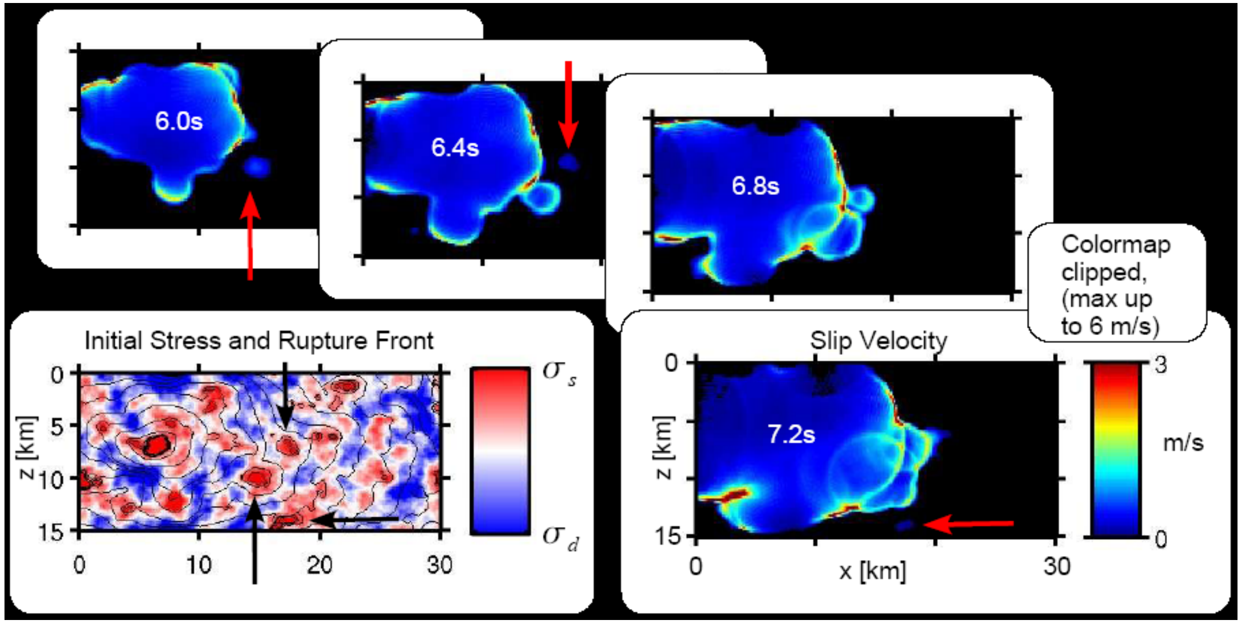
IMAGING EARTHQUAKE RUPTURE COMPLEXITY WITH DENSE ARRAYS

Pablo Ampuero (Caltech Seismolab)

Simons et al (Science, 2011)
Meng, Inbal and Ampuero (subm. GRL, 2011)

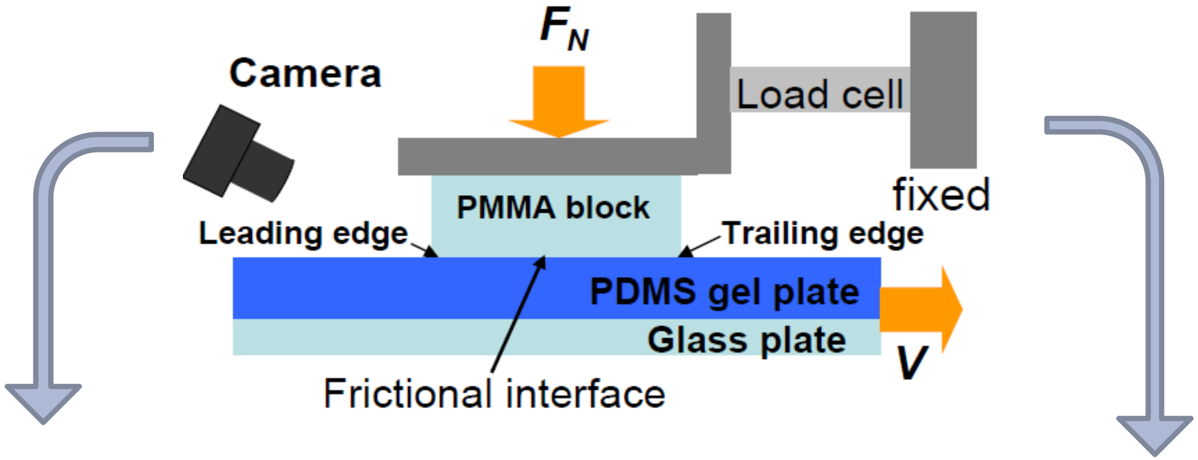
Complexity of Dynamic Rupture

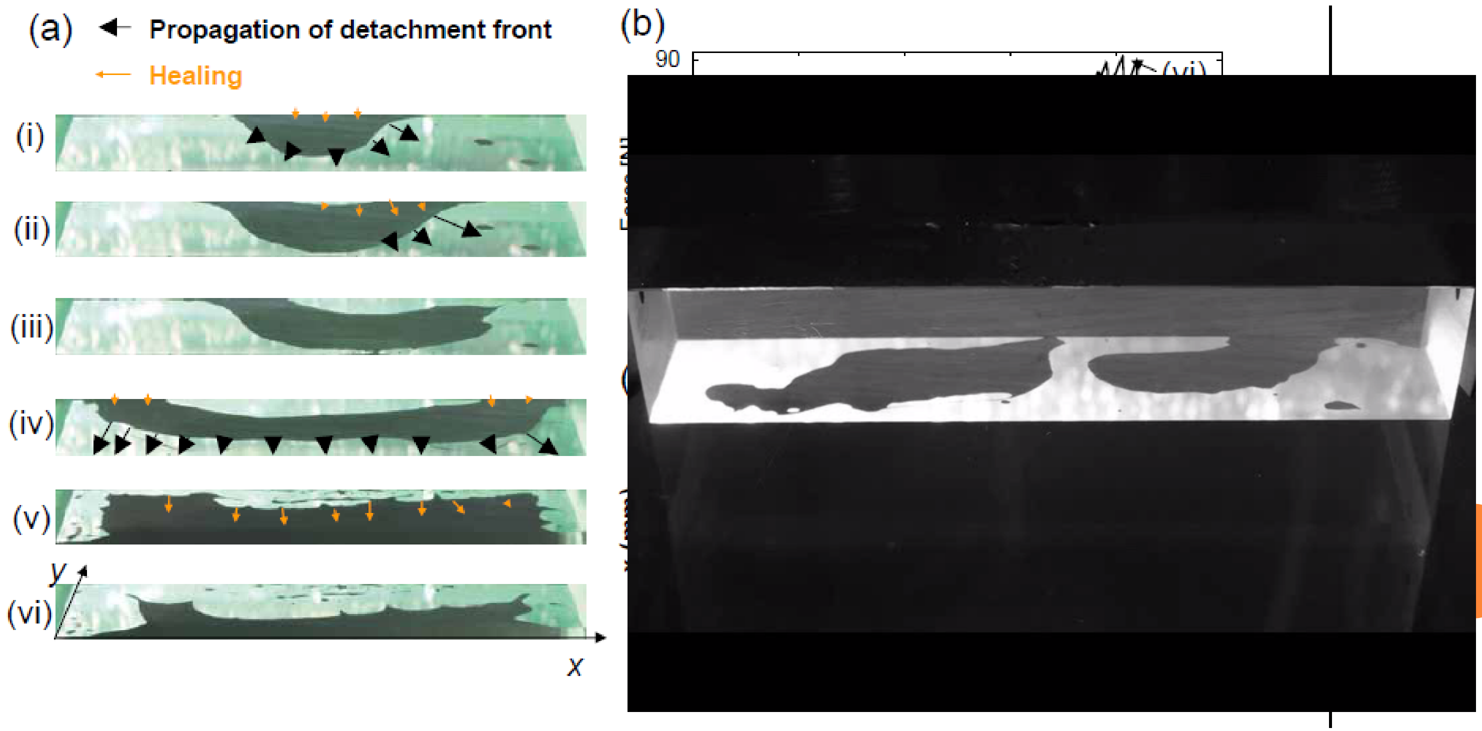


Ripperger, Ampuero, Mai (2008)

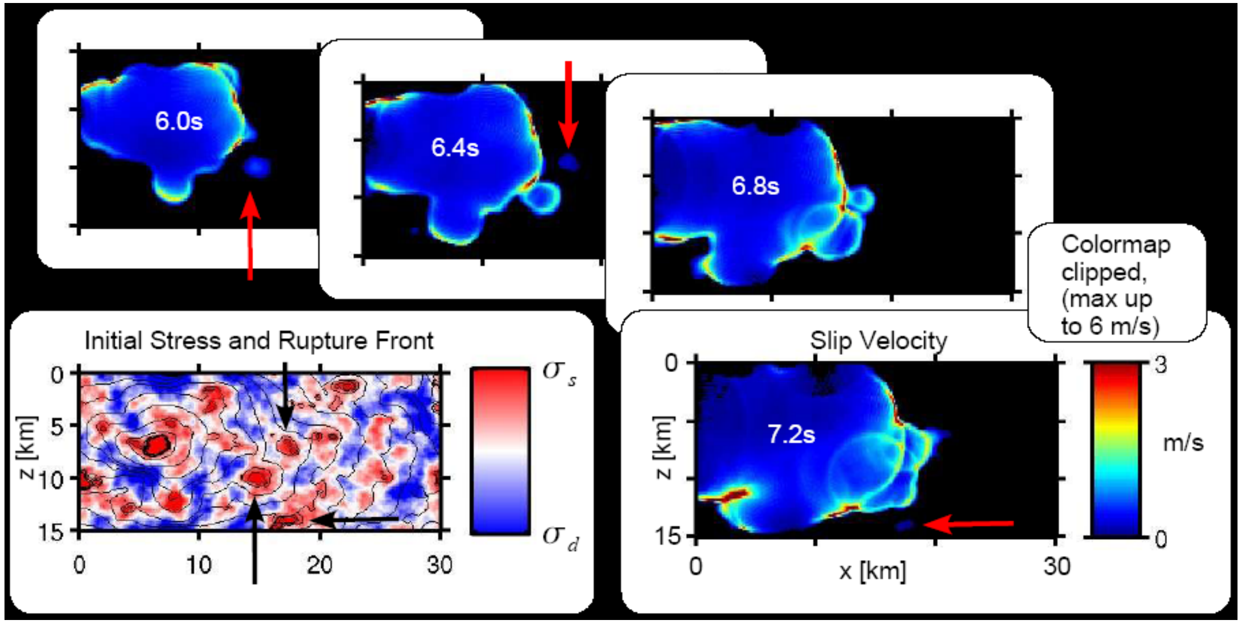
- Complicated rupture patterns emerge in dynamic simulations
  → HF seismic radiation
- Hard to see in traditional source inversions based on seismic/geodetic observations (<1Hz)

LAB EXPERIMENTS ON GELS (T. YAMAGUCHI)





COMPLEXITY OF DYNAMIC RUPTURE

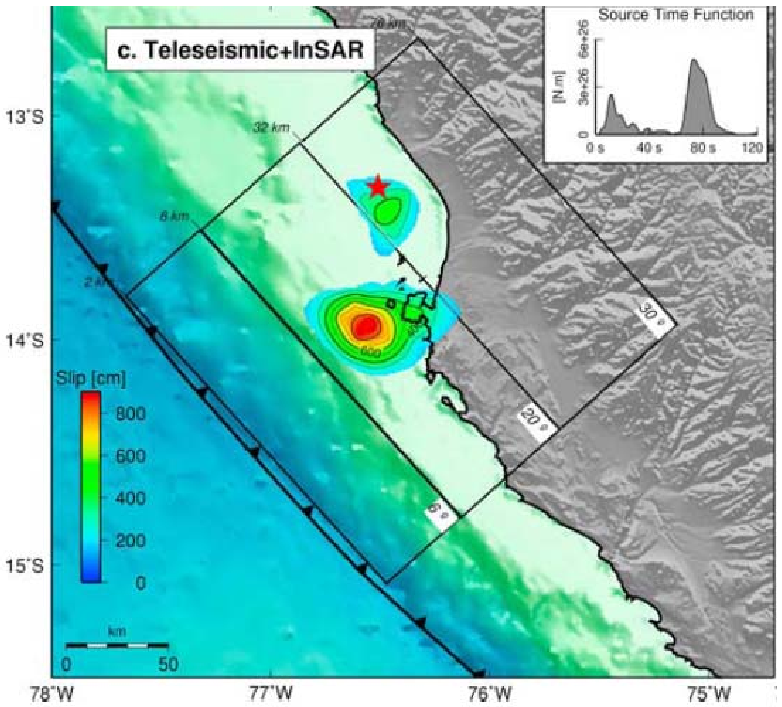


Ripperger, Ampuero, Mai (2008)

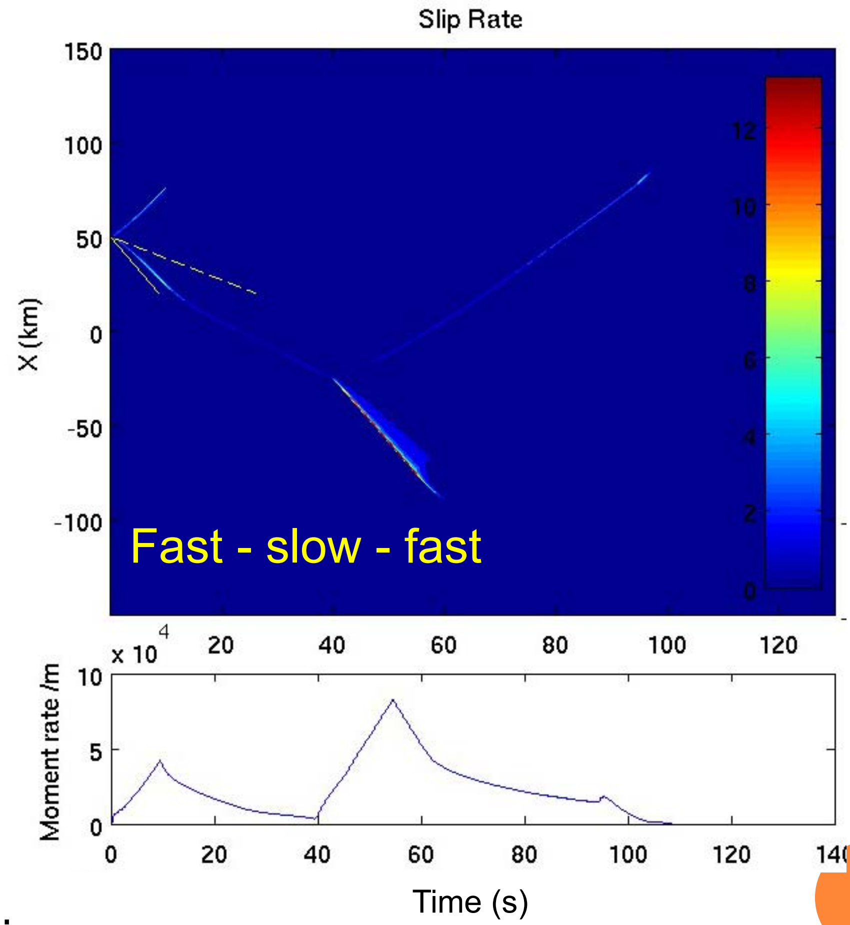
How to improve the resolution of earthquake source observations?

- Improve HF, non-parametric source imaging capabilities
  → array seismology
- Study slower rupture processes
  → slow slip and tectonic tremors, slow but dynamic ruptures

A SLOW RUPTURE STAGE DURING THE 2007 M8 PISCO (PERU) EARTHQUAKE



Sladen et al (2010)



Slow rupture (~1 km/s)
Consistent with a low stress drop region

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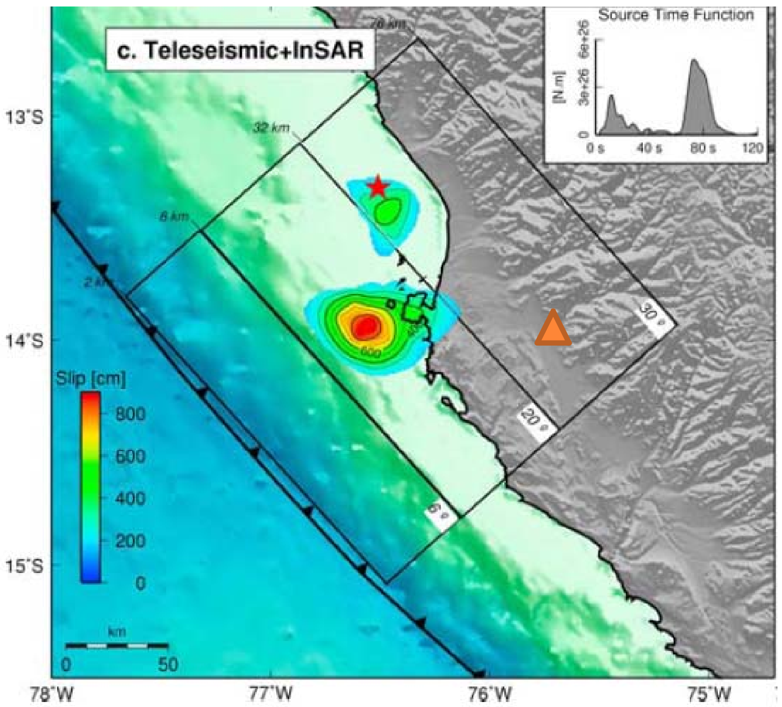
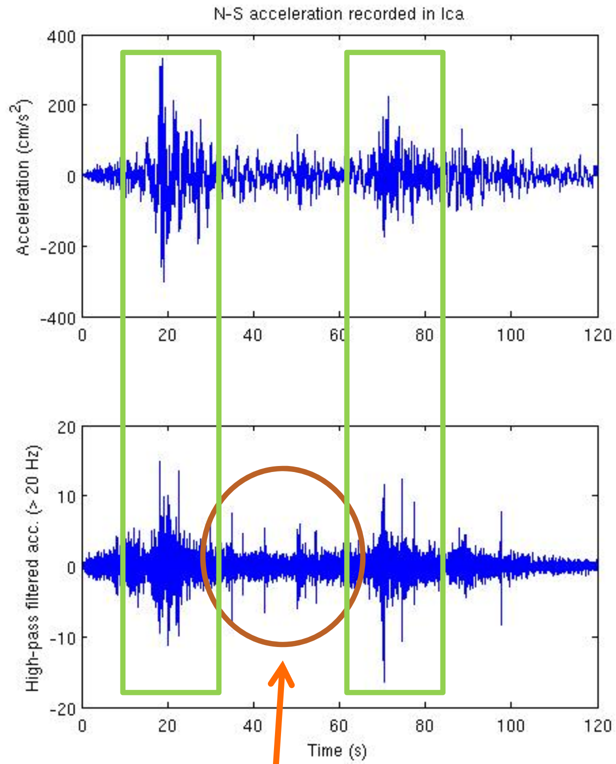


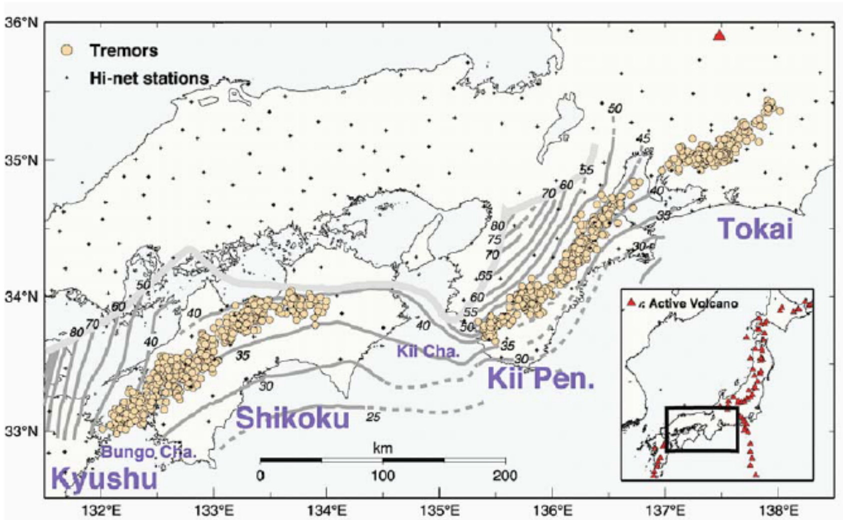


Slow rupture (~1 km/s)
Consistent with a low stress drop region

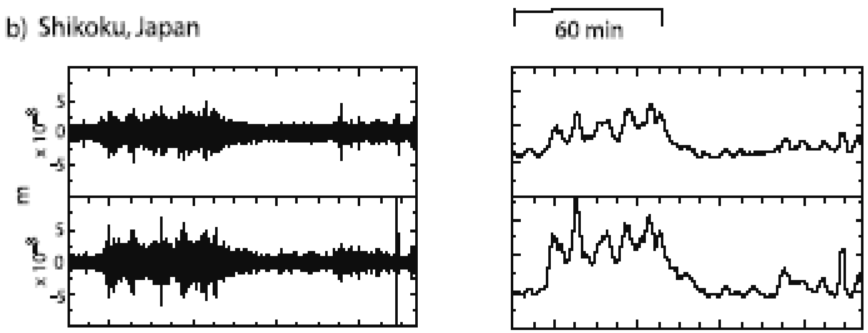
HF sources during slow phase?

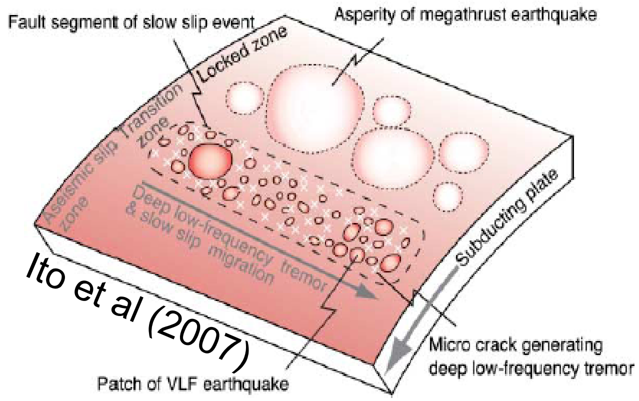
TECTONIC TREMOR

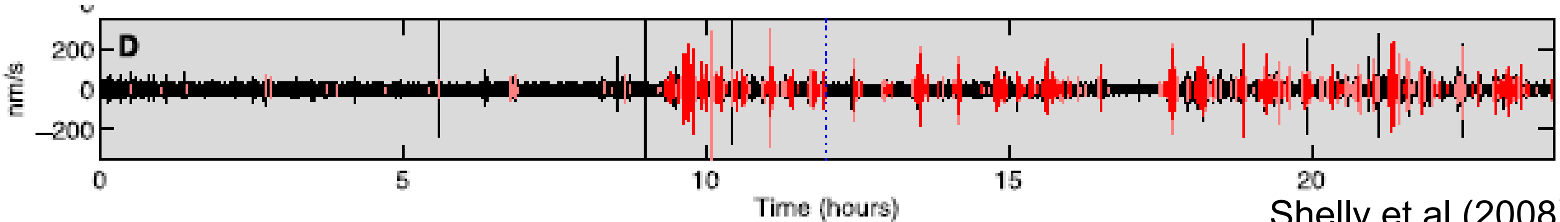
- Spatially coherent seismic transients (1-10 Hz) detected by seismic networks
- A mixture of low frequency earthquakes (LFE) and very low frequency earthquakes (VLF)
- Located on a belt 35-45 km deep
- Source consistent with slip on asperities on the megathrust, beneath the usual seismogenic zone



Tremor / LFEs in Japan (Obara 2002)

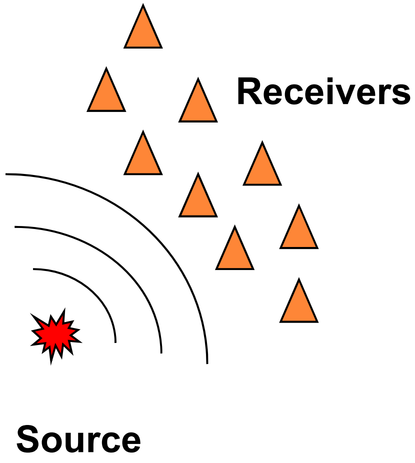


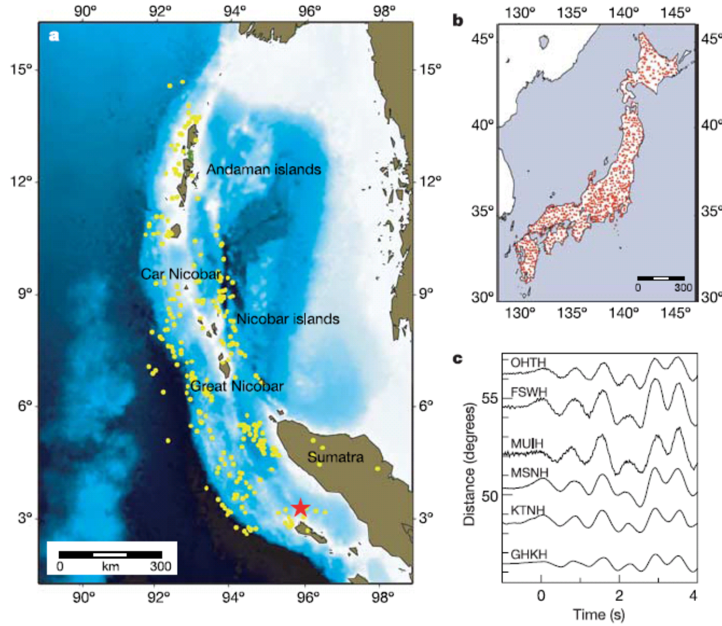




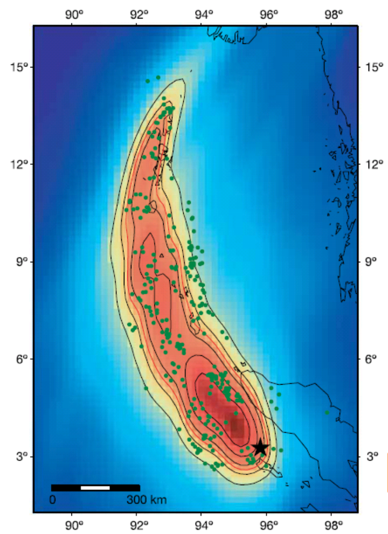
Shelly et al (2008)

EARTHQUAKE SOURCE IMAGING BY BACK-PROJECTION OF ARRAY DATA



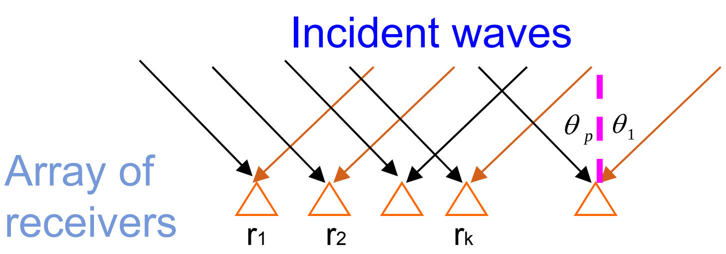


2004 Sumatra earthquake (Ishii et al, 2005)



- Based on body waves recorded at teleseismic distance by large seismic arrays
- Capability to track areas of high-frequency energy radiation as the rupture grows
- Requires fewer assumptions than traditional source inversion

EARTHQUAKE SOURCE IMAGING BY BACK-PROJECTION OF ARRAY DATA



Principle of classical beamforming:

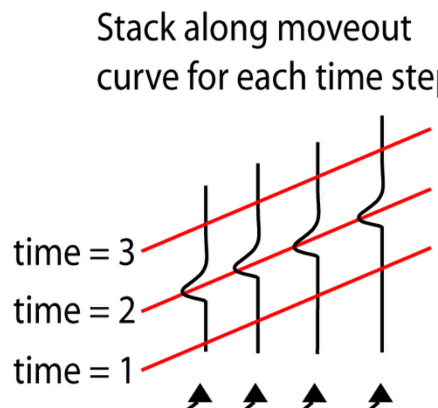
Array data = sum of incident waves

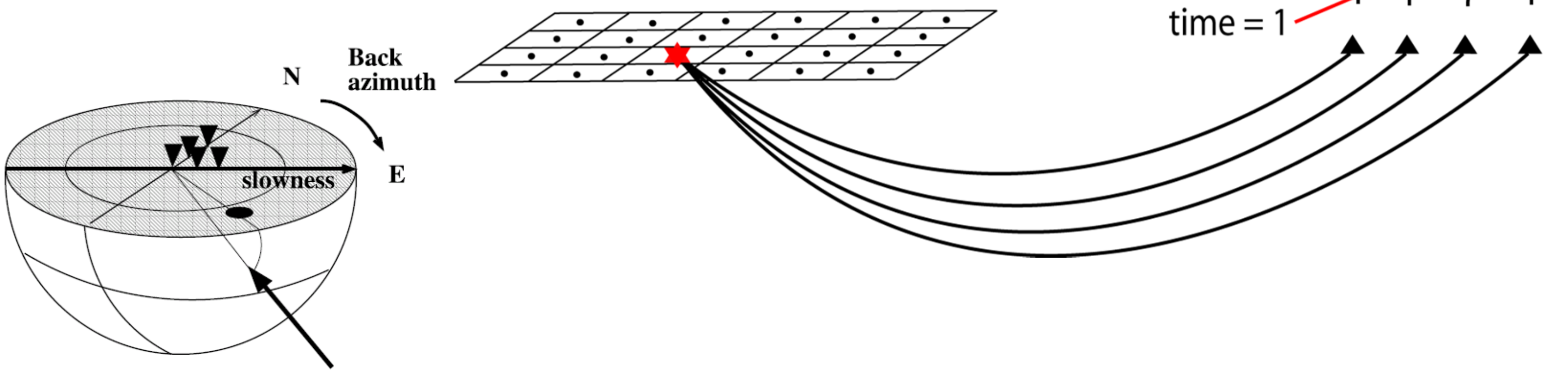
The pattern of time delays across the array depends on the **direction of arrival** of each wave, hence on **source location** (azimuth and distance to the array)

Beamforming with back-projection:

$$stack(t) = \sum_k seismogram_k(t + \tau_k)$$

$$\tau_k = travel\_time(x_k, x_{source})$$





Rayleigh Criteria (Resolution Limit)

Minimum resolvable distance between two sources:

$$L = 1.22 \frac{F\lambda}{D \sin\phi}$$

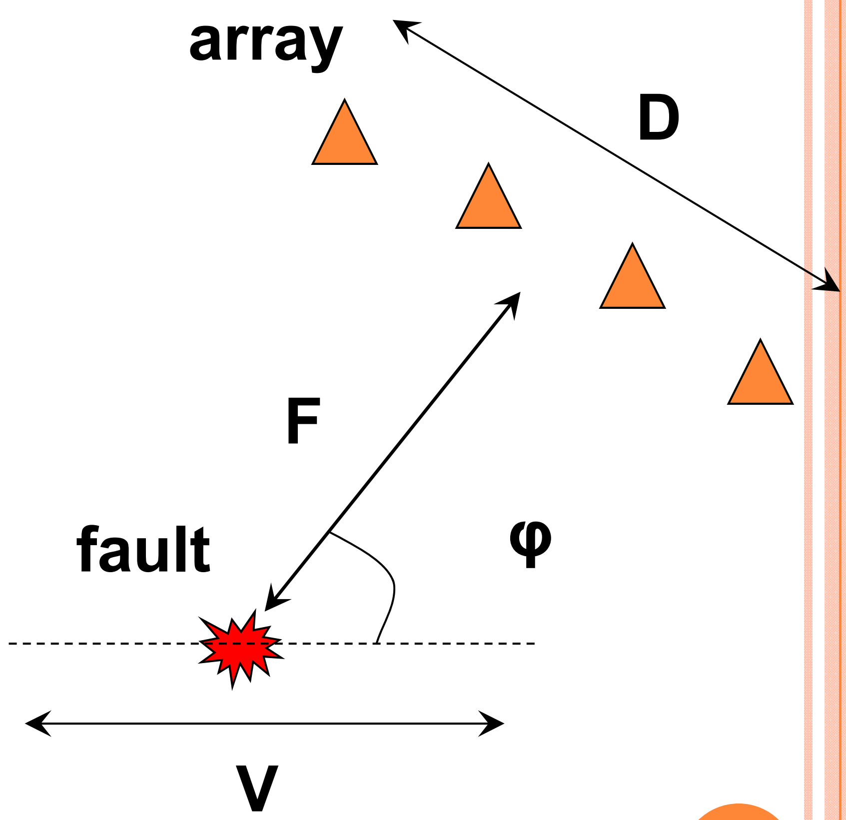
L, resolution length along the fault

F, source-array distance

λ, apparent wavelength (apparent speed times frequency)

D, array aperture

Φ, array orientation with respect to fault strike



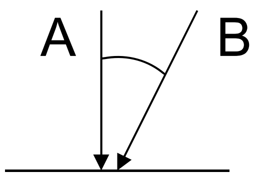
RECENT DEVELOPMENTS IN THE METHOD

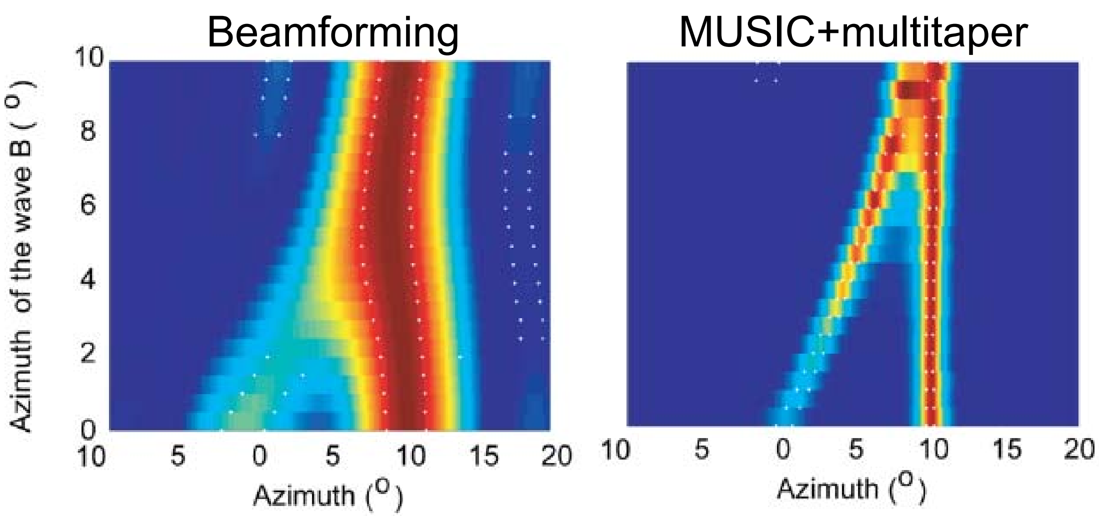
- Beamforming has low resolution (can't separate sources that are too close)

  → we implemented a high-resolution technique, Mutiple Signal Classification (**MUSIC**)
- MUSIC was developed for long stationary signals but earthquake seismograms are highly transient

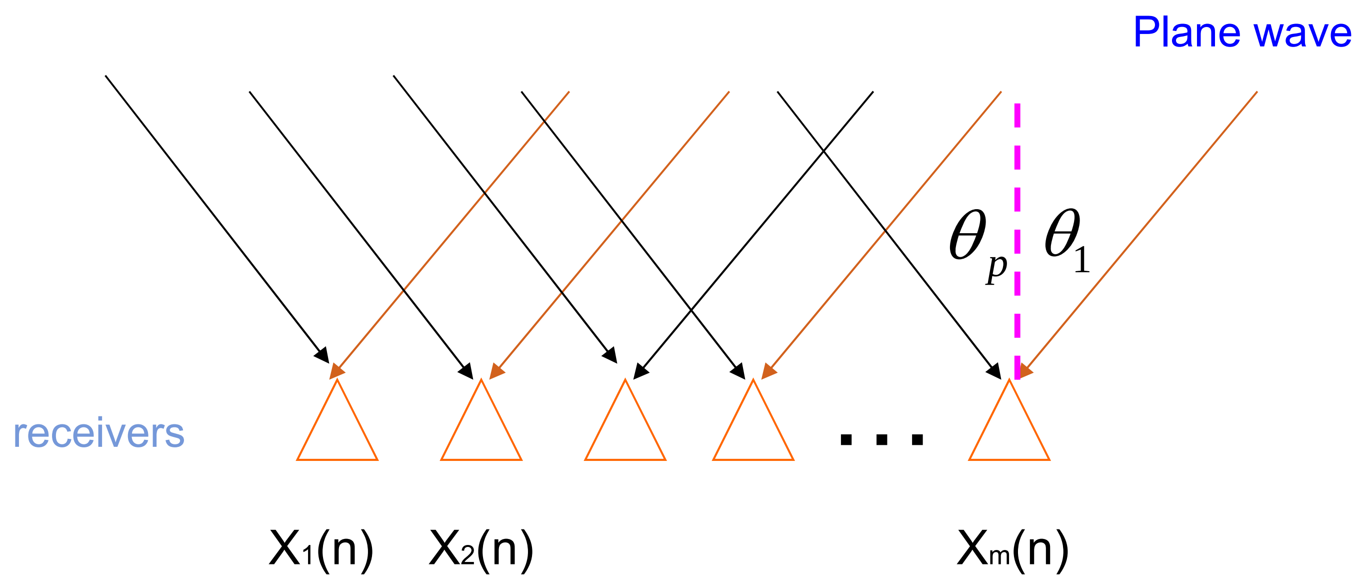
  → we combined MUSIC with **multitaper** cross-spectral estimation

Synthetic test: separation of two plane waves by a linear array
→ MUSIC has higher resolution than beamforming





MATHEMATICAL SIGNAL MODEL



Signal model $$x_k(n) = \sum_{j=1}^{p} a_k(\theta_j) s_j(n) + e_k(n), k = 1, \ldots, m$$

Steering vector $$a_k = e^{i\omega\tau_k}$$

Signal $$s_j(n)$$

Gaussian white noise $$e_k(n)$$

Matrix form $$X(n) = A(\theta)S(n) + e(n)$$

Given X(n), solve for θ

Multiple Signal Classification (MUSIC)

Array data covariance matrix

Rxx = E{**x**(t) **x**^{H}(t)}

Eigenvalues of Rxx

$$\lambda_i = \begin{cases} \alpha_{ii}^2 + \sigma^2, & i = 1, \ldots, p \\ \sigma^2, & i = p+1, \ldots, m \end{cases}$$

Eigen vectors of Rxx

$$\mathbf{U} = \left[\mathbf{S} \middle| \mathbf{G} \right] = [\underbrace{\mathbf{u}_1, \ldots, \mathbf{u}_p}_{\text{signal Subspace}} \mid \underbrace{\mathbf{u}_{p+1}, \ldots, \mathbf{u}_m}_{\text{noise Subspace}}]$$

signal Subspace   noise Subspace

MUSIC pseudo-spectrum

$$P(\theta) = \frac{1}{\left\| a(\theta)^H G \right\|} = \frac{1}{a(\theta)^H G G^H a(\theta)^H}$$

=1/(projection of steering vector on the noise space)

Signal space is orthogonal to noise space:

$$\theta_0 = \arg\max(P)$$

→ **source location**

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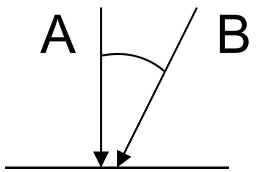
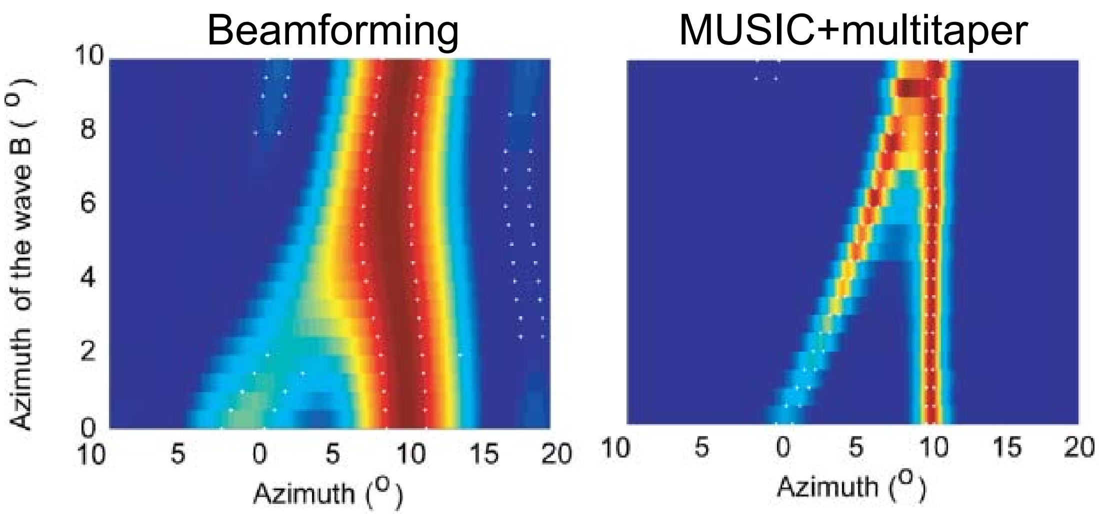
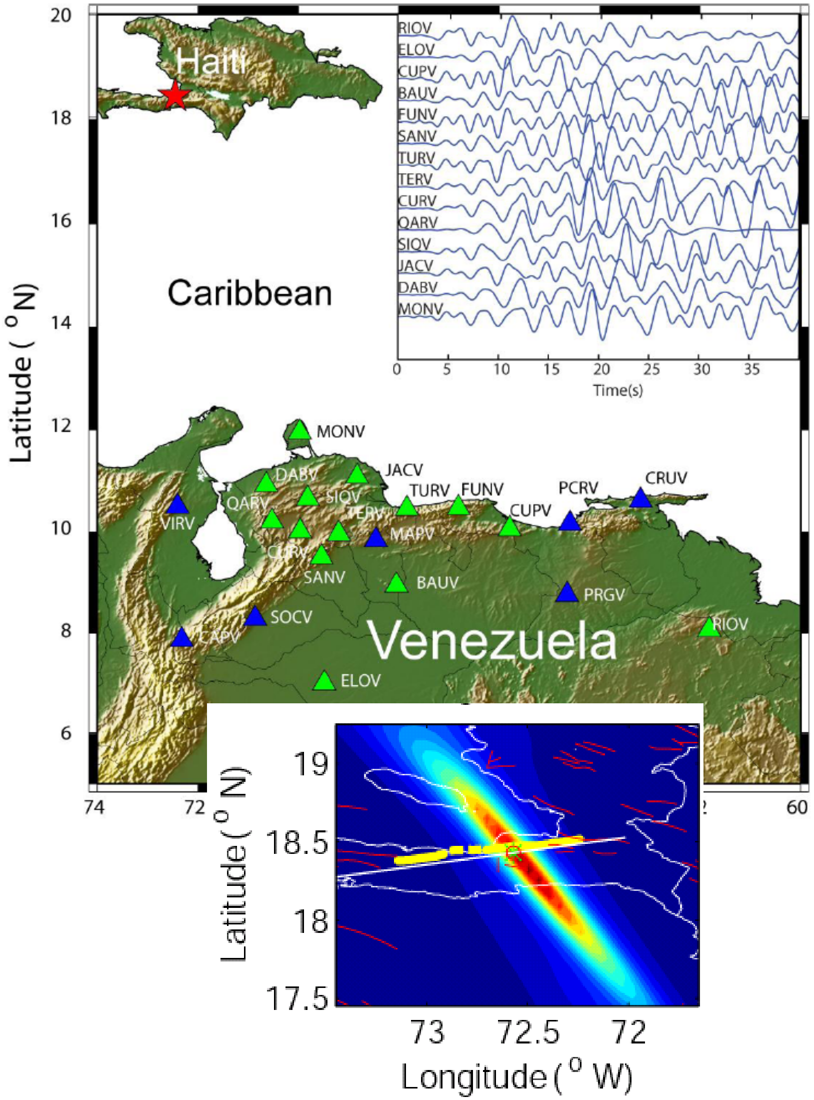


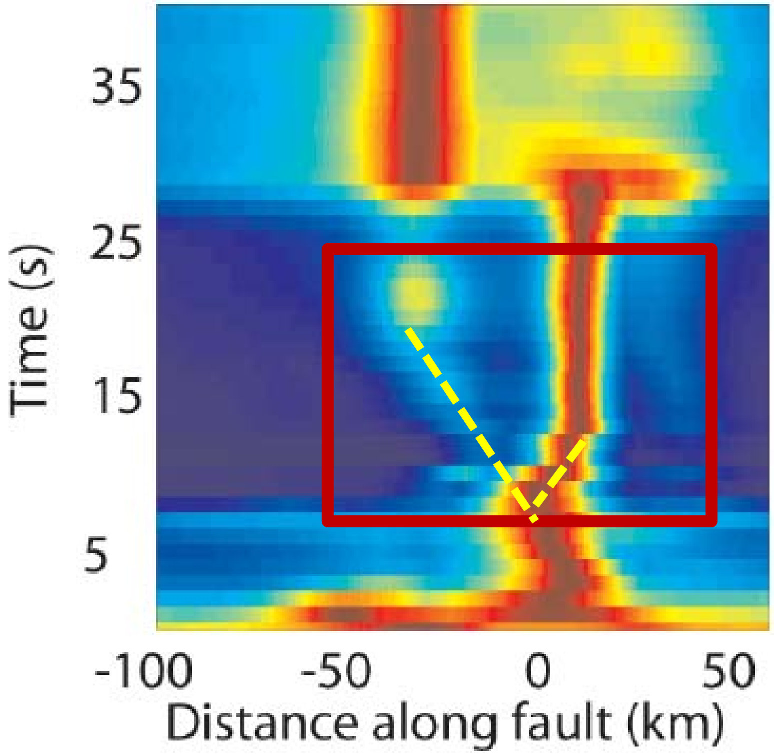


2010 M7 Haiti earthquake

Recorded at regional distance by the Venezuela National Seismic Network



MUSIC pseudo-spectrum projected on the fault trace

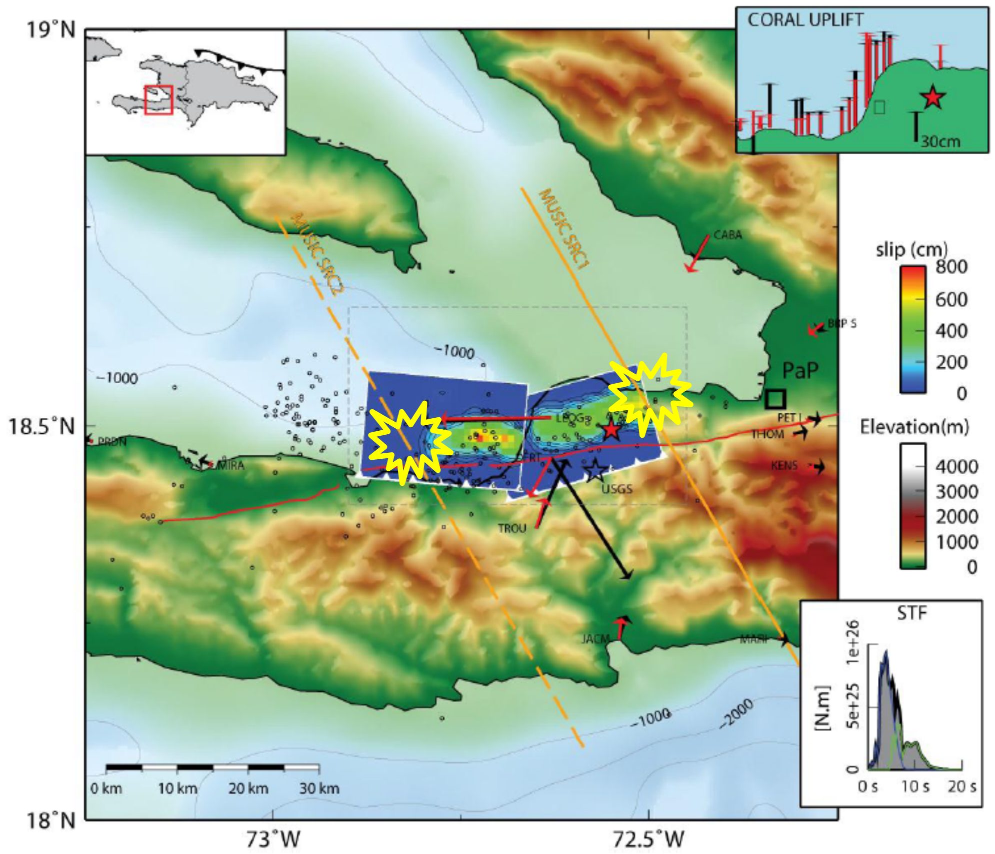


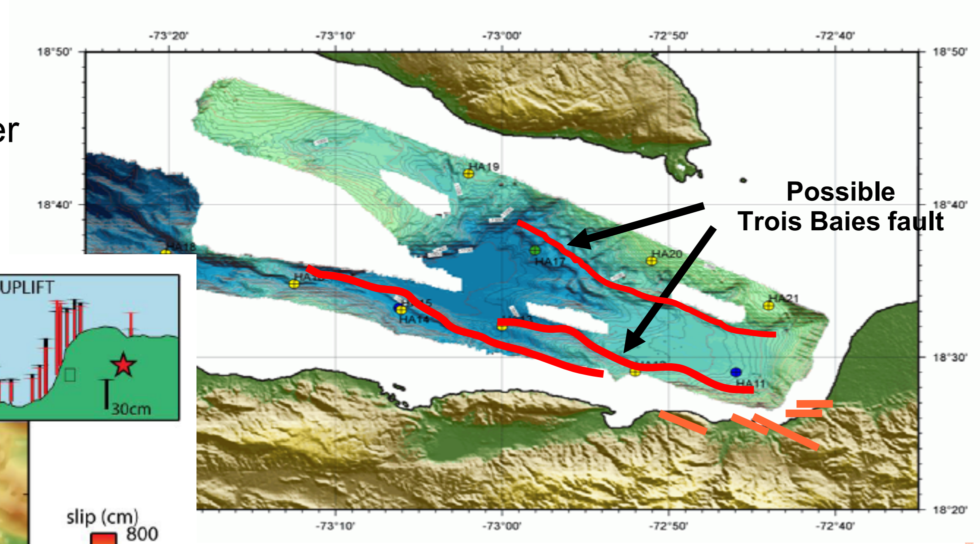
Bilateral rupture ~35 km long
Short Eastward front
Longer Westward front
Subshear rupture speed

INTEGRATION WITH OTHER DATA

Teleseismic+GPS+InSAR source inversion

Aftershocks from Haiti-OBS campaign (Mercier de Lepinay et al, 2010)





The rupture length in the array back-projection images is longer than in the finite source inversion.

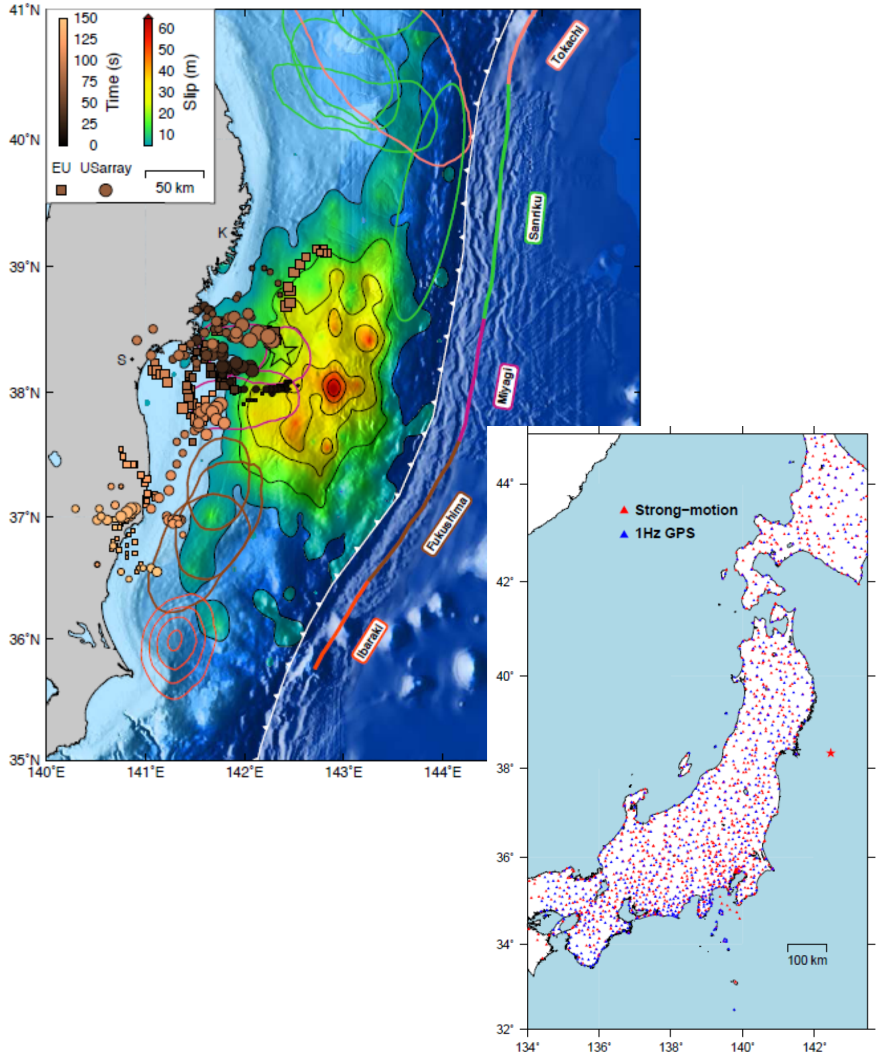
These techniques use data at different frequencies.

Are high-frequencies imaging the edges of rupture?

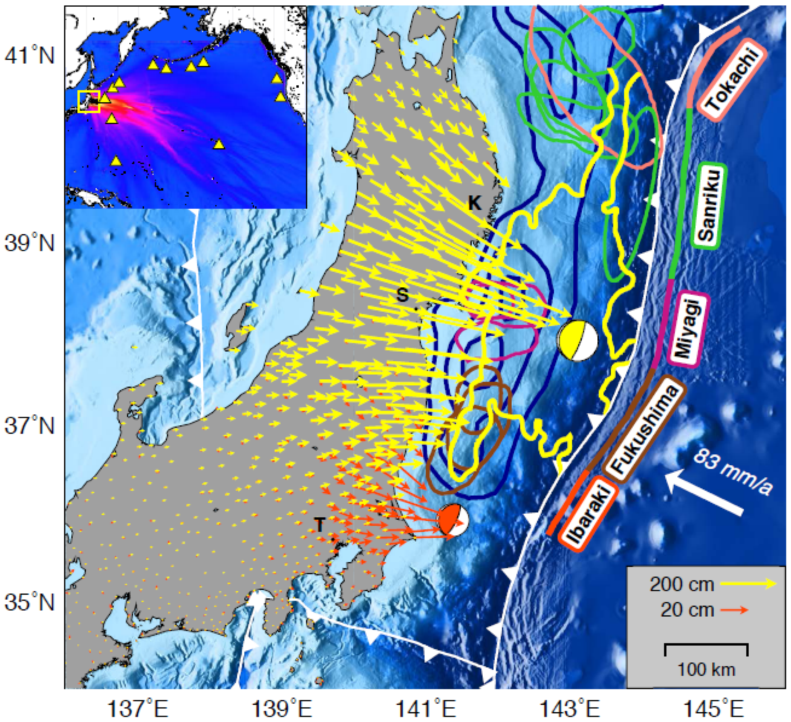
THE 2011 TOHOKU EARTHQUAKE

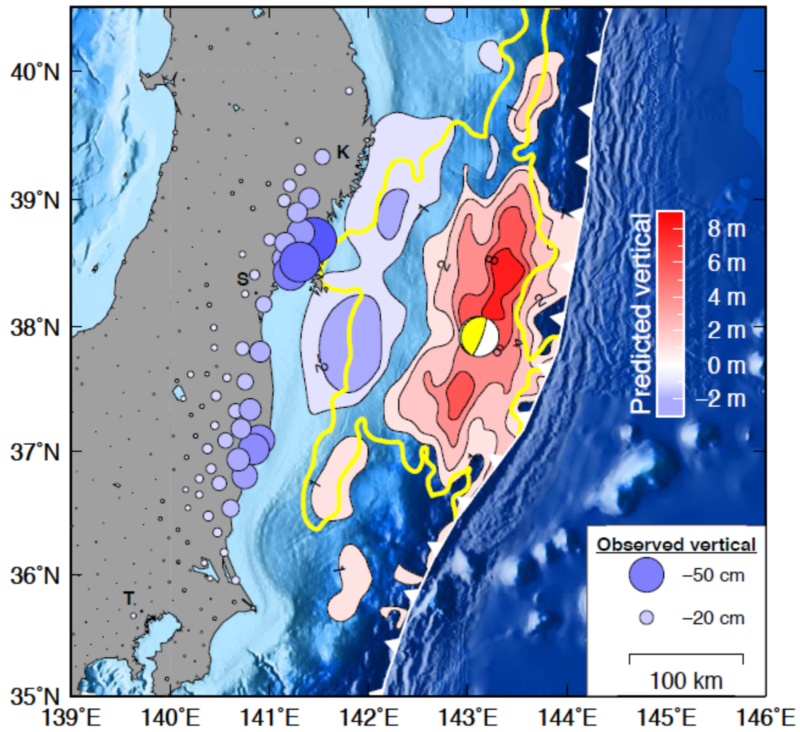
A transformative event:

- Largest and most damaging modern earthquake (+tsunami) in Japan
- Broke a portion of the subduction zone which seismic hazard was underestimated
- Recorded by thousands of sensors in Japan: new opportunities for seismology, geodesy and earthquake engineering



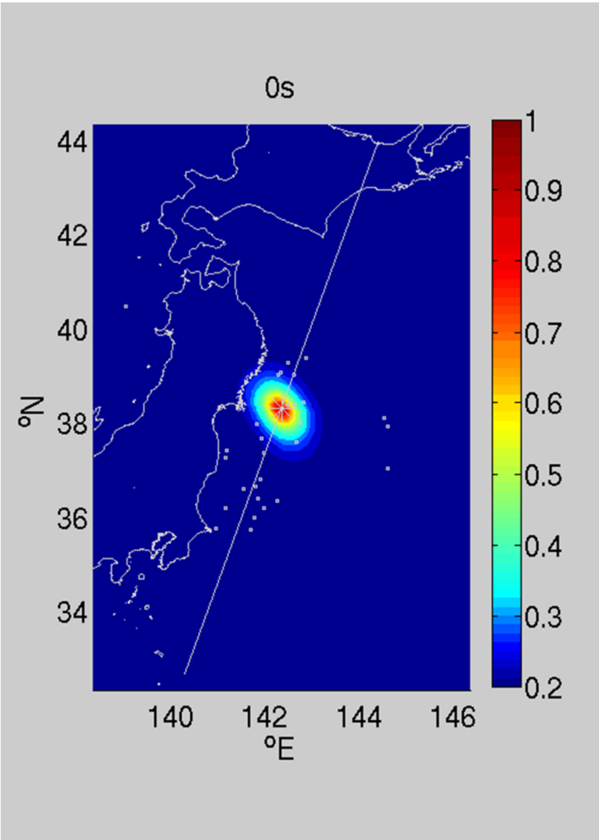
THE 2011 TOHOKU EARTHQUAKE FROM A GEODETIC PERSPECTIVE

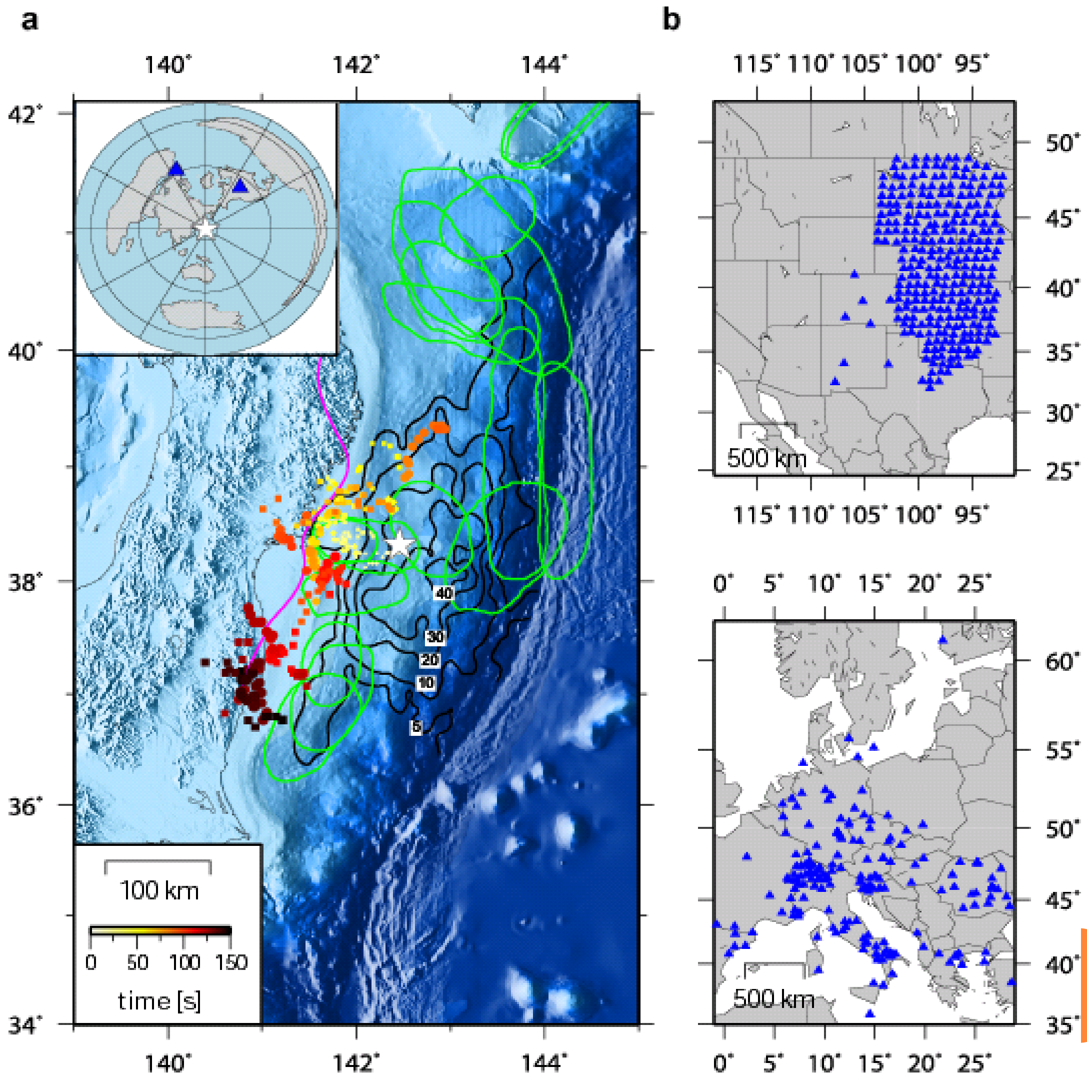




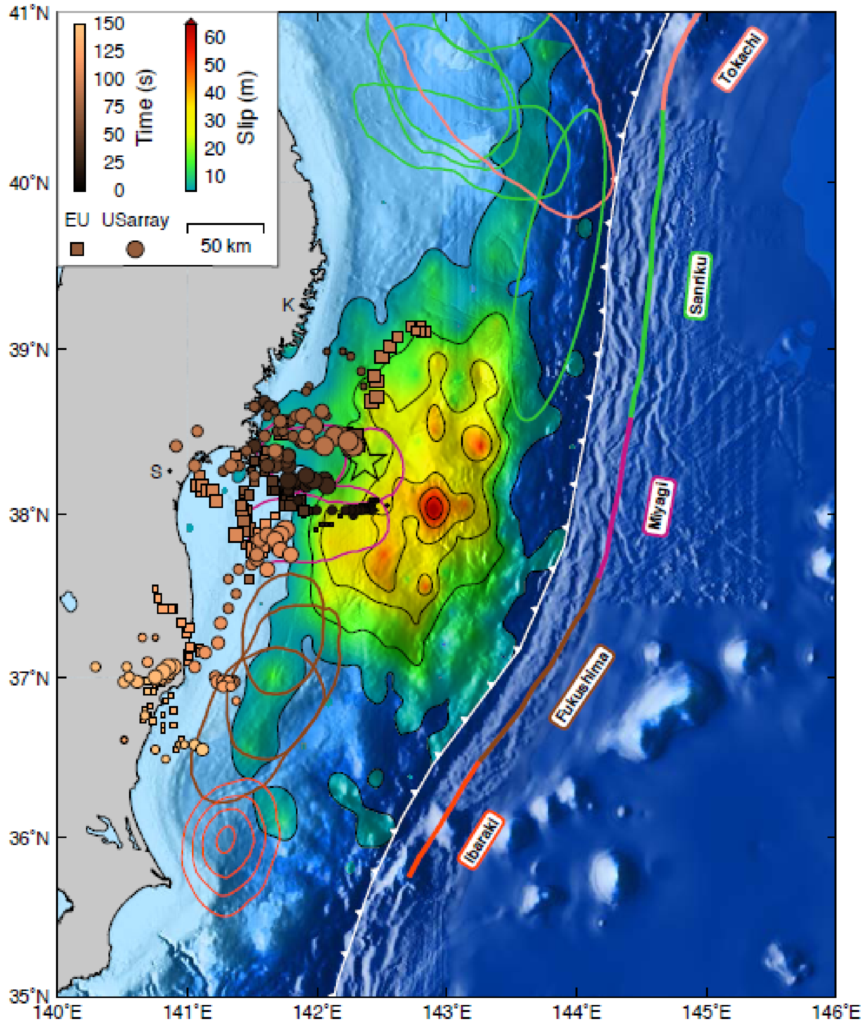
Yellow contour: slip = 5 m
Simons et al (Science, 2011)

HIGH-FREQUENCY SOURCE IMAGING OF THE TOHOKU EARTHQUAKE BY TELESEISMIC ARRAYS



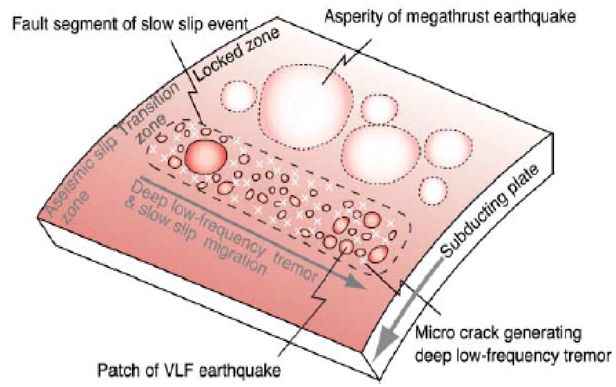


HIGH-FREQUENCY RADIATION IS DEEP

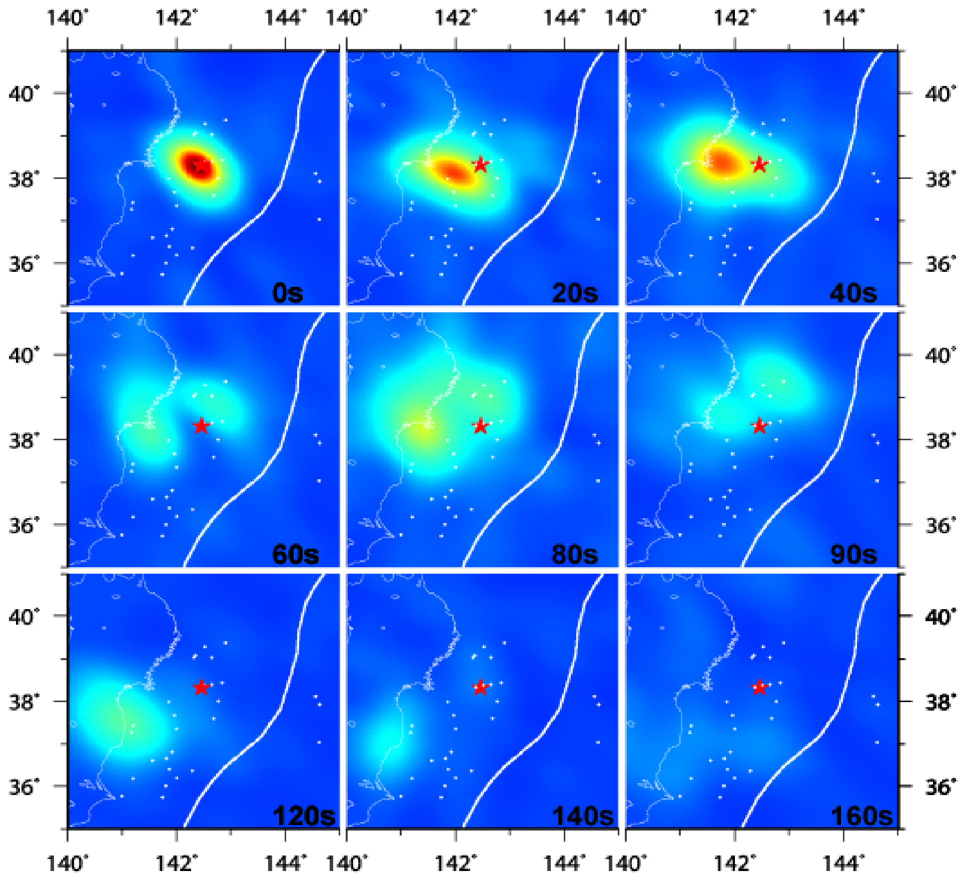


Possible models:

1. “Stopping phases” at the final edge of the rupture
2. Stress concentrations at the edge of past earthquakes
3. Deep brittle asperities surrounded by creep
4. Dynamic triggering of faults above the megathrust



DETAILS OF THE RUPTURE PROCESS



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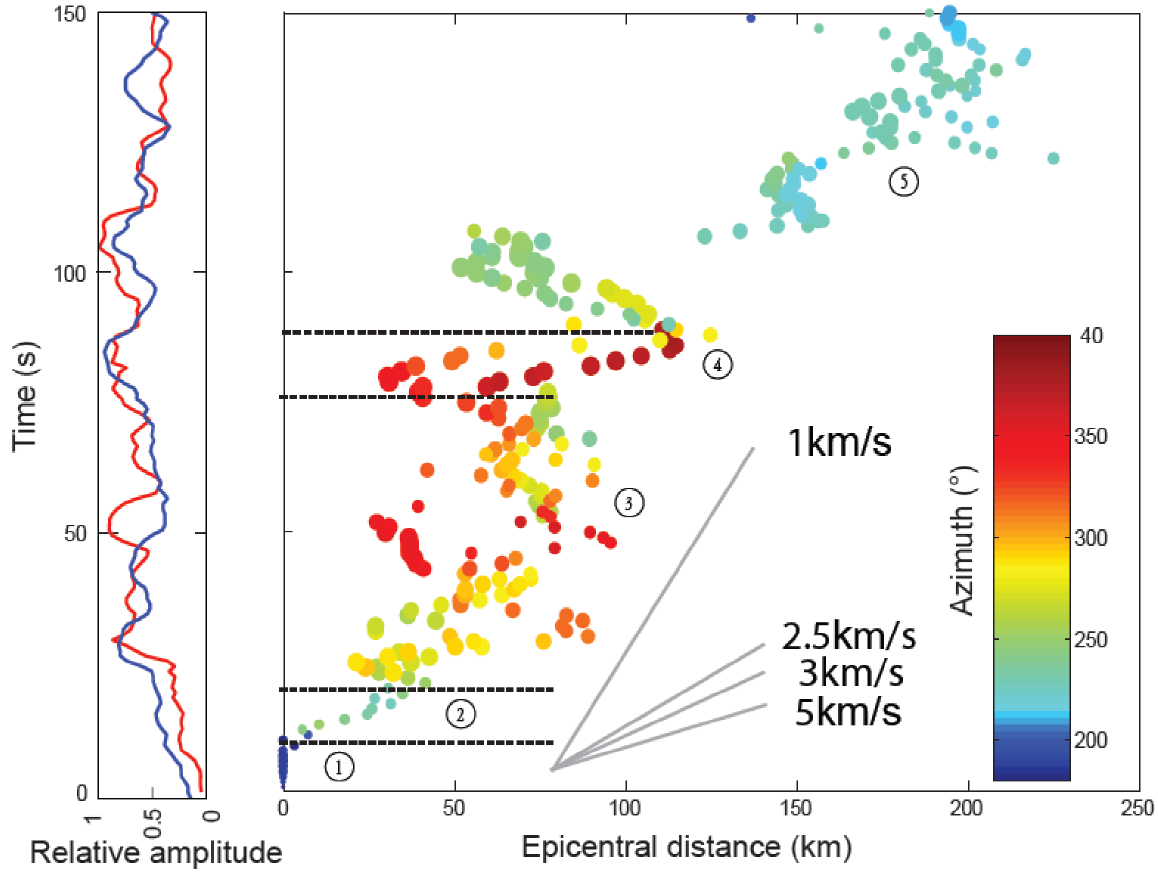
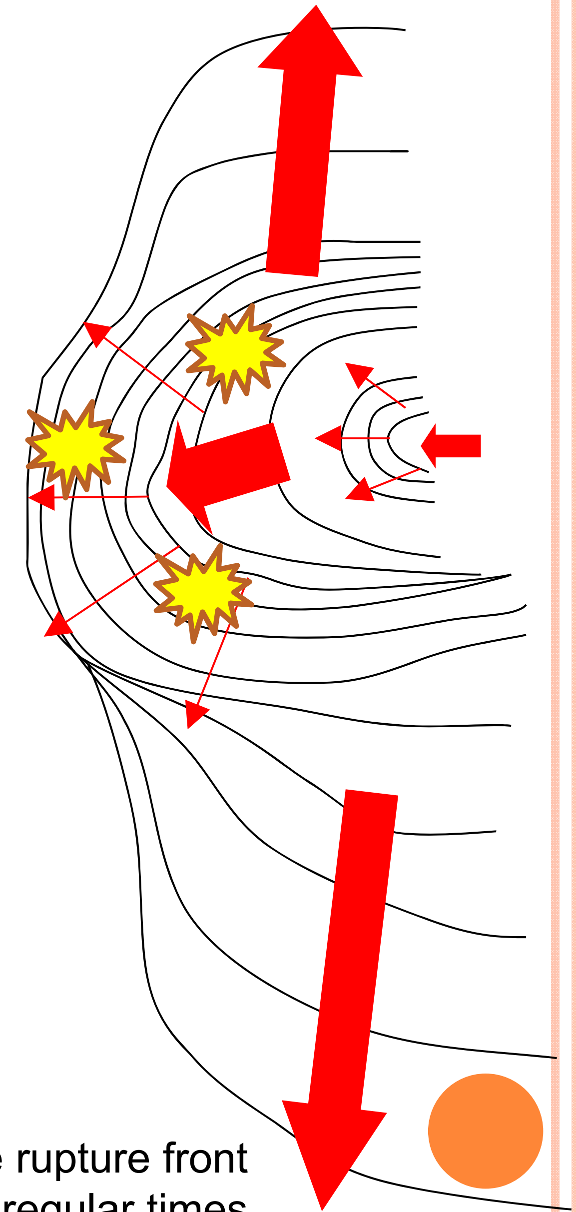


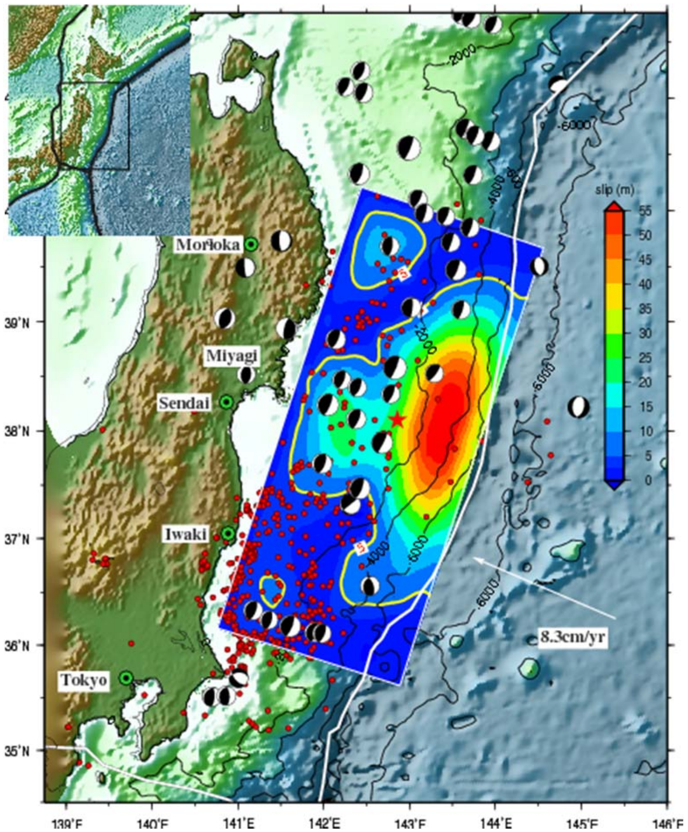


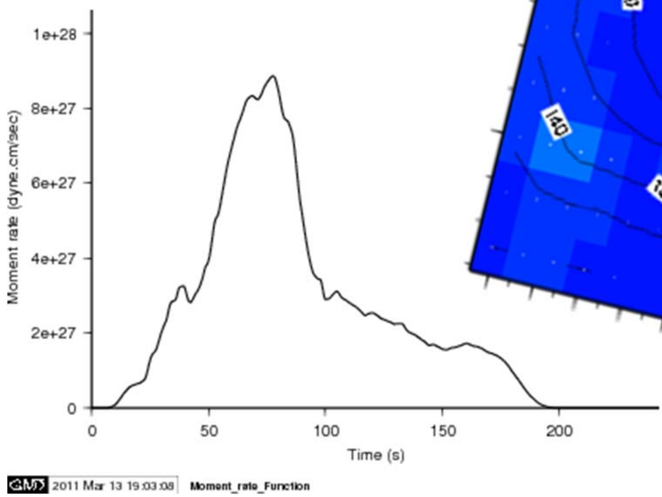
Sketch: position of the rupture front at regular times

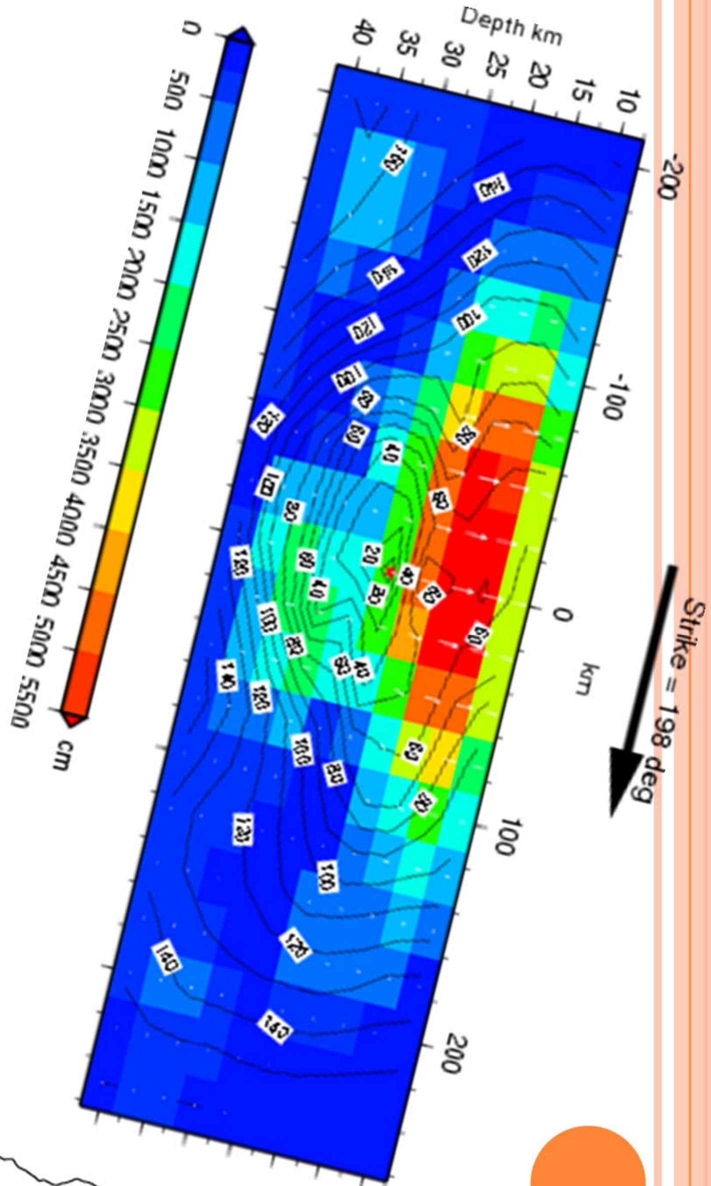
SOURCE INVERSION (CHEN JI)

http://www.geol.ucsb.edu/faculty/ji/big_earthquakes/2011/03/0311_v3/Honshu.html

Based on teleseismic body waves (dominant period ~ 30 s) and surface waves (~200 s)

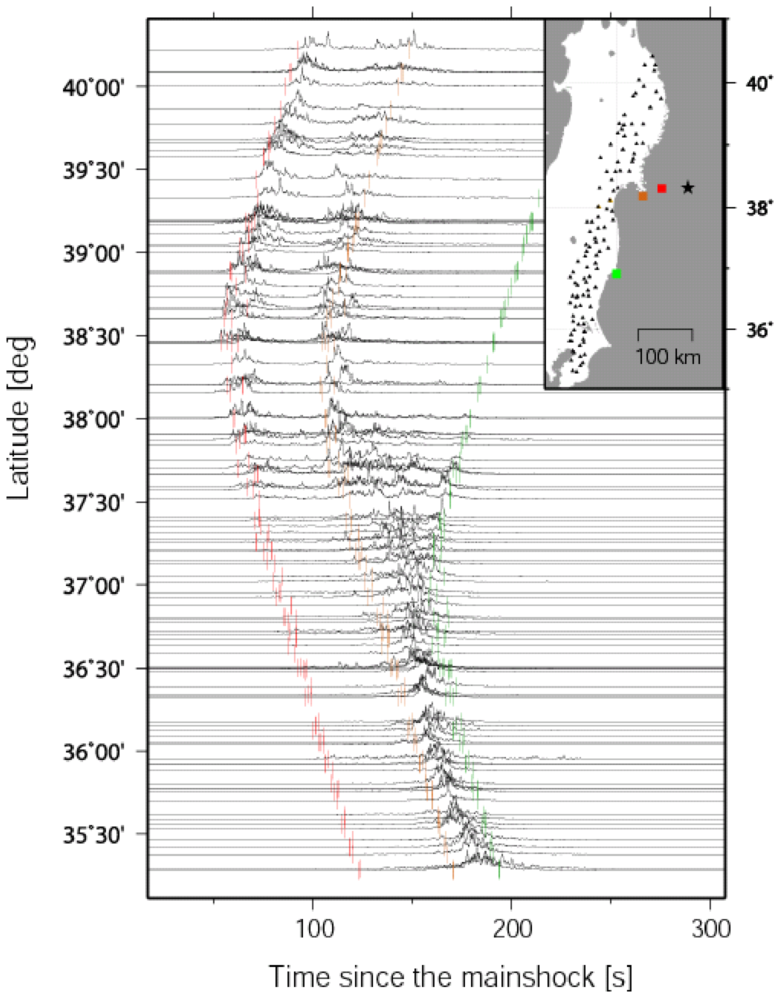




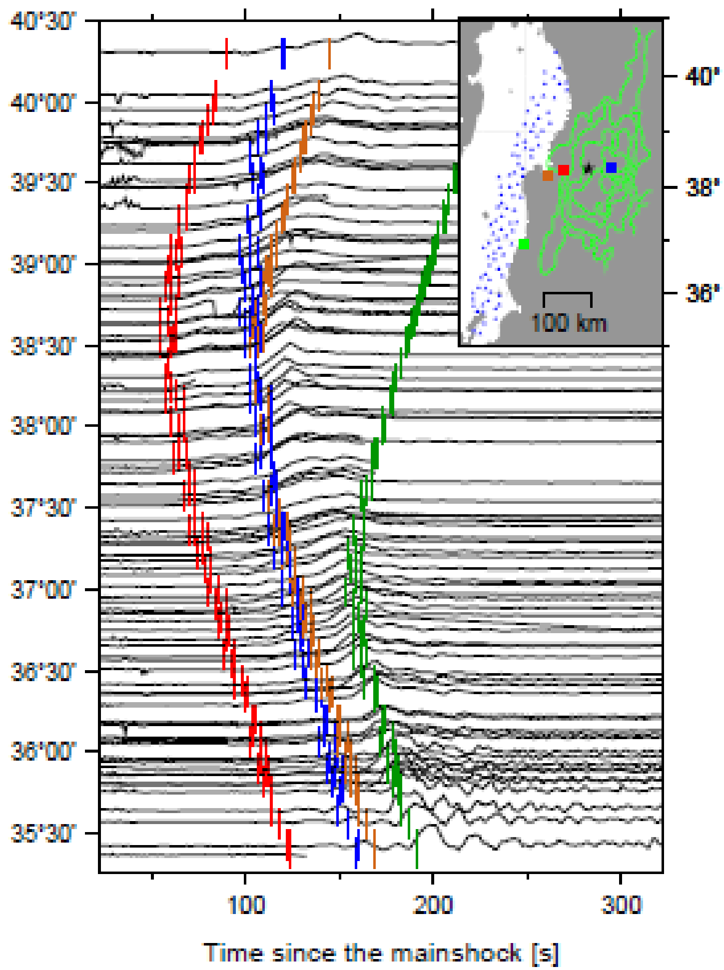


COMPARISON TO LOCAL DATA

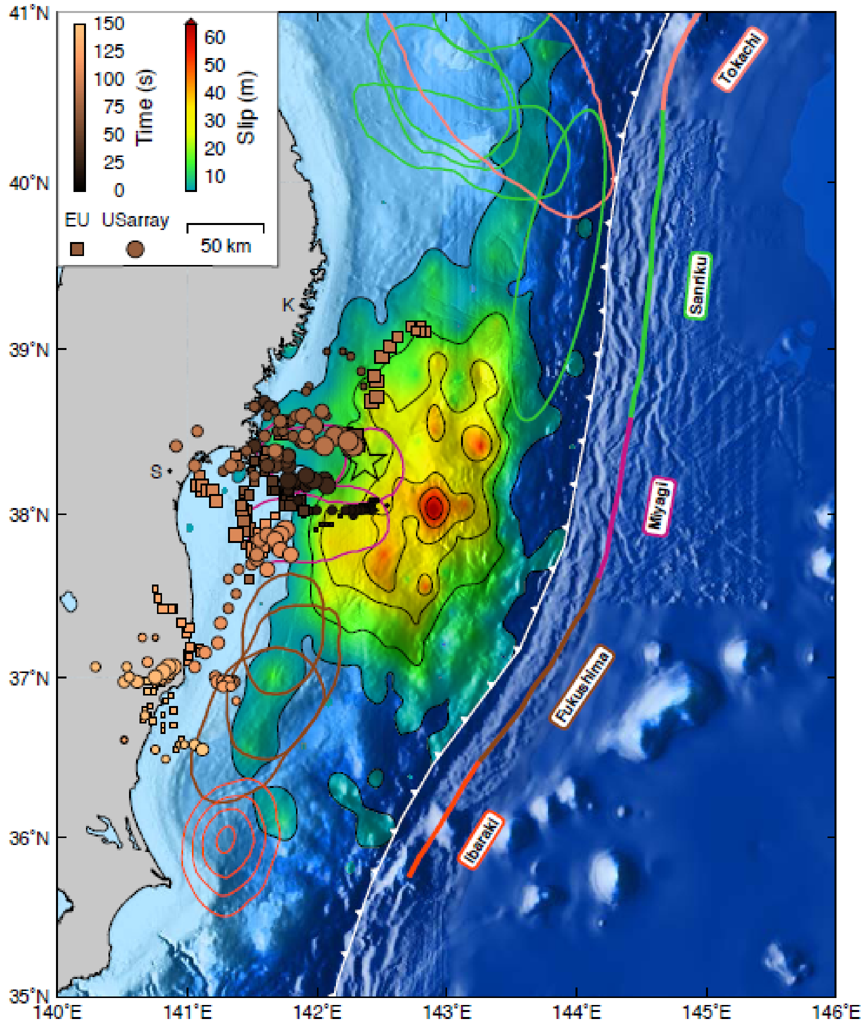
Hi-freq (5-10 Hz) strong motions



Low-freq (1 Hz) GPS



HIGH-FREQUENCY RADIATION IS DEEP



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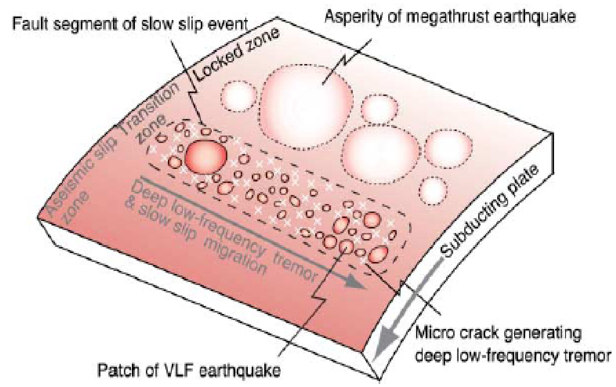
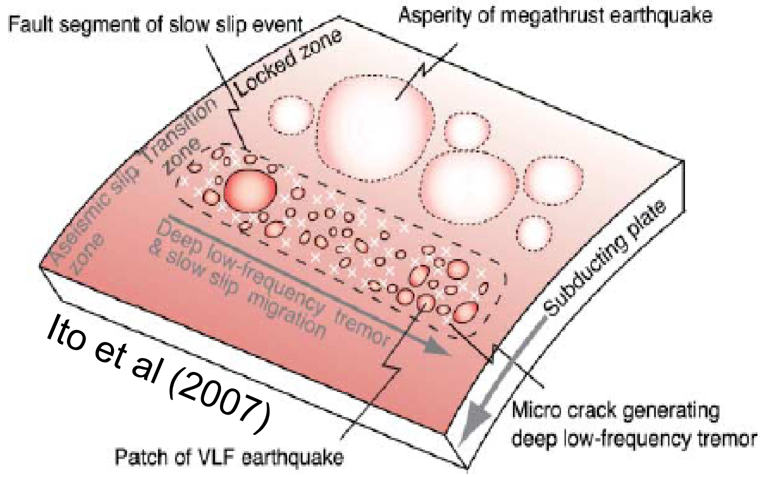
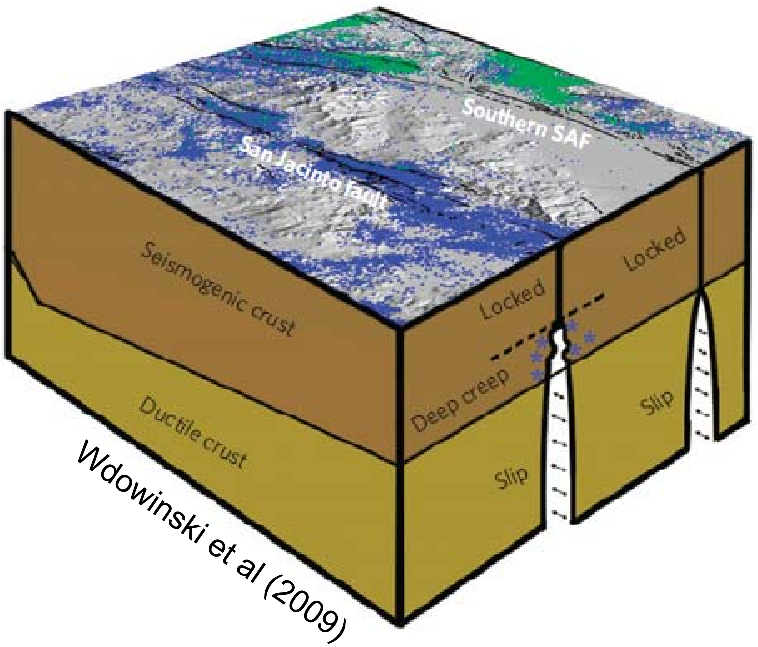
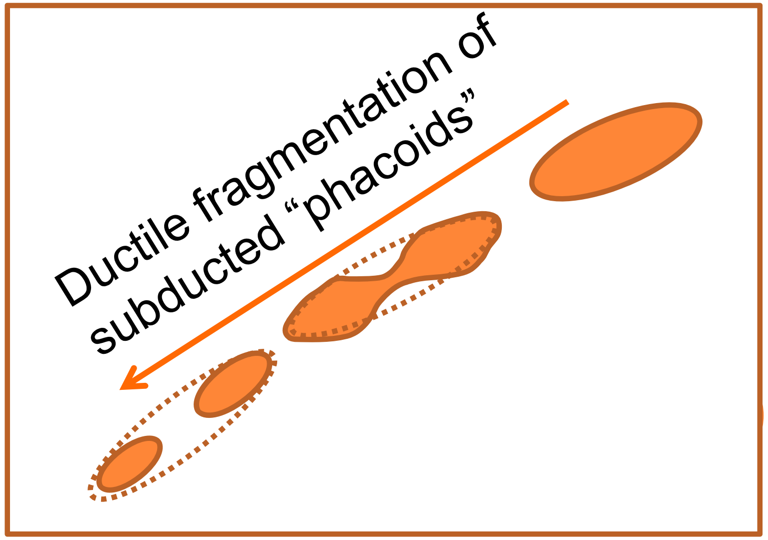


The bottom of the Seismogenic zone

- Rheological brittle-ductile transition
- Transition could be heterogeneous







Fault zone structure

- Fault zone melange (intermingled lithologies)
- Fractal distribution of phacoid sizes

(Fagereng, 2011)

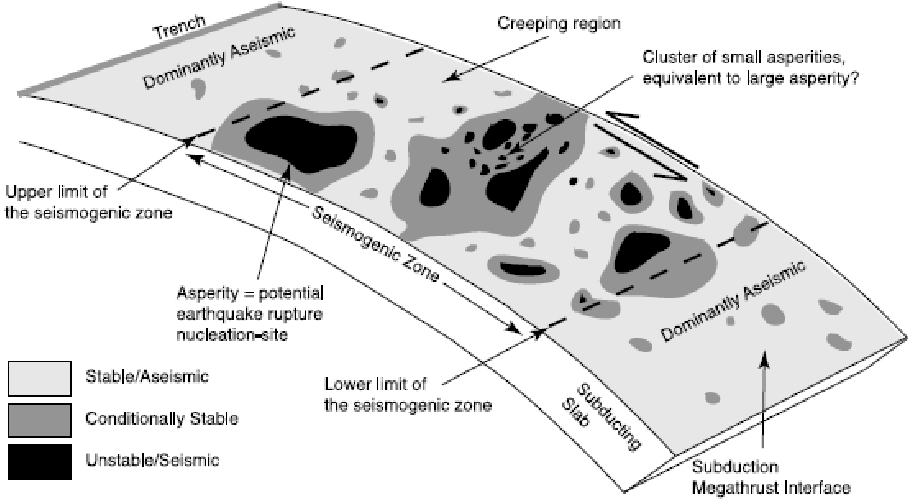
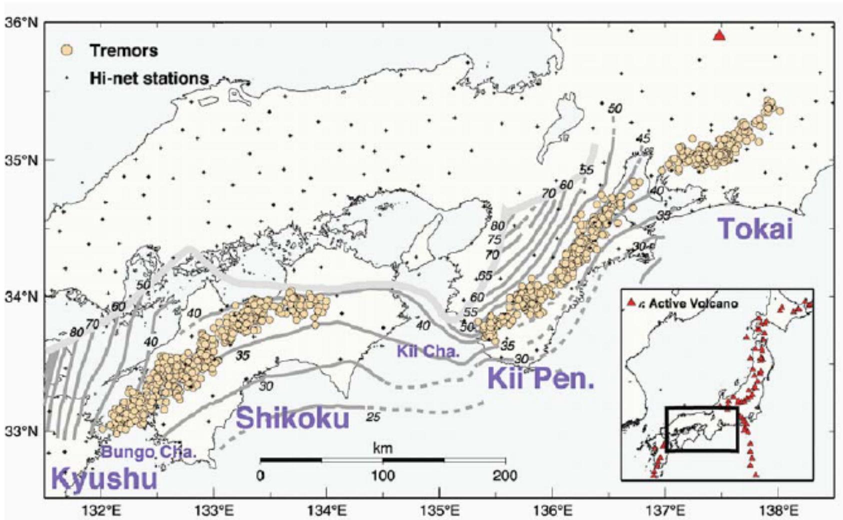


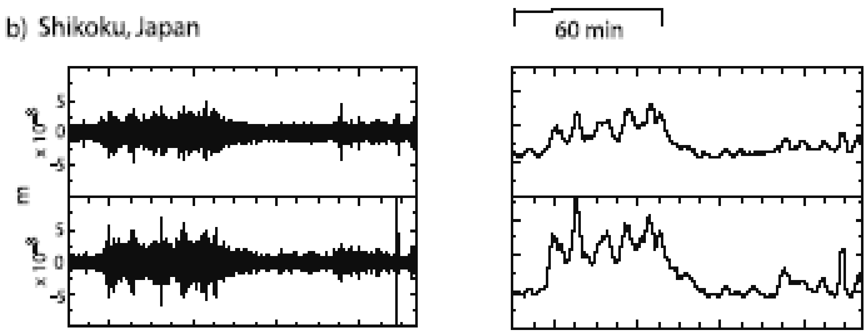
Figure 3. Photographs of competent lenses at different scales: (a) 4 m long sandstone phacoid enclosed by mudstone. The long axis of the lens is subparallel to slickenfibres in surrounding shear veins. (b) The 4 cm long sandstone lens surrounded by a mudstone matrix. Note vertical extension vein in the sandstone lens from brittle extension of the phacoid. (c) Photomicrograph (plane polarized light) of ~1 mm long lithic clasts in a mudstone matrix.

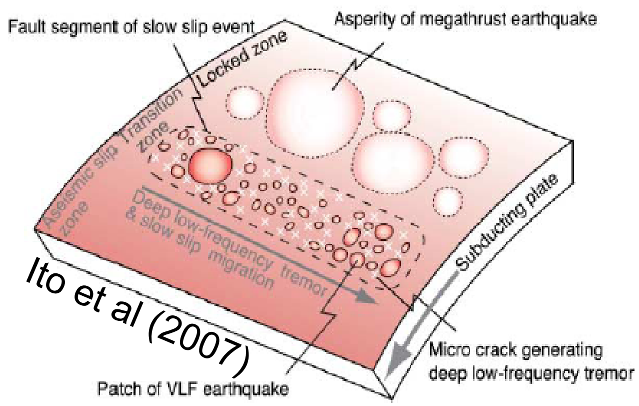
TECTONIC TREMOR

- Spatially coherent seismic transients (1-10 Hz) detected by seismic networks
- A mixture of low frequency earthquakes (LFE) and very low frequency earthquakes (VLF)
- Located on a belt 35-45 km deep
- Source consistent with slip on asperities on the megathrust, beneath the usual seismogenic zone

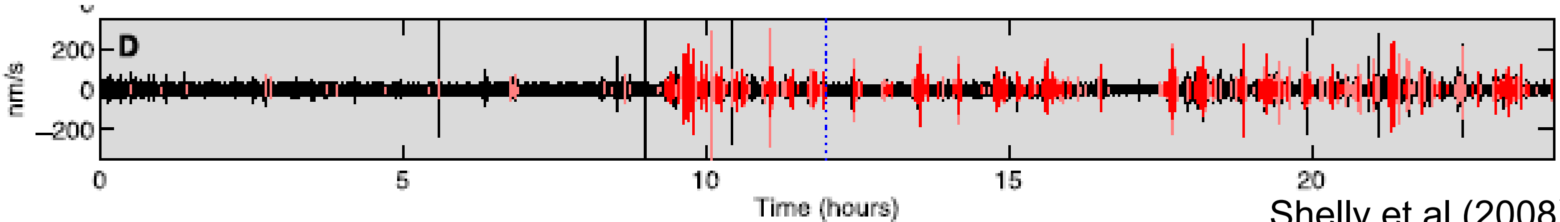


Tremor / LFEs in Japan (Obara 2002)



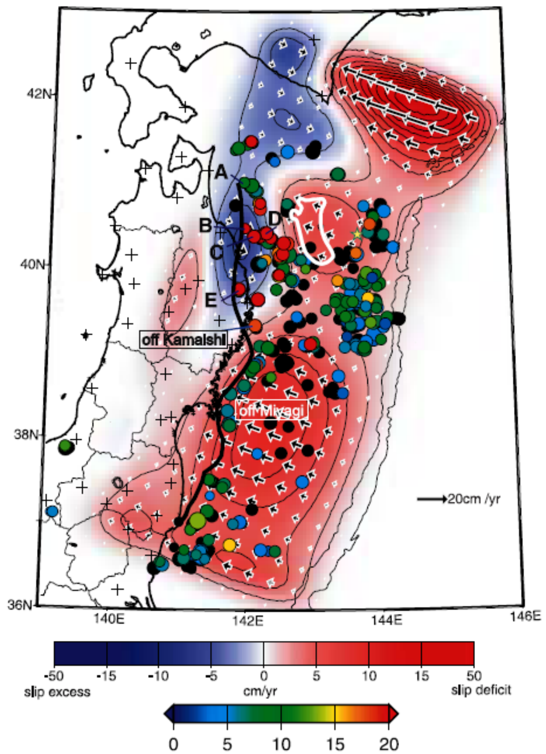


Ito et al (2007)

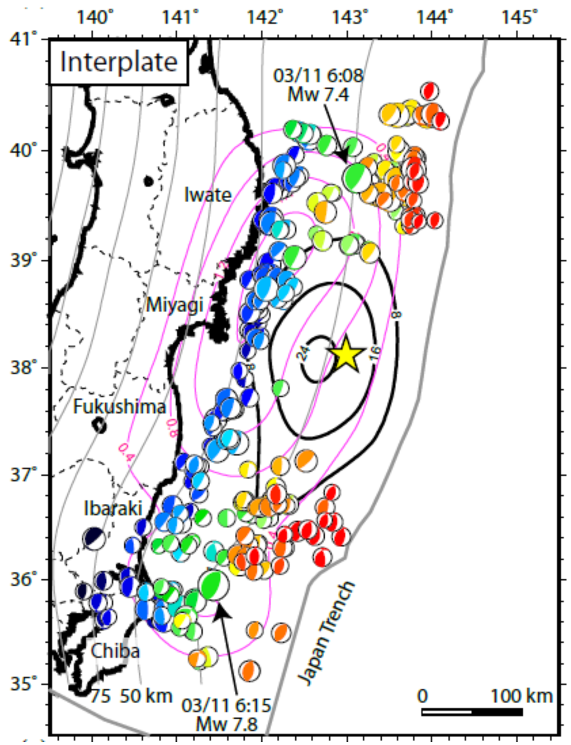


Shelly et al (2008)

THE BOTTOM OF THE SEISMOGENIC ZONE



Circles: small repeating earthquakes.
Thick line: bottom of interplate seismicity
(Igarashi et al 2003)



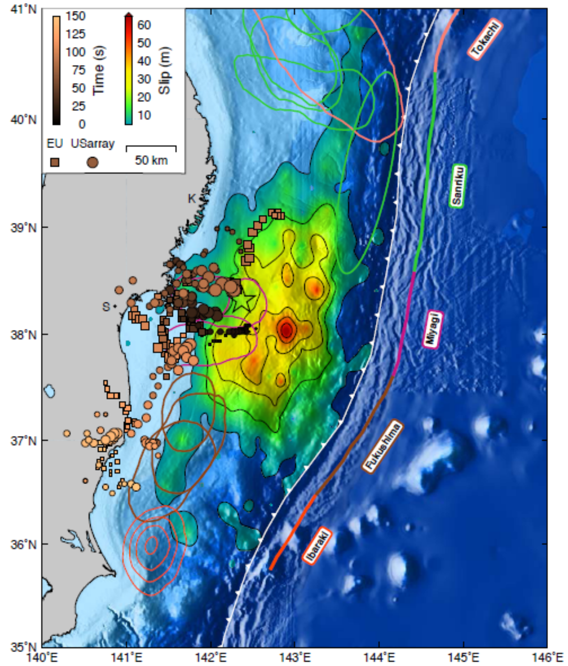
Interplate aftershocks
(Asano et al, 2011)

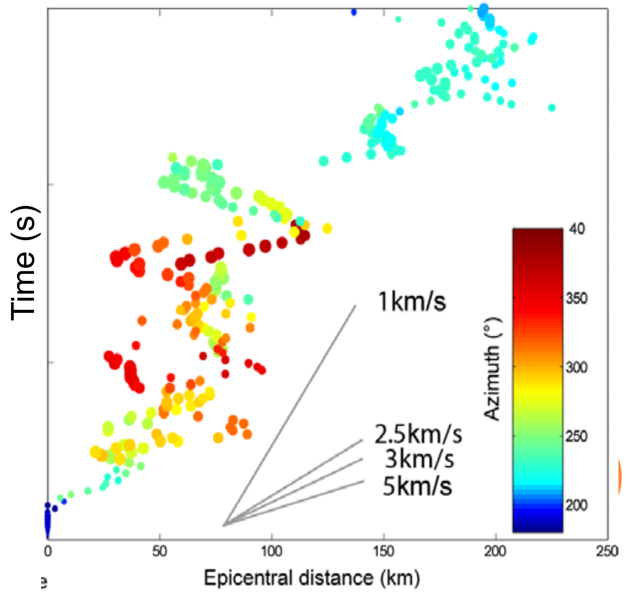
CONCLUSIONS

- The 2011 M9 Tohoku (Japan) earthquake featured a mixture of slow and fast rupture styles: a stage of slow, deep rupture propagation punctuated by bursts of high-frequency radiation
- These phenomena probe the mechanics of the brittle-ductile transition of natural faults
- Insight on fundamental up-scaling problems (micro/macro) in the physics of friction

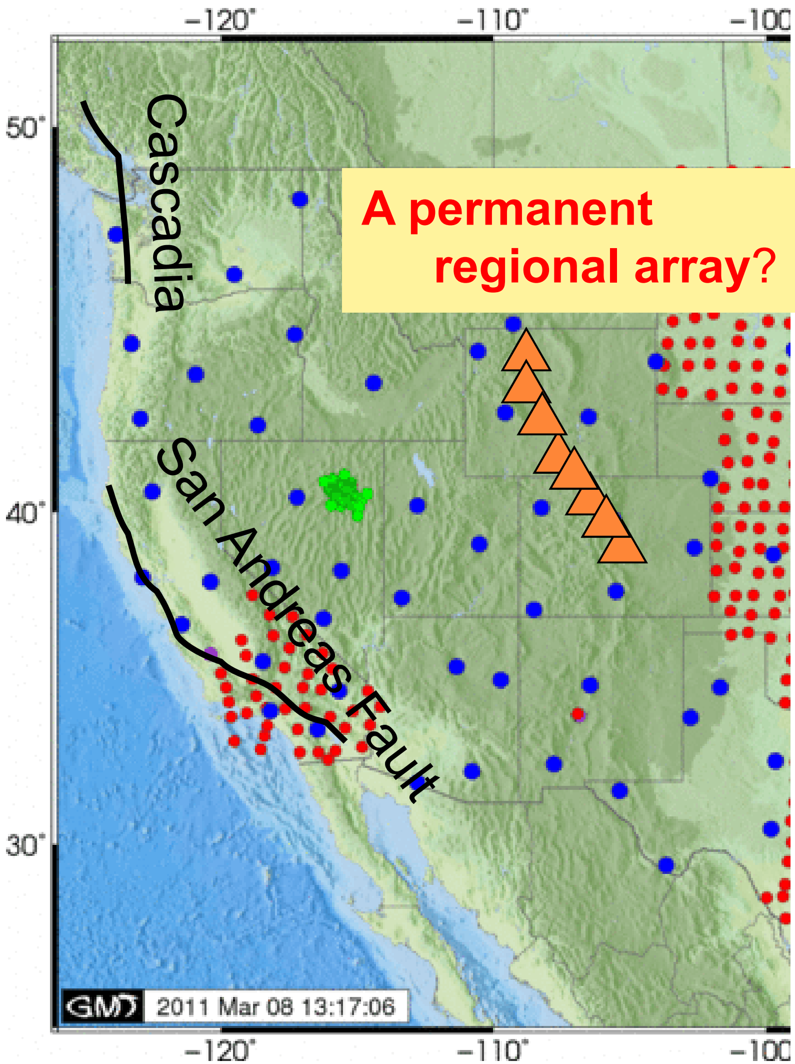
Perspectives:

- Mapping HF radiation sources in advance → strong ground motion prediction
  → earthquake hazard assessment
- Tracking the rupture in real-time
  → earthquake early warning systems for large ruptures

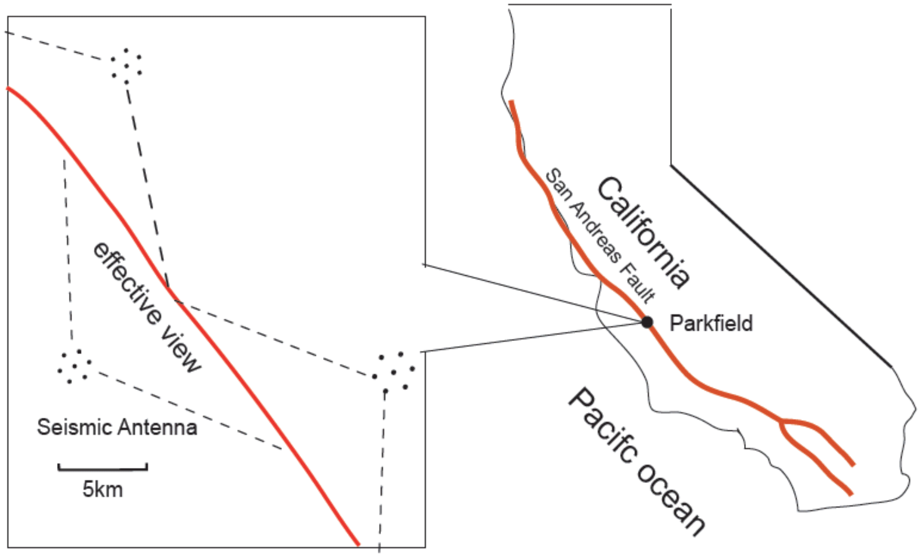




A permanent regional array?



A network of strong motion arrays?



A circum-Pacific OBS/floating array?