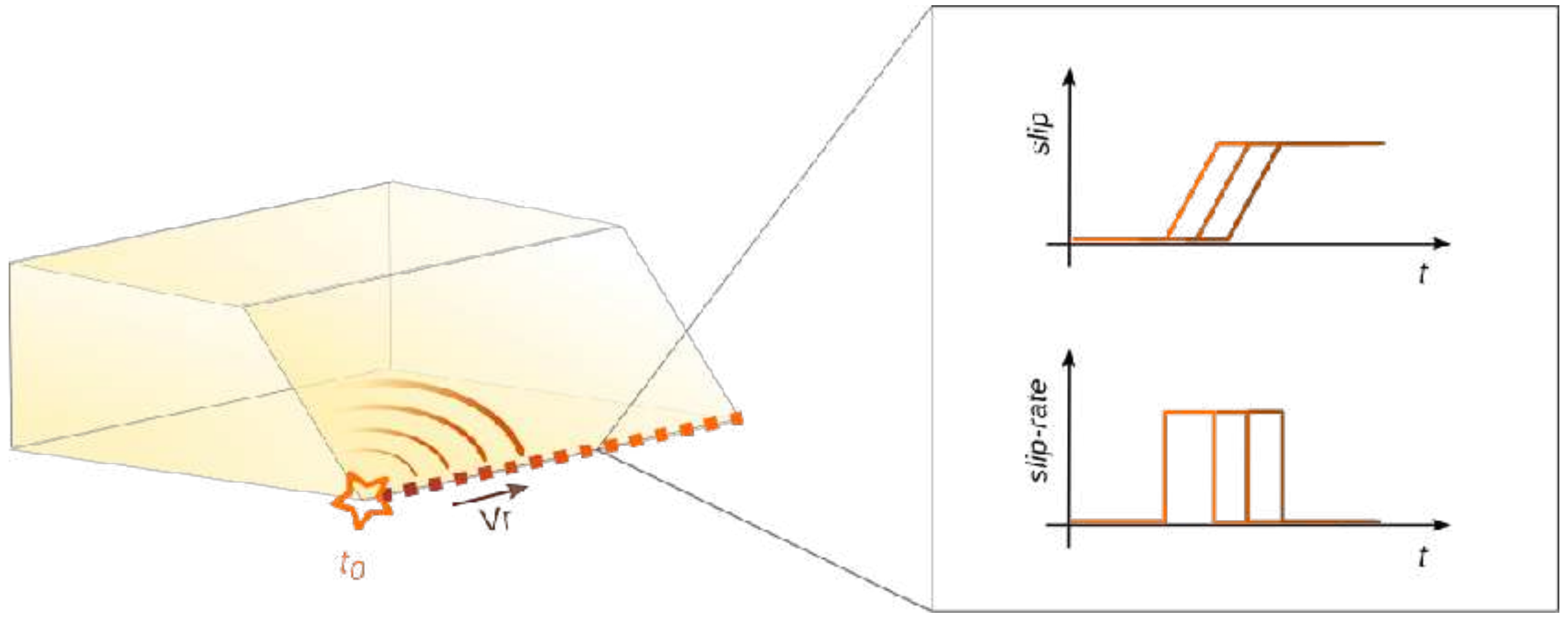


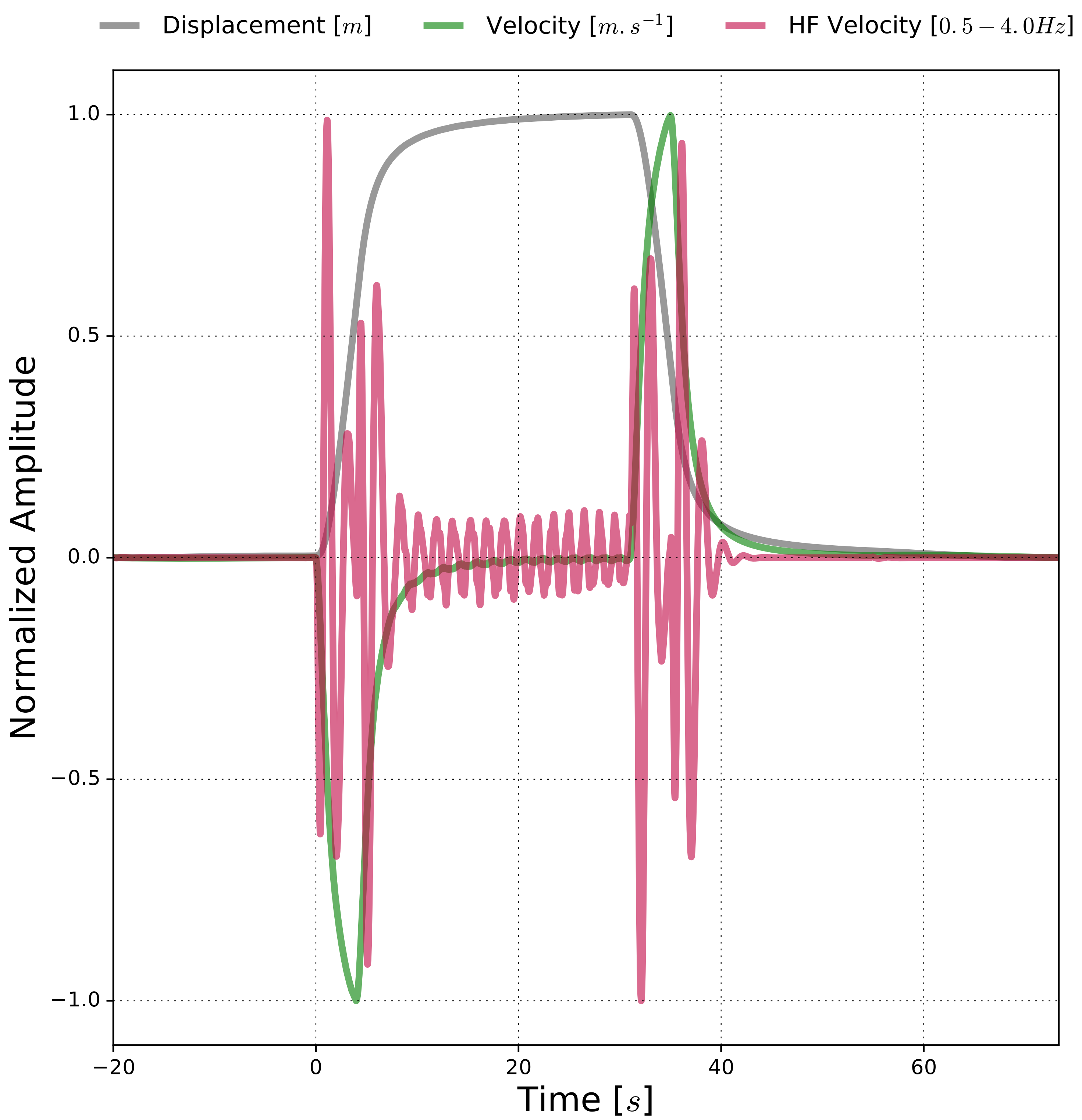
Heterogeneous: variable rise time

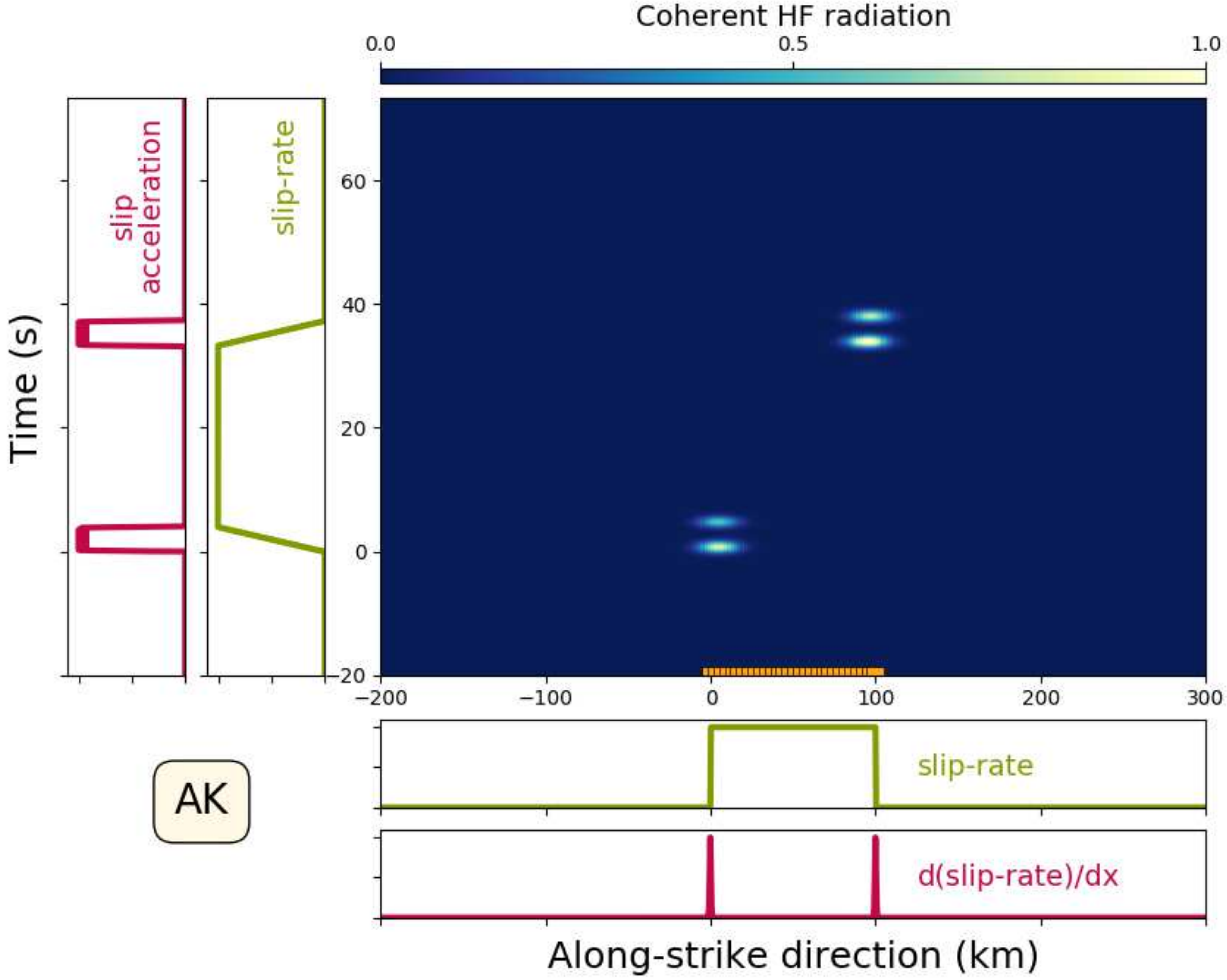


Marina Corradini: PhD project

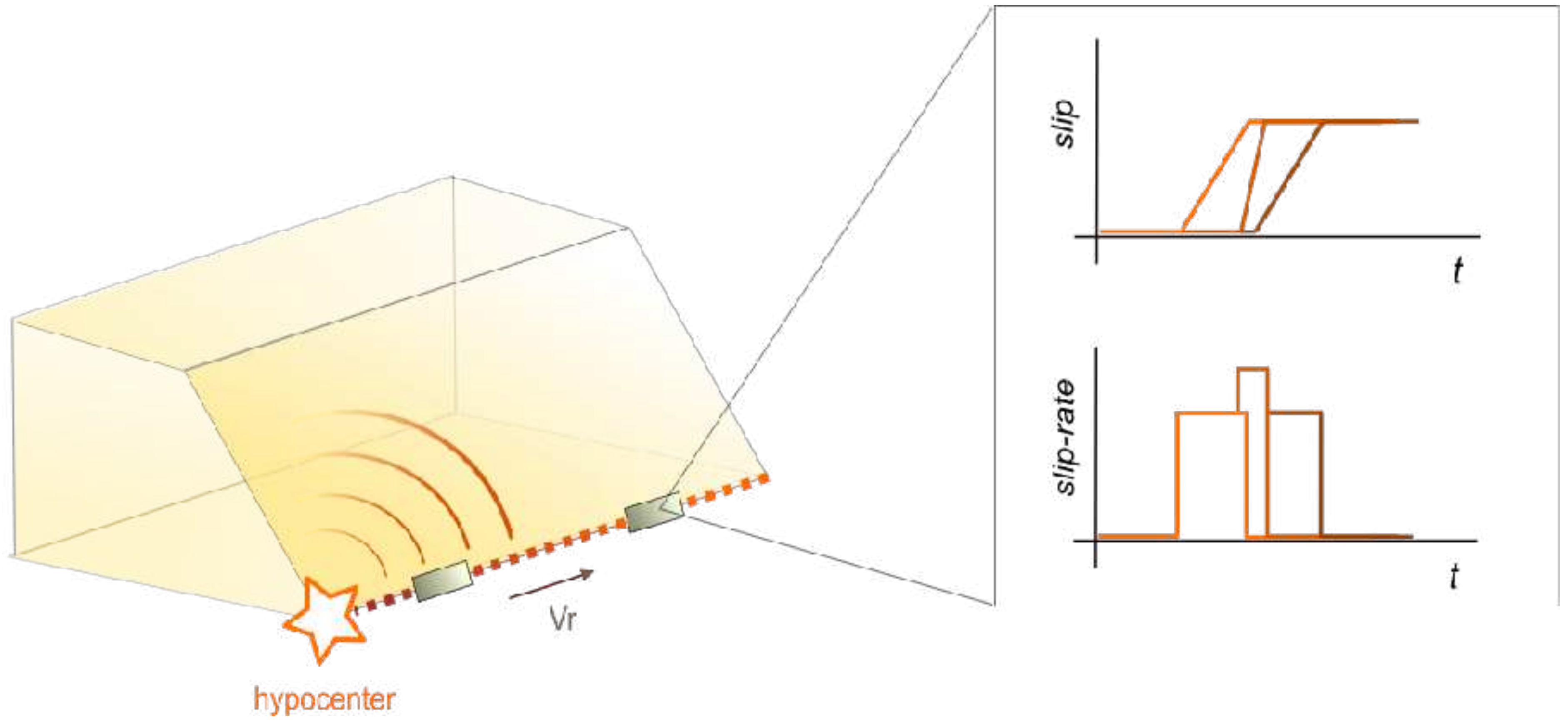
Synthetic test: homogenous model

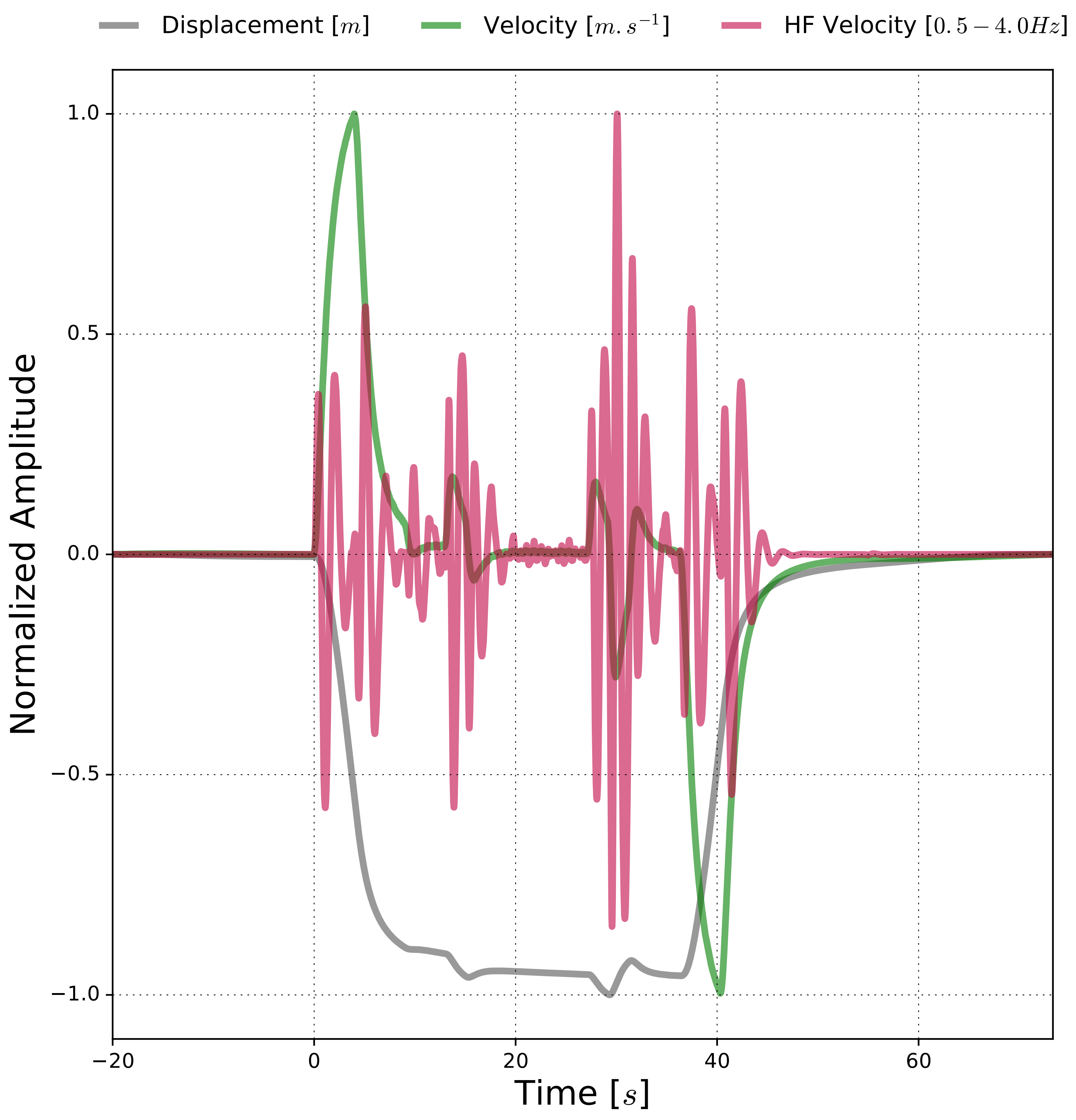


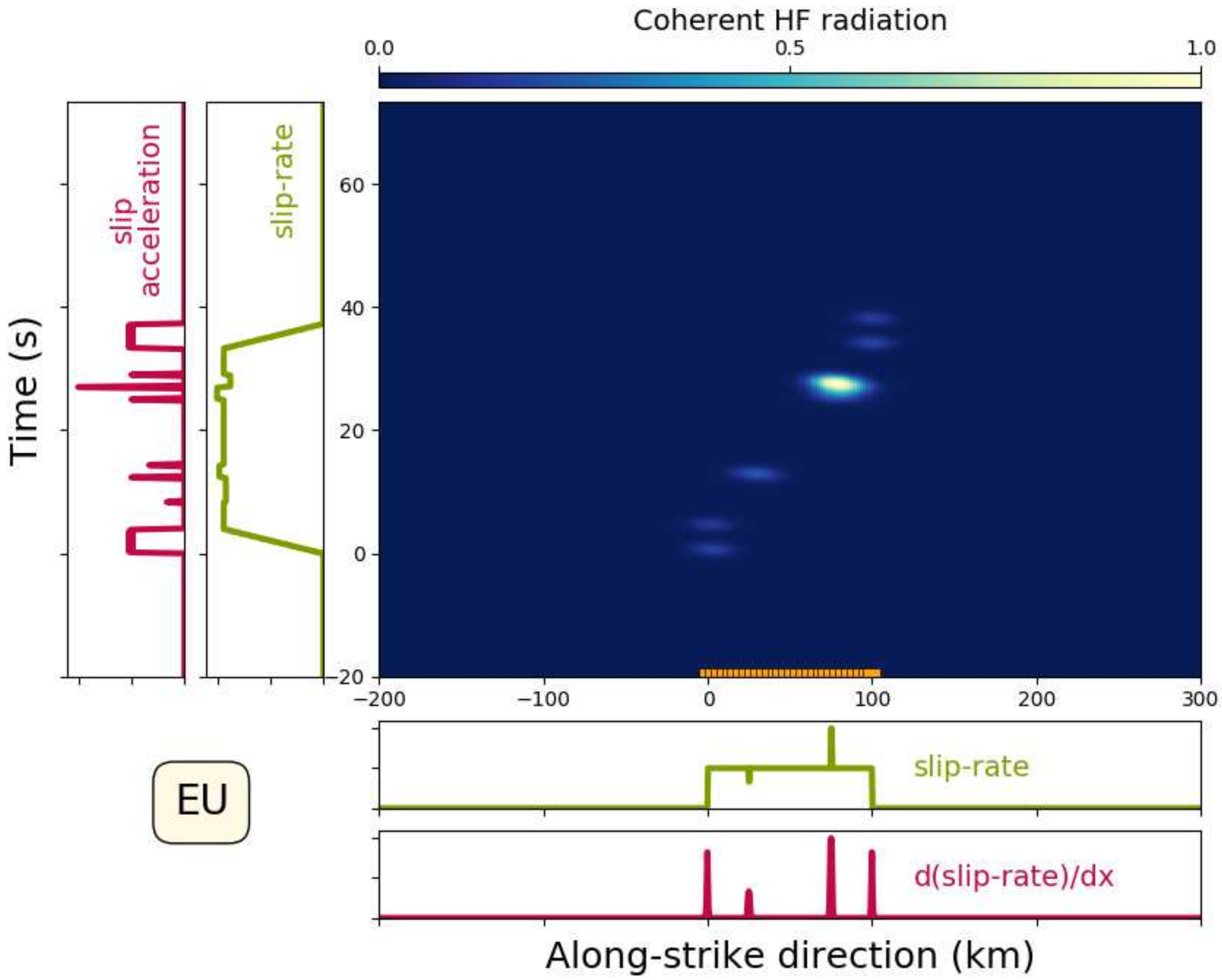




Synthetic test: variable rise time

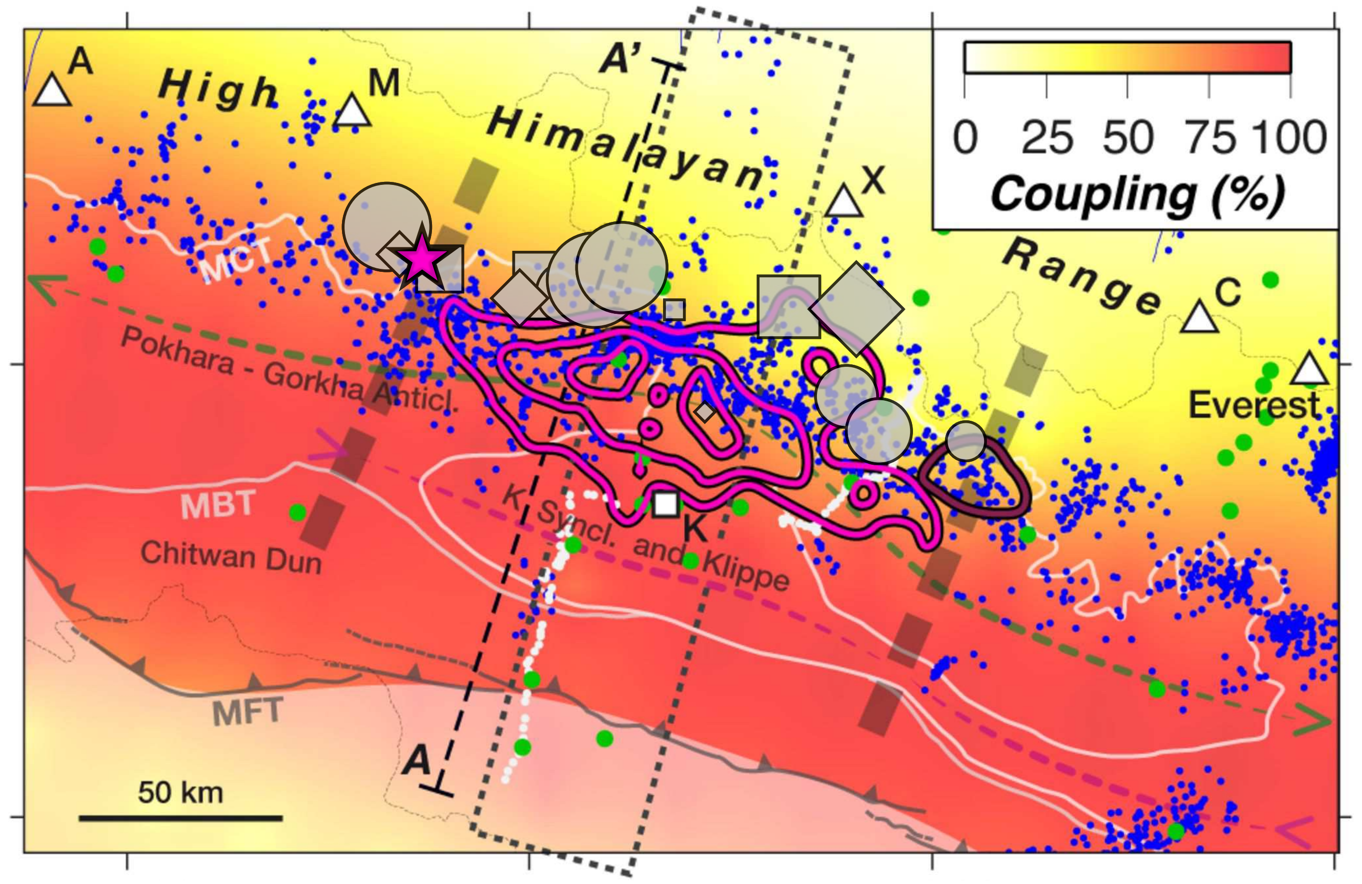






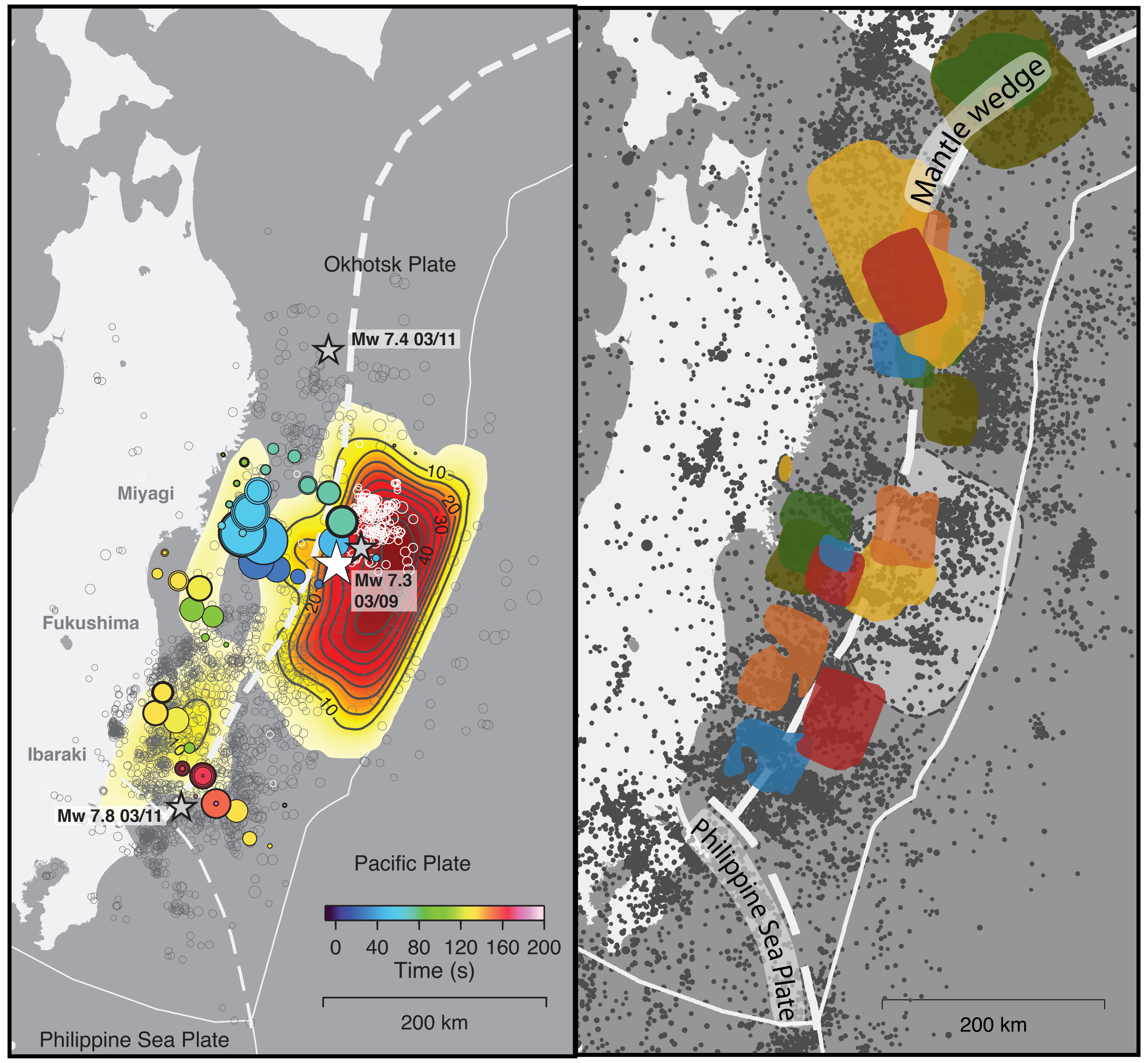
High-frequency radiation linked to space-time variability of slip rate on the fault

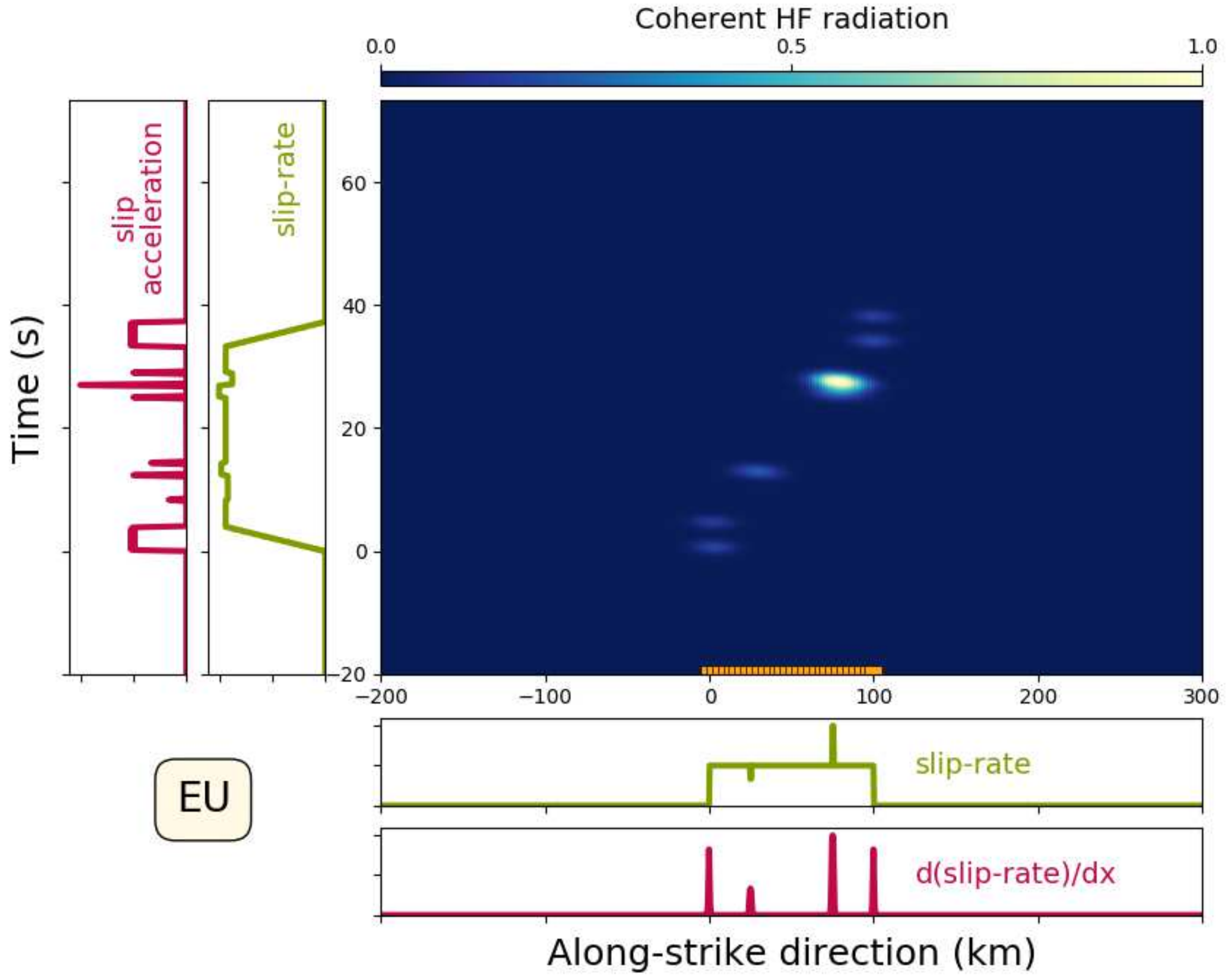
Conclusions



Variability of fault-zone mechanical properties (e.g., coupling, asperities, geometry) controls the variability of earthquake radiation (high-frequency - low-frequency).

Study of seismicity and deformation before large earthquakes is necessary to characterize those properties and define future large earthquake scenarios.





New imaging techniques like back projection can help in illuminating the complex nature of earthquake rupture. Still need to better understand the link between high-frequency images and rupture process.