Insights on earthquake dynamics from high-frequency source imaging with dense seismic arrays

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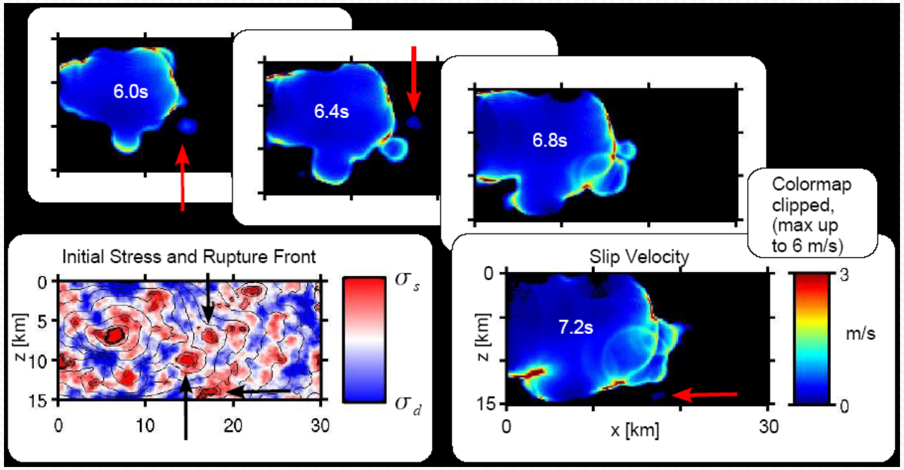
Acknowledgements:
Lingsen Meng, Alice Gabriel, Yihe Huang, Percy Galvez, Yingdi Luo, Asaf Inbal (Caltech and ETH Zurich)

Overview

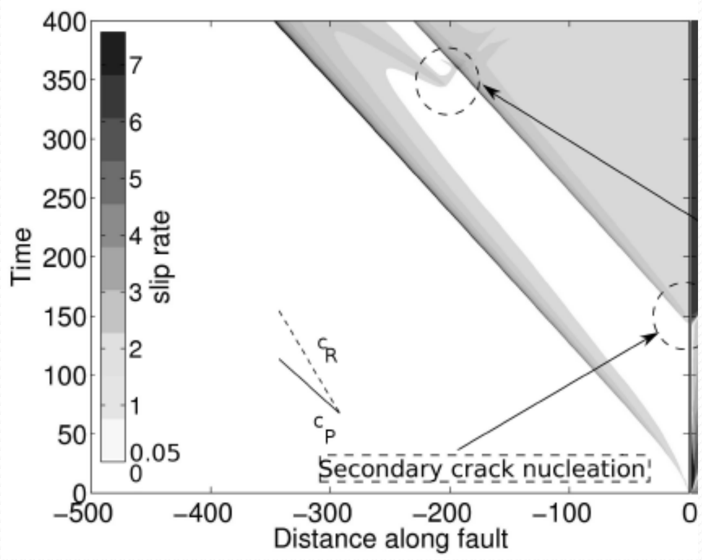
- Motivations: open questions in earthquake dynamics and limitations of finite source inversion
- Back-projection source imaging: basic principles and recent advances
- ~~Example 1: Tohoku 2011, fast and slow slip processes at the bottom of the subduction seismogenic zone~~
- Example 2: Indian Ocean 2012, rupture branching and the mechanics of the oceanic lithosphere
- Outlook: challenges and opportunities

Some open questions about earthquake source physics

- Fault rheology: which weakening mechanisms are dominant in real faults?
- Pulse vs crack ruptures: how short are earthquake rise times? (healing mechanisms)
- Earthquake source complexity: geometry and evolution of the rupture front, broad-scale heterogeneity, variability of rupture speed, high vs low frequency slip

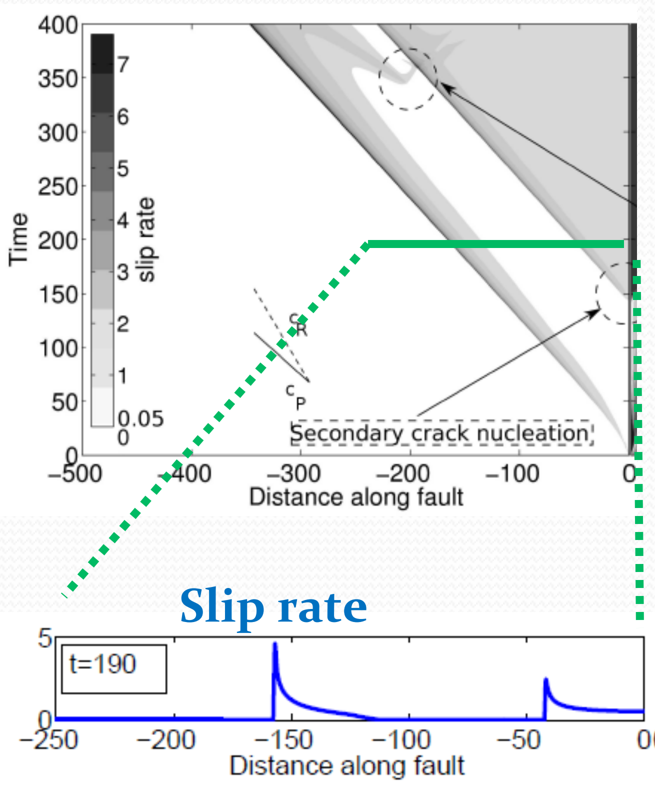


from Rippeger et al (2007)

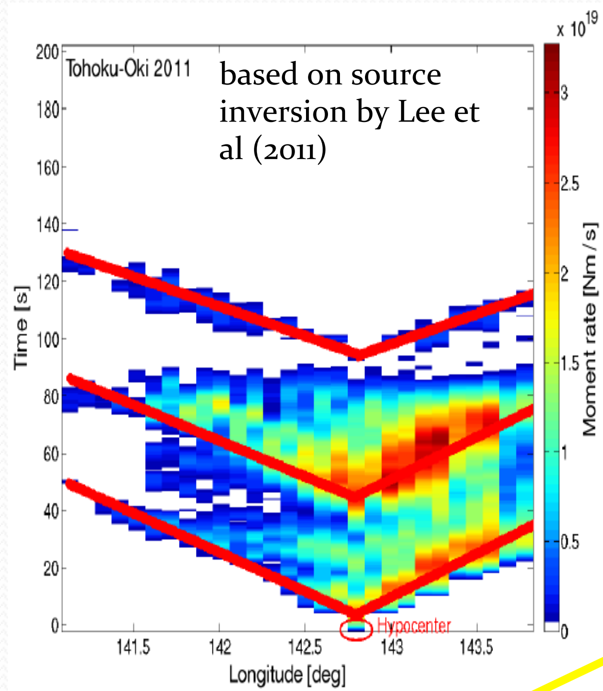


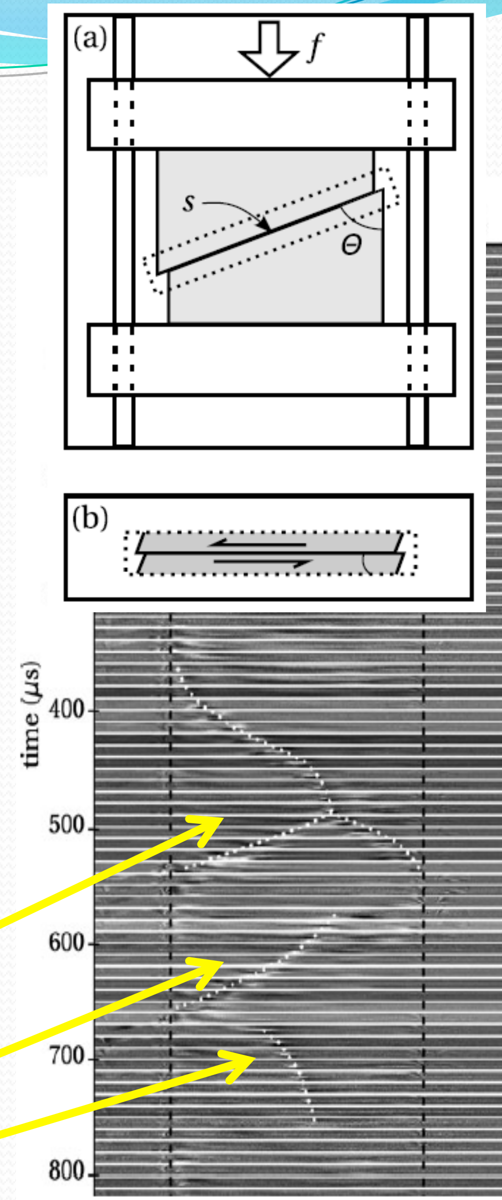
Gabriel et al (2012)

Rupture complexity: multiple rupture fronts



Gabriel et al (2011)





Rupture front splitting

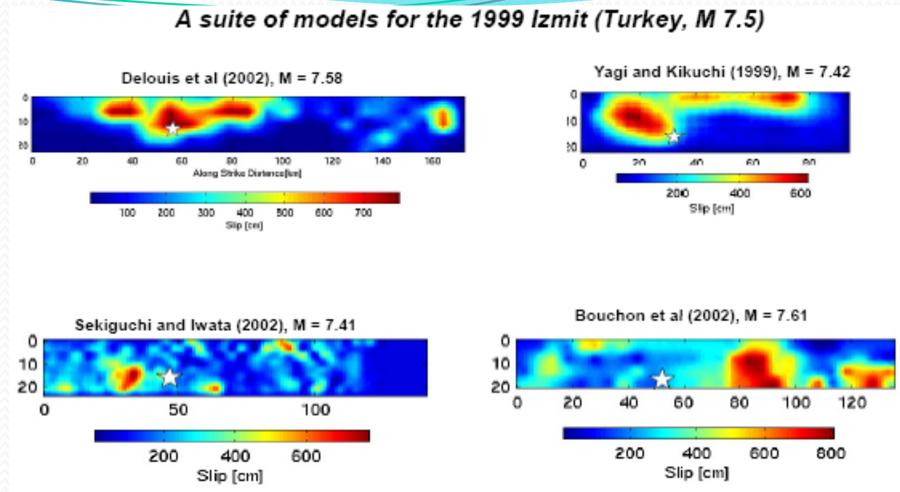
Repeated front

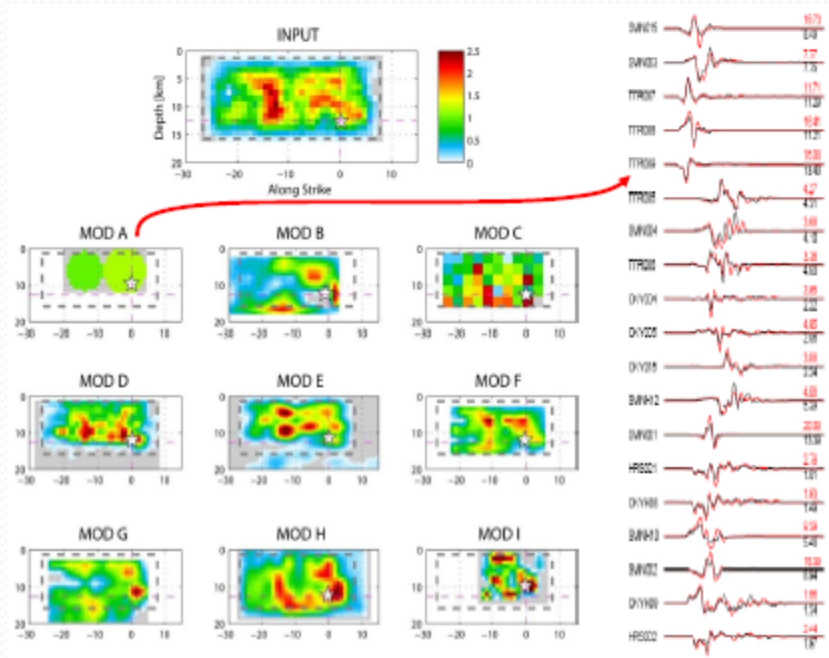
Reverse front

Nielsen et al (2010)

Intrinsic limitations of source inversion

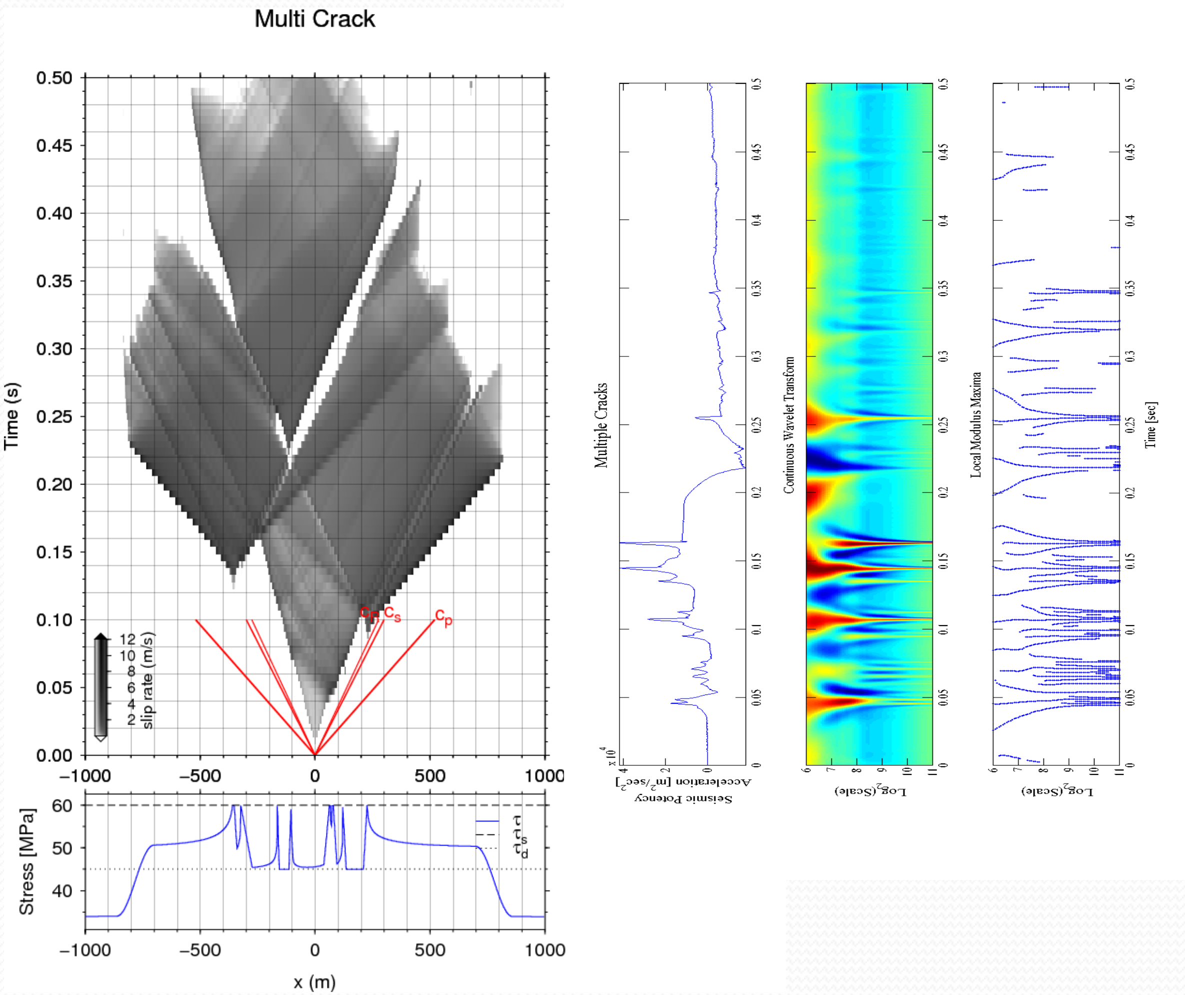
- Source inverse problem: infer the space-time distribution of slip from seismological + geodetic + field data
- Poor knowledge of the crust structure at small scales → only low frequencies (<1Hz) are exploited
- Resulting slip models are notoriously heterogeneous (spatial variability)
- However, the inverse problem is intrinsically ill-posed → limited spatial resolution (>10km)
- Can we distinguish real source complexity from inversion artifacts?





from Mai and SIV

High-frequency source radiation

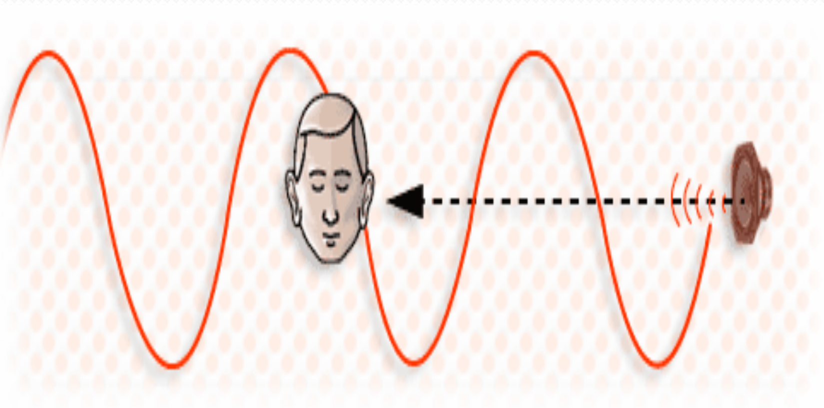


A dynamic rupture model with initial stress concentrations

Multi-scale (wavelet) analysis of source time function

→ relation between high-frequency radiation and rupture complexity

Array processing, examples from daily life
Goal: estimate direction of arrival of waves → locate the source



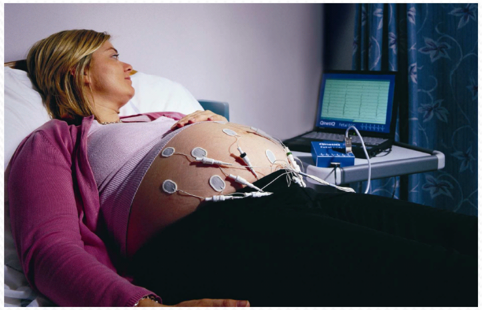
Sound localization:

Our ears use the arrival time delay of sound to pinpoint the location of the source

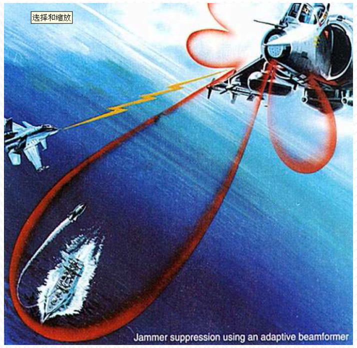
This works also for a moving source

Telecommunication

Sonar



Medicine



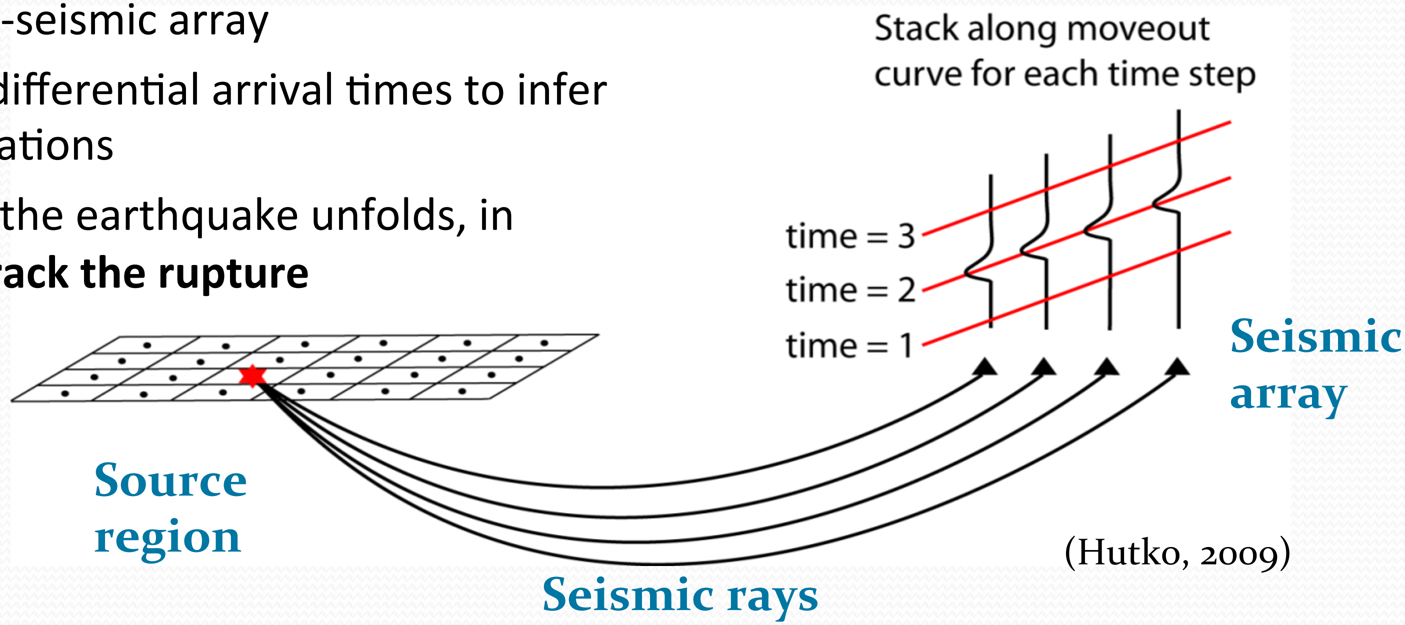
Radar

Earthquake source imaging by back-projection of teleseismic array data

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**



(Hutko, 2009)

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

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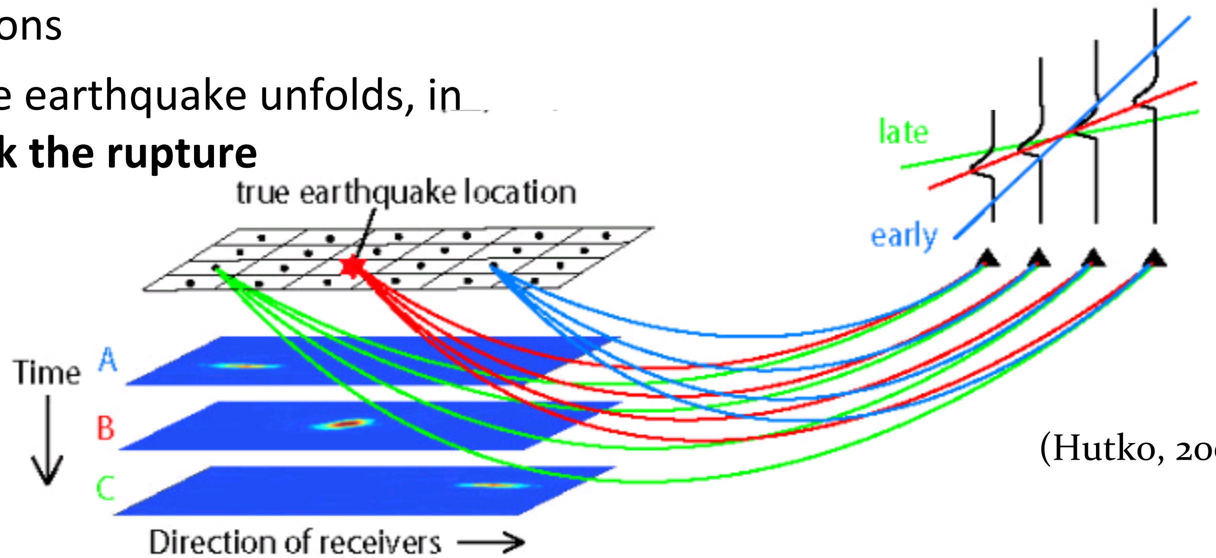
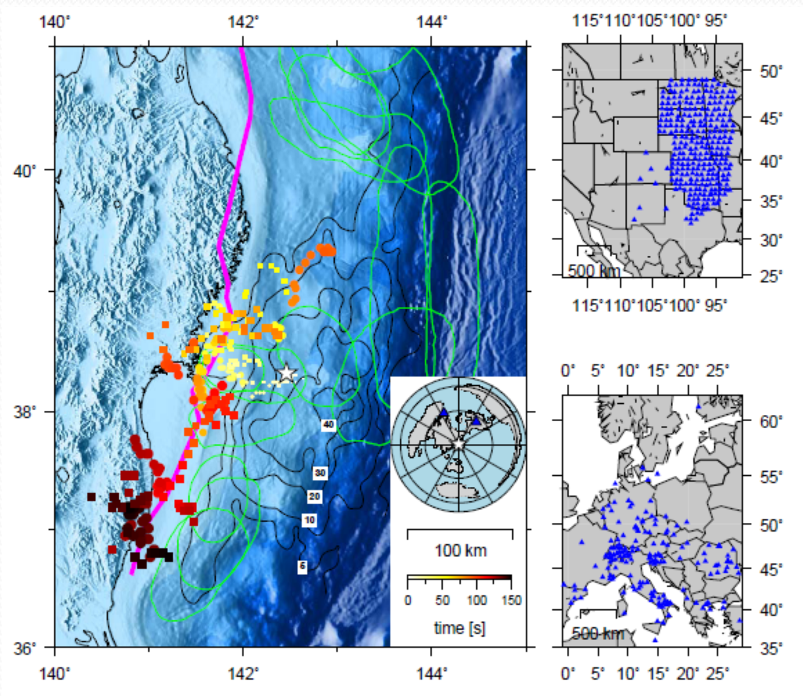


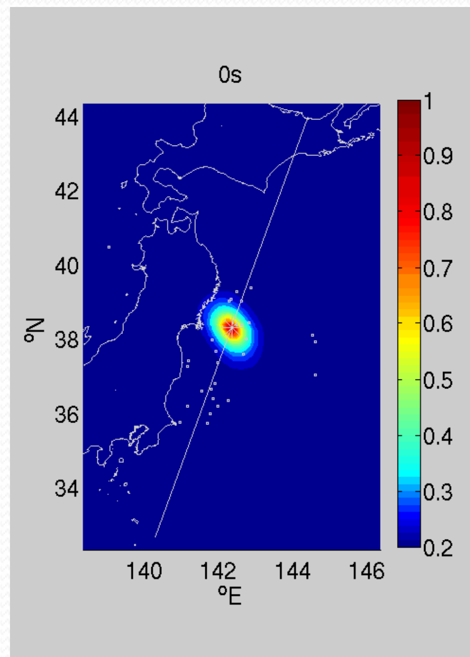
(Hutko, 2009)

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

ADVANCES IN BACK-PROJECTION SOURCE IMAGING

MUSIC → resolve multiple simultaneous sources
+ multitaper → resolve non-stationary signals
+ reference window → avoid swimming artifacts





2011 Tohoku-Oki earthquake (Meng et al, 2011)

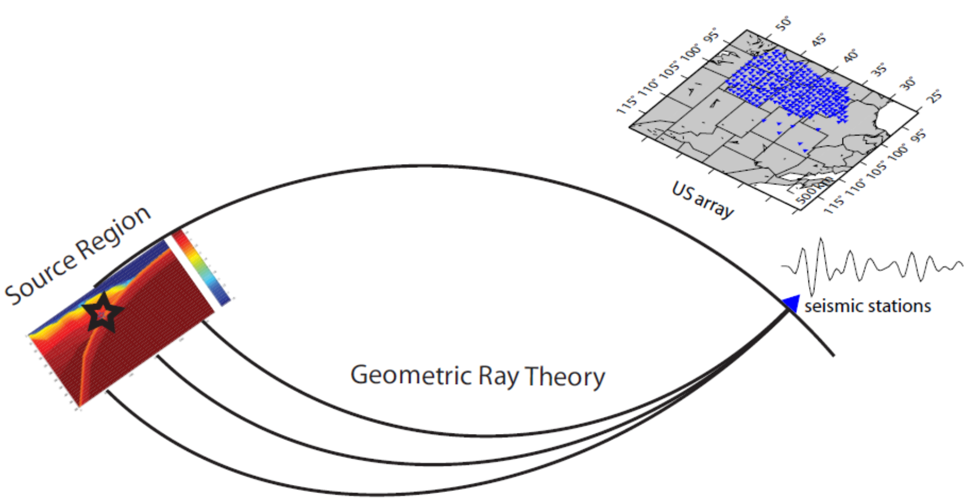
Benefits:

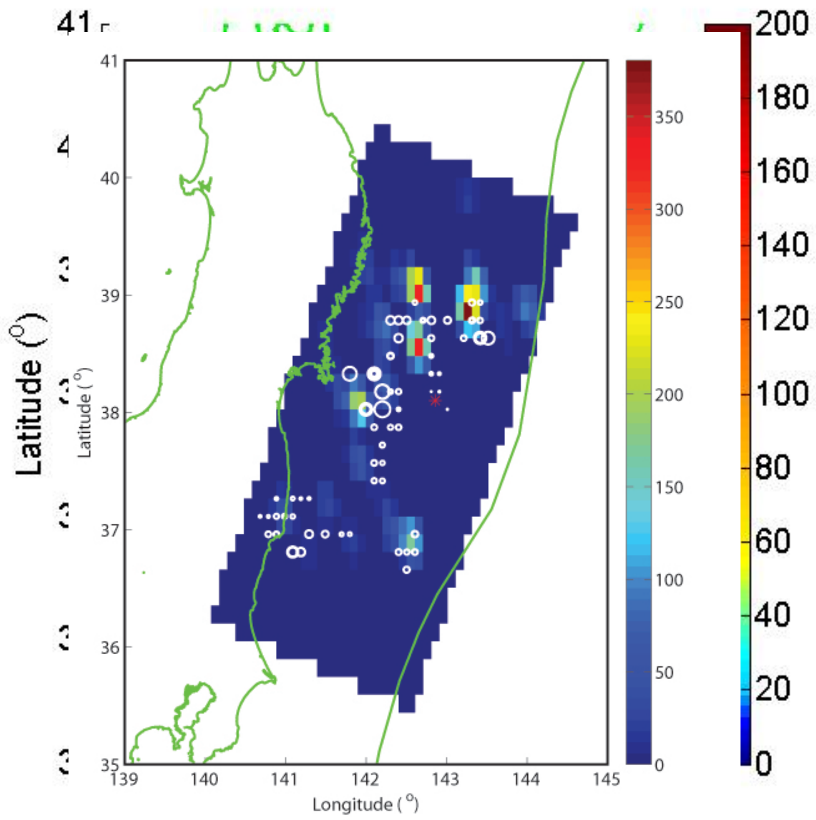
No a priori assumptions on rupture kinematics and size

High frequency view of the rupture process, complementary to low frequency finite fault modeling

Robustness of back-projection source imaging

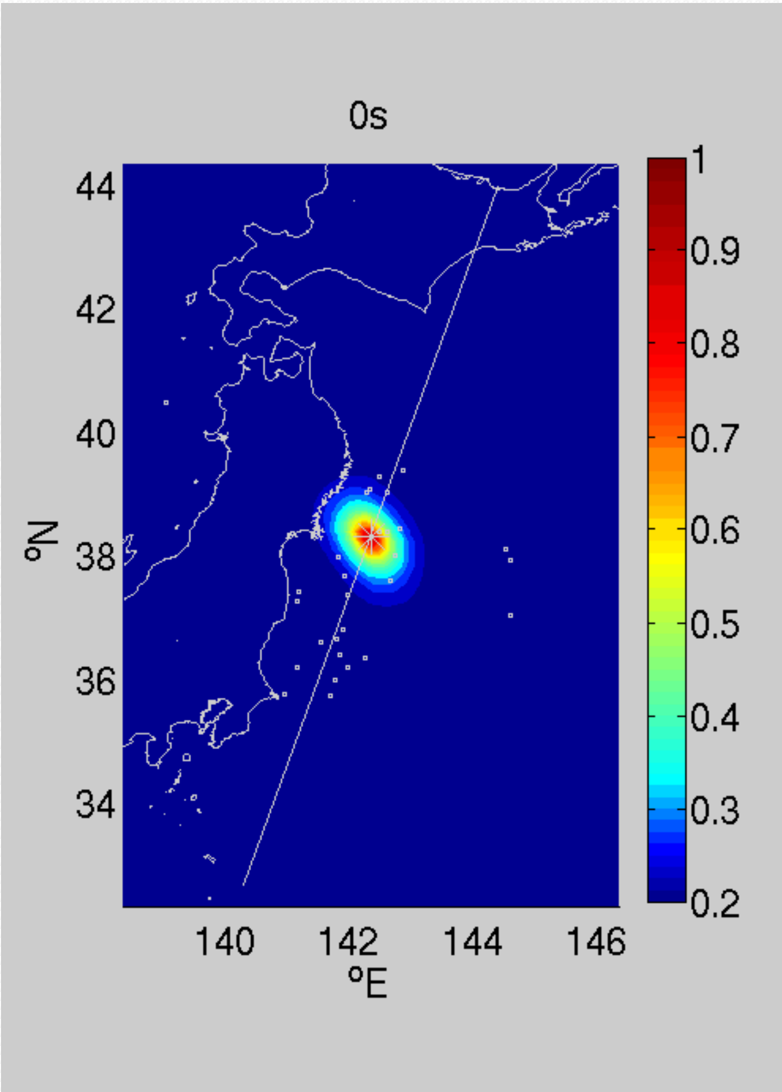
Synthetics tests with realistic source and velocity model

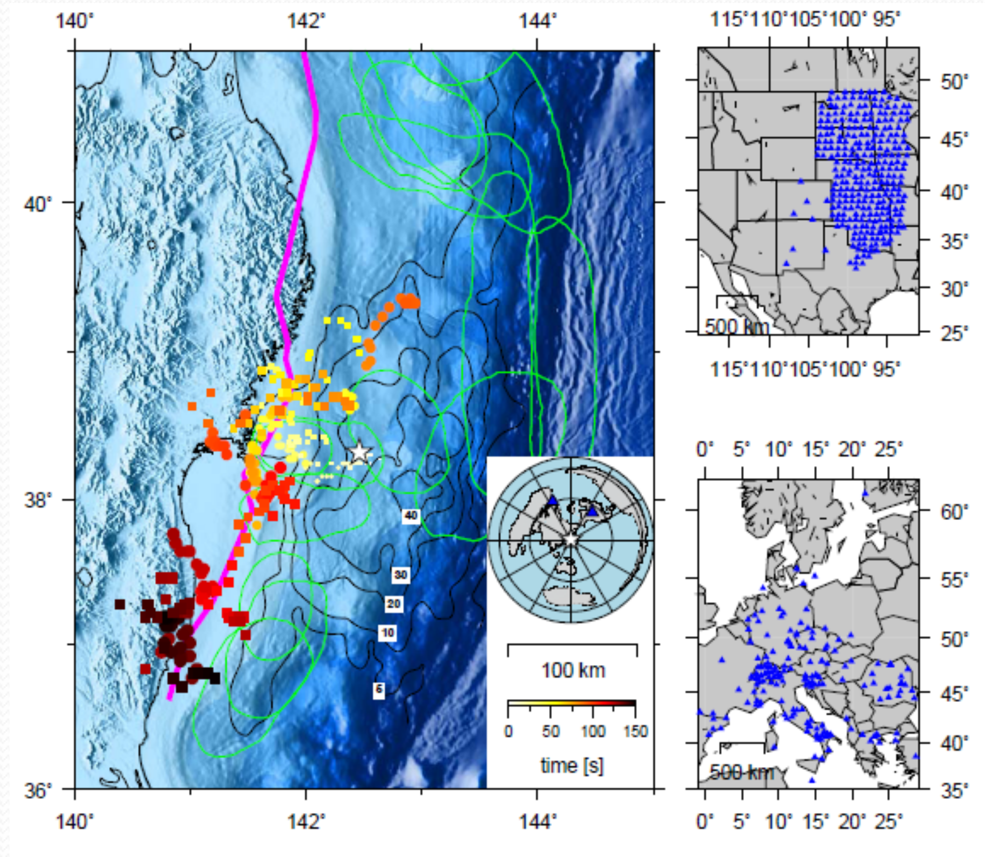




- Source locations are well retrieved at 1 Hz
- Absolute amplitudes are less reliable (interference, incoherency)
- How to combine multiple arrays?
- How to integrate with (low freq) finite source inversion?

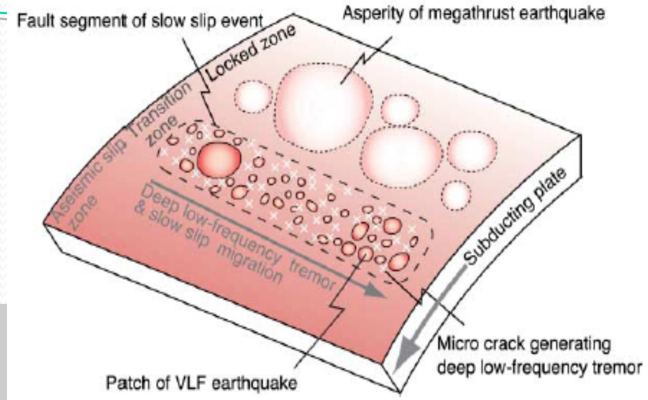
2011 Tohoku earthquake



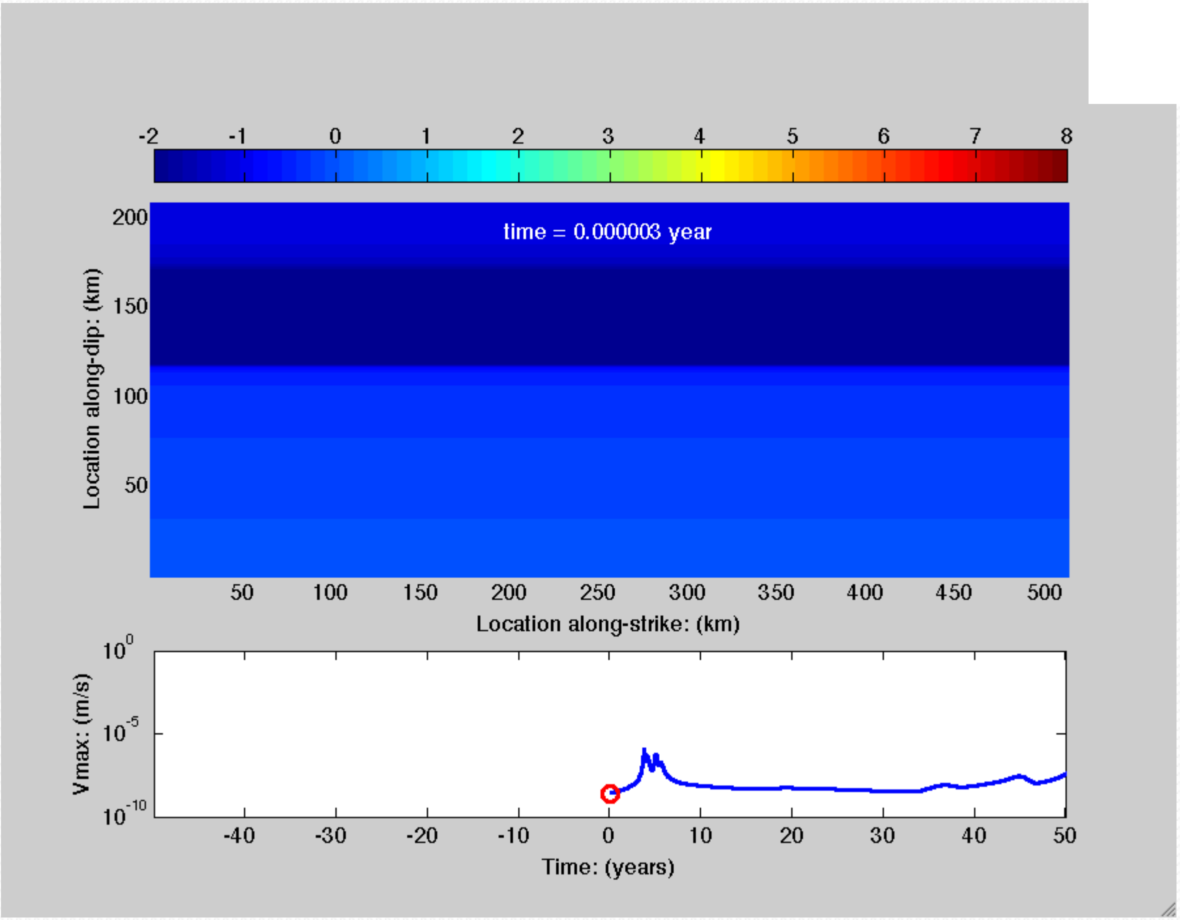


High-freq slip at the deep edge of the low-freq slip
Downdip slow rupture with high freq bursts
(Simons et al, Meng et al 2012)

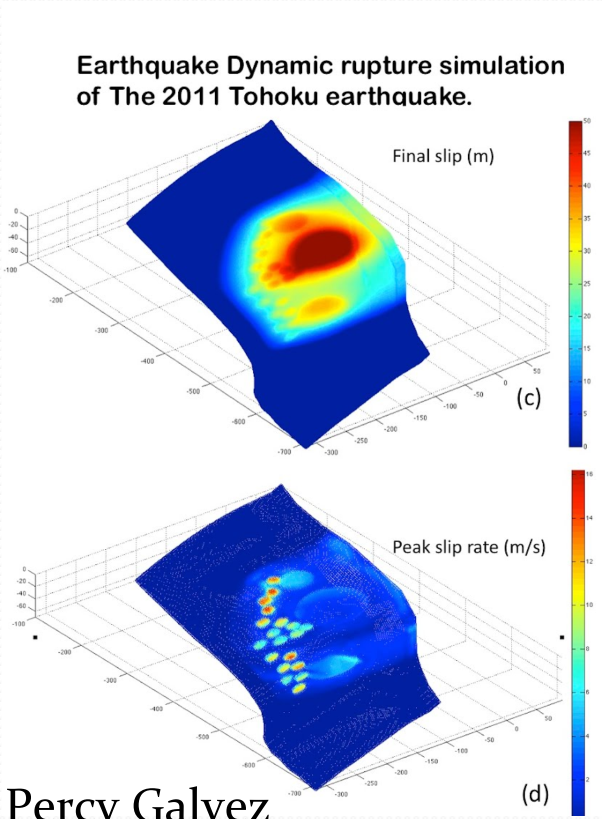
Dynamic modeling



Ito et al (2007)

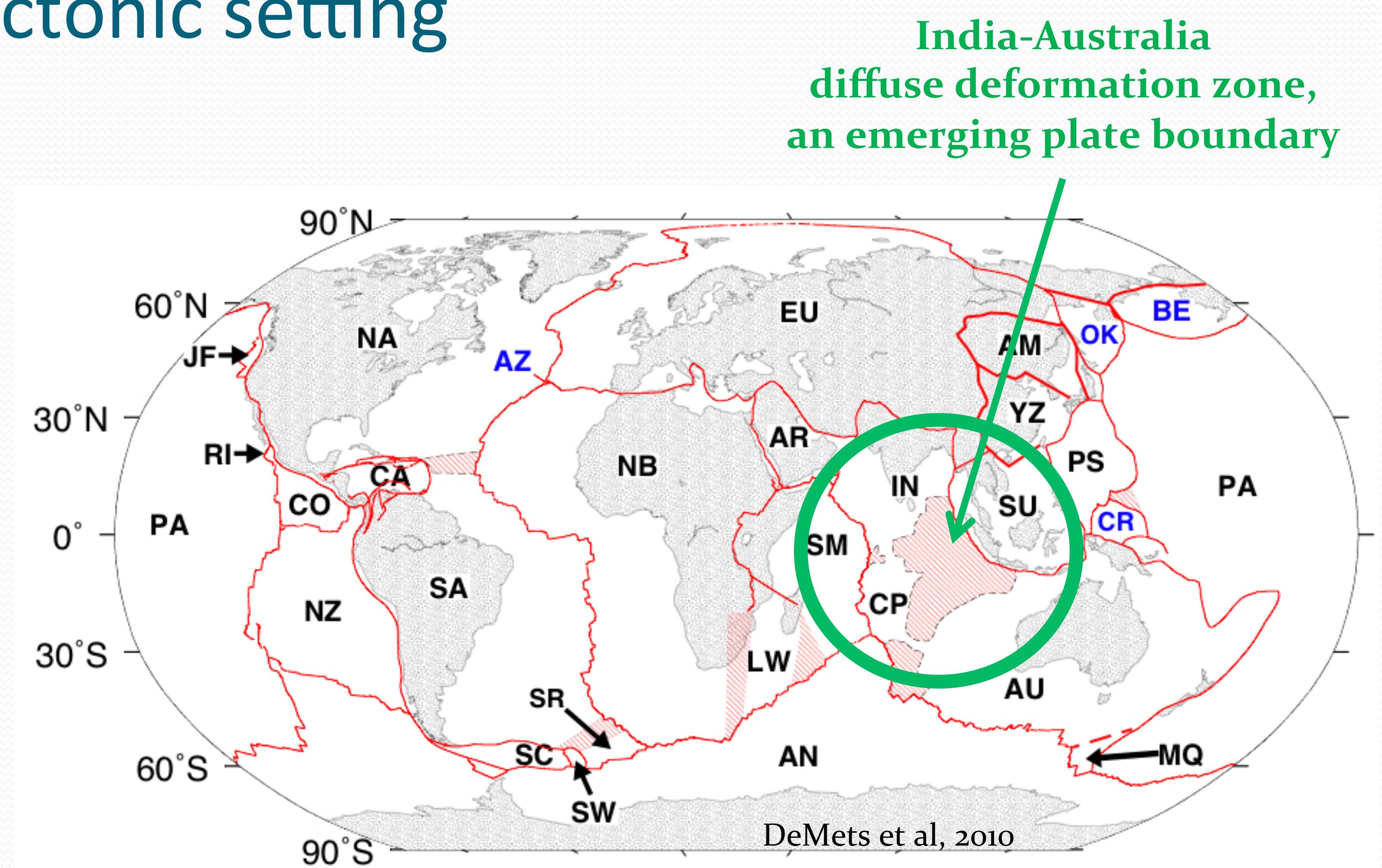


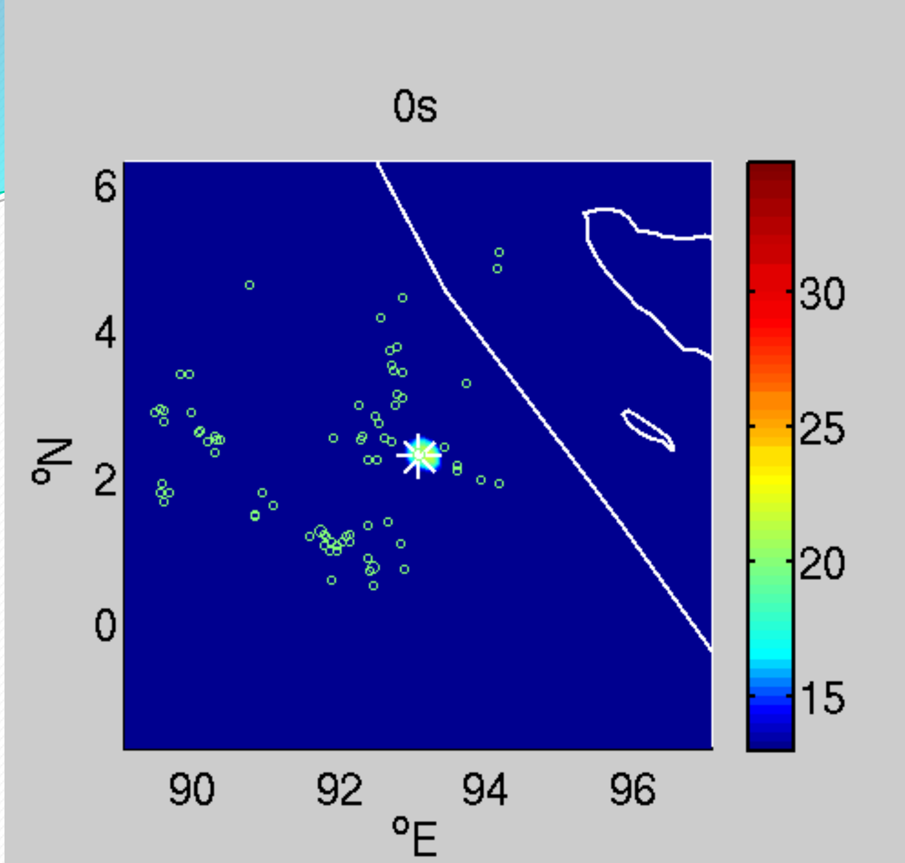
Yingdi Luo, earthquake cycle simulations



Percy Galvez

The 2011 M8.6 Indian Ocean earthquake
Tectonic setting

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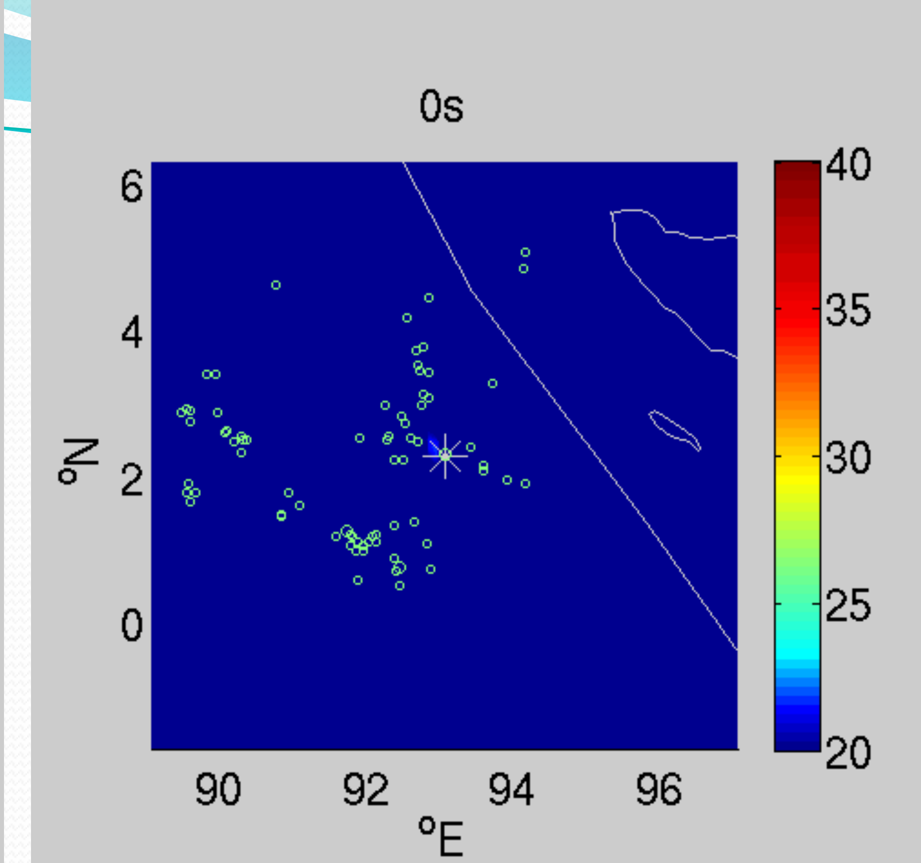
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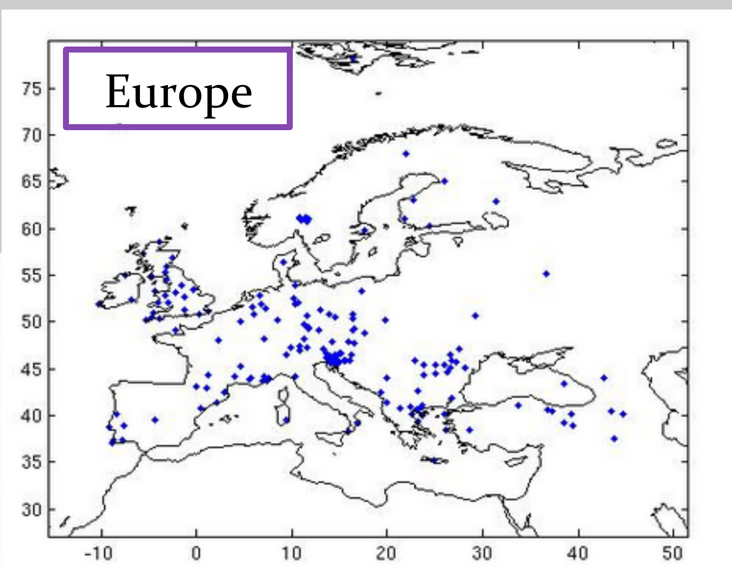
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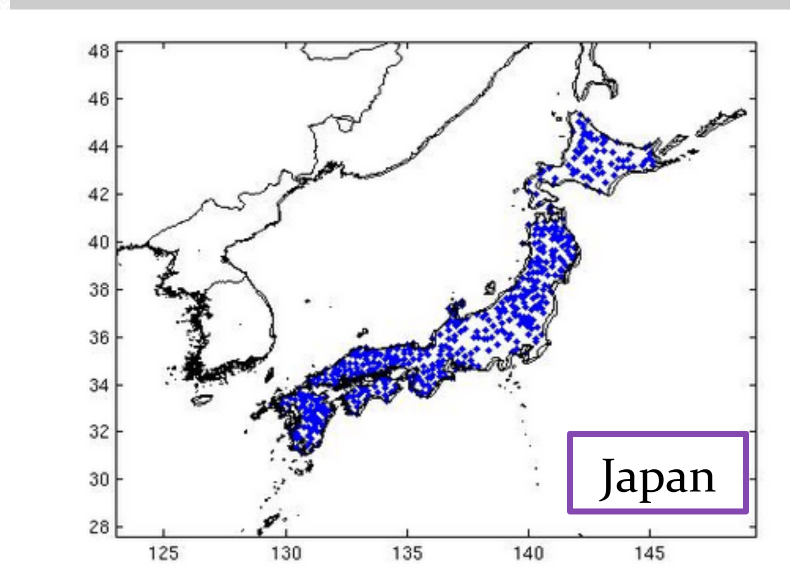
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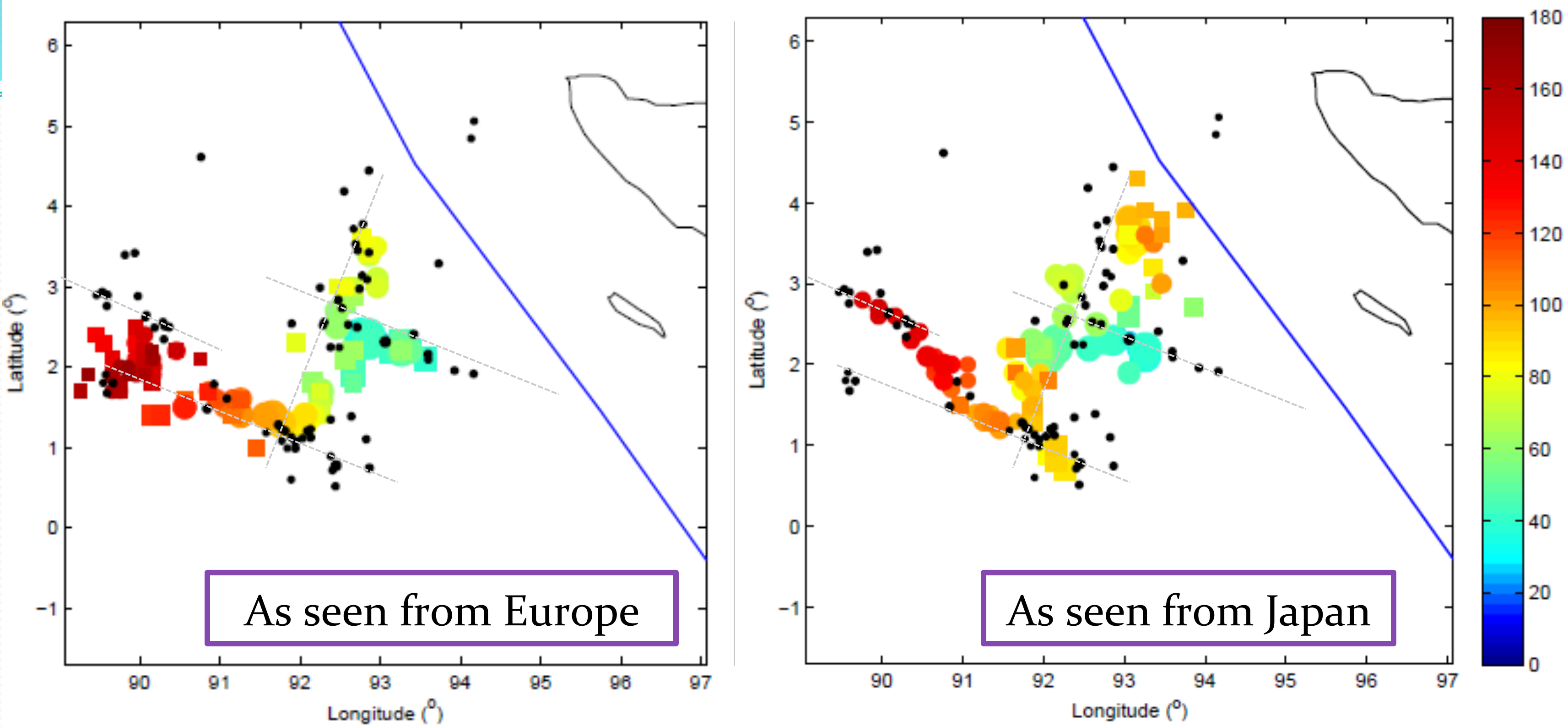
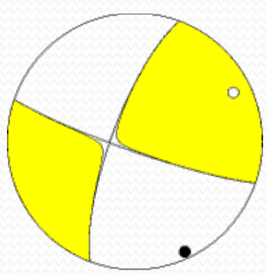
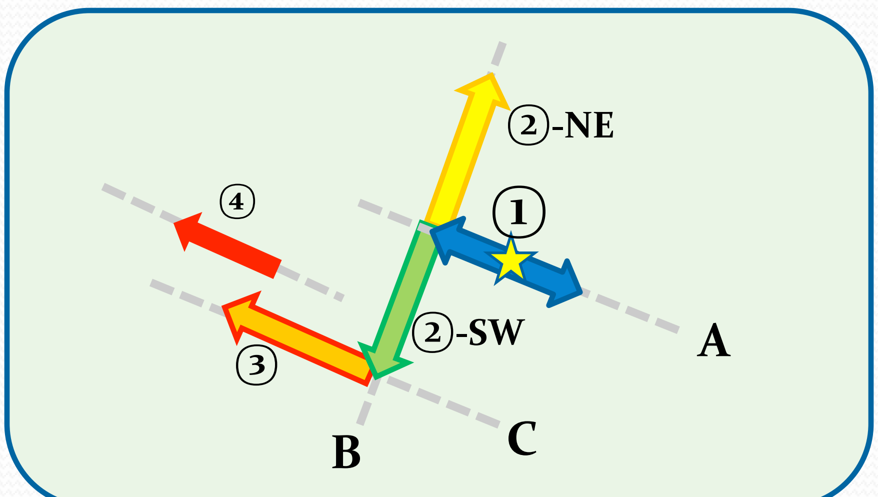
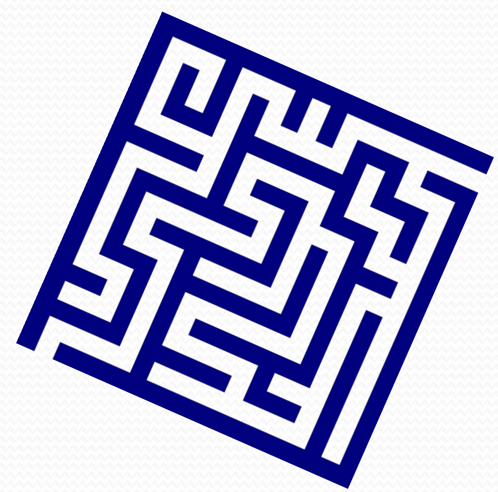


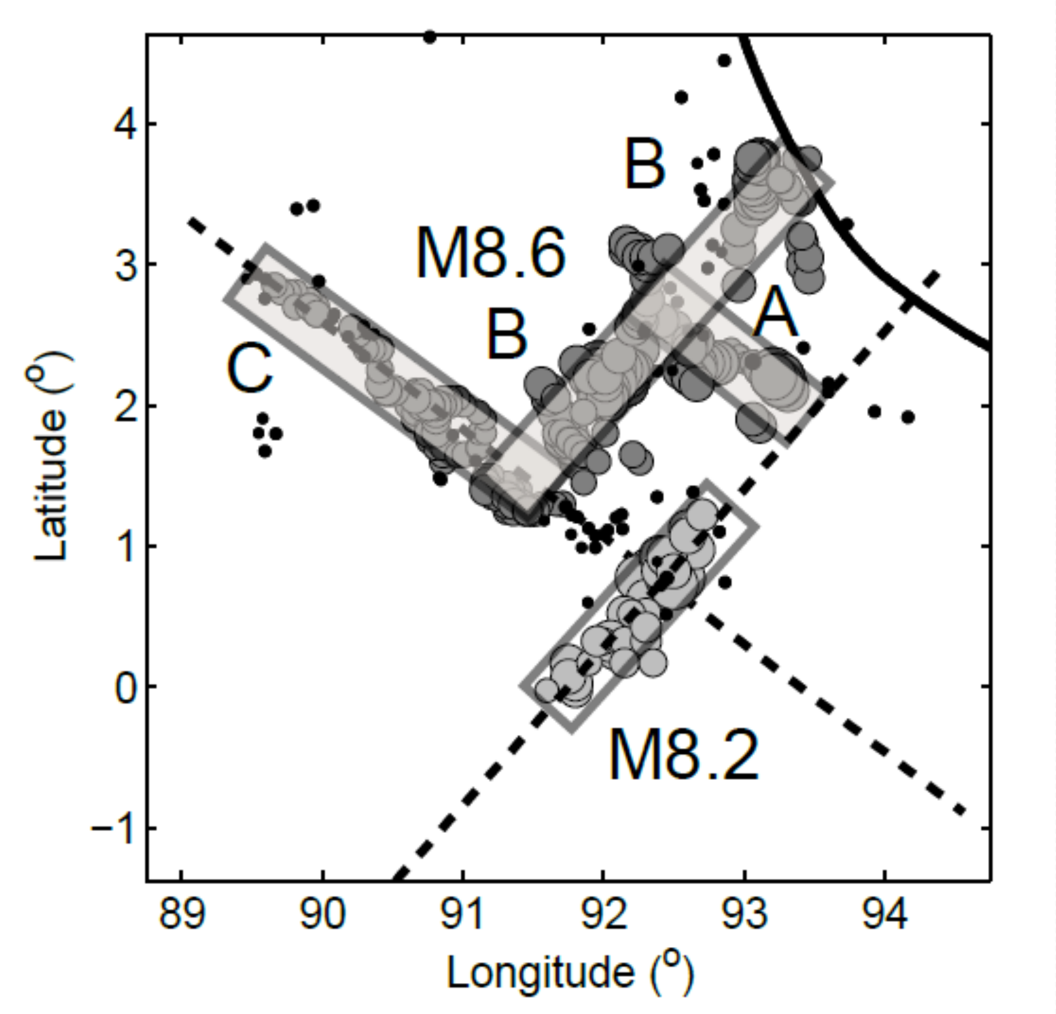






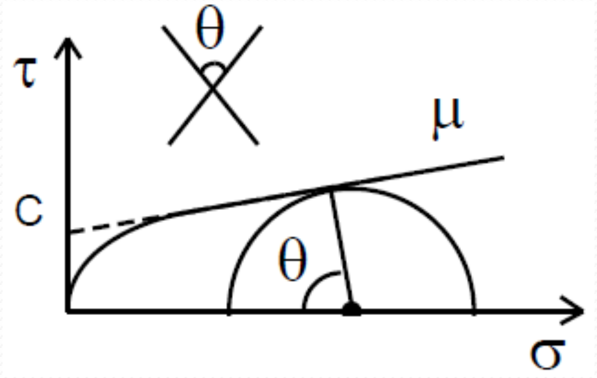
Meng et al (2012)

Conjugate orthogonal faults

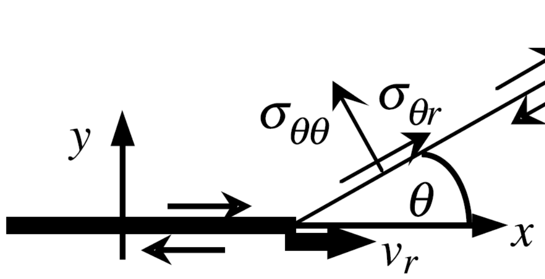


Orthogonal faulting confirmed by the rupture pattern of the largest (M8.2) aftershock

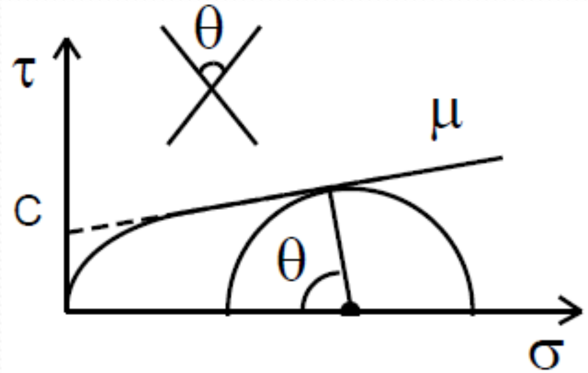
Mechanical implication: pressure-insensitive strength (low apparent friction coefficient μ)

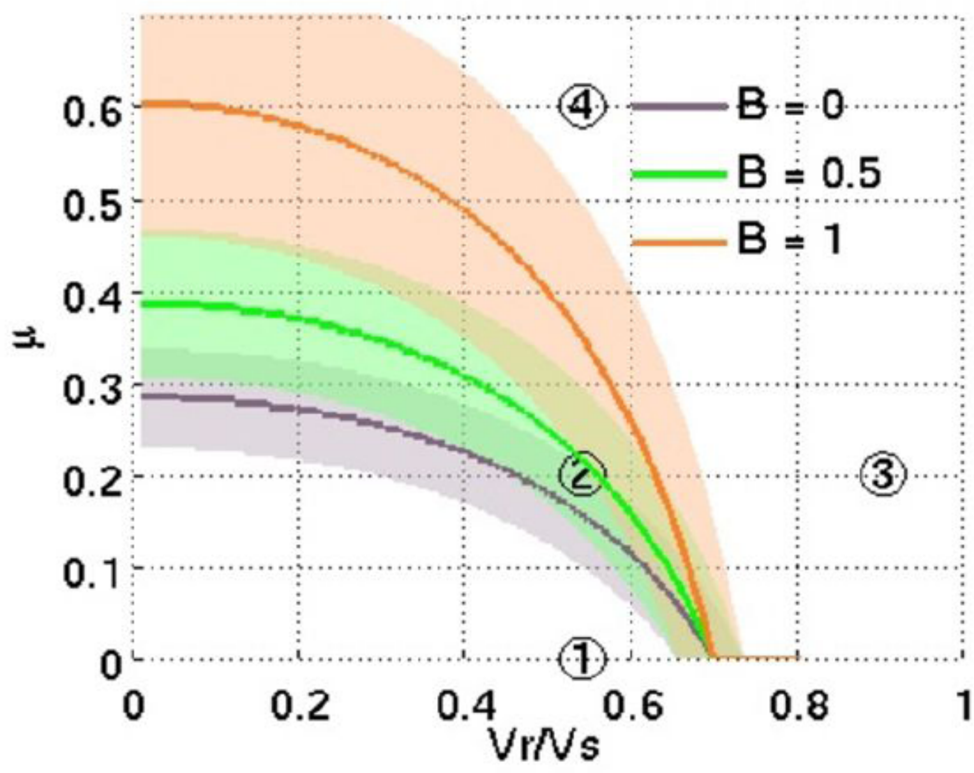


How can a rupture take the “wrong turn” ?



Poliakov et al (2002)



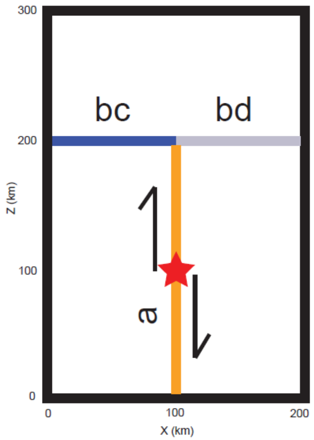


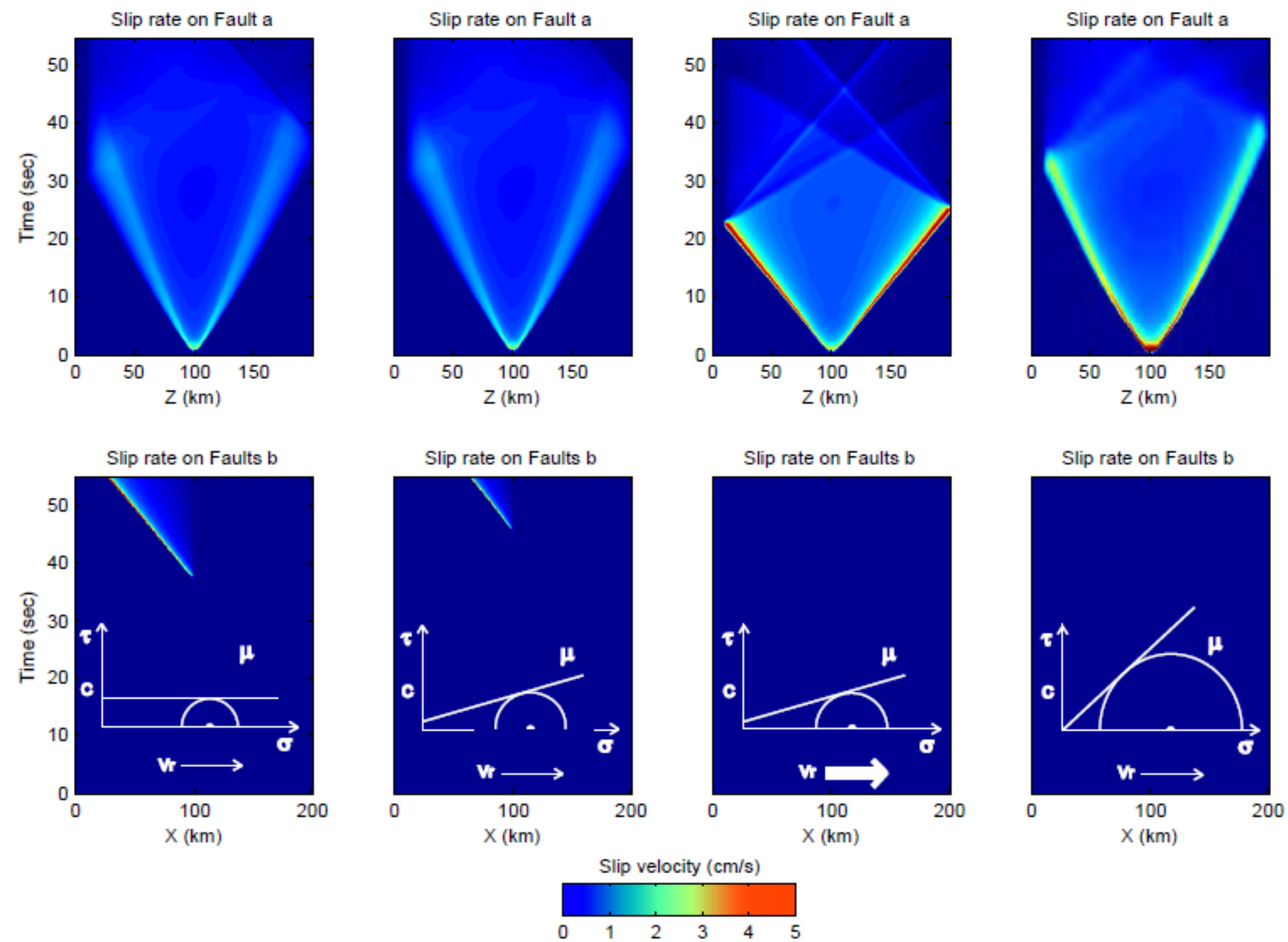
Dynamic stress analysis: compressional branching requires

- Low pressure-sensitivity (low apparent friction coefficient μ) and
- Low rupture speed

(Poroelasticity helps equalizing the chances of rupture branching to either side)

Theoretical expectations confirmed by dynamic rupture simulations



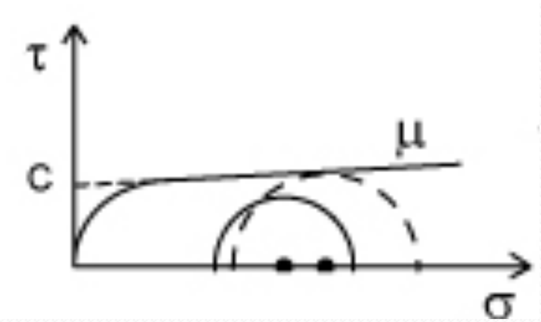


Implications on the rheology of the oceanic lithosphere

Compressional branching requires

- Low pressure-sensitivity (low apparent friction coefficient μ):
- Low rupture speed
- Fluids can help (poroelastic effect)

But why was the compressional branch preferred?



Origin of low friction and dynamic weakening?

• Serpentinized(hydrated) upper mantle, requires deep fluid infiltration trough fault zone channels. But serpentinization reaction is limited to ~25 km depth

• Shear heating instability (Kelemen and Hirth, 2007) possible from 40 to 60 km depth

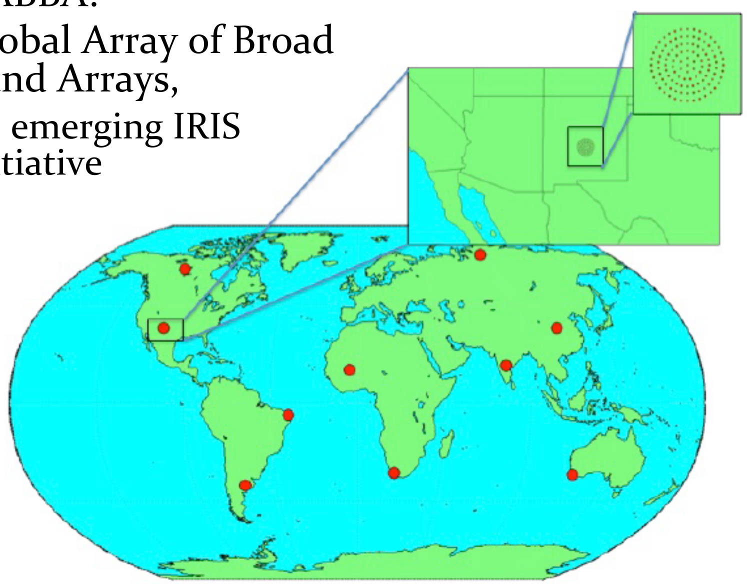
• Dynamic rupture through ductile region at intermediate depth (25-40 km)

How deep can a rupture propagate?

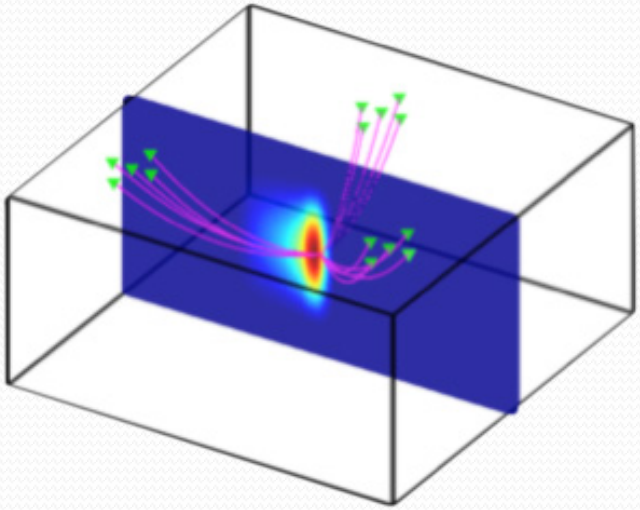
Can rupture break through a creeping fault section?

Array of Arrays: from global to local scales

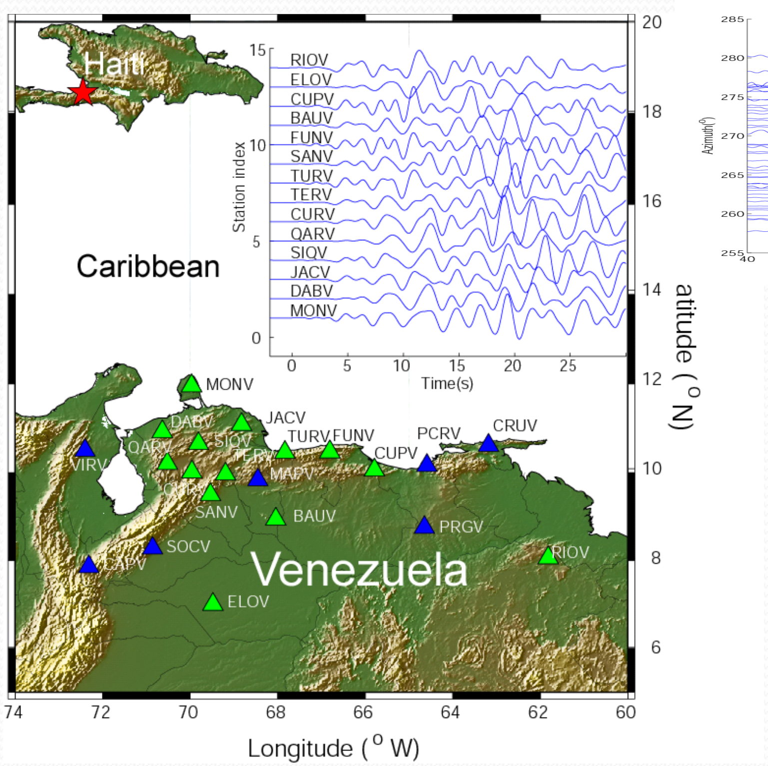
GABBA:
Global Array of Broad Band Arrays,
an emerging IRIS initiative



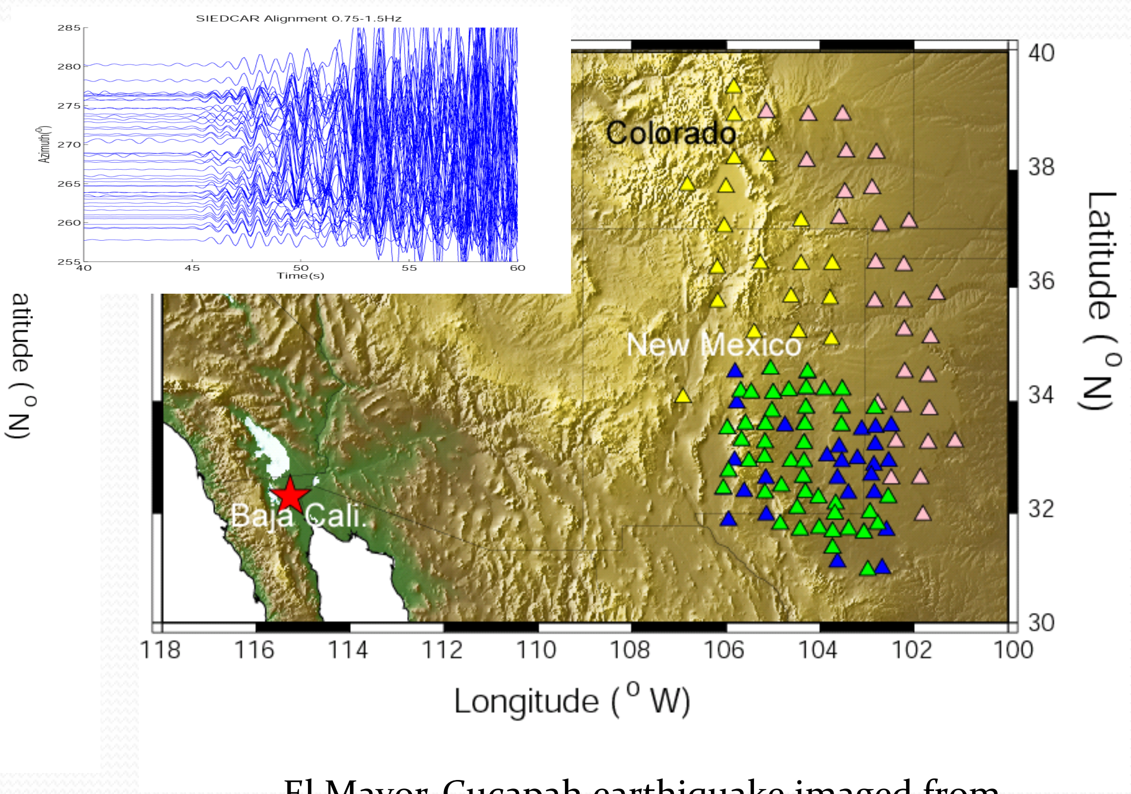
ANTS:
Arrays Networked to Track Sources
an emerging concept for Earthquake Early Warning



Back-projection at regional scales



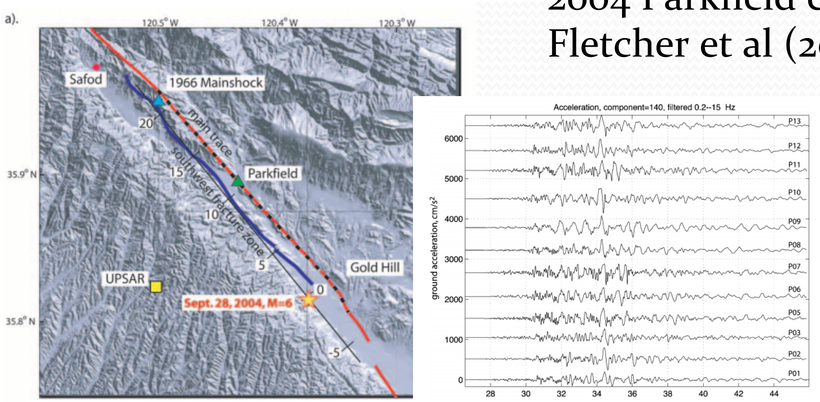
Haiti earthquake imaged from Venezuela (Meng et al, 2012)

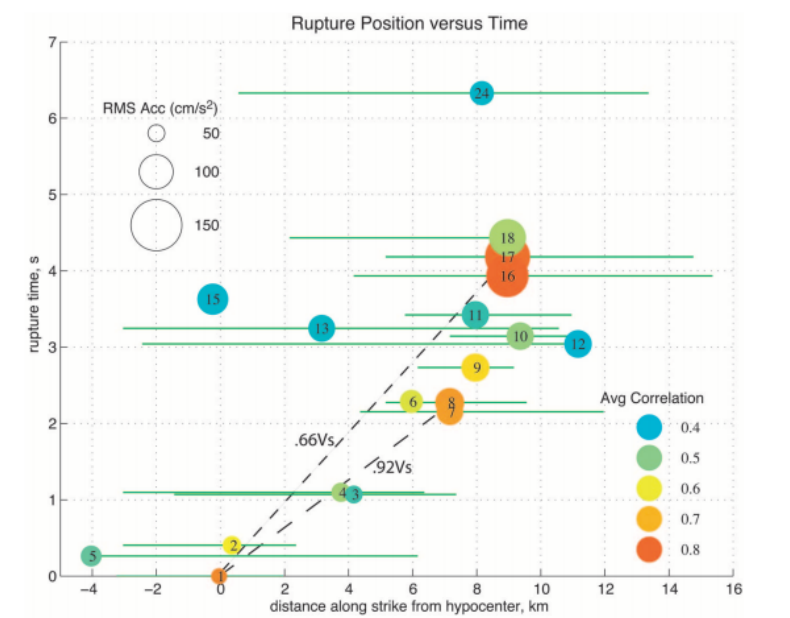


El Mayor-Cucapah earthjquake imaged from New Mexico (Meng et al)

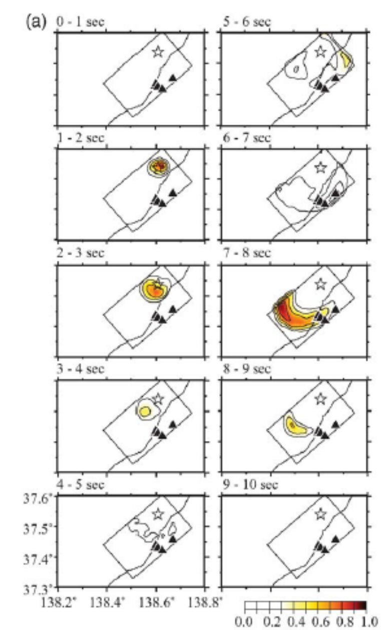
Source imaging with strong motion arrays

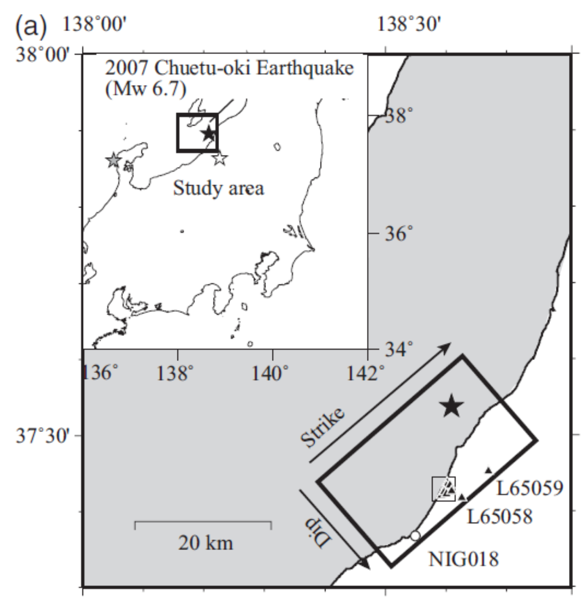
2004 Parkfield earthquake
Fletcher et al (2006)

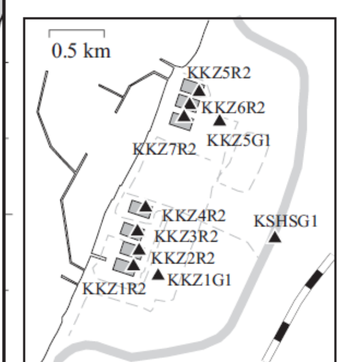




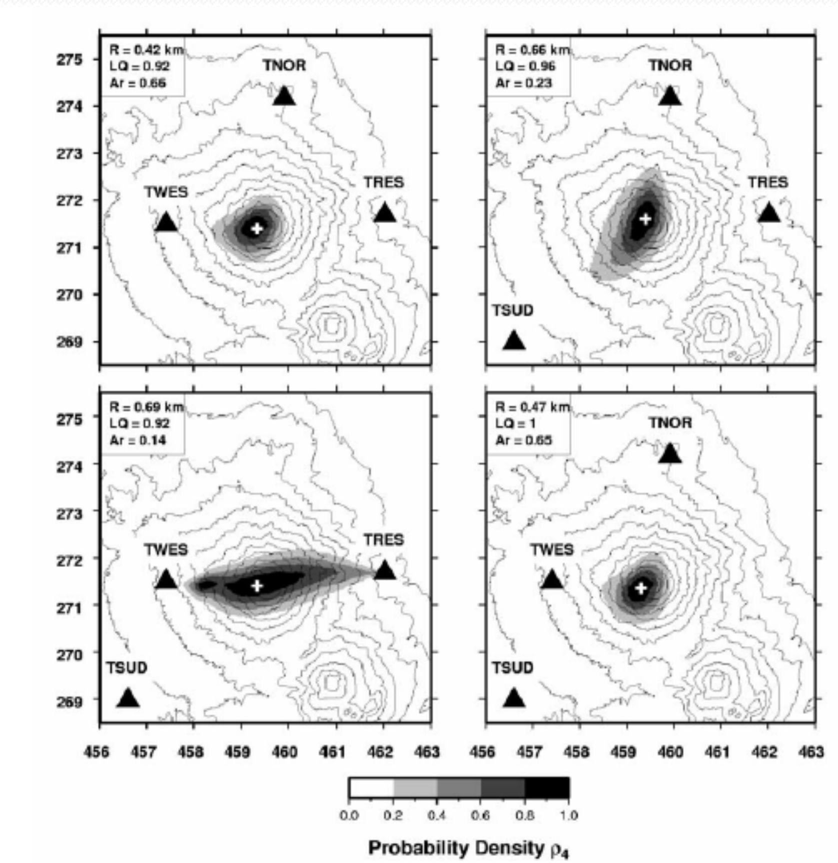
2007 Chuetsu-Oki earthquake
Honda and Aoi (2009)



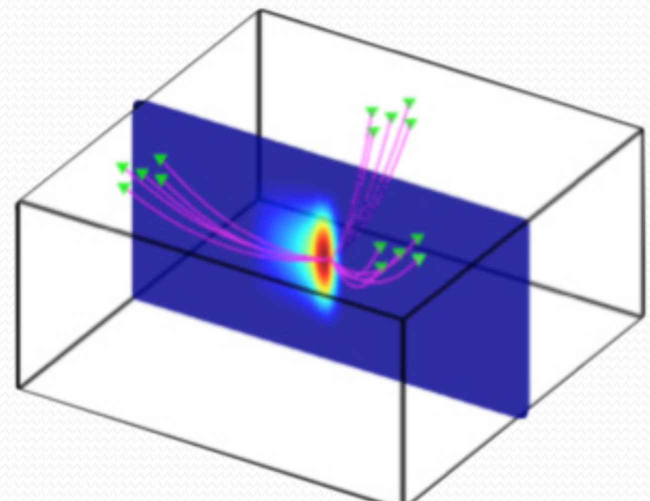




Multiple arrays monitoring volcanic tremors



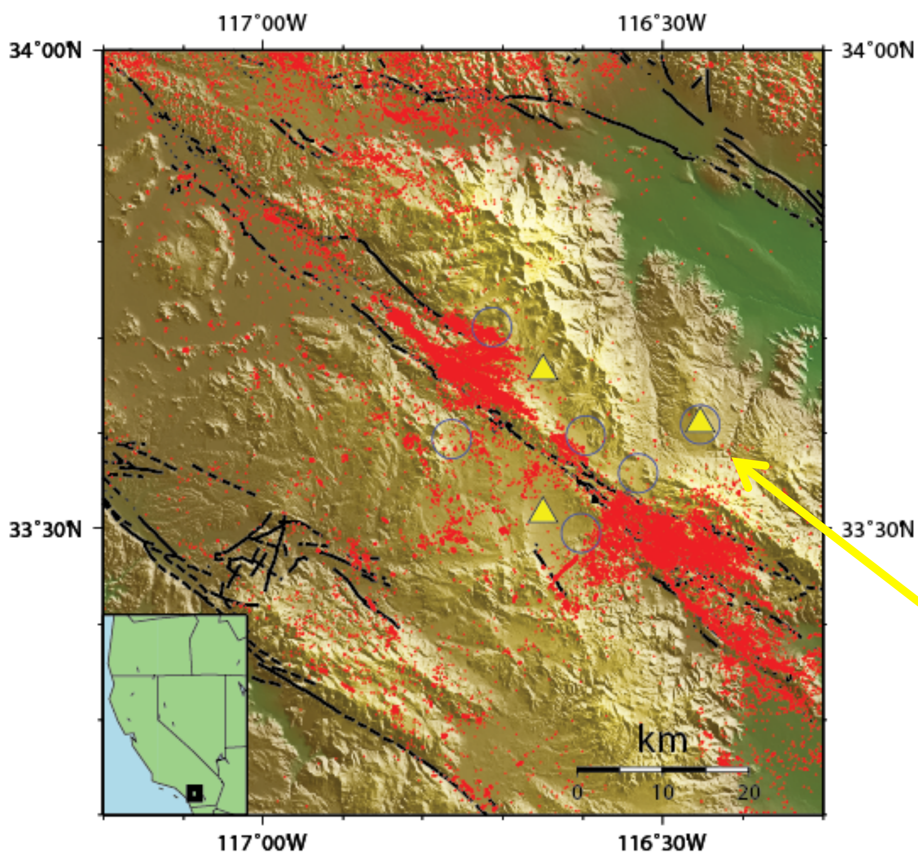
Each array estimates an azimuth
The azimuths from all arrays are then combined to estimate the source location (Metaxian et al, 2002)



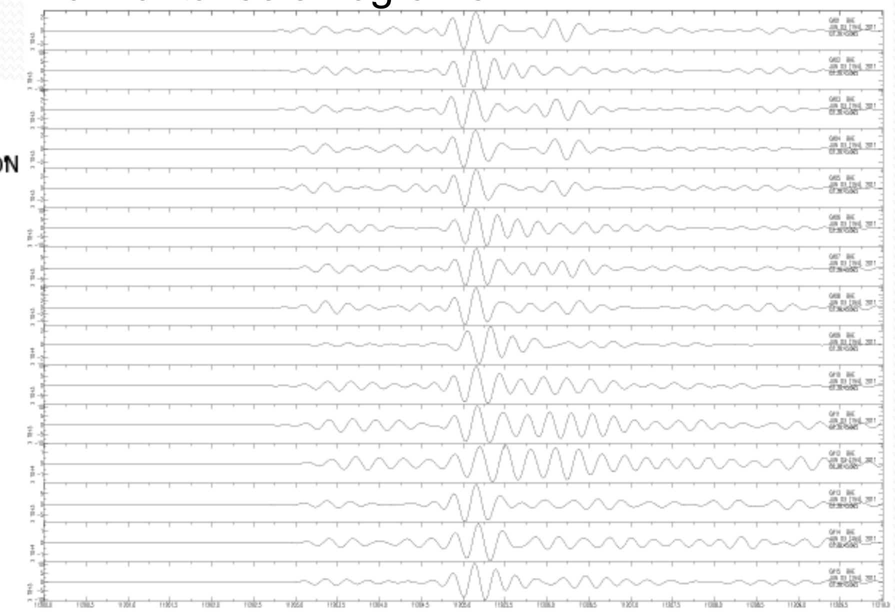
ANTS concept:

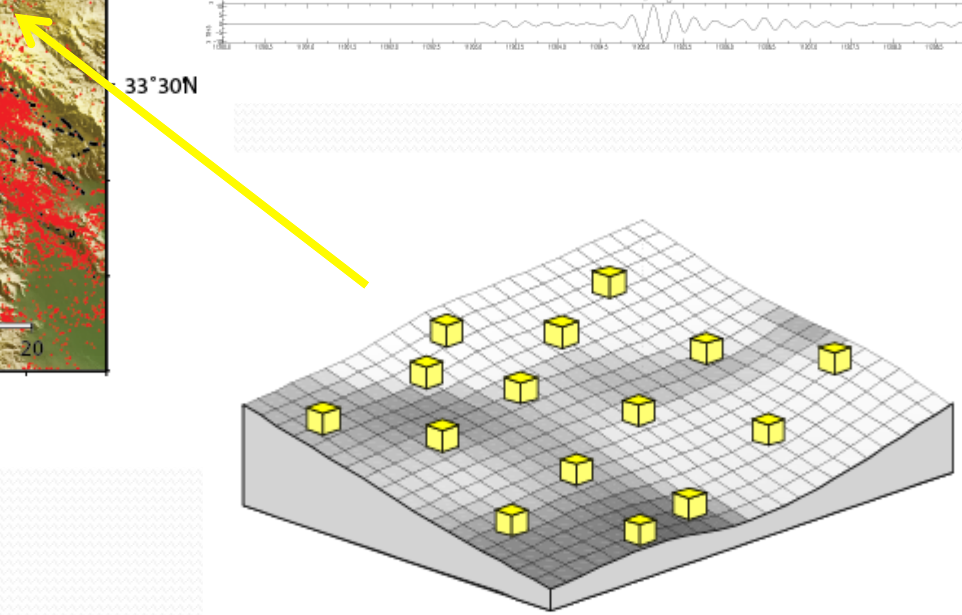
Arrays Networked to Track Sources

Anza arrays experiment



Horizontal seismograms 2-4 Hz





Asaf Inbal

Long Beach ultra-dense array

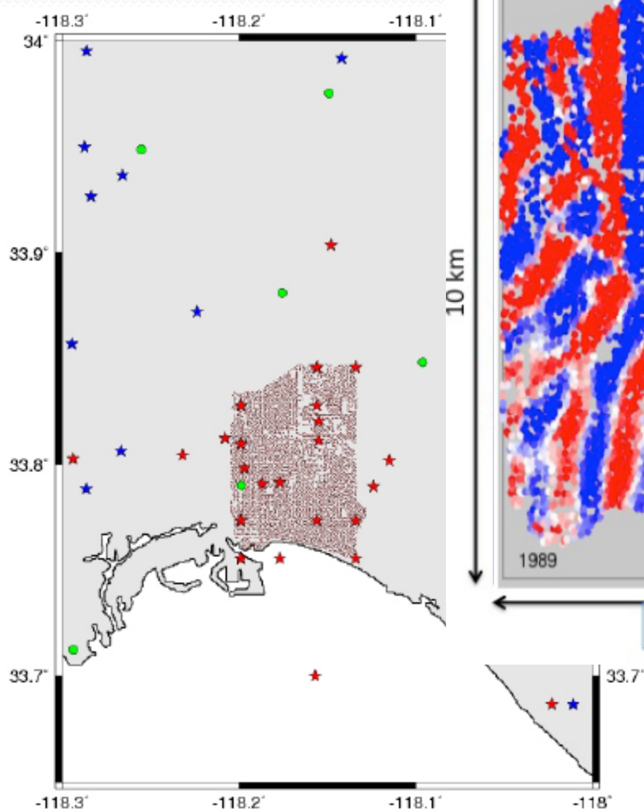
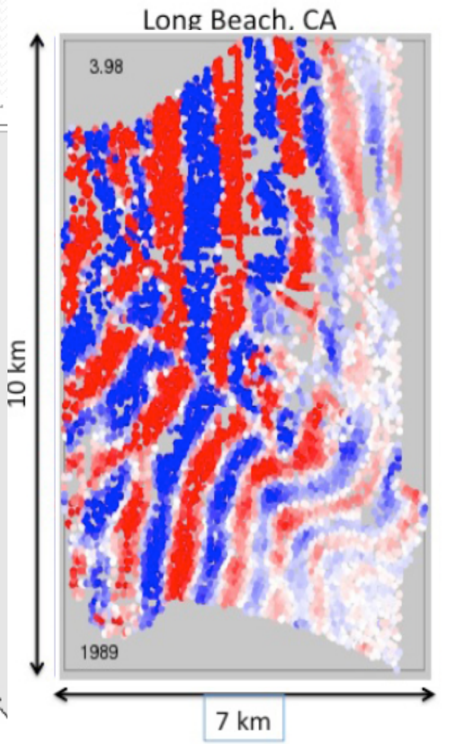


Figure 8. Event Location by Long Beach Network. The red stars are events located by the LB Network during the first week in May, 2011 (5% of the data). The blue stars are from the SCSN catalog for the first 6 months of 2011. The green dots are the SCSN stations.



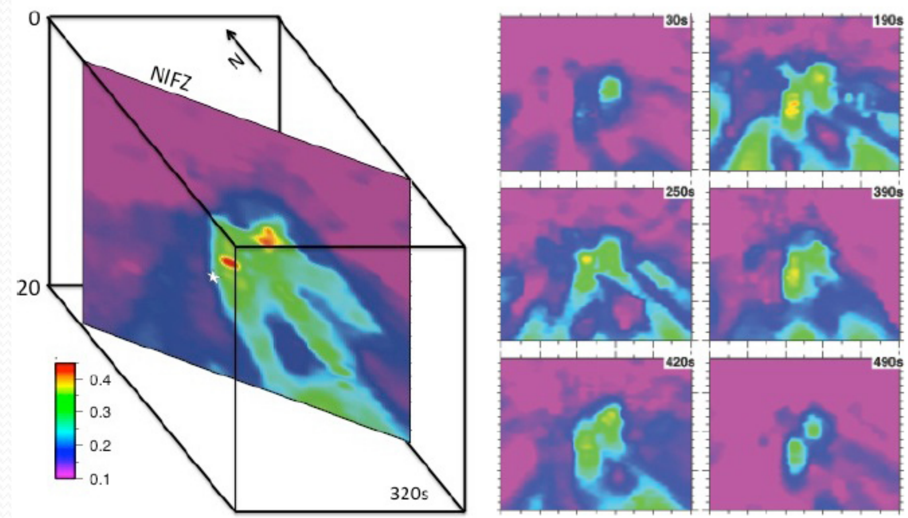
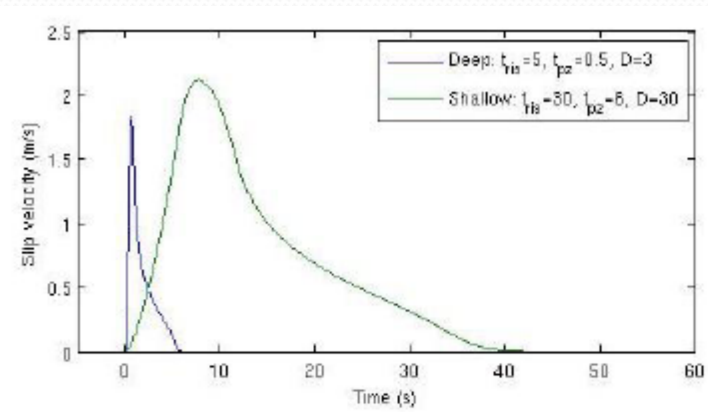


Figure 9. Backprojection onto the plane of the Newport-Inglewood Fault Zone (NIFZ). On the right are snap shots of the backprojection at selected times over a 600 sec period. On the left is an enlargement of the 320s snapshot display in the approximate location of the NIFZ. The white star is the location of one of the events identified in Fig. 8.

Asaf Inbal

We cannot drill down to the seismogenic zone, but a large **and coherent** array can focus imaging on a deep fault patch (patch size ~ wavelength <1km for f>5Hz)

What are we hoping to learn?



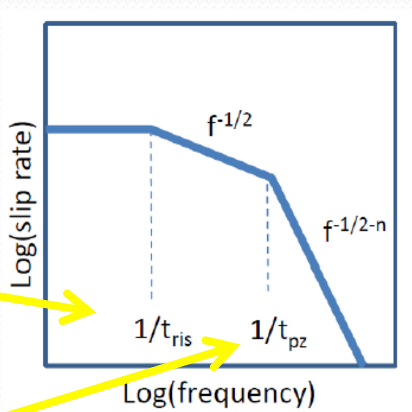
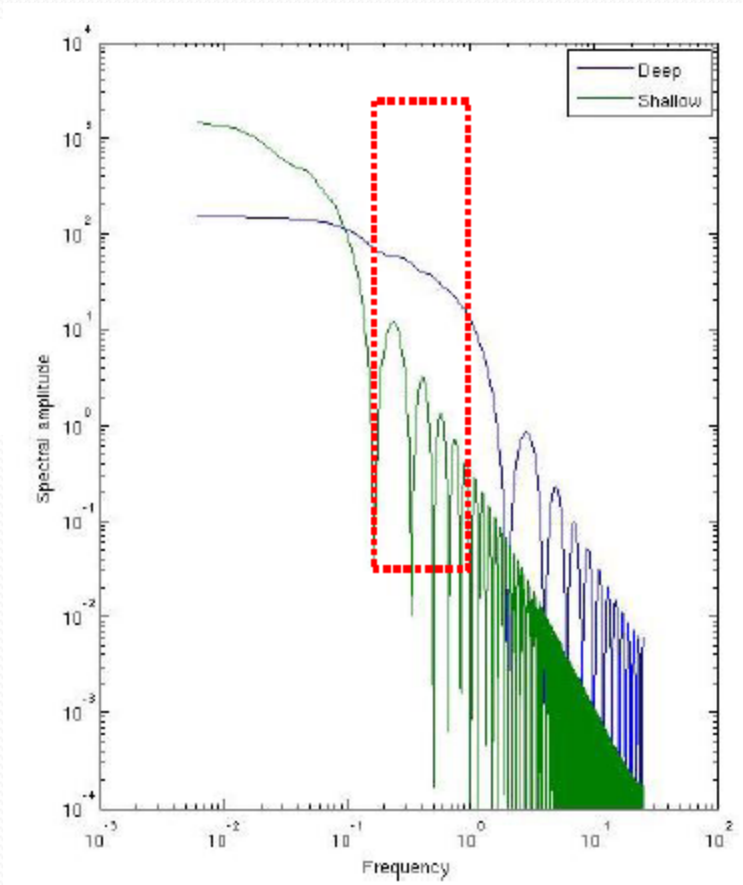


Figure 1: spectrum of a smoothed Yoffe function

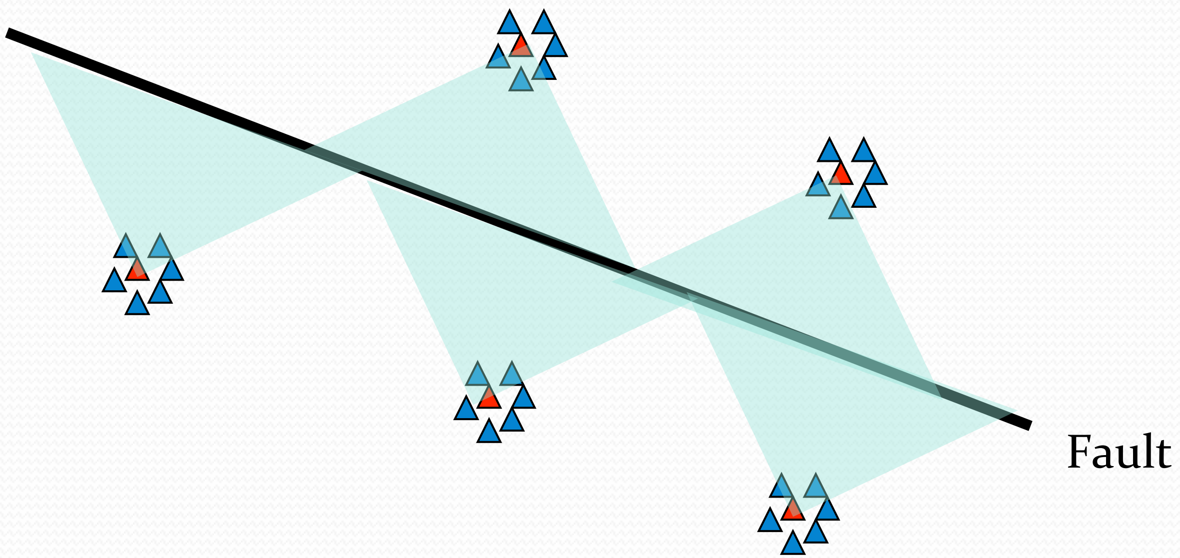


Rise time / pulse width scale

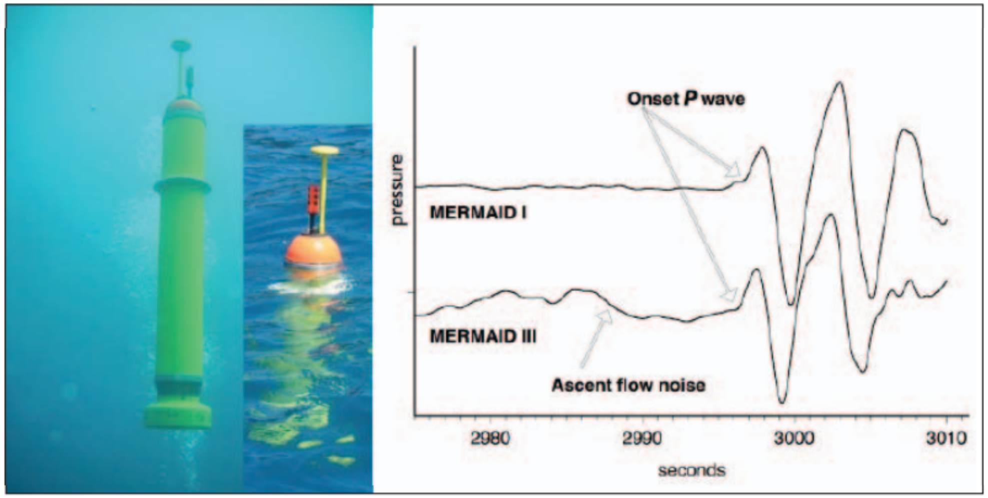
Process zone scale

Summary

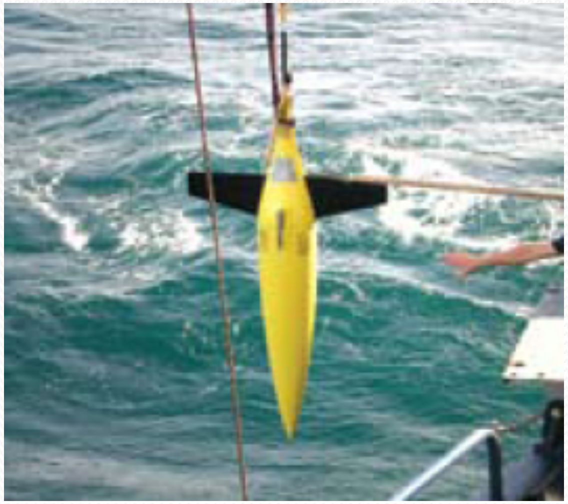
- Unique insights on rupture dynamics can be obtained from back-projection of high-frequency waves recorded by dense arrays at teleseismic distances
- The future: adapt the concept to near-field, multiple arrays, higher frequencies
- And beyond: real time → early warning



Subduction earthquakes: off-shore acoustic arrays



MERMAID (Simmons et al)



Sea glider