Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations

ICTP, Trieste, Sept 2-14 2019

Lecture 1: introduction

Jean Paul Ampuero (IRD/UCA Geoazur)

About us

IPGP
INSTITUT DE PHYSIQUE
DU GLOBE DE PARIS

PRINCETON
UNIVERSITY

ETH zürich

Caltech
SEISMOLOGICAL LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

UNIVERSITÉ
CÔTE D'AZUR

French National Research
Institute for Sustainable
Development
IRD
Institut de Recherche
pour le Développement
FRANCE

GeO
AZUR
TERRE - OCÉAN - ESPACE

UNIVERSIDAD
DE CHILE

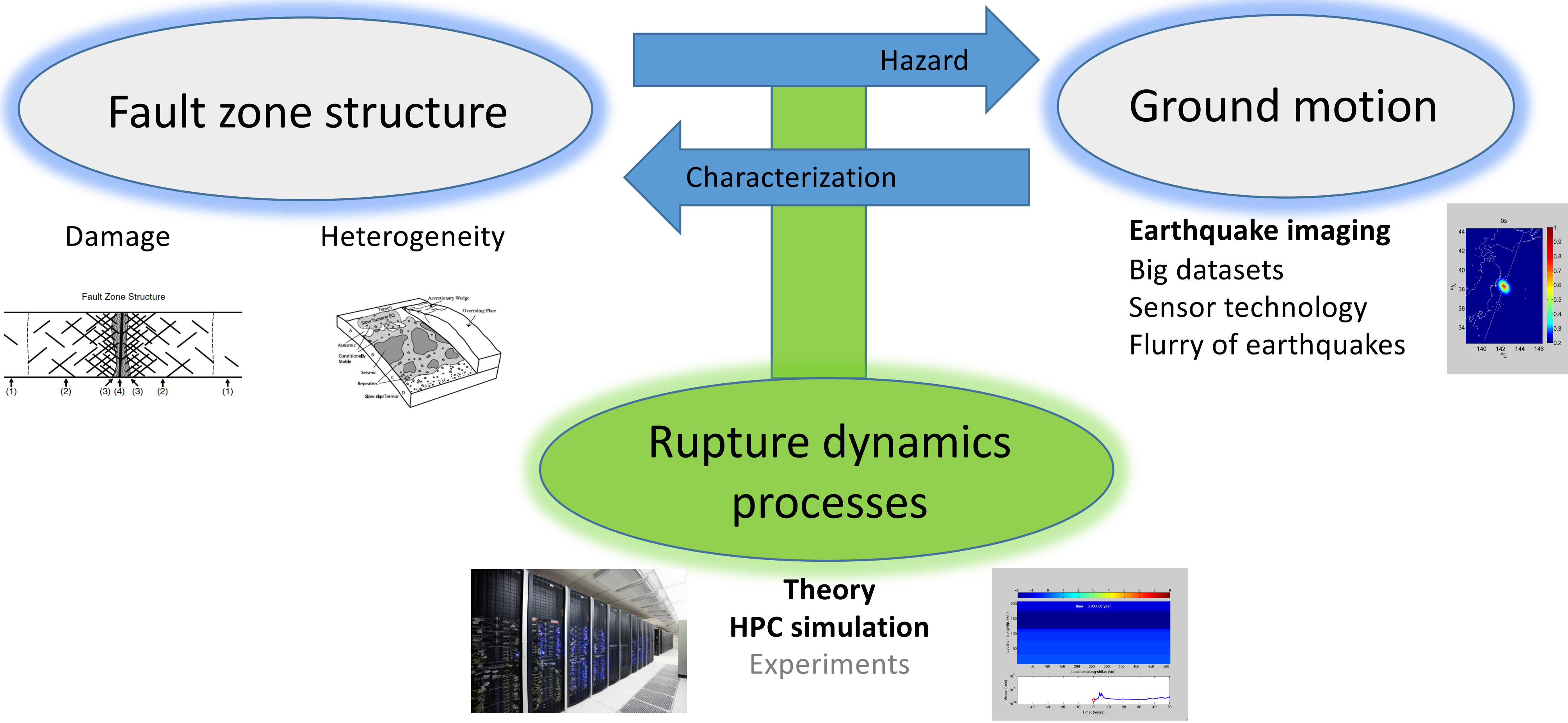
UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO
POR MI RAZA HABLARÁ EL ESPÍRITU

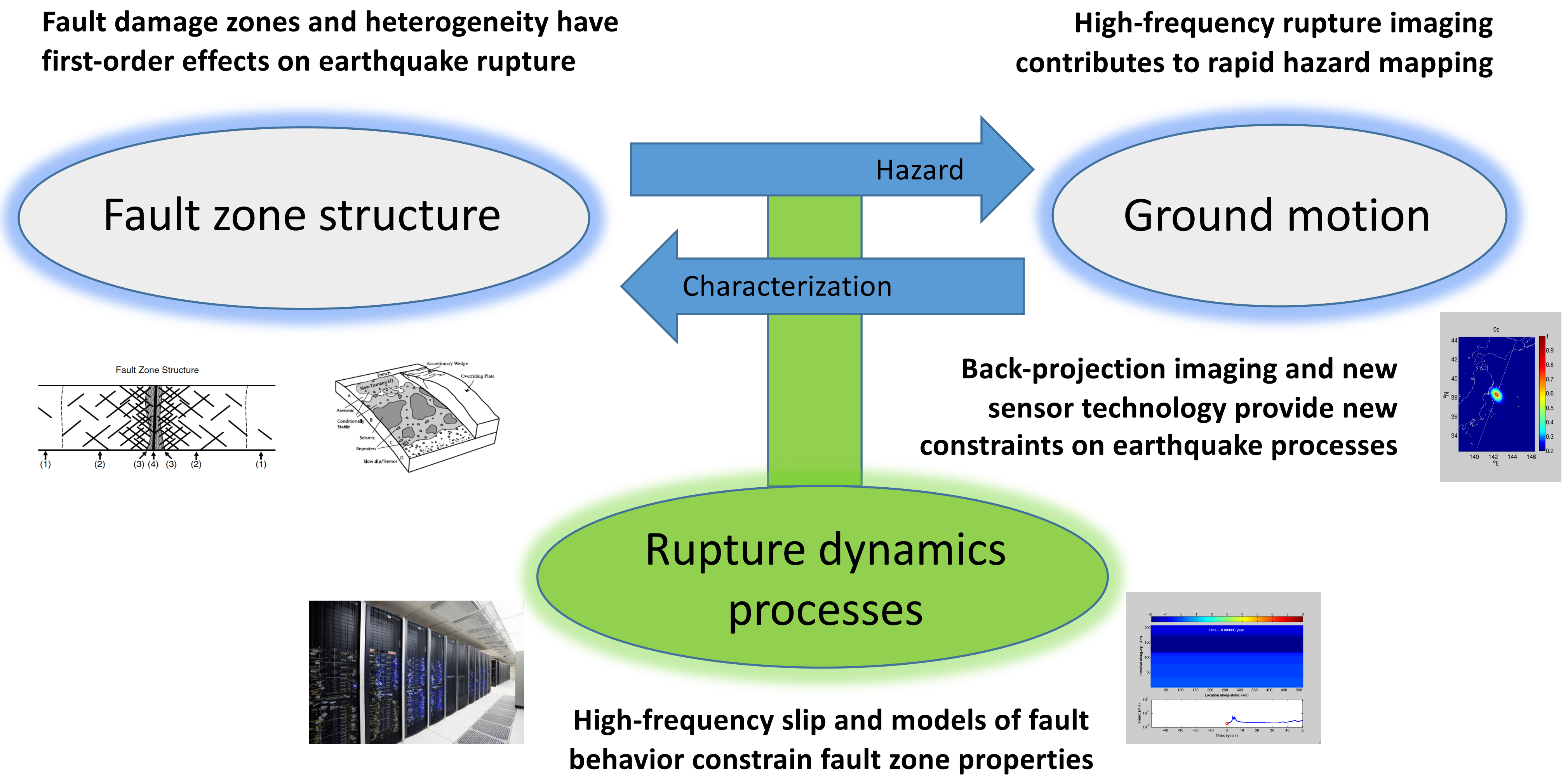
funvisis
Fundación Venezolana de
INVESTIGACIONES SISMOLÓGICAS

EARTHQUAKE RESEARCH INSTITUTE
UNIVERSITY OF TOKYO

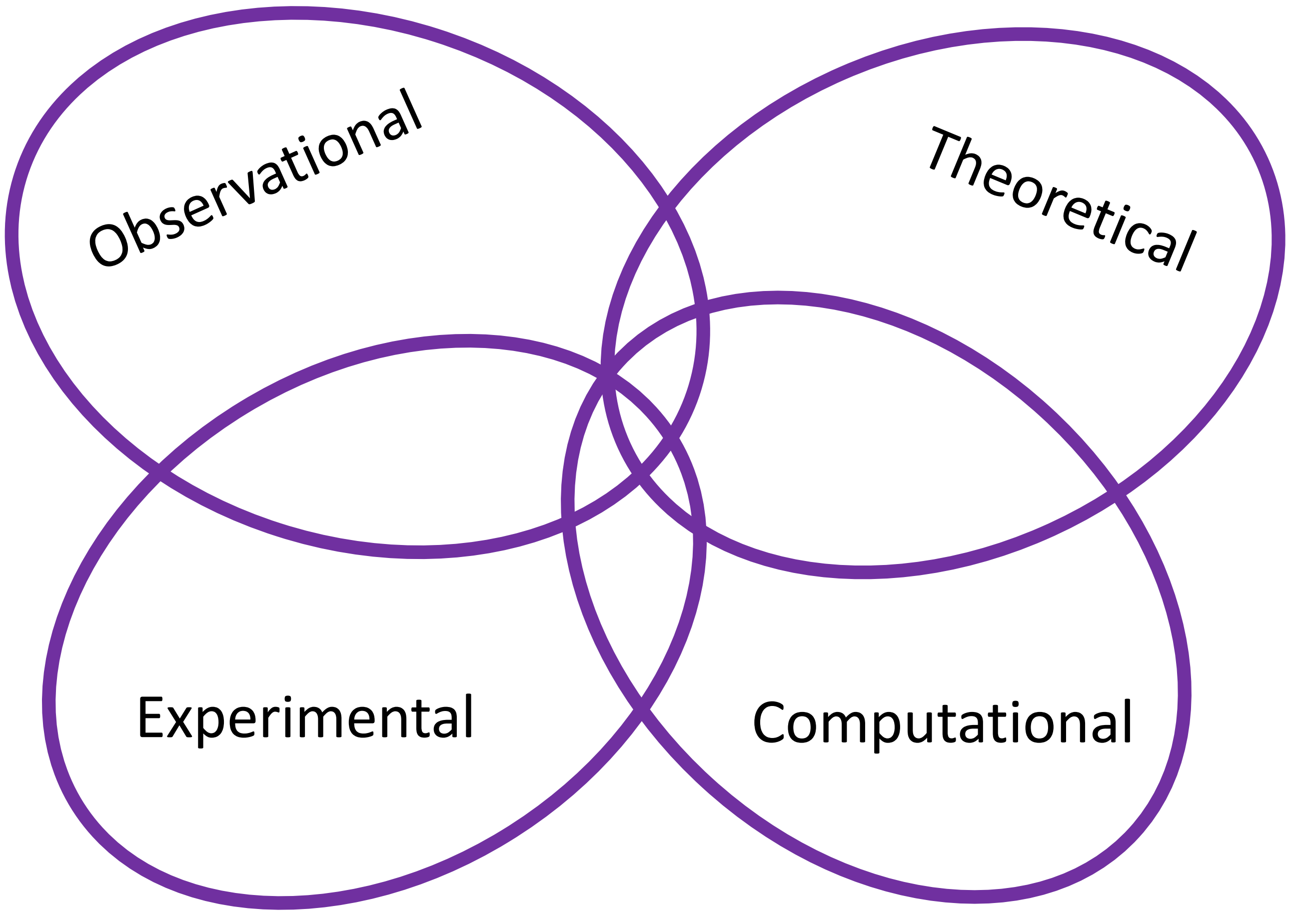
SOL IUSTITIAE ILLUSTRA NOS
Universiteit Utrecht

Overview of my research

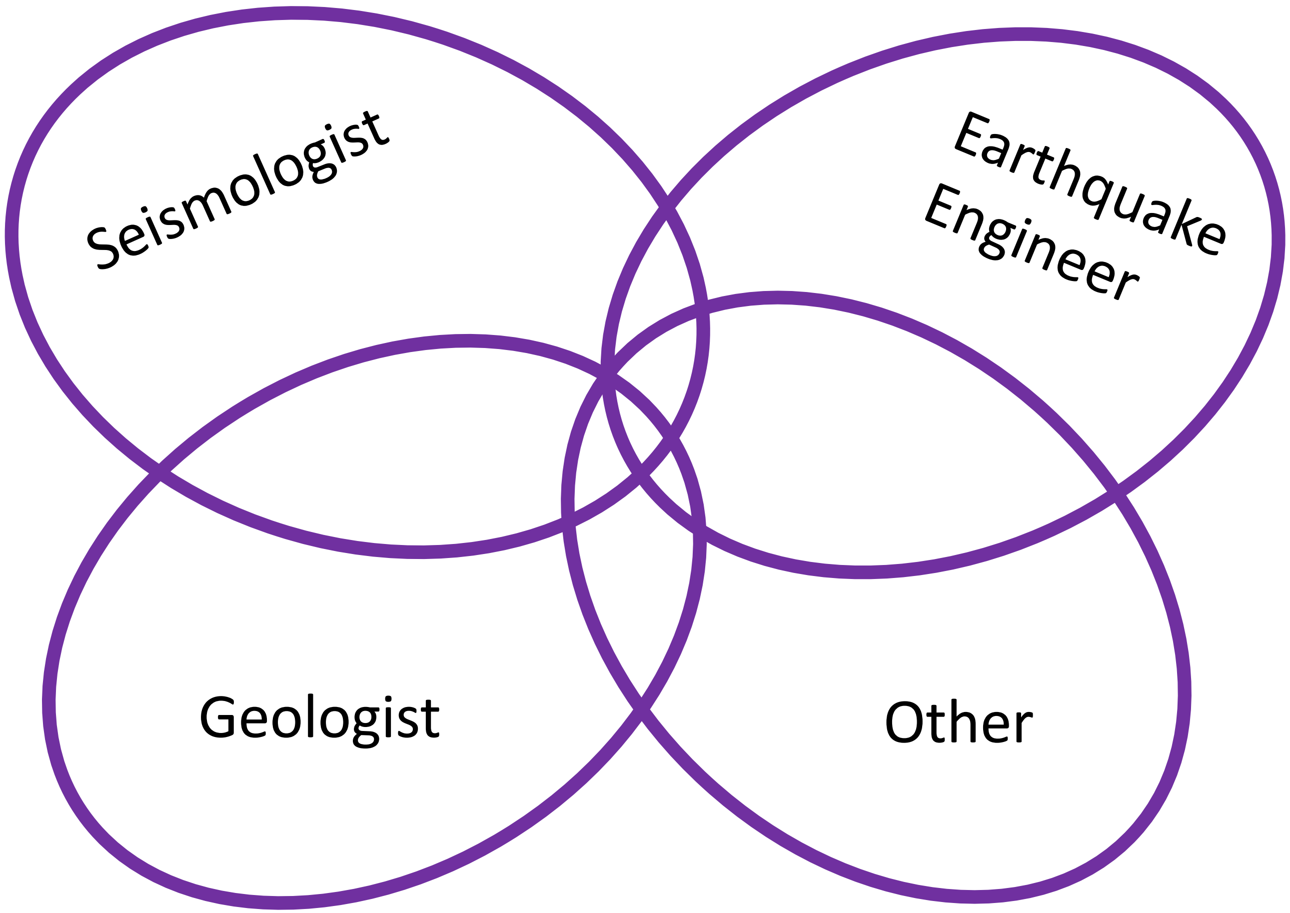



Fault damage zones and heterogeneity have first-order effects on earthquake rupture
High-frequency rupture imaging contributes to rapid hazard mapping
Fault zone structure
Hazard
Characterization
Ground motion
Fault Zone Structure
(1) (2) (3) (4) (3) (2) (1)
Back-projection imaging and new sensor technology provide new constraints on earthquake processes
Rupture dynamics processes
High-frequency slip and models of fault behavior constrain fault zone properties

You?



You?

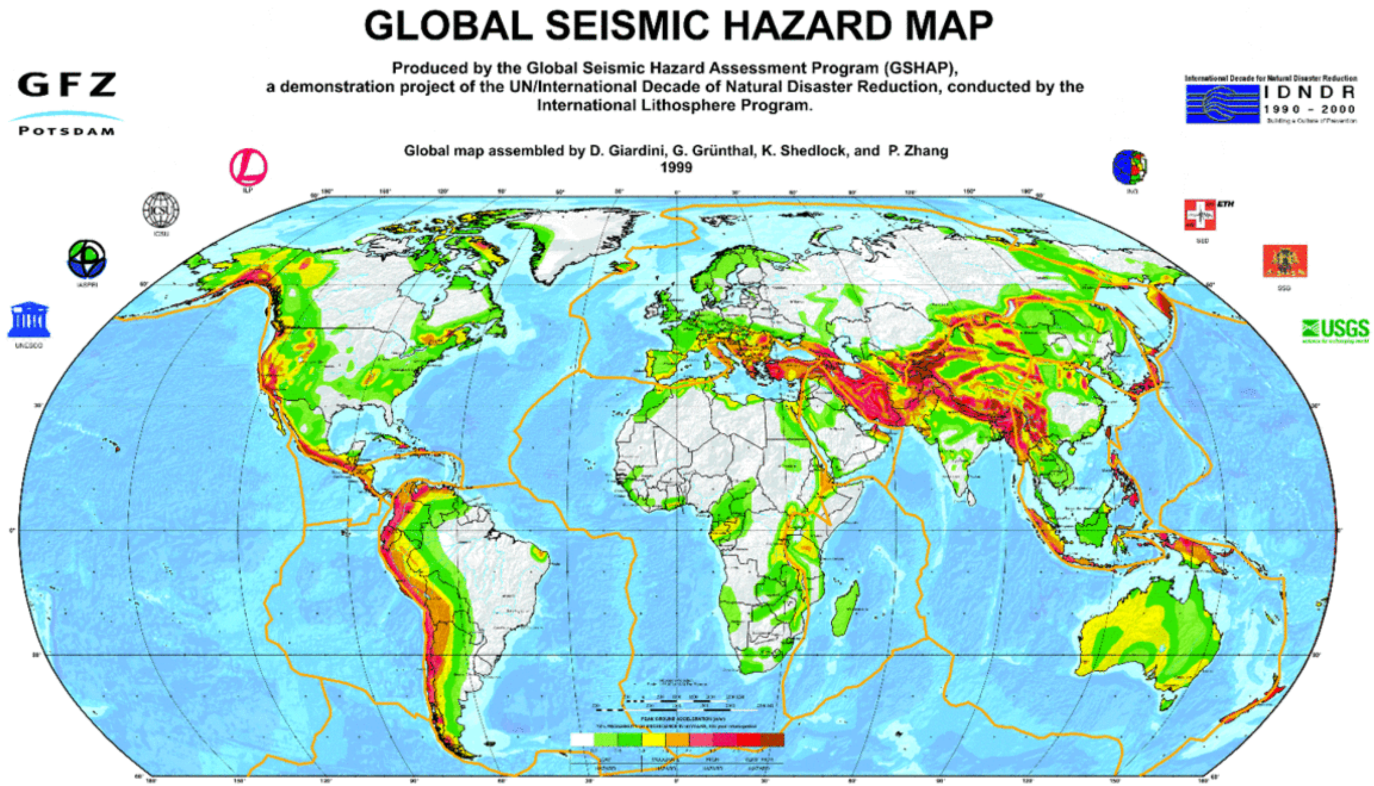


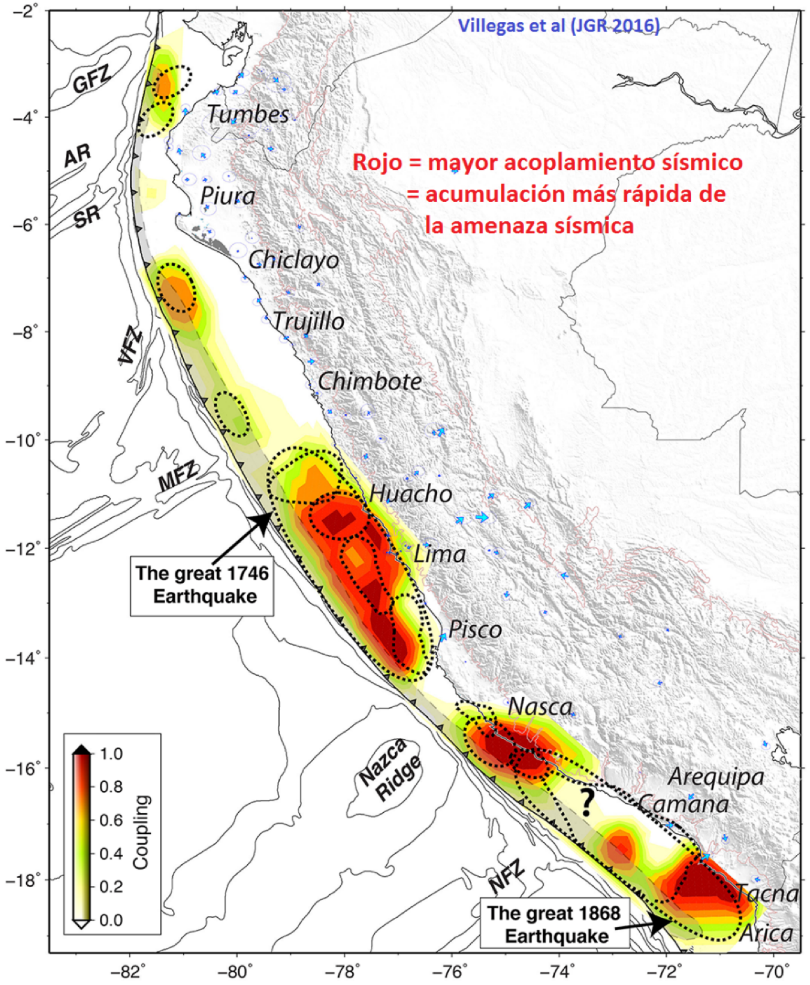
Why earthquake research?

Mitigate earthquake hazard

Understand the physical process

Earthquakes: a global hazard





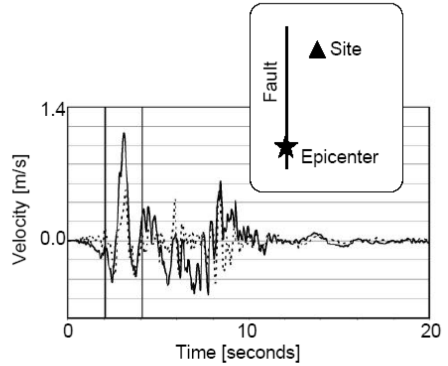
- Lima, Peru: vulnerable mega-city where a mega-earthquake can happen anytime soon
- An opportunity to oberve and understand subduction earthquake processes with high resolution

Empirical ground motion prediction

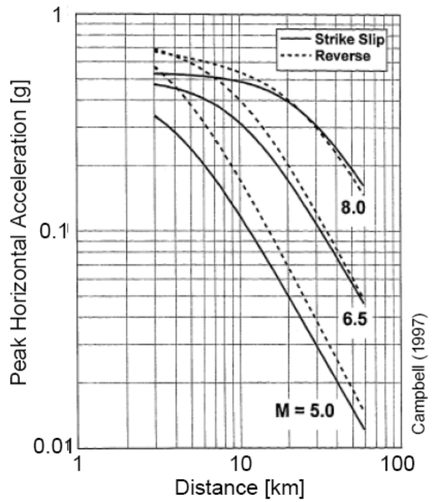
Basic steps in seismic hazard assessment:

- **Step 1:** estimate the probability of occurrence of an earthquake of a given magnitude
- **Step 2:** estimate the amplitude of the resulting ground motions

In engineering practice, step 2 is based on **empirical attenuation relations:** regressions between ground motion parameters (peak ground acceleration PGA, velocity PGV, etc) and source/site parameters (magnitude, source distance, soil class, etc) **derived from recorded seismograms**.

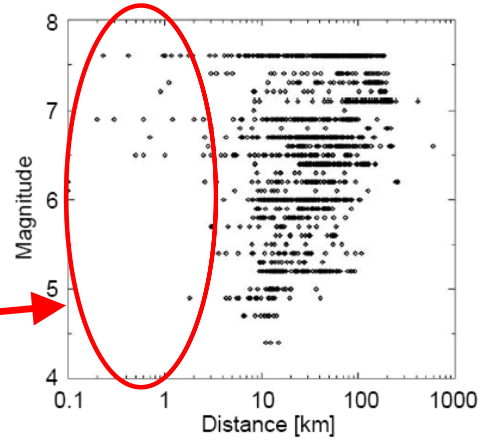


Modified after Howard et al. (2005)



Empirical vs. physics-based ground motion prediction

Each dot is an available recording



Modified after Stewart et al. (2002)

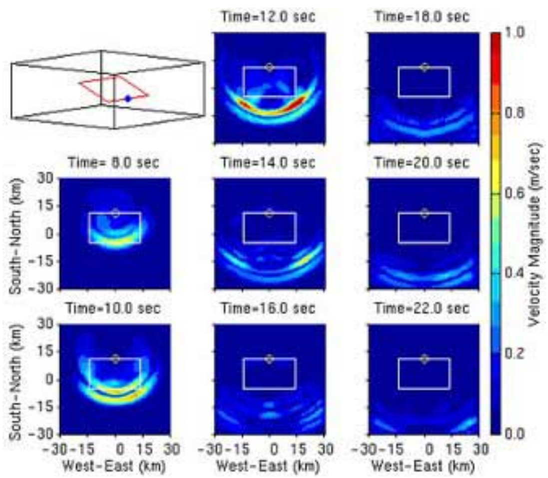
Problem with the empirical approach:

strong motion data is scarce close to active faults

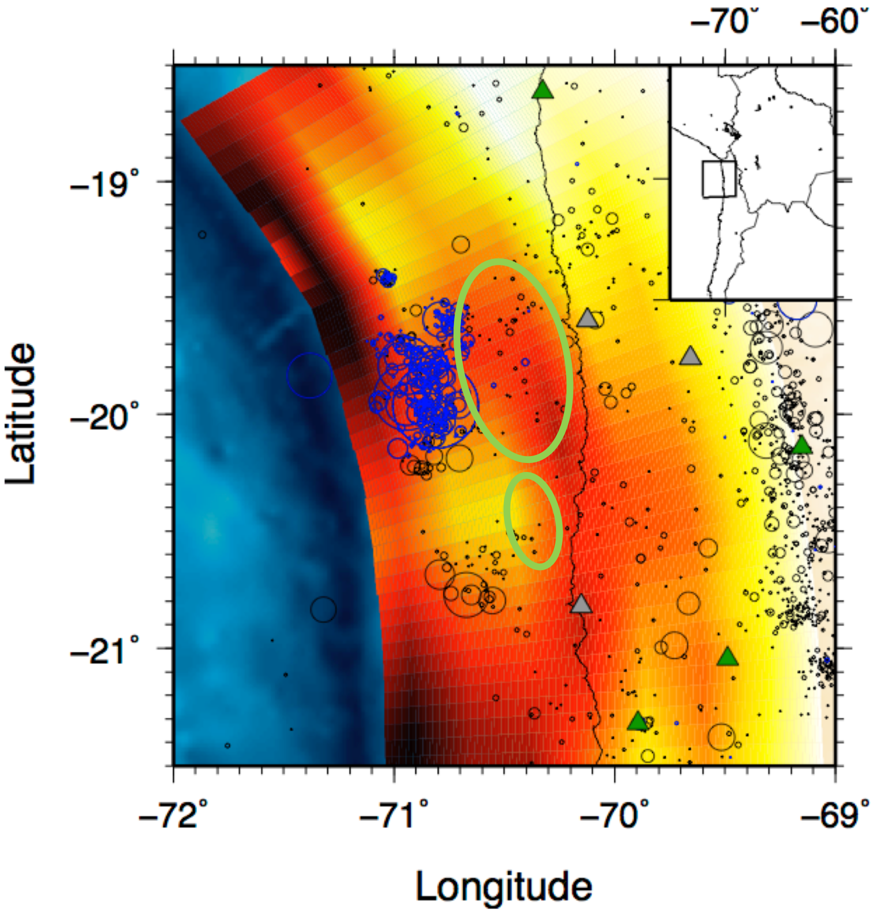
… where the strongest shaking occurs !

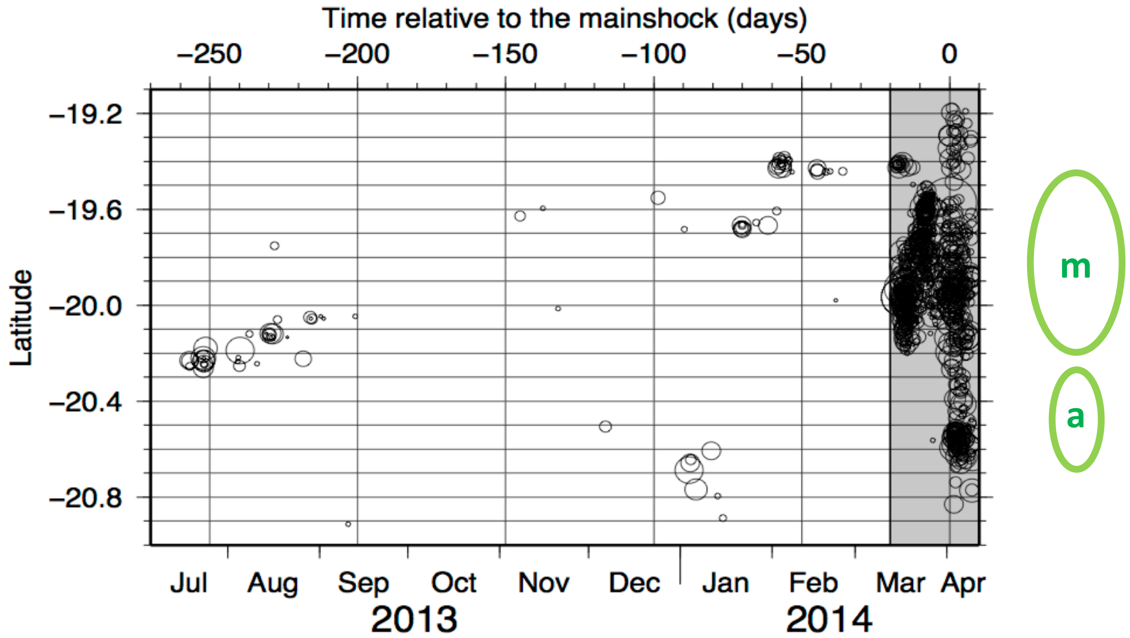
Complementary **physics-based approach**:

simulation of earthquake source and wave propagation



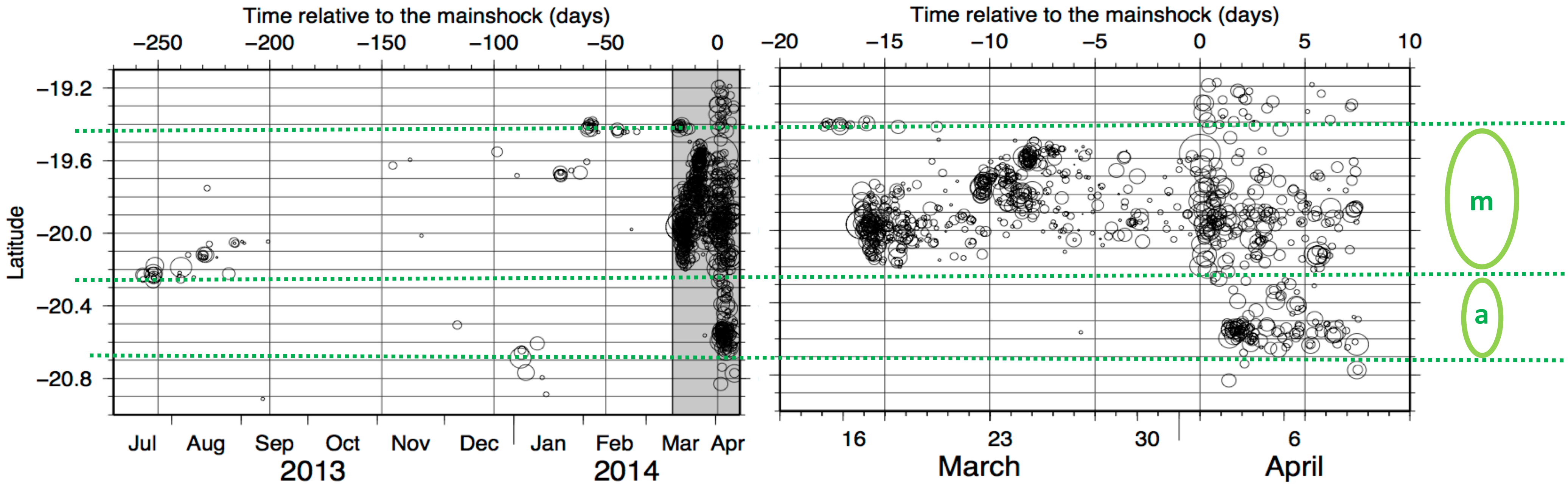
Earthquake predictability
2014 Iquique earthquake + foreshock sequence



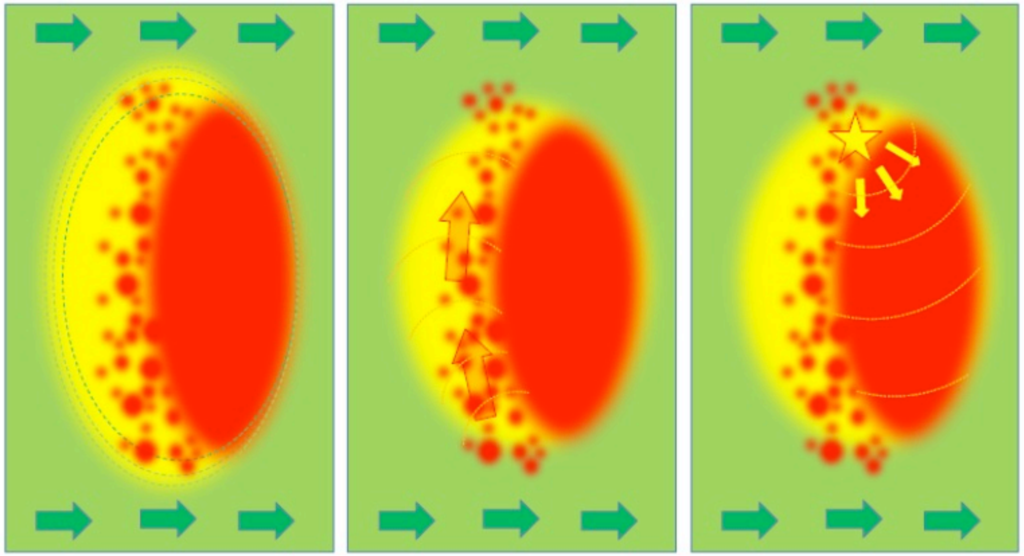


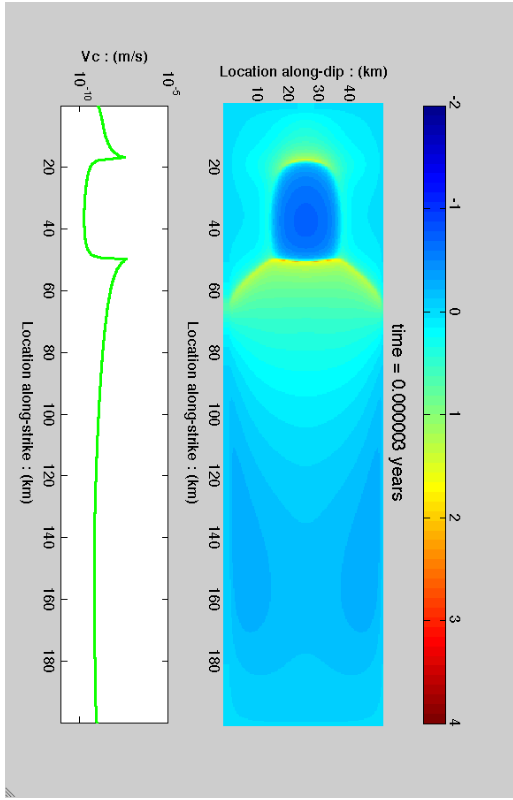
IPOC stations
Regional catalog by CSN Chile
Seismic coupling by Metois et al (2013)

2014 Iquique foreshock sequence



Rate-and-state models
of slow slip and foreshock swarms





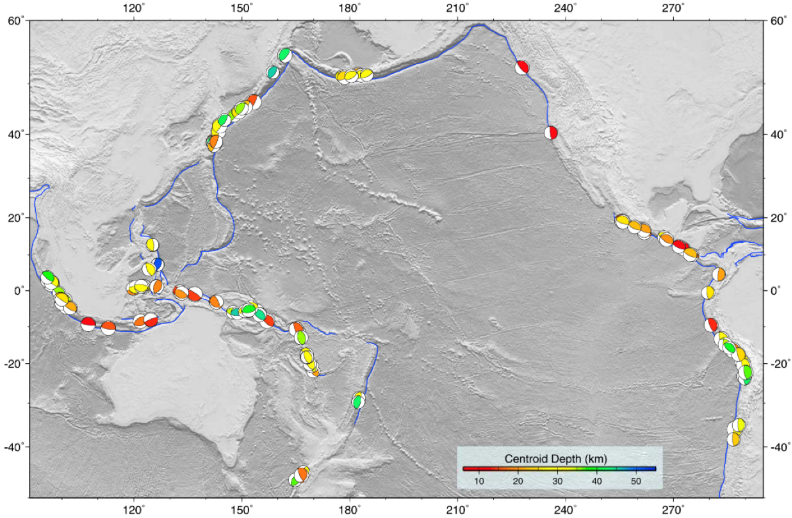
Do small and large earthquakes start the same?

Important question for Earthquake Early Warning and earthquake physics

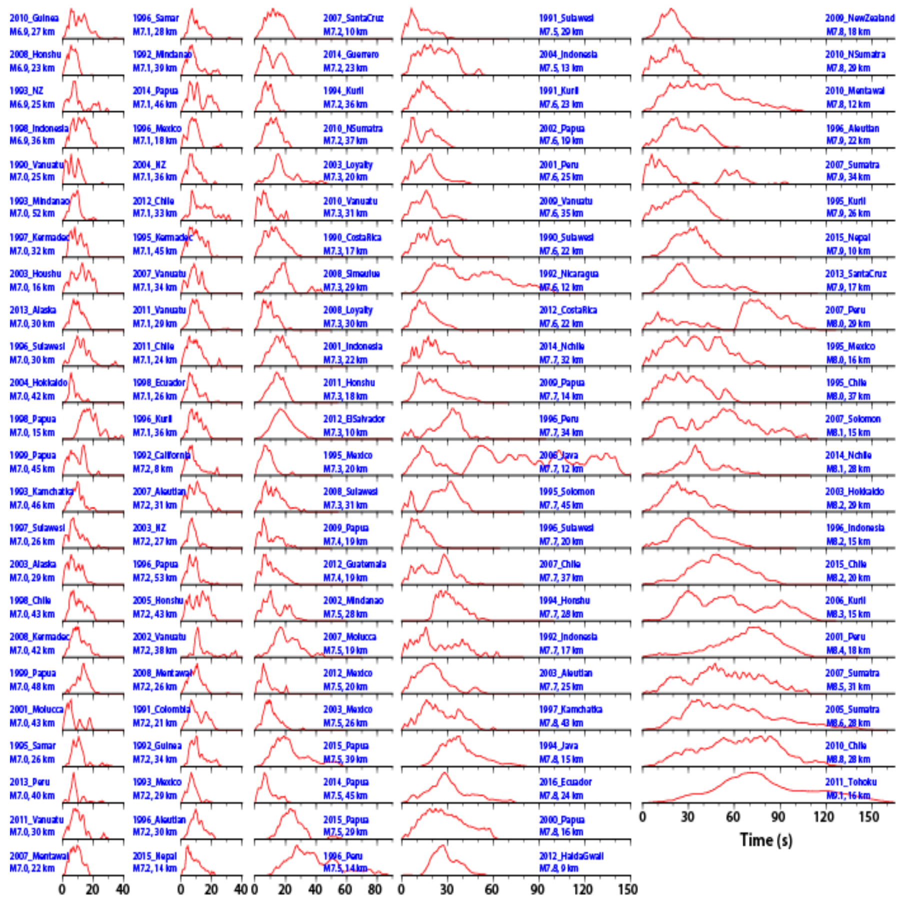
Meier *et al.*, *Science* **357**, 1277–1281 (2017)

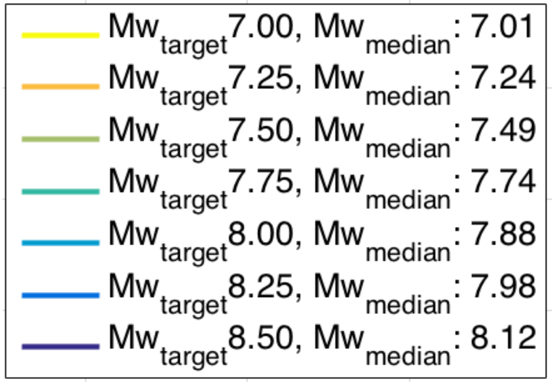
The hidden simplicity of subduction megathrust earthquakes

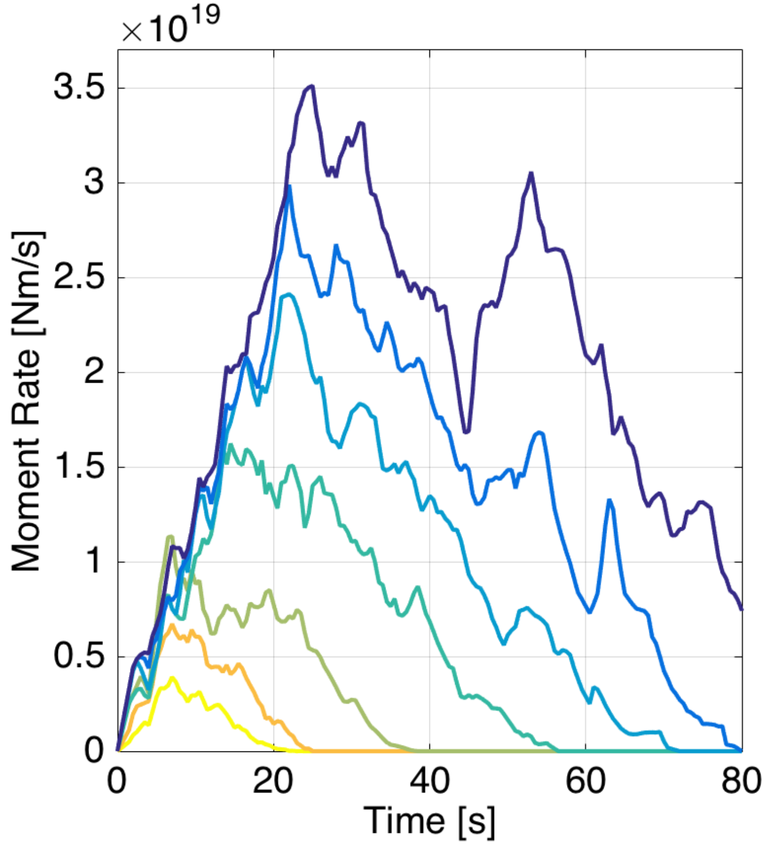
M.-A. Meier,* J. P. Ampuero, T. H. Heaton



Ye et al (JGR 2016)
Source time functions of 116 **M7+ subduction** earthquakes, derived from teleseismic data with a unified method

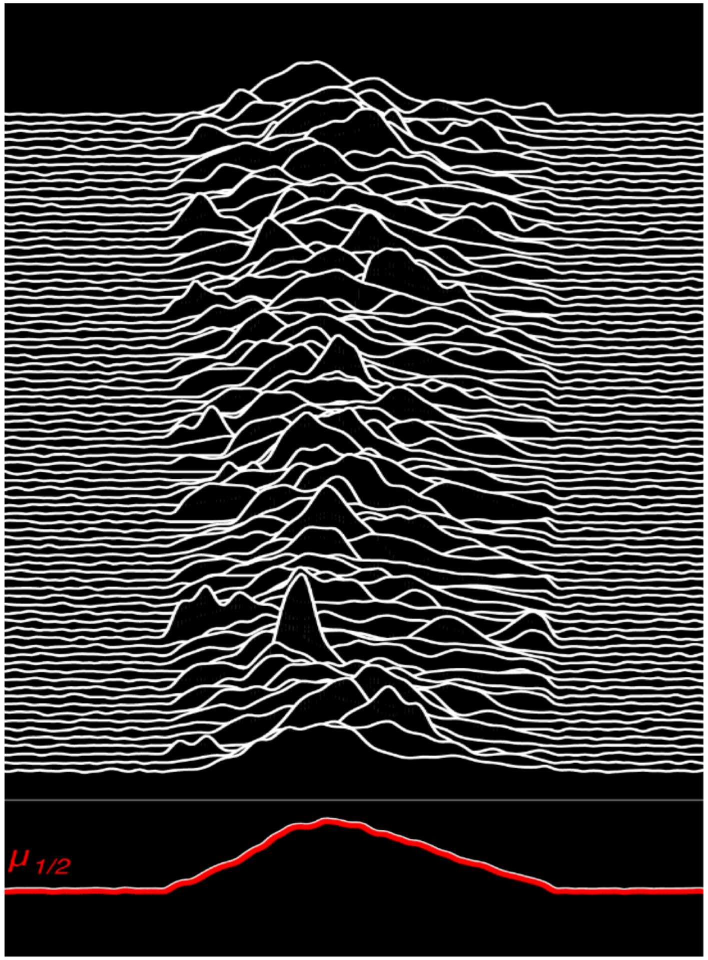




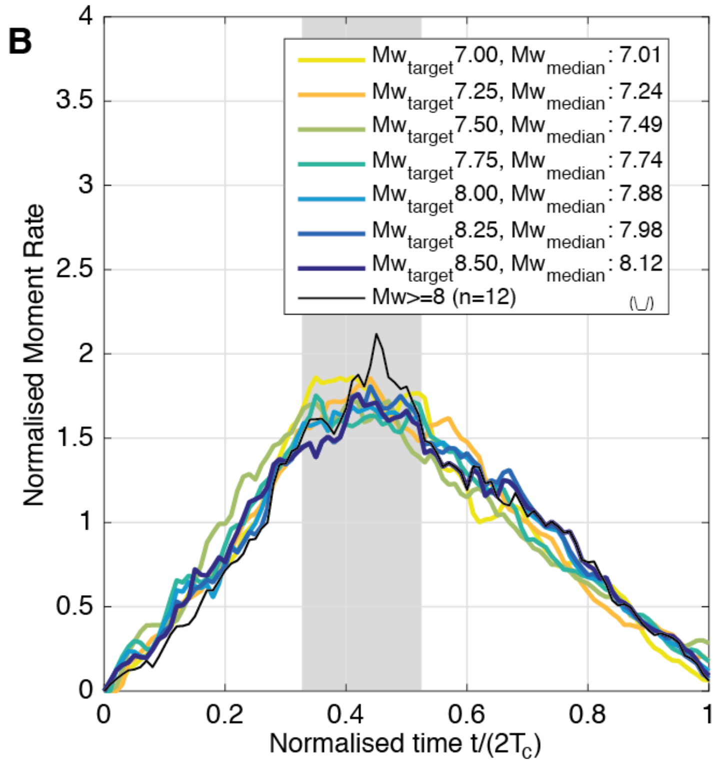


Median STFs have **linear onset, same** for all magnitudes Mw>7.2

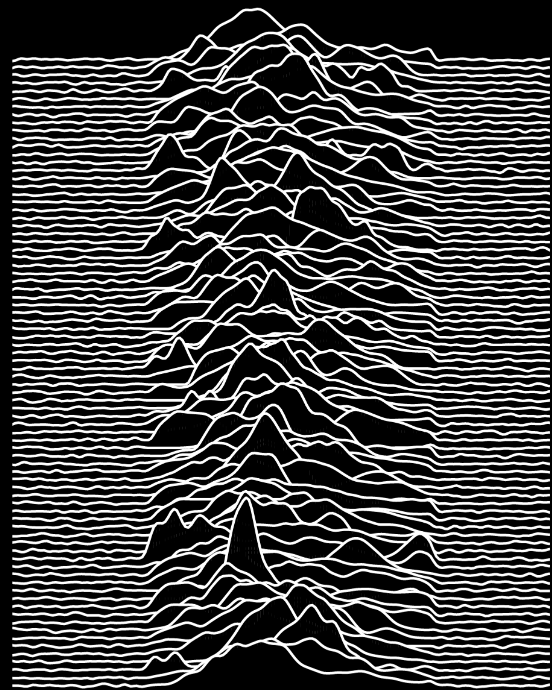
Meier, Ampuero and Heaton (2017)



On average (median), all STFs can be scaled to a very simple, quasi-triangular shape



Meier, Ampuero and Heaton (2017)



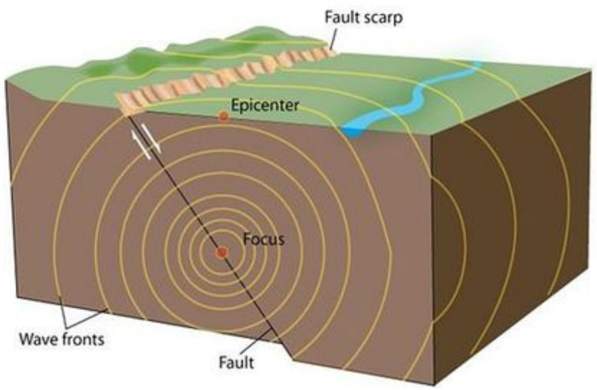
Pulses?

Dynamic gravity changes induced by earthquakes

Earthquake **slip**

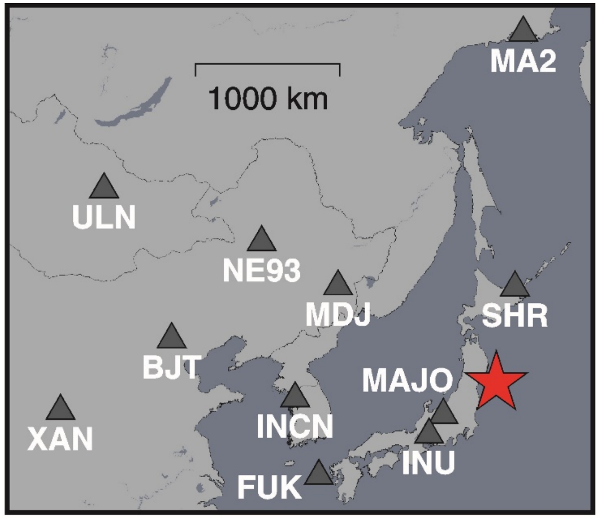
Static + **transient deformation** (seismic waves)

Density perturbations: P waves
+ deformation of material interfaces (e.g. free surface)



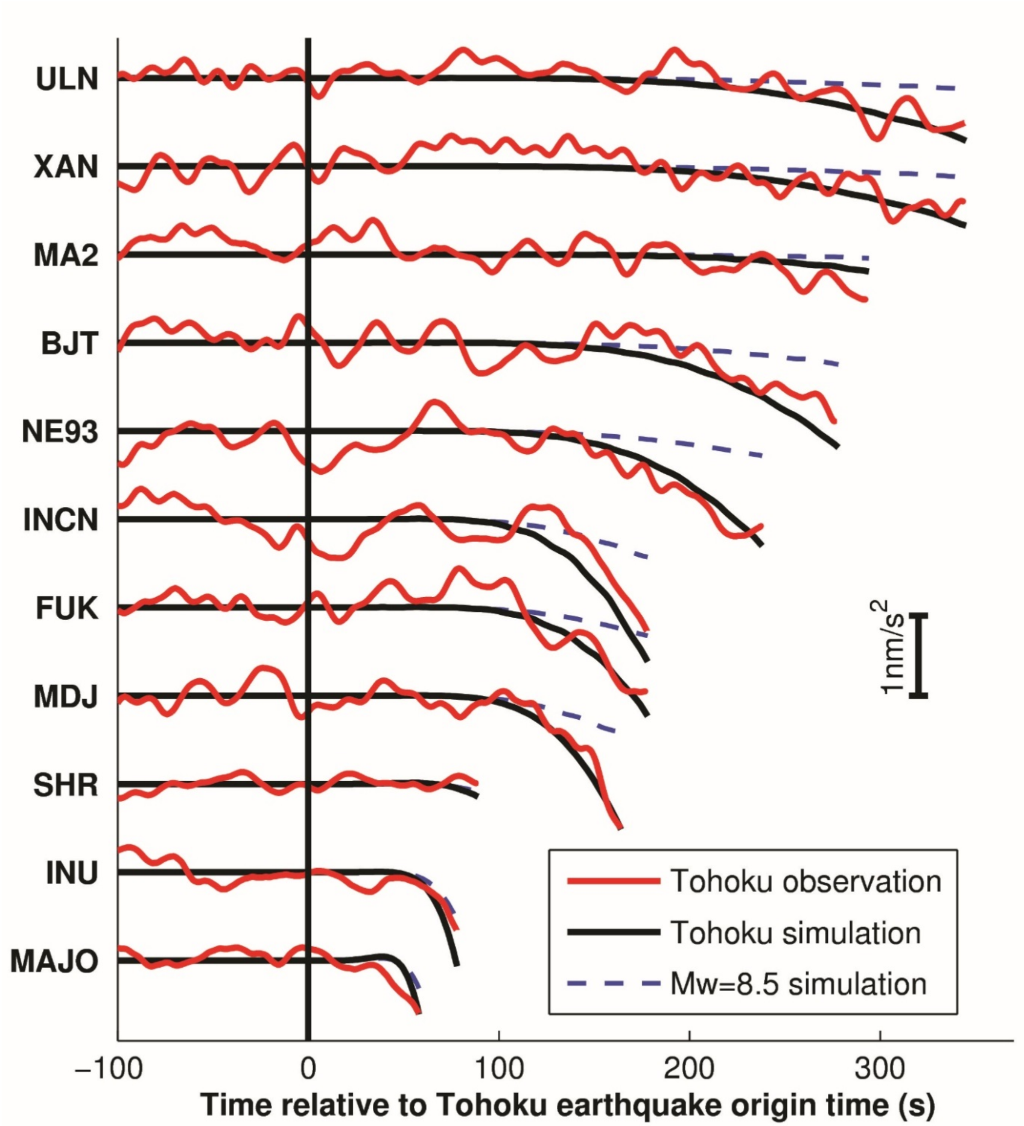
Perturbations of gravity field
long-range and instantaneous (speed of light)

Harms et al (2015)



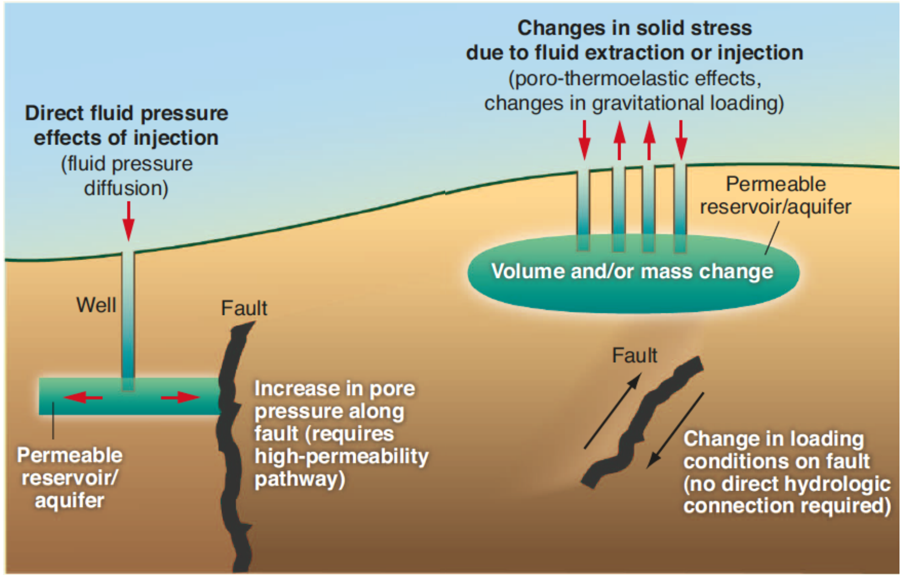
Good agreement between observed and modeled signals

Strong sensitivity to earthquake magnitude

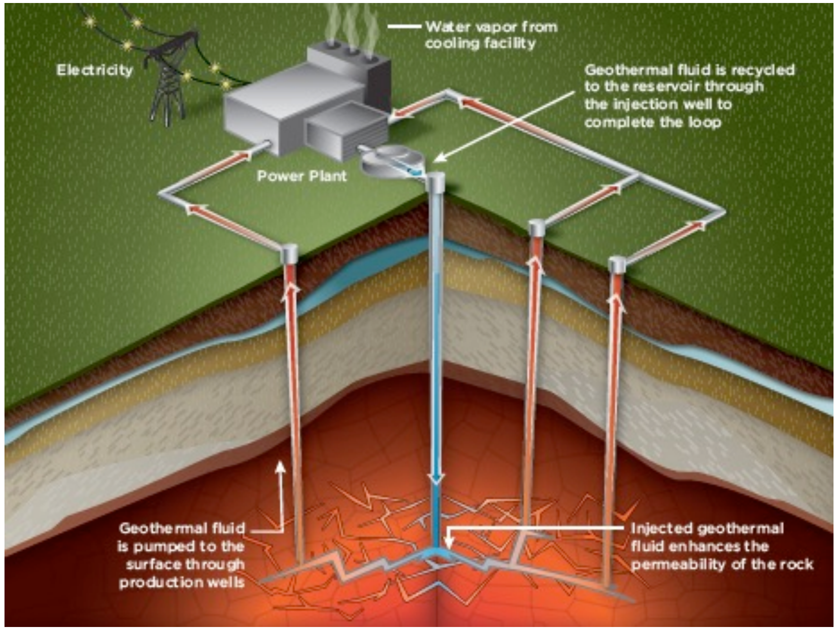


Vallée et al., Science, 2017

Induced/triggered earthquakes



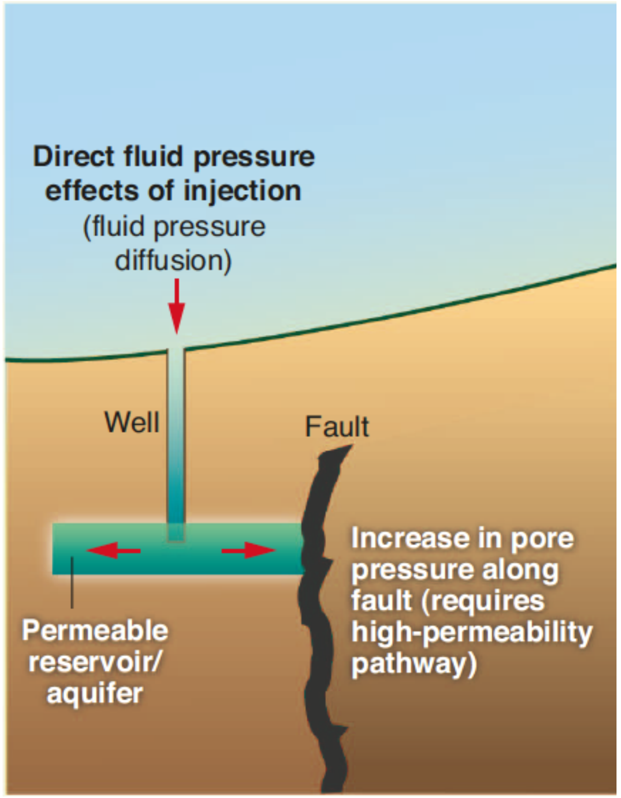
Ellsworth (2013)

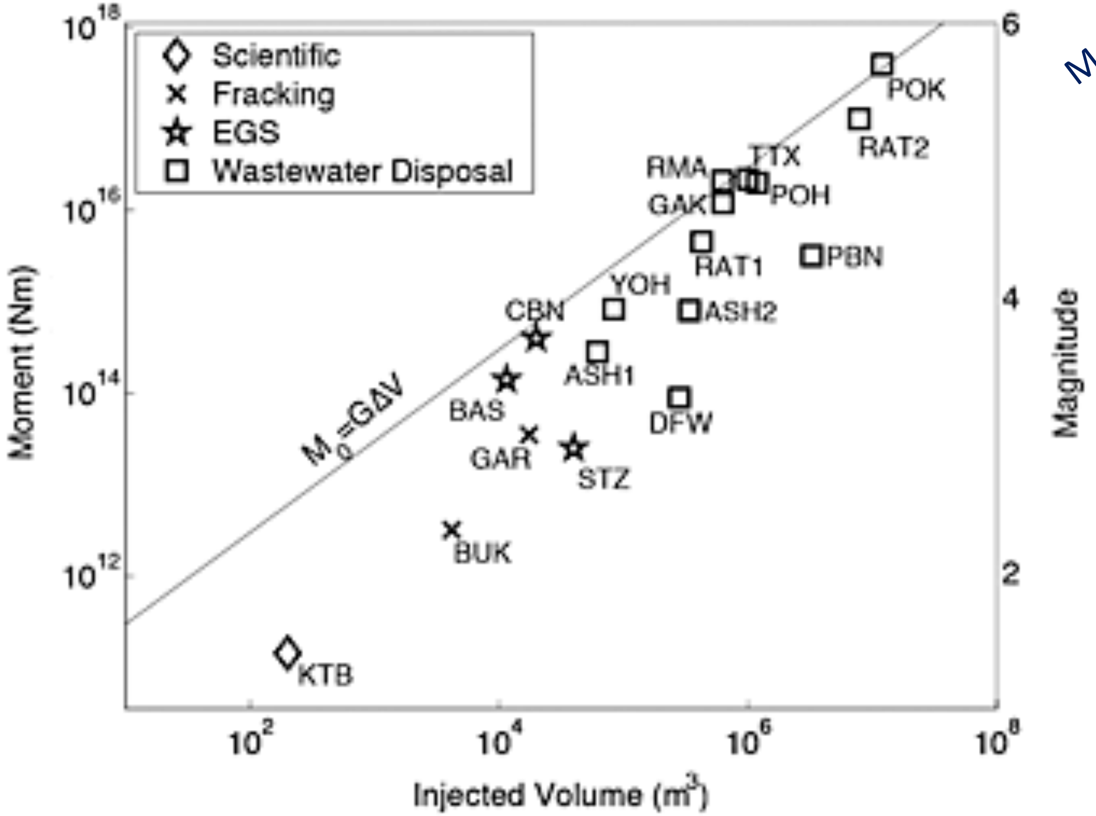


Enhanced geothermal systems

What controls the maximum earthquake magnitude
that can be induced by fluid injection?

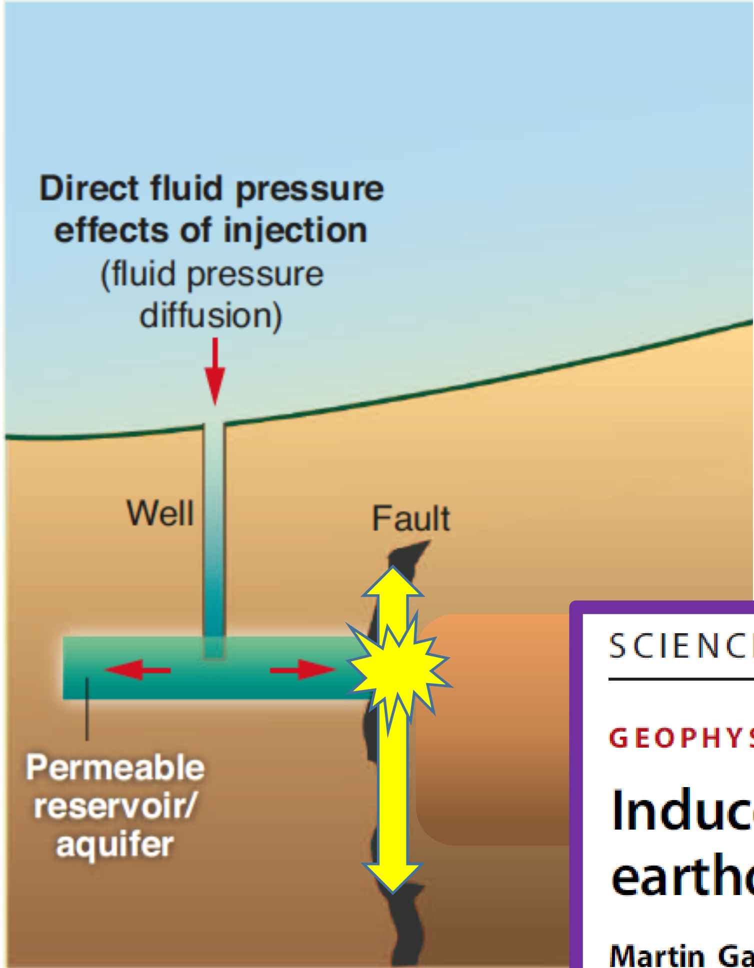
Magnitude limited by injected fluid volume?





McGarr (2014)

$M_{max} \propto \Delta V$



A rupture triggered by injection
can propagate beyond
the pressurized zone
if the fault has enough pre-stress.

SCIENCE ADVANCES | RESEARCH ARTICLE

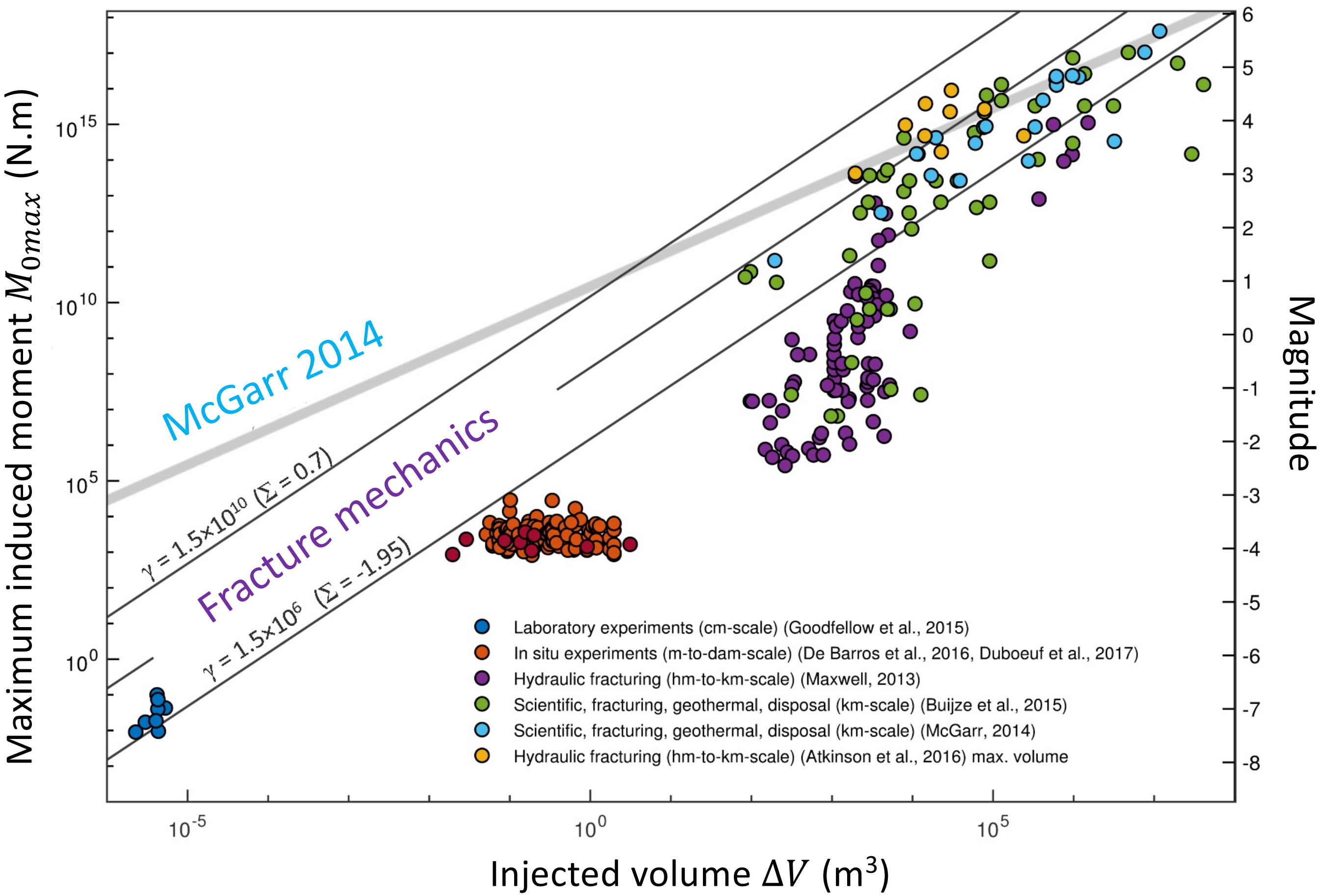
GEOPHYSICS

Induced seismicity provides insight into why earthquake ruptures stop

Martin Galis,[1*†] Jean Paul Ampuero,[2] P. Martin Mai,[1] Frédéric Cappa[3,4]

Fracture mechanics: $M_{0max} \propto \Delta V^{3/2}$

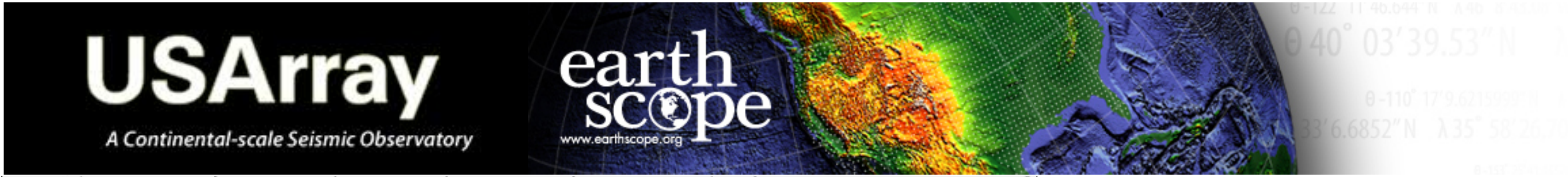
Galis et al (2017)

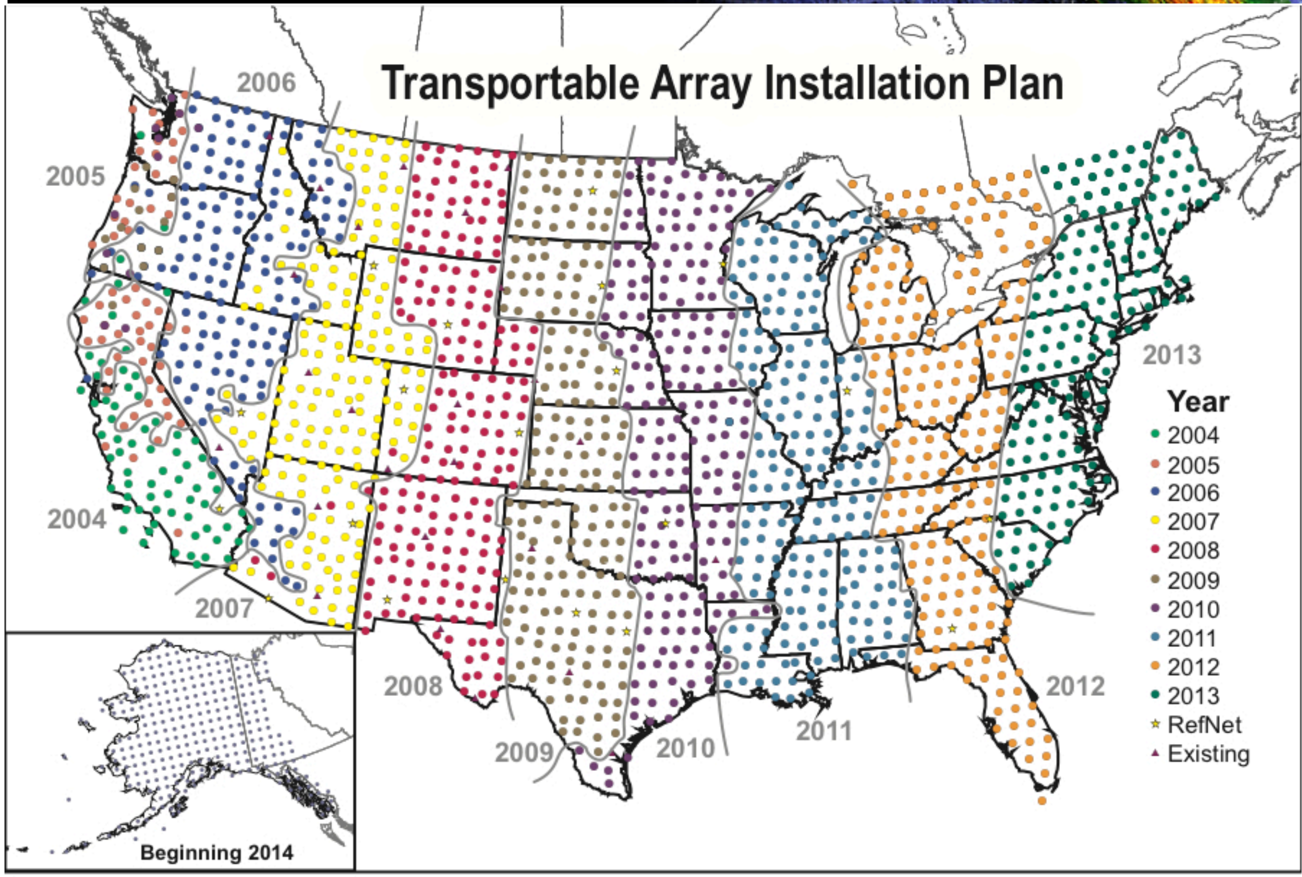


What is enabling progress in earthquake research?

What is enabling progress in earthquake research?

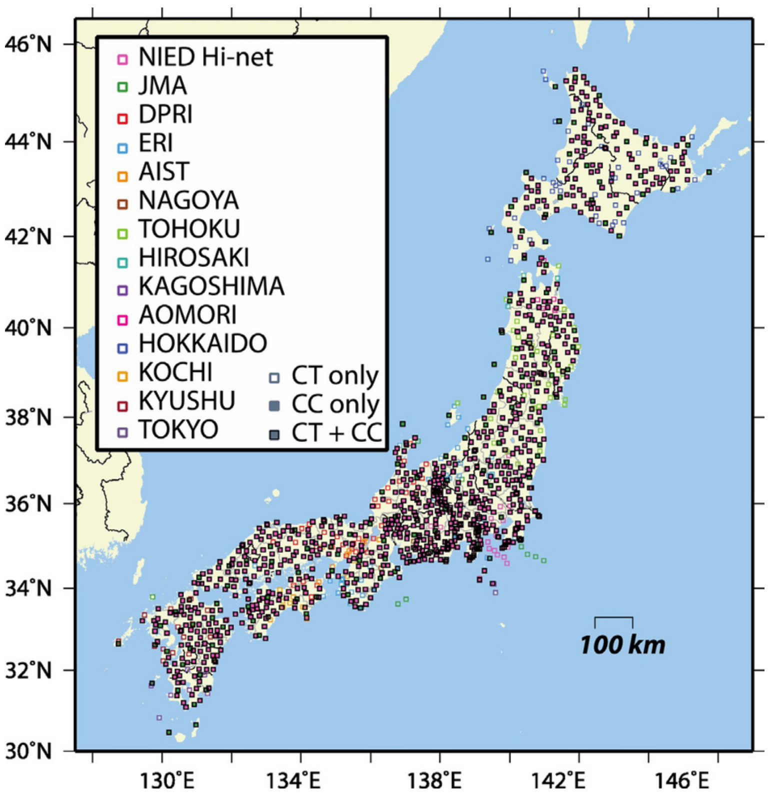
New data and new sensors

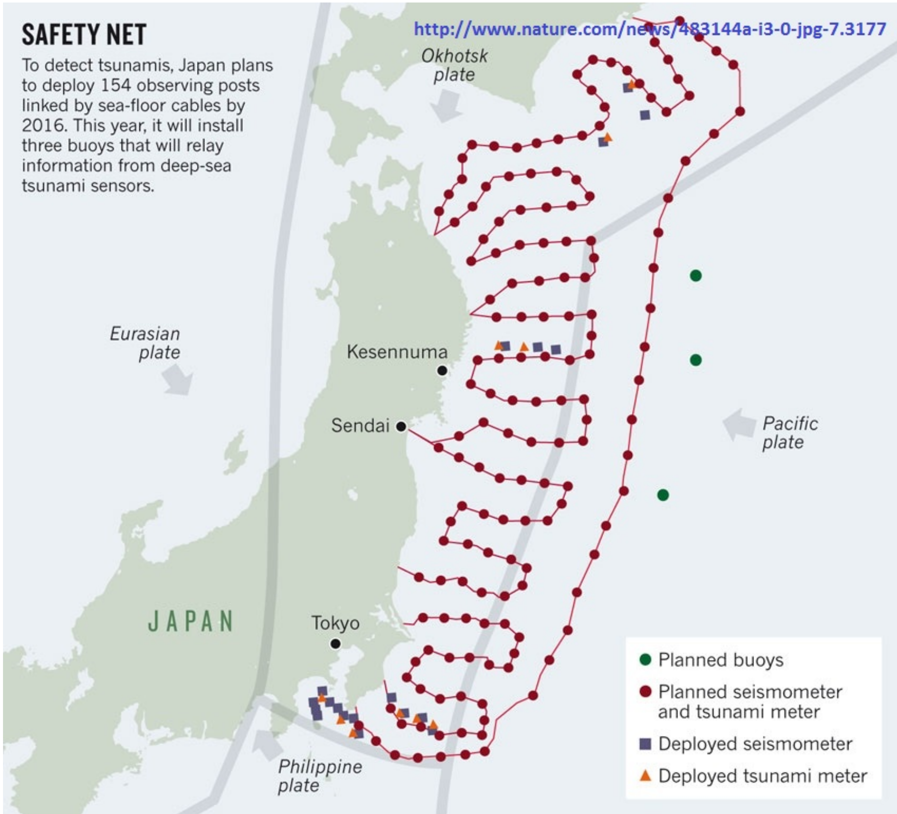




J:\GIS-data\All_states\Special_maps\Install_Year\Install_plan_2011 12/13/2011

Dense seismic networks in land and off-shore





Ultra-dense Nodal arrays

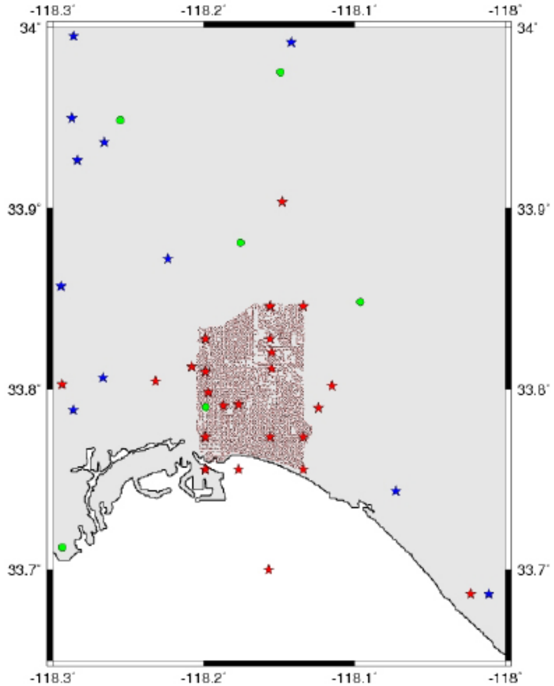
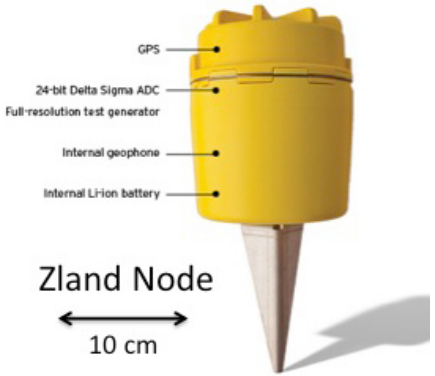
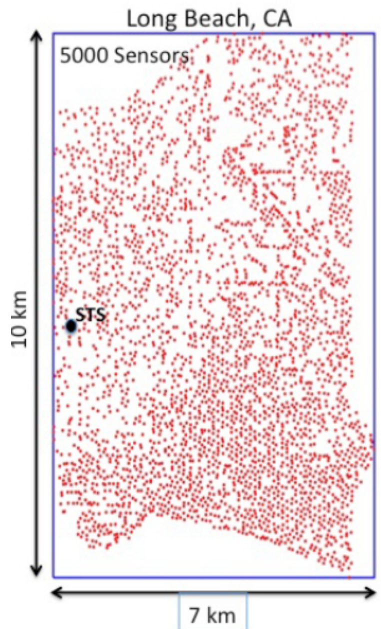
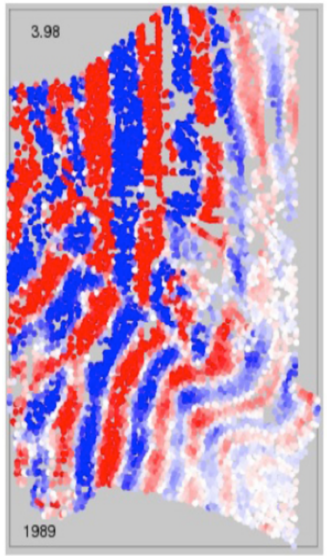


Figure 8. Event Location by Long Beach Network. The red stars are events located by the LB Network during the first week in May, 2011 (5% of the data). The blue stars are from the SCSN catalog for the first 6 months of 2011. The green dots are the SCSN stations.







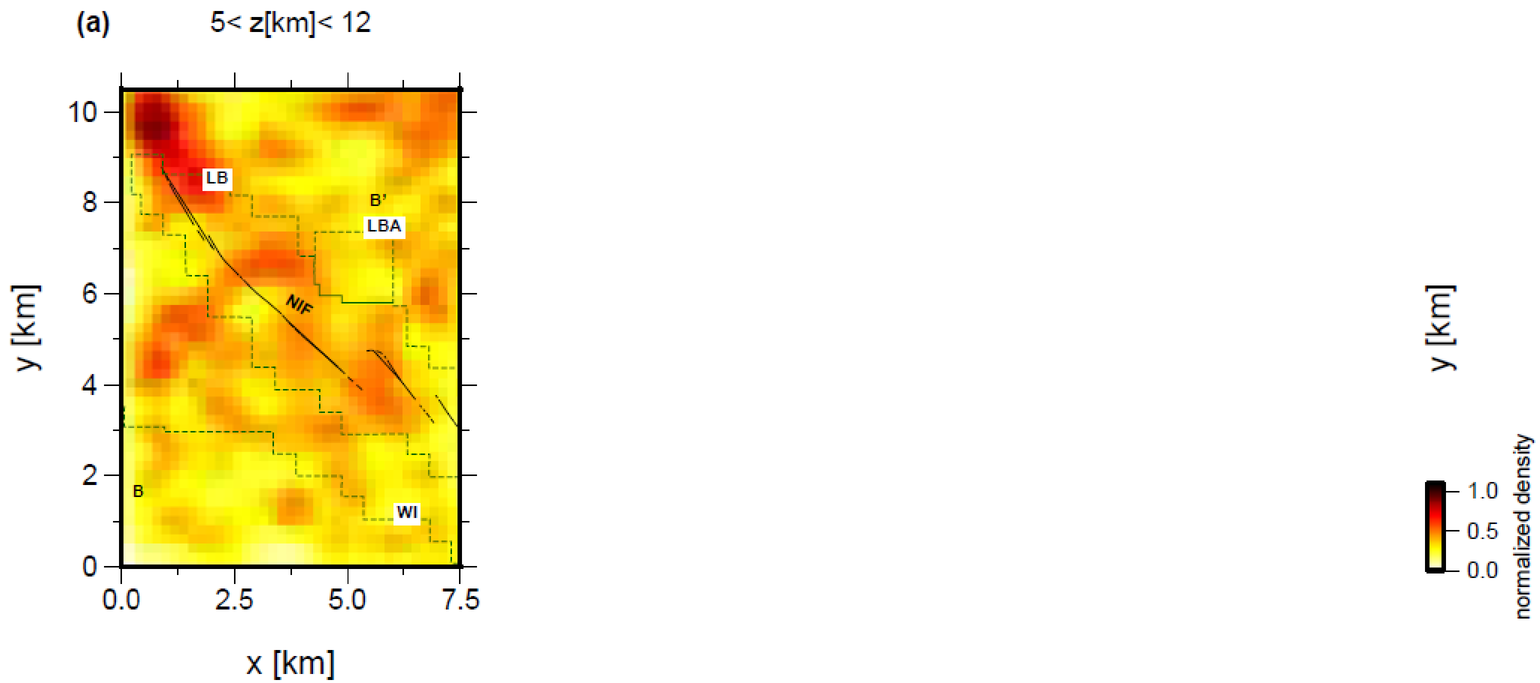
We cannot drill down to the seismogenic zone, but a large **and coherent** array can focus imaging on a deep fault patch (patch size ≈ wavelength <1km for f>5Hz)

Inbal et al (2015)

Localized seismic deformation in the upper mantle revealed by dense seismic arrays

Asaf Inbal,* Jean Paul Ampuero, Robert W. Clayton

sciencemag.org SCIENCE (2015)

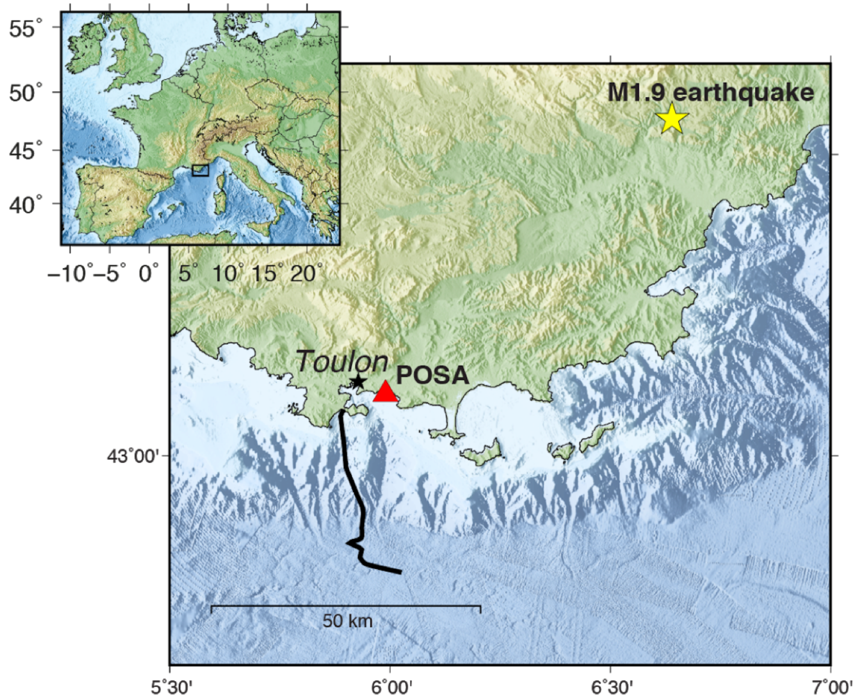


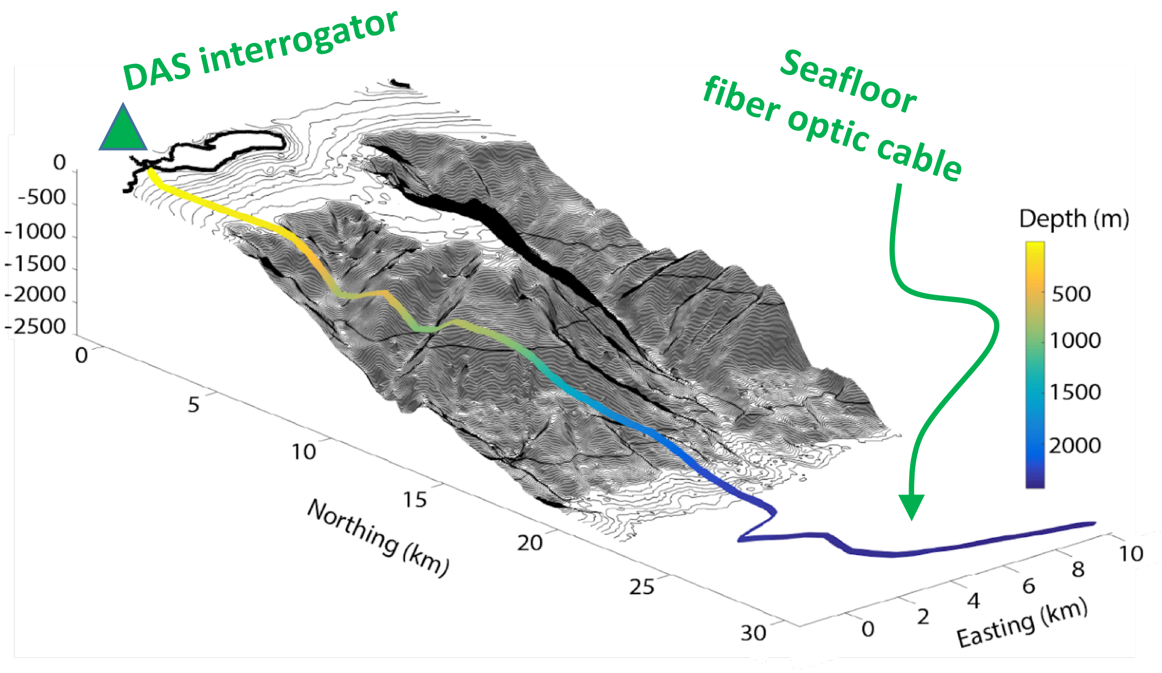
Deep micro-earthquakes beneath Long Beach

Distributed sensing of earthquakes and ocean-solid Earth interactions on seafloor telecom cables

A. Sladen et al.

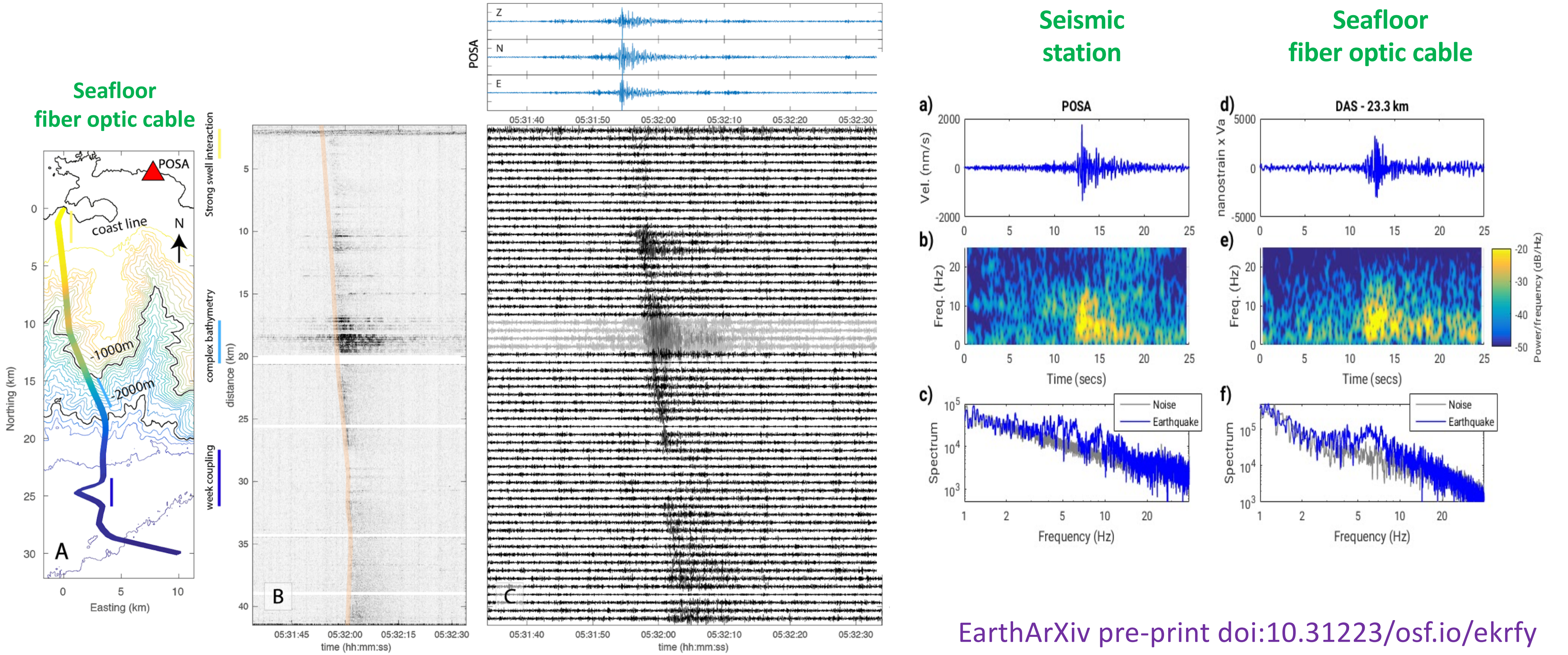
EarthArXiv pre-print doi:10.31223/osf.io/ekrfy





Distributed sensing of earthquakes and ocean-solid Earth interactions on seafloor telecom cables

A. Sladen et al.

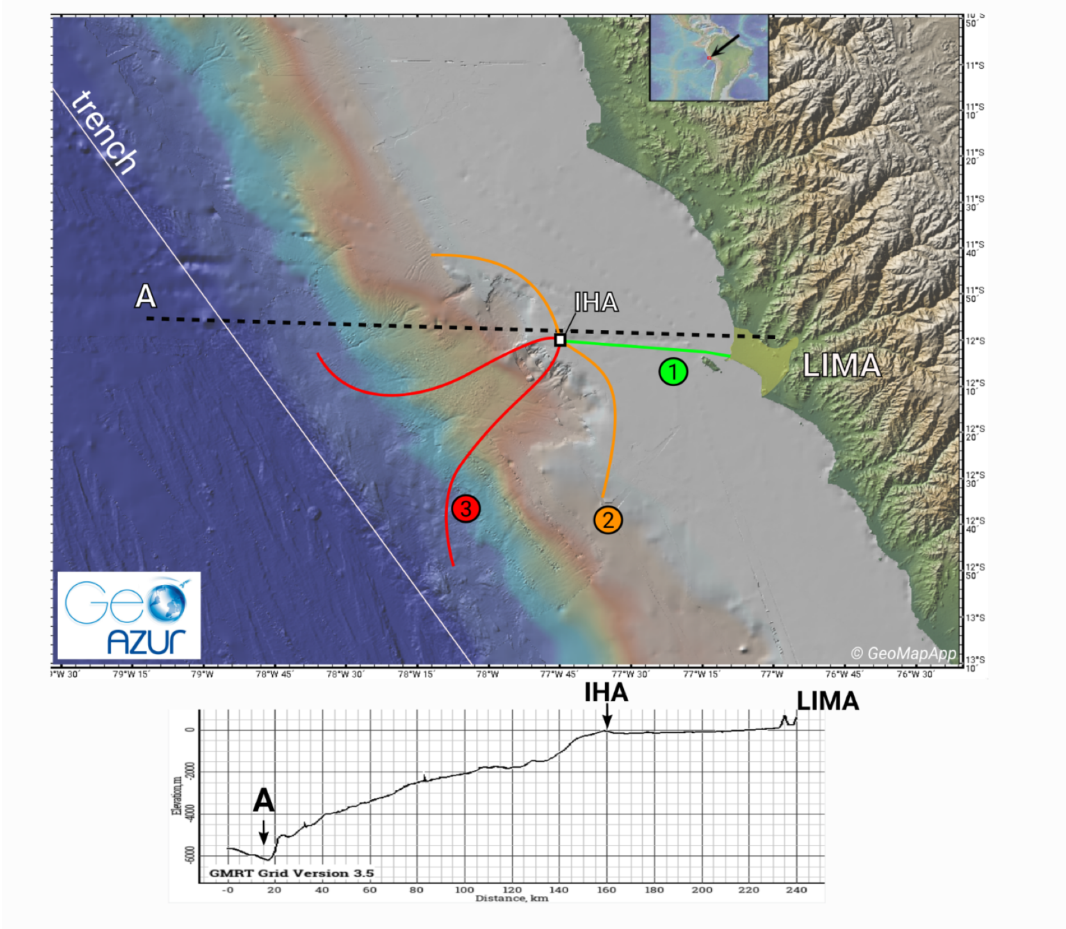


EarthArXiv pre-print doi:10.31223/osf.io/ekrfy

MEDUSA – Monitoring Earthquakes with DistribUted Seafloor Arrays

Proposal concept:

1. Develop the first ocean-bottom observatory of earthquake processes based on Distributed Acoustic Sensing on fiber optic cables
2. Decipher the physics of the initiation and rupture of subduction mega-earthquakes
3. Create an earthquake early warning system for the coastal mega-city of Lima



Institut de Recherche pour le Développement FRANCE

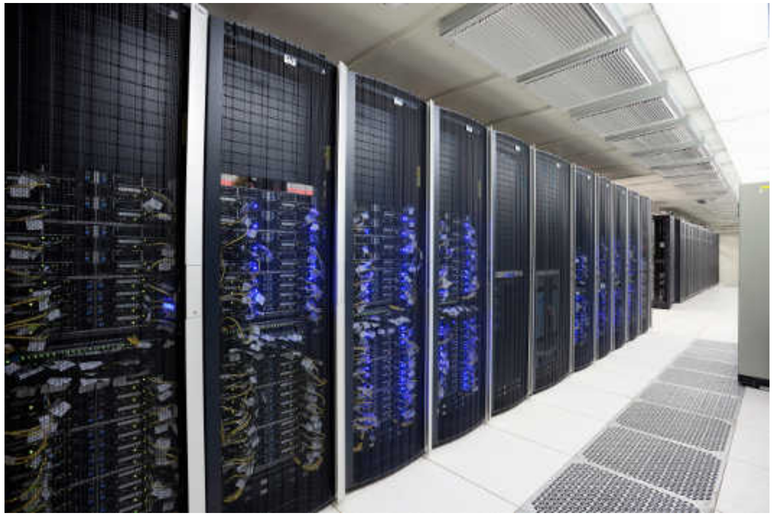
GeoAZUr

Membre de UNIVERSITÉ CÔTE D'AZUR

What is enabling progress in earthquake research?

Increasing computing capabilities

High Performance Computing



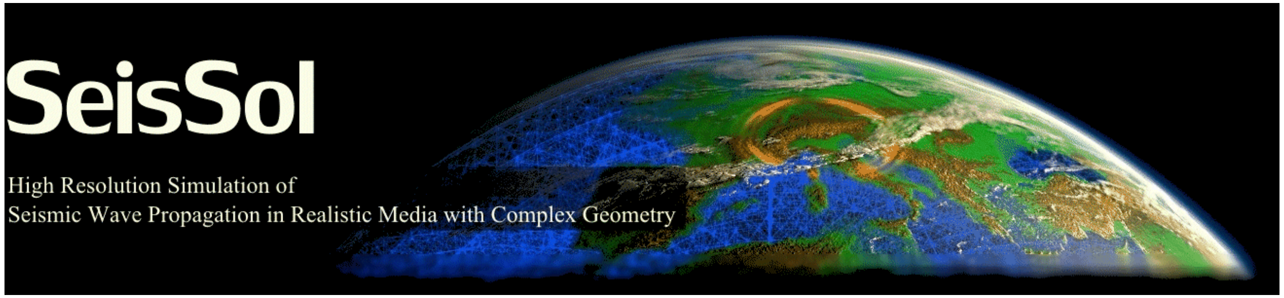
Parallel computing

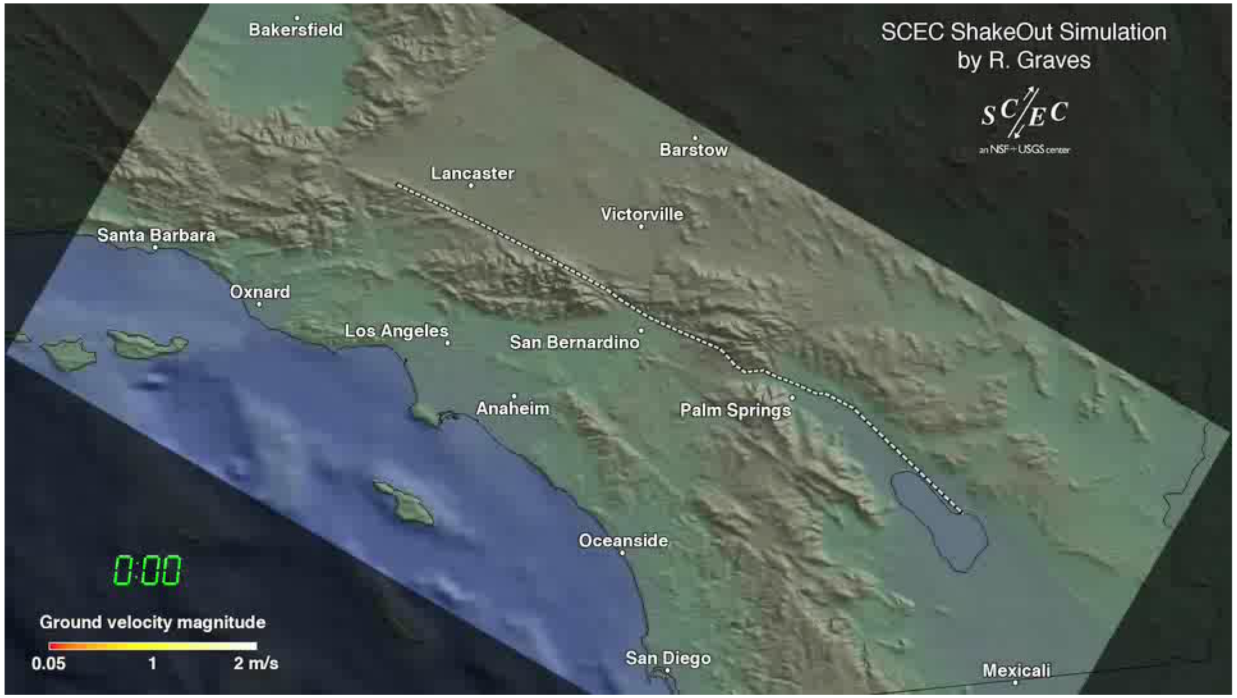
Graphical Processor Units

Scientific software ecosystem

ObsPy

A Python Framework for Seismology




SCEC ShakeOut Simulation
by R. Graves
SCEC
an NSF+USGS center
Bakersfield
Barstow
Lancaster
Victorville
Santa Barbara
Oxnard
Los Angeles
San Bernardino
Anaheim
Palm Springs
Oceanside
San Diego
Mexicali
0:00
Ground velocity magnitude
0.05
1
2 m/s

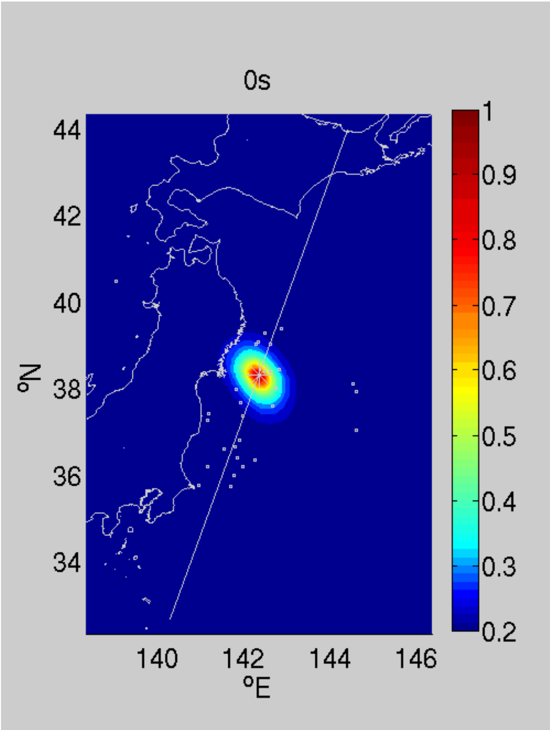

16km
50 km
Every 10th Timestep
0
2.5
5.0
10.0 m/s

+ experimental rock mechanics (lab & field scales)

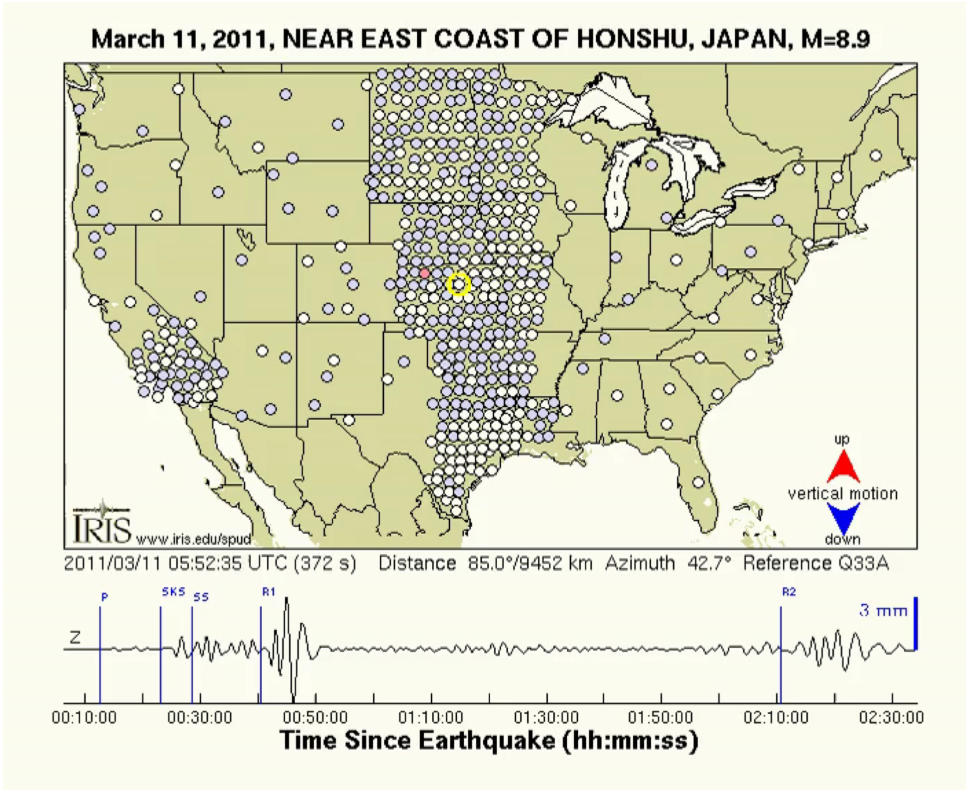
+ theoretical advances

Surprising earthquakes are opportunities

High resolution rupture imaging enabled by large and dense seismic arrays

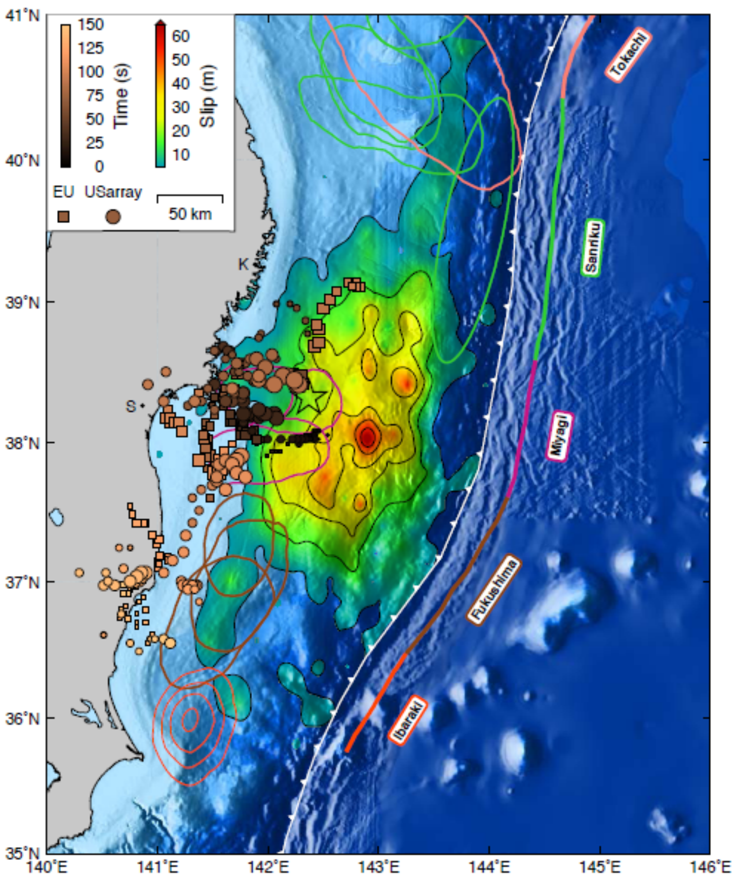


The 2011 M9 Tohoku (Japan) earthquake imaged by back-projection of USArray data (Meng, Inbal and Ampuero, 2011)



→ Rapid imaging of high-frequency wave sources

Tohoku: high-frequency radiation deeper than low-freq slip

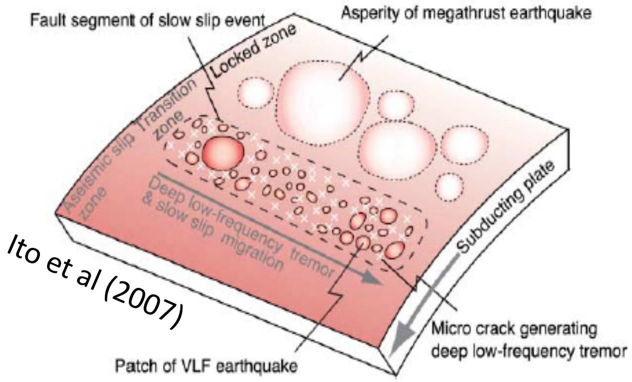


Brownish symbols: 1Hz radiators extracted from back-projection movies

Colored contours: static slip from GPS & tsunami data

Spatial complementarity of high- and low-frequency slip:
HF radiation is deeper than static slip

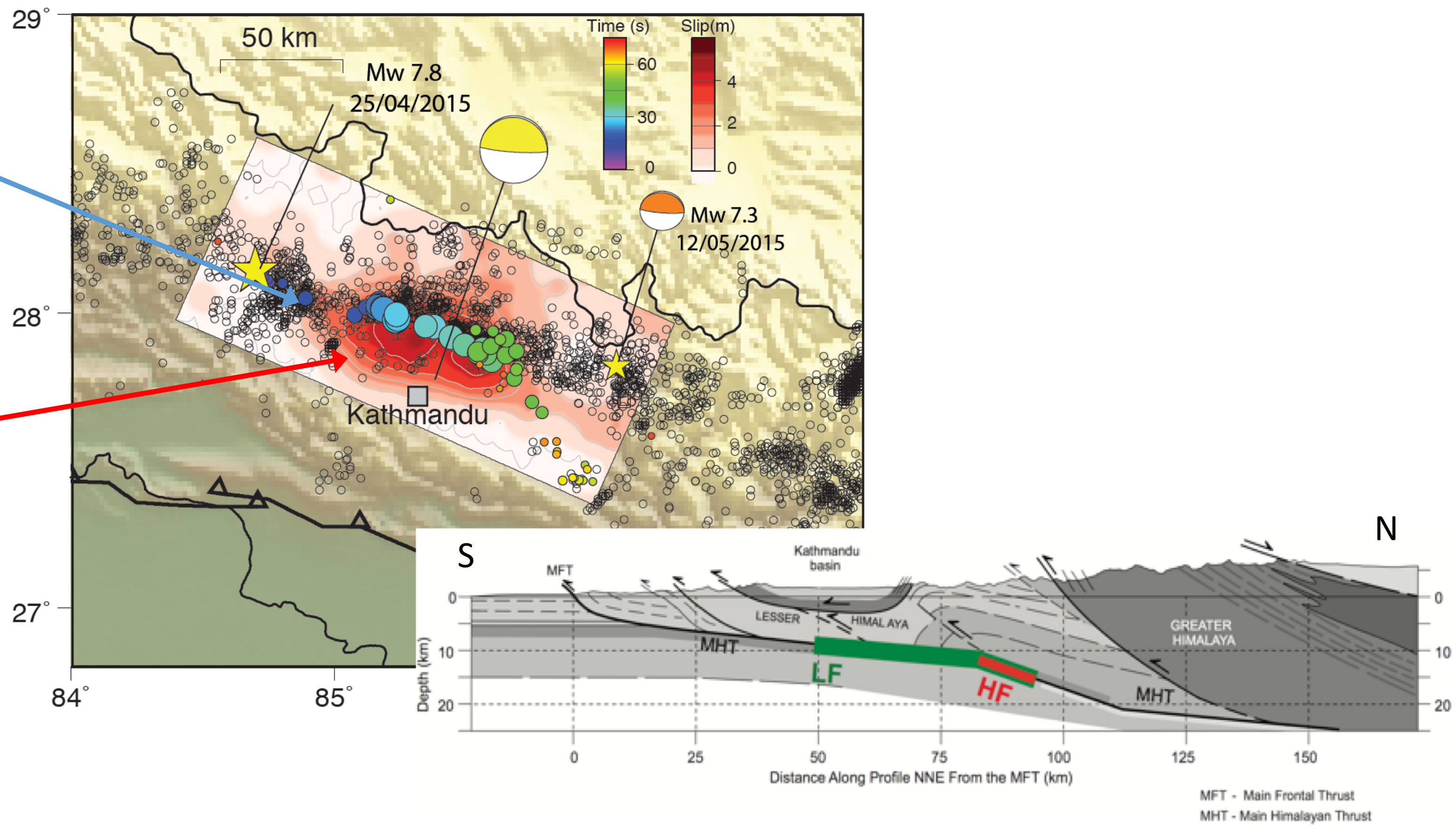
HF radiation occurs even where the rupture is slow



2015 Mw7.8 Nepal earthquake

Colored circles: High-frequency radiation (1 Hz back-projection)

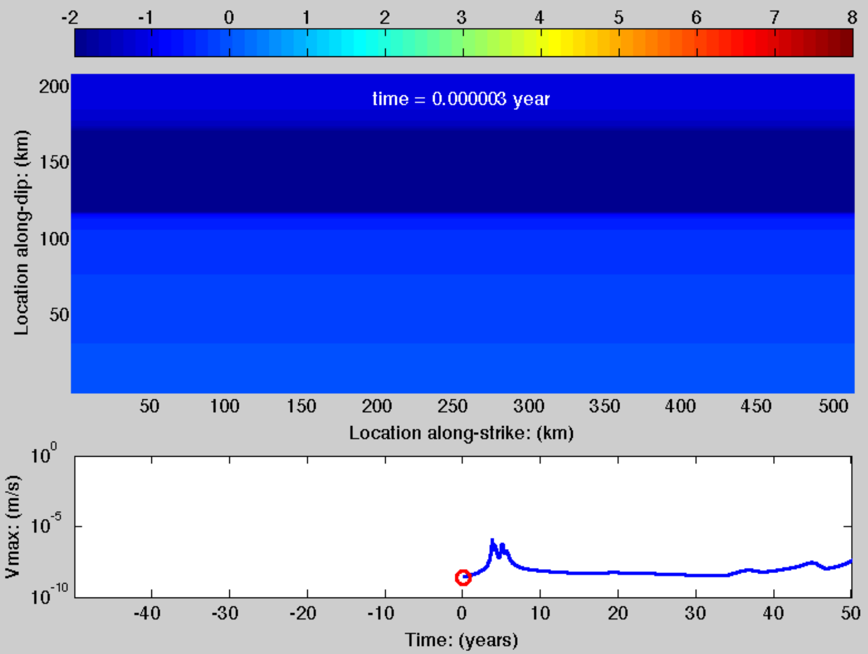
Reddish contours: Low-frequency slip (finite source inversion)



Avouac et al (2015), Ampuero et al (2016)

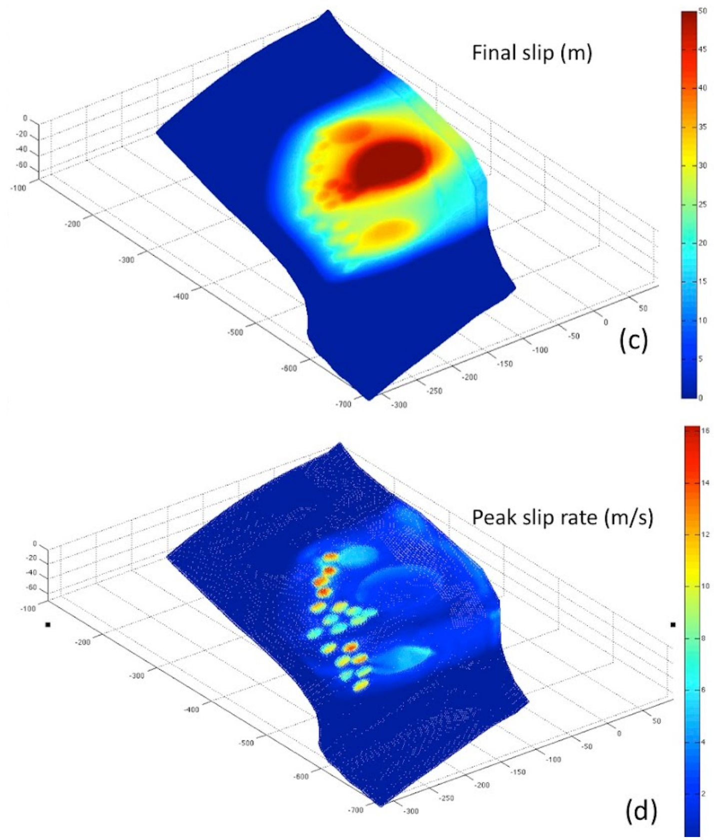
Integration with dynamic rupture modeling

Yingdi Luo, earthquake cycle simulations



Percy Galvez

Earthquake Dynamic rupture simulation of The 2011 Tohoku earthquake.



The April 11 2012 M8.6 Indian Ocean earthquake

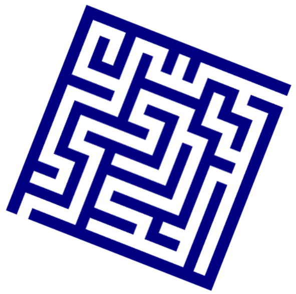
A record-breaking event: Largest strike-slip earthquake ever recorded

- Tectonic setting: a nascent plate boundary
- A complex and unexpected rupture process revealed by teleseismic back-projection source imaging
- Implications for earthquake physics

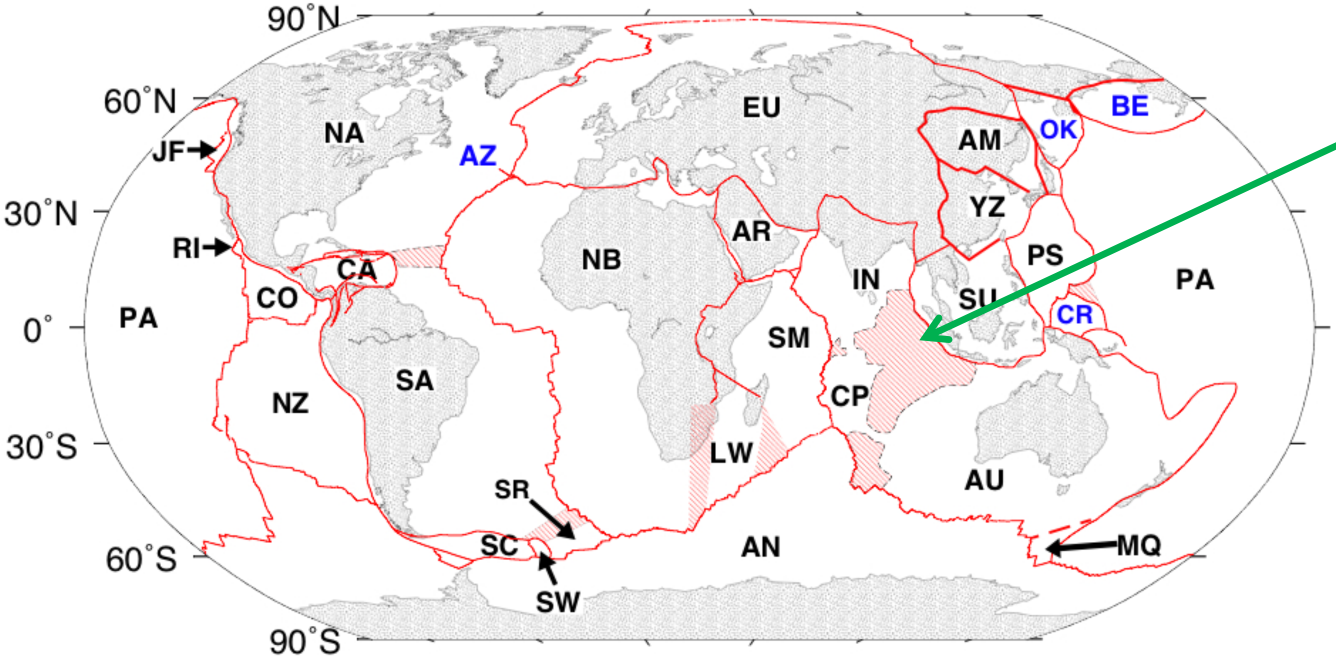
Earthquake in a Maze: Compressional Rupture Branching During the 2012 M_w 8.6 Sumatra Earthquake

L. Meng,* J.-P. Ampuero, J. Stock, Z. Duputel, Y. Luo, V. C. Tsai

10 AUGUST 2012 VOL 337 **SCIENCE** www.sciencemag.org



Tectonic setting

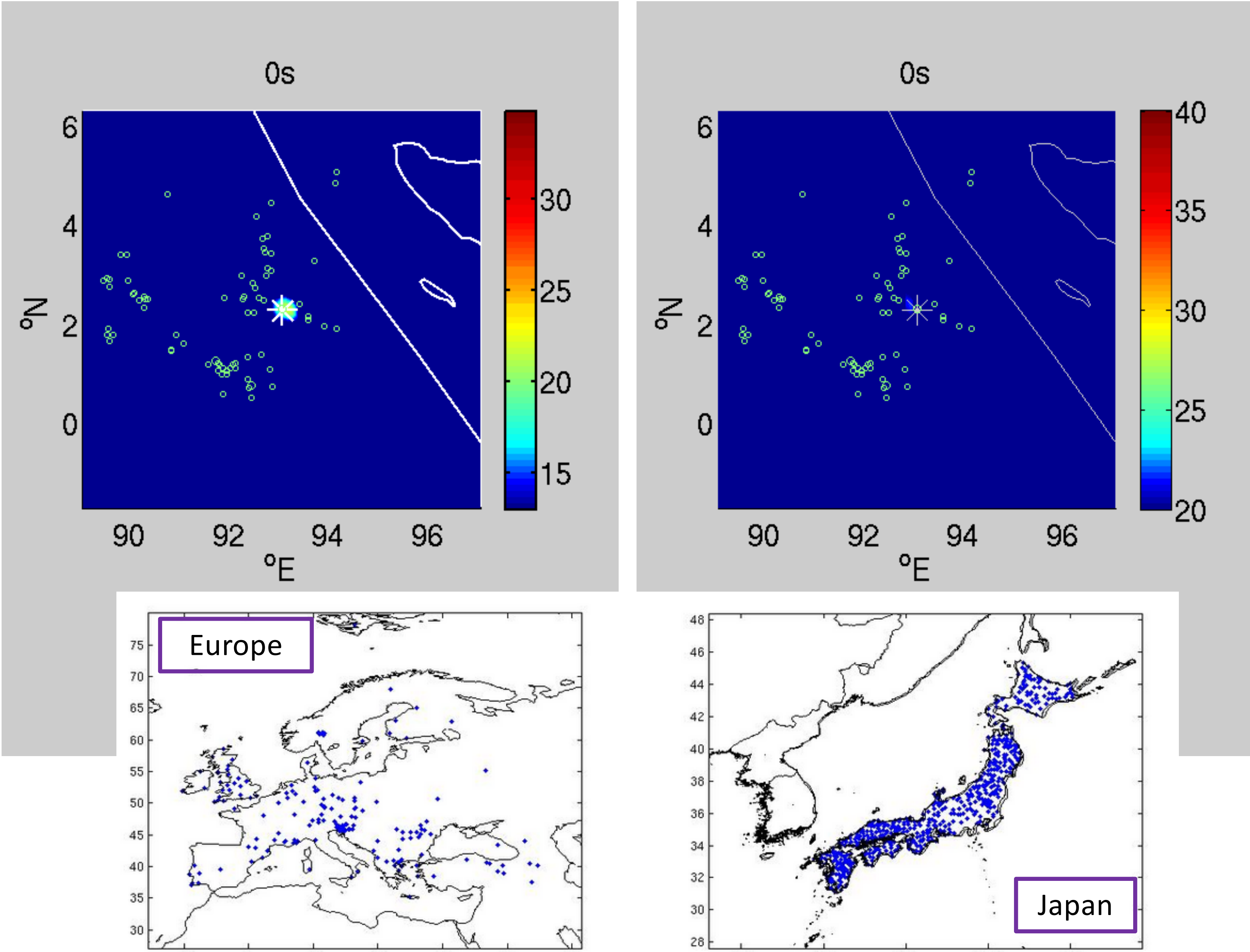


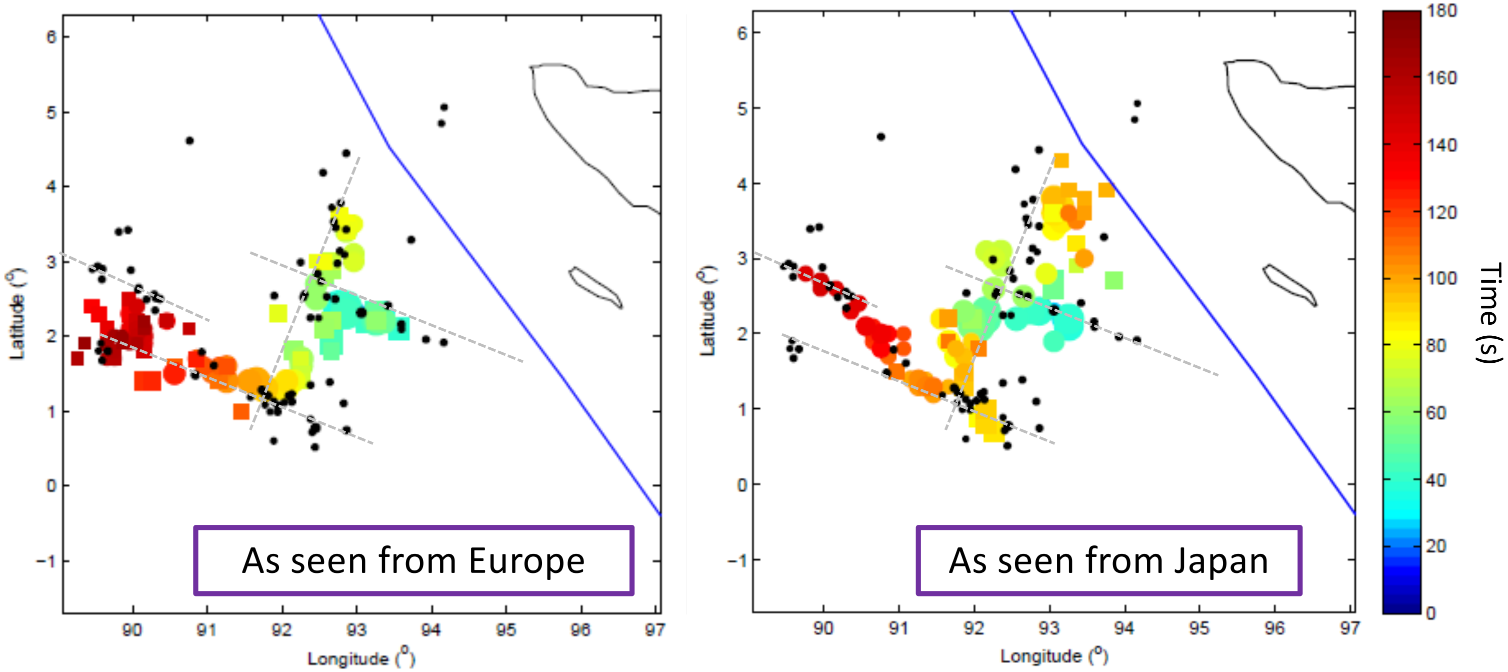
DeMets et al, 2010

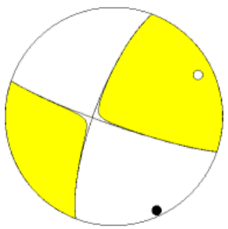
The 2012 off-Sumatra earthquake is not really an intra-plate event

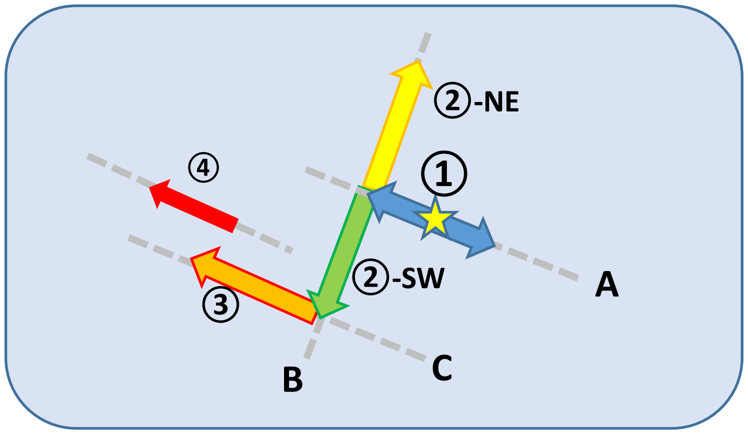
It occurred in the India-Australia diffuse deformation zone, an emerging plate boundary

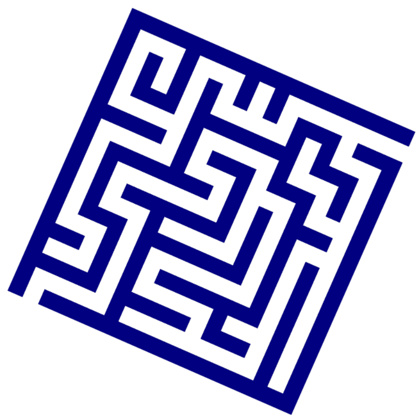
A late aftershock of the 2004 Sumatra mega-earthquake


0s
6
4
2
0
°N
90
92
94
96
°E
30
25
20
15
0s
6
4
2
0
°N
90
92
94
96
°E
40
35
30
25
20
Europe
75
70
65
60
55
50
45
40
35
30
-10
0
10
20
30
40
50
Japan
48
46
44
42
40
38
36
34
32
30
28
125
130
135
140
145

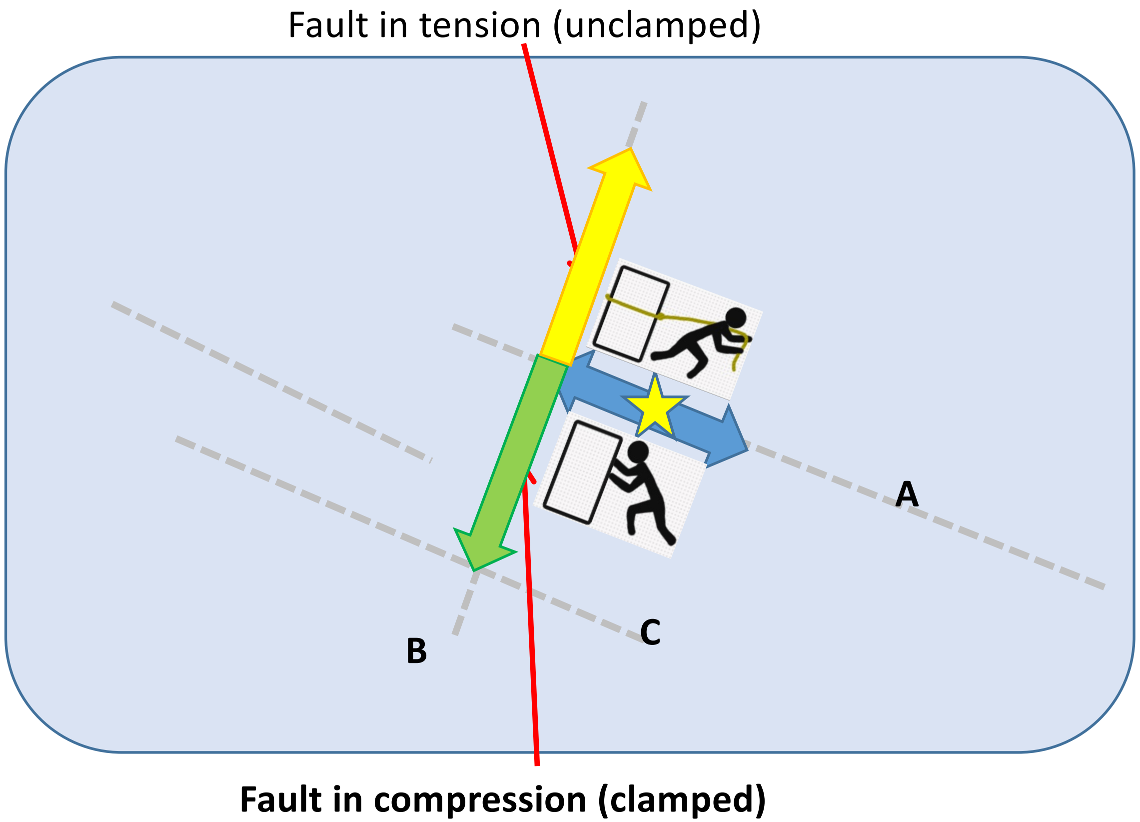

As seen from Europe
As seen from Japan
Latitude (°)
Longitude (°)
Time (s)
0
20
40
60
80
100
120
140
160
180
90
91
92
93
94
95
96
97
−1
0
1
2
3
4
5
6

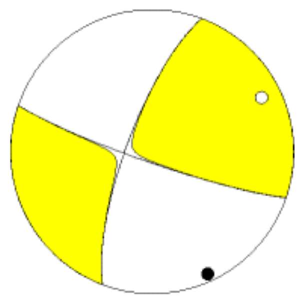



②-NE
①
④
②-SW
③
A
B
C

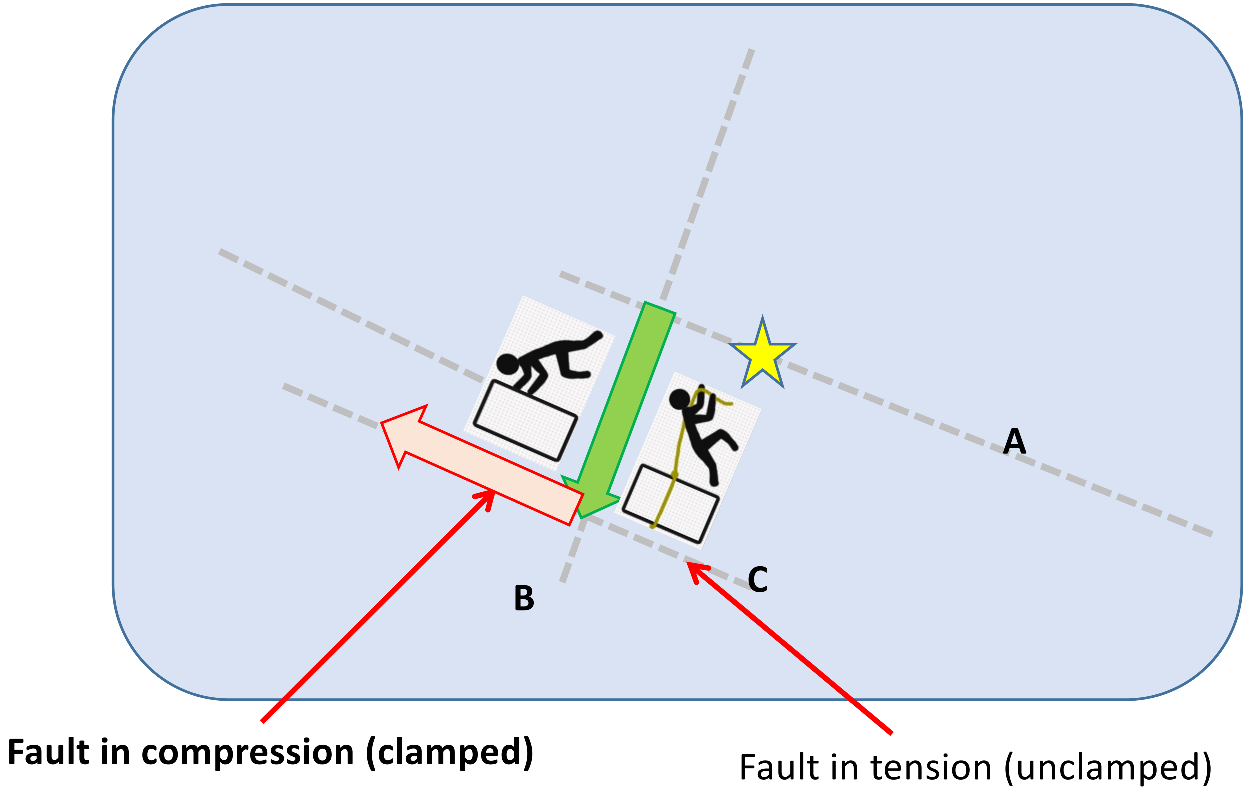


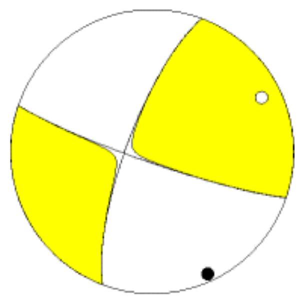
Compressional rupture branching



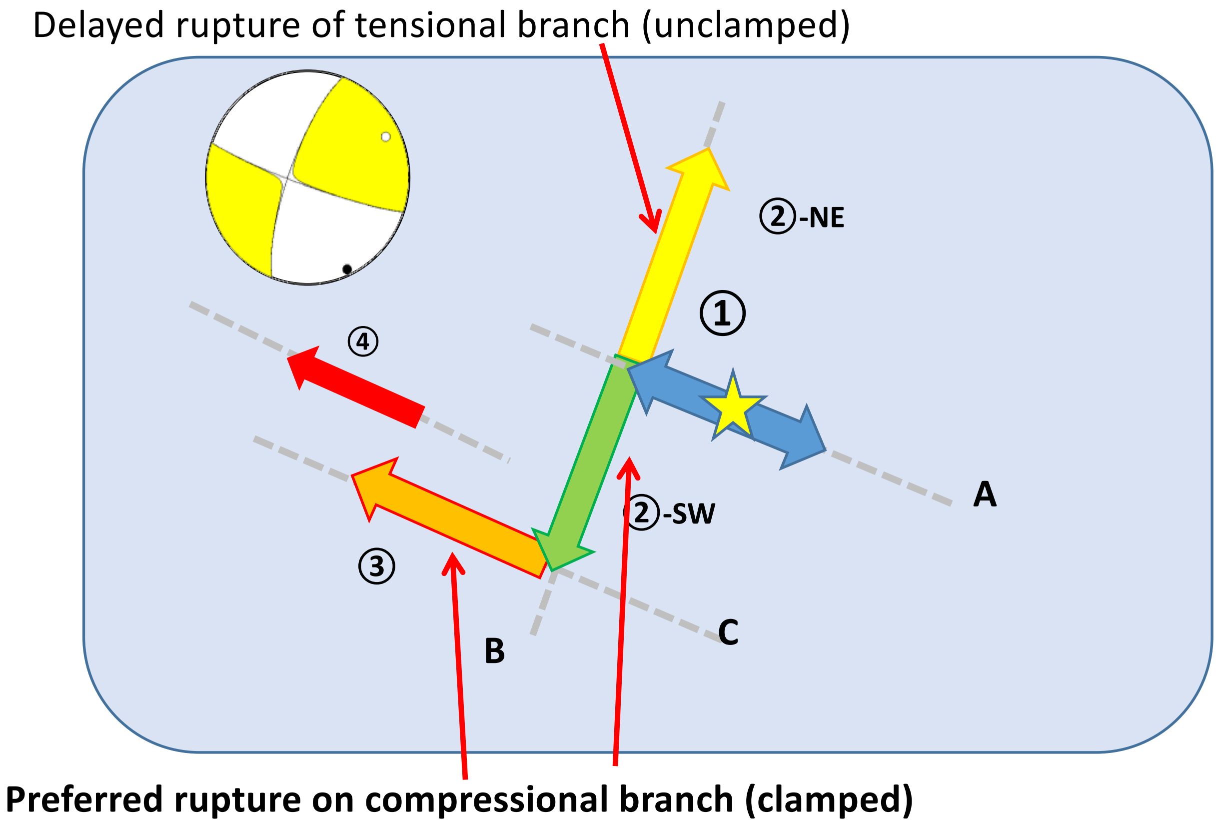


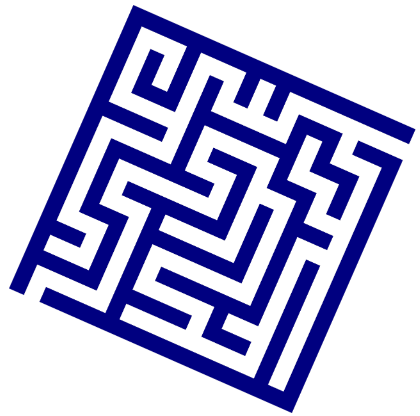
Compressional rupture branching





Compressional rupture branching

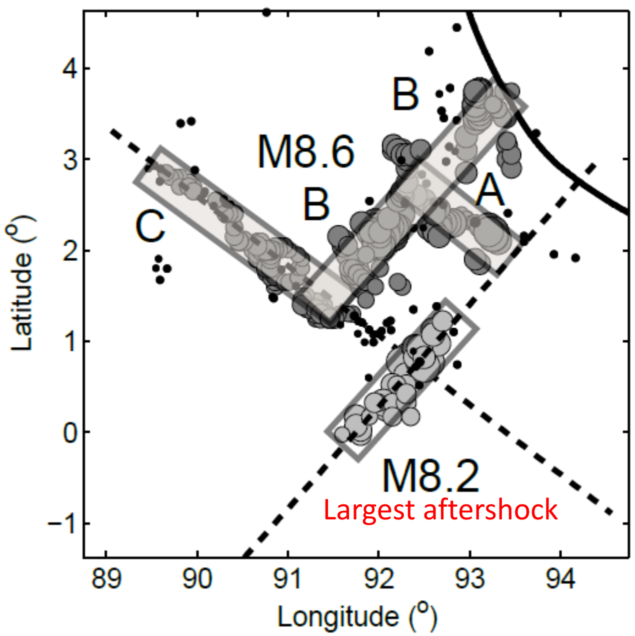




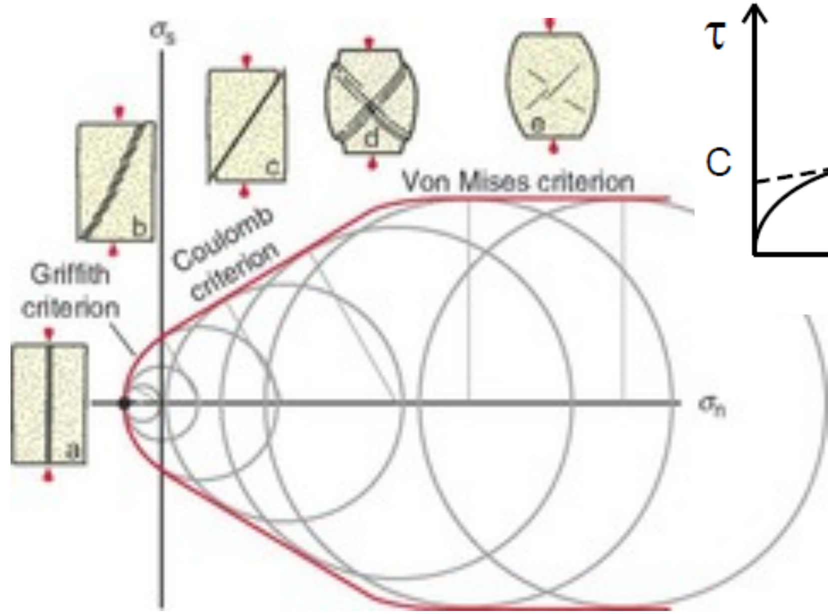
Earthquake in a maze
Complicated and unexpected rupture path challenges our classical view of fault friction

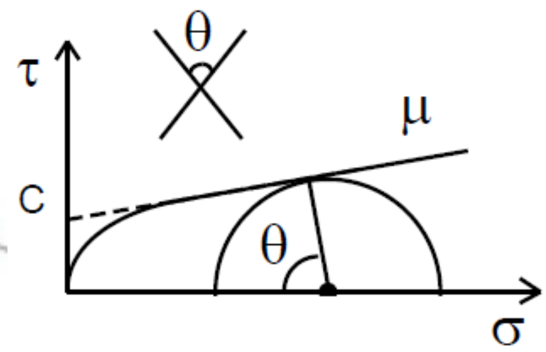
Conjugate orthogonal faults

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

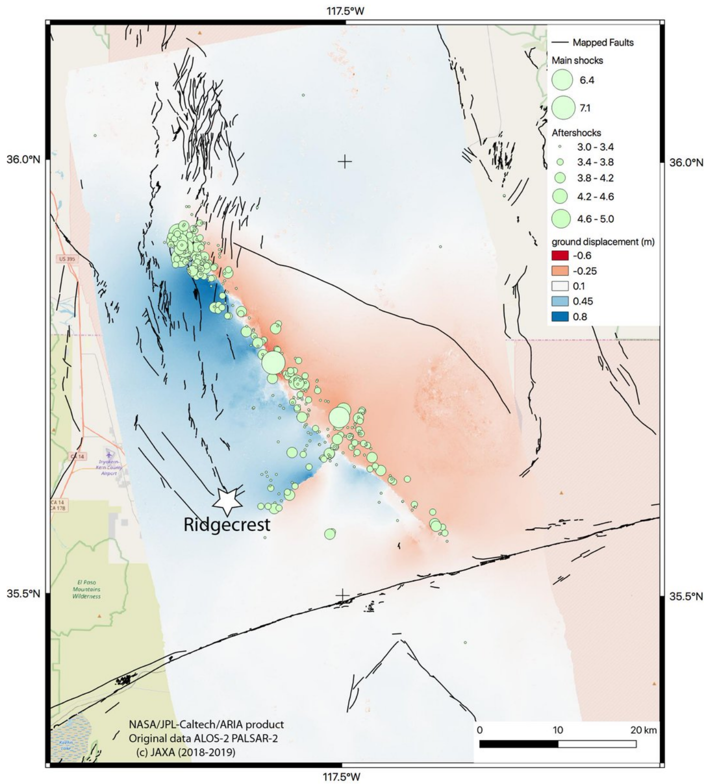


Mechanical implication: pressure-insensitive strength (low apparent friction coefficient μ)

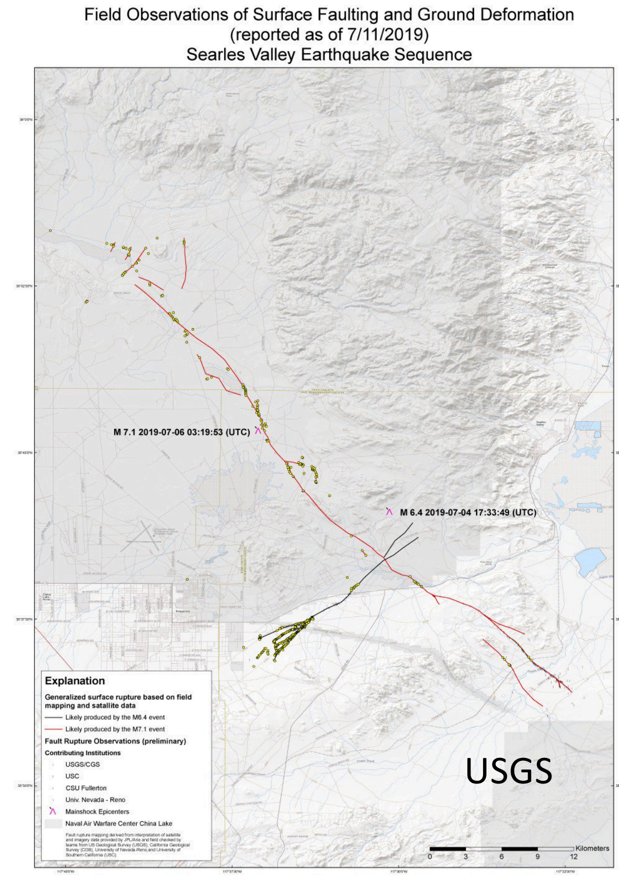




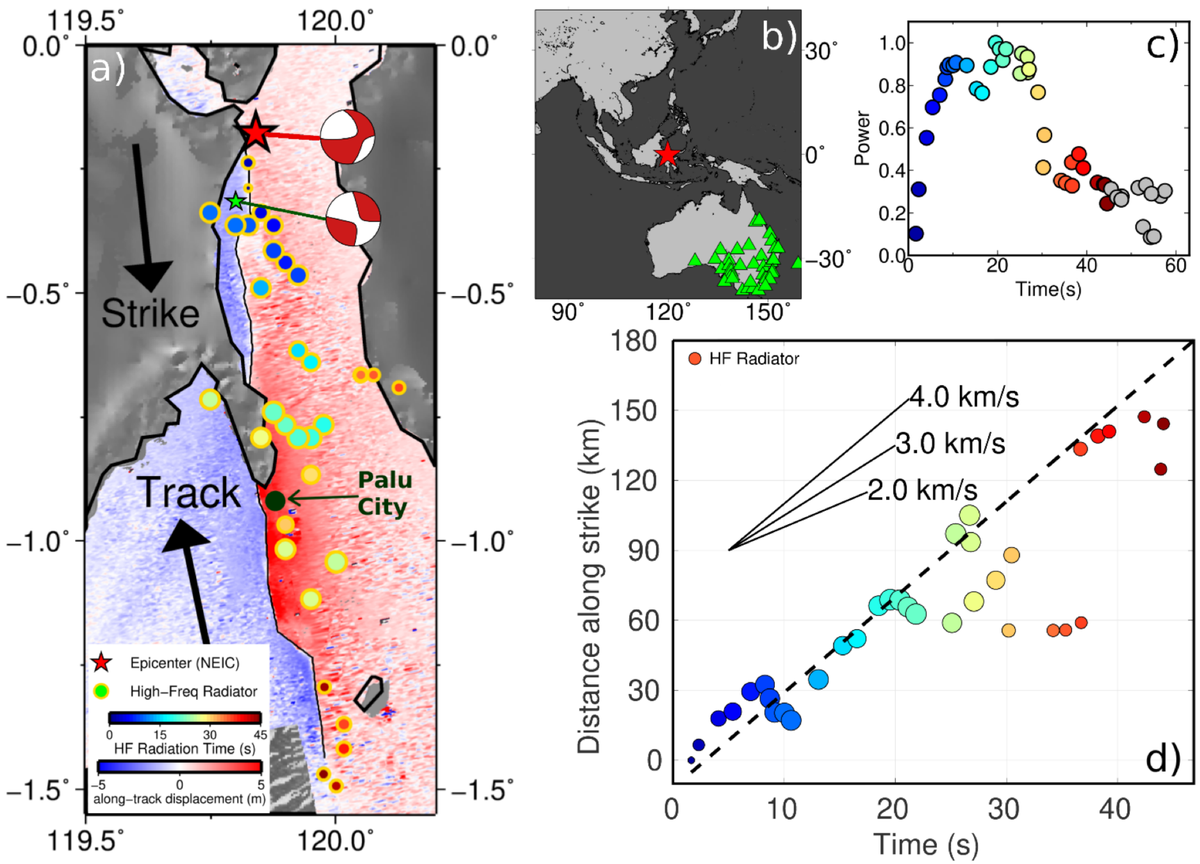
2019 Ridgecrest earthquake sequence on orthogonal faults



Caltech / NASA JPL



Supershear – 2018 Palu, Indonesia earthquake



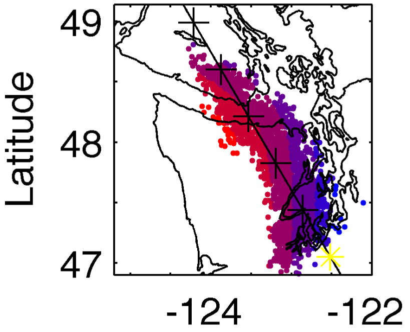
Bao et al (2018)

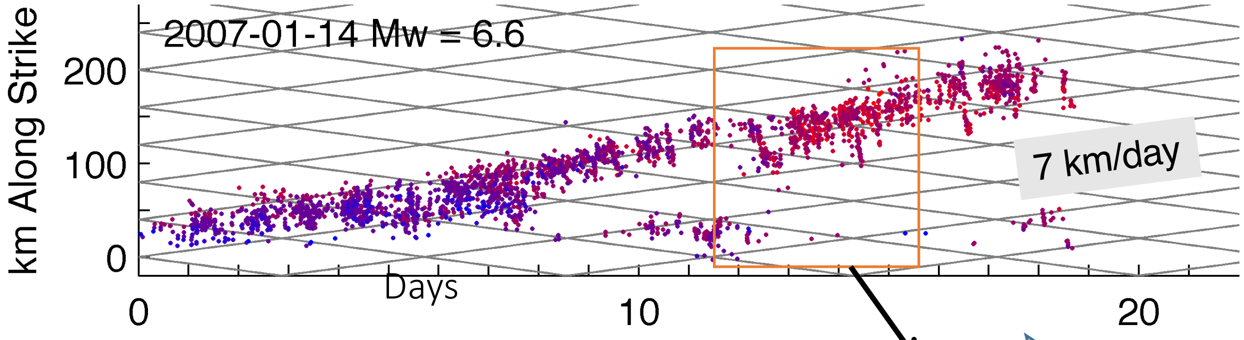
Multitaper-MUSIC teleseismic back-projection with aftershock-based slowness calibration

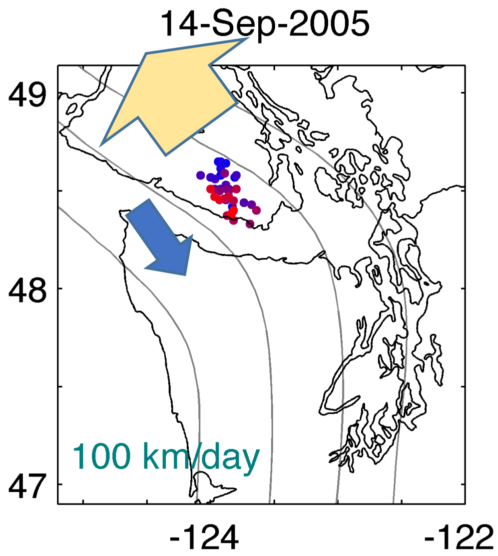
Rupture speed = 4.1 km/s from the outset!

Slower than Eshelby's speed (unstable in homogeneous media): **Evidence for rupture inside a damaged zone**

Slow slip and tremor migration patterns

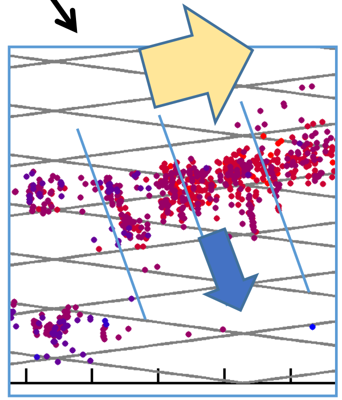






Non-volcanic tremor migration patterns in Cascadia, USA

Tremor migrates slowly along strike (~10 km/day) tracking the front of the slow slip event



Houston et al (2010)

Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations

Goals:

- Training on earthquake modeling and observations is often dissociated, PhD students often focused on one or the other
- Gain advanced knowledge for earthquake research that integrates the three perspectives: theoretical, computational and observational
- Lectures and practical training
- Emphasis on dynamic time scales and seismology