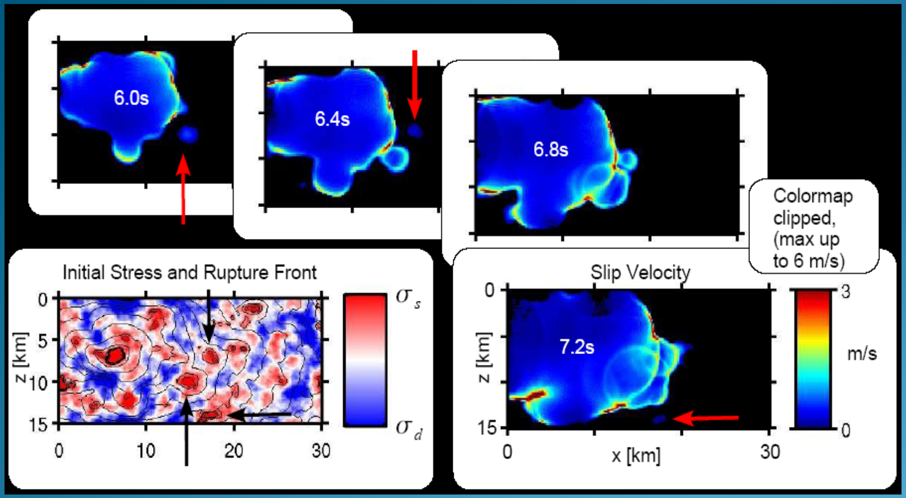
Strong motion seismology from space
Proof of concept



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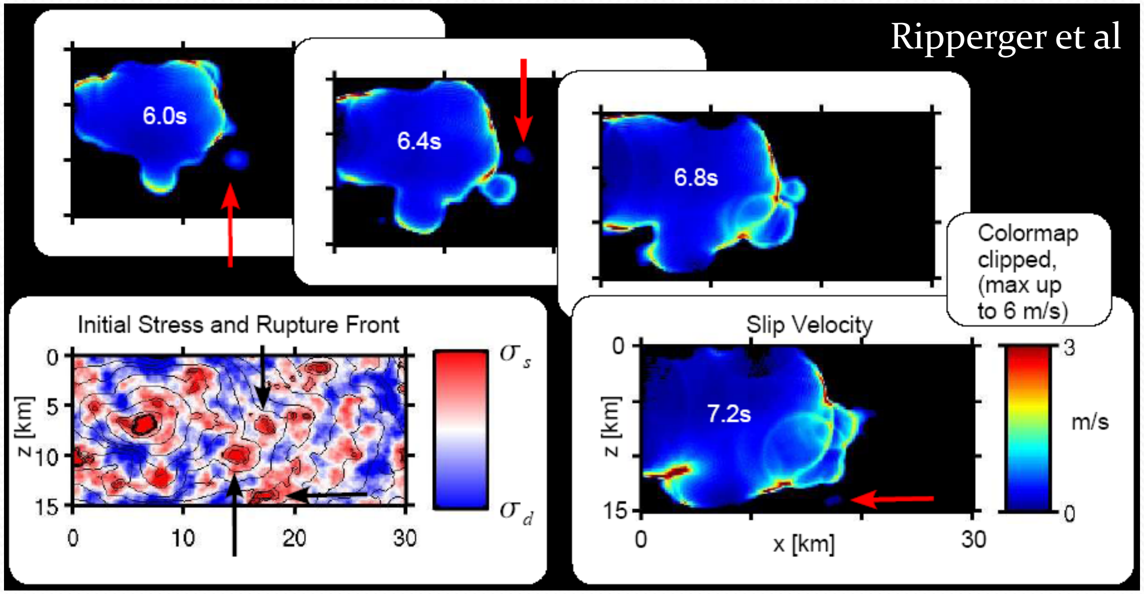
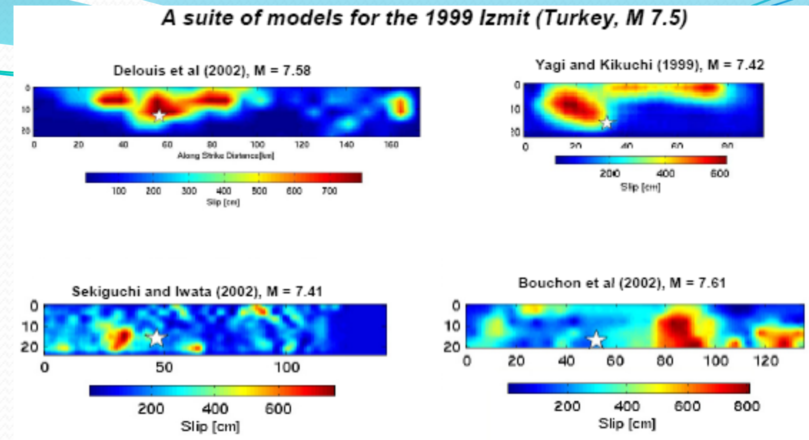
Some open questions about earthquake dynamics

- **Earthquake source complexity**: geometry and evolution of the rupture front, broad-scale heterogeneity, variability of rupture speed
- Pulse/crack rupture styles: how short are earthquake rise times?
- **Rupture speed**: how usual are supershear ruptures?
- Fault rheology: which weakening mechanisms are dominant in real faults?
  Is rupture dominated by rheology or by heterogeneities?

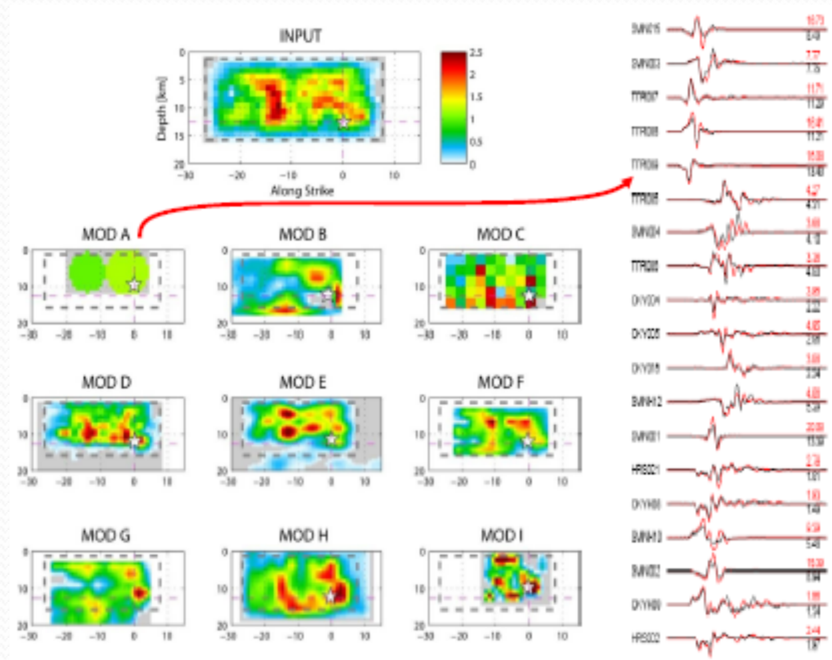


Source imaging today: Intrinsic limitations



- Source inverse problem: retrieve the **space-time distribution of fault slip** from seismological, geodetic, field data
- Due to our poor knowledge of the propagation media at small scales, seismic data is usually exploited in a **limited frequency band** (< 0.5 Hz)
- Data is sparse: the **inverse problem is ill-posed** (severe non uniqueness), sensitive to regularization and data selection. Different teams often obtain very different models of the same earthquake.
- **Low resolution**: models suffer from limited spatial resolution (> 10 km).
  - Little detail about the friction law can be retrieved
  - Resulting slip models are notoriously heterogeneous but how much of that spatial variability is real?

SIV first blind test results (Mai et al)



Rationale for specs of remote imaging system

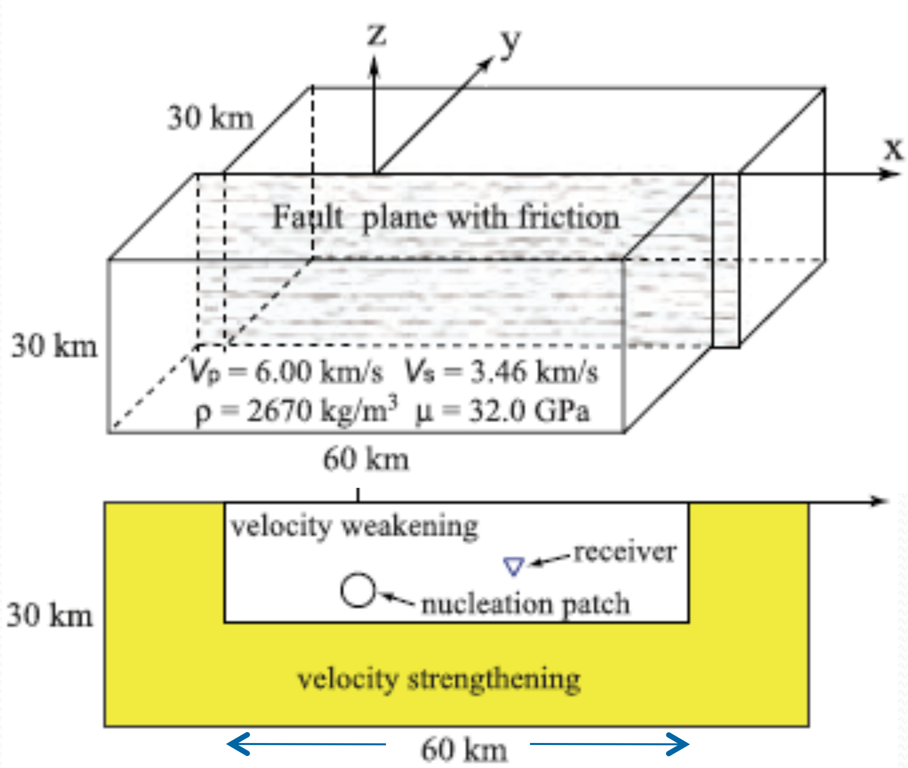
- Amplitude sensitivity on ground velocity = few cm/s, dictated by technical capabilities → Strong-motion, near-field seismology
- Wide field of view, several 100km, to capture a M7.8 earthquake on the San Andreas Fault and its largest aftershocks
- Temporal sampling at 1Hz, the *nominal* frequency limit of current inversions
- Spatial sampling at 100m spacing = 1/5 minimum wavelength at 1Hz considering S wave speeds ~500 m/s at shallow depth

Expected outcomes:

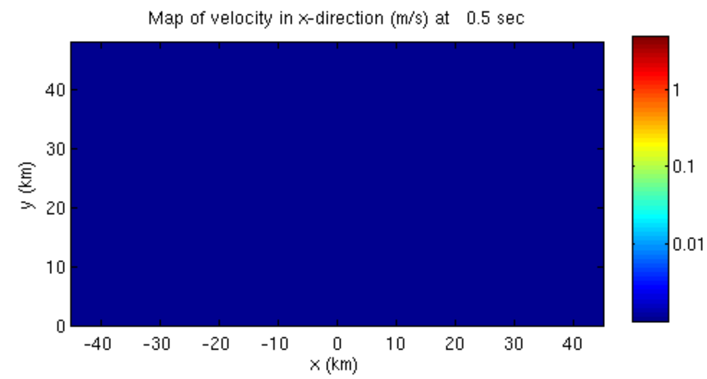
- robust source imaging down to few km spatial resolution on the fault
- distinguish between sub-shear and super-shear rupture speed
- distinguish real spatio-temporal complexity of earthquake rupture
- assess the quality of and revisit source images of past earthquakes

Note: Pushing to 5-10Hz might yield new constraints on fault rheology (friction)

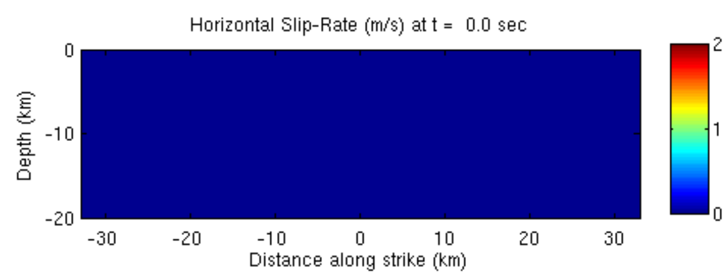
M7 earthquake scenario setup



Ground motions



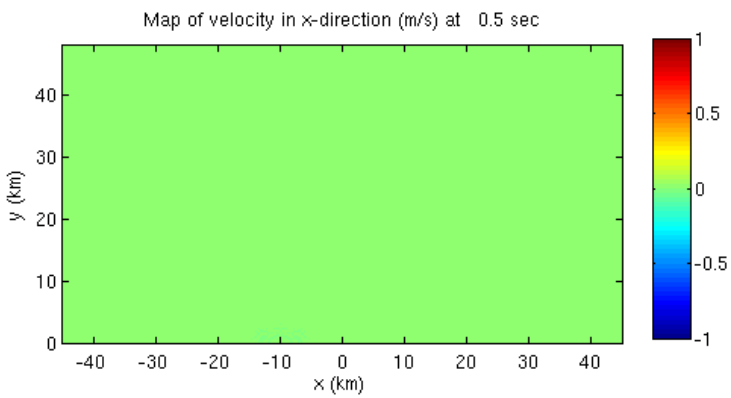
Fault slip rate



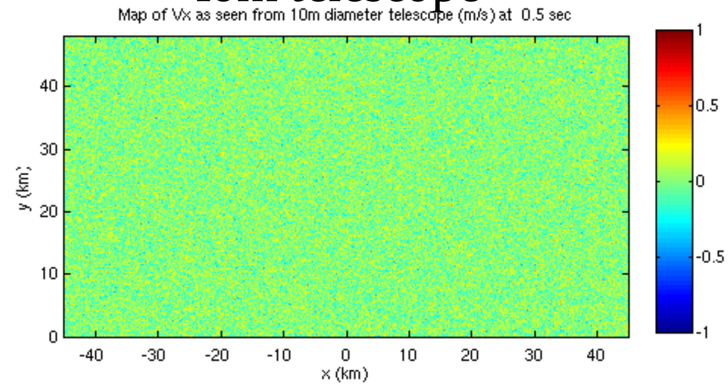
Kaneko, Lapusta and Ampuero (2008) : Spectral Element modeling of faults governed by rate-and-state friction

Scenario ground motions

Fault-parallel ground velocity

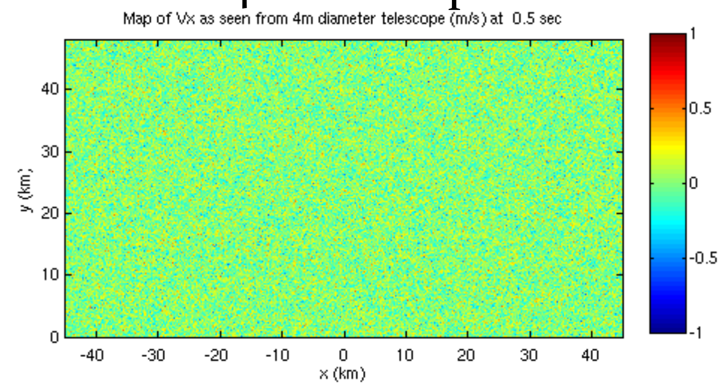


10m telescope



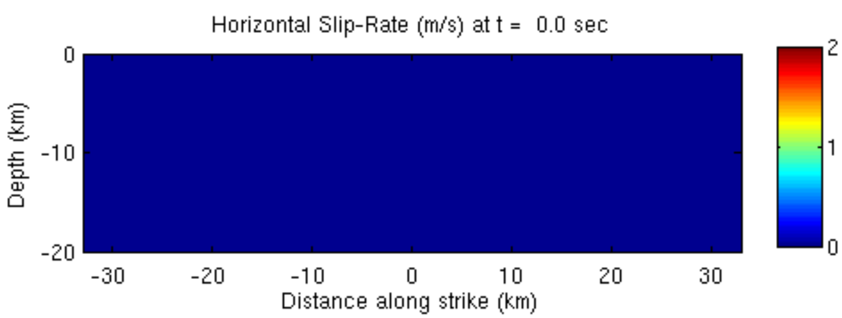
Processed ground motions

4m telescope

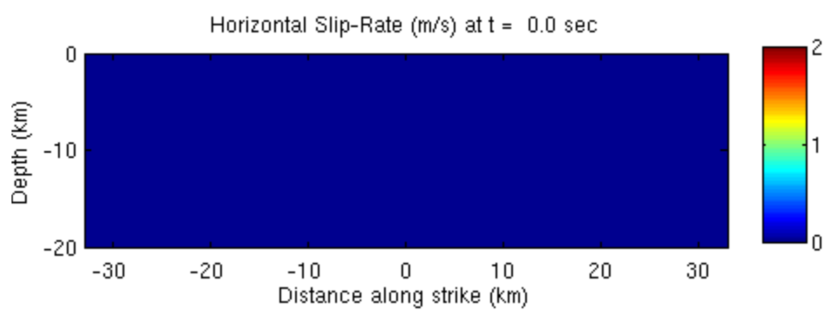


Sub-shear vs. super-shear rupture speed

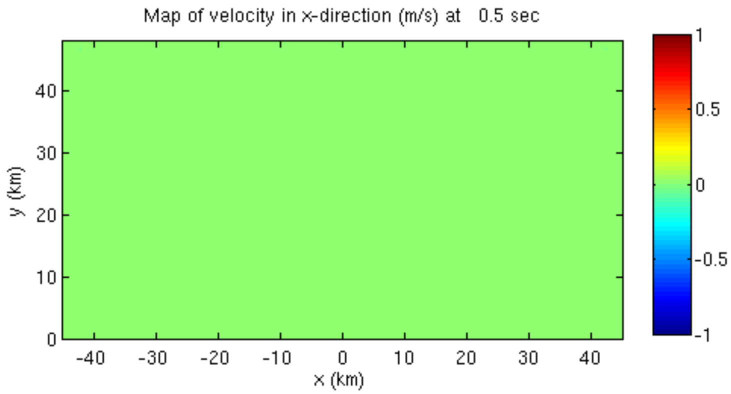
Subshear scenario



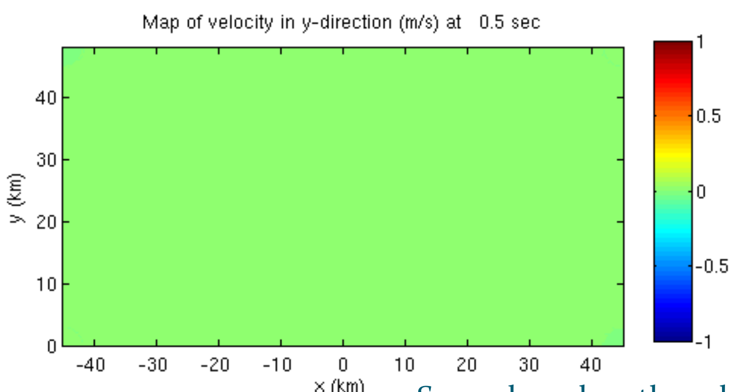
Supershear scenario

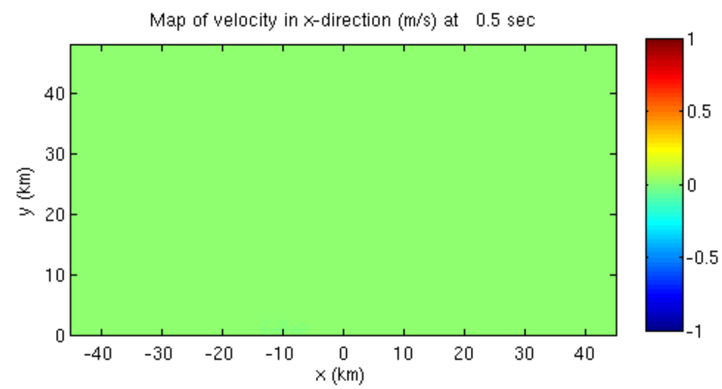


Sub-shear vs. super-shear rupture

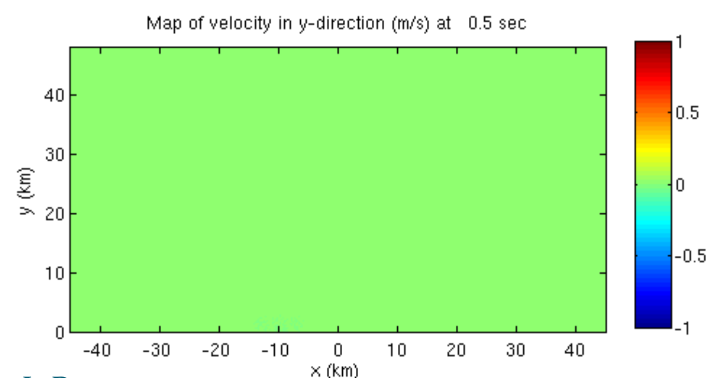


Sub-shear



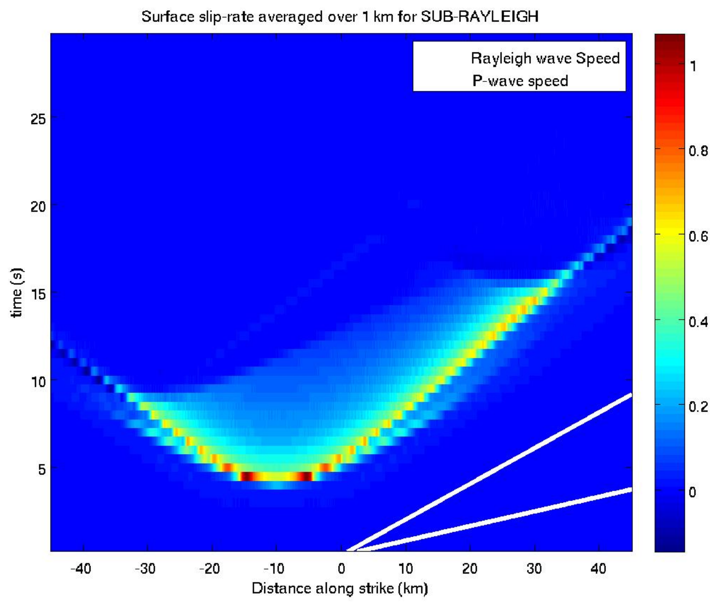


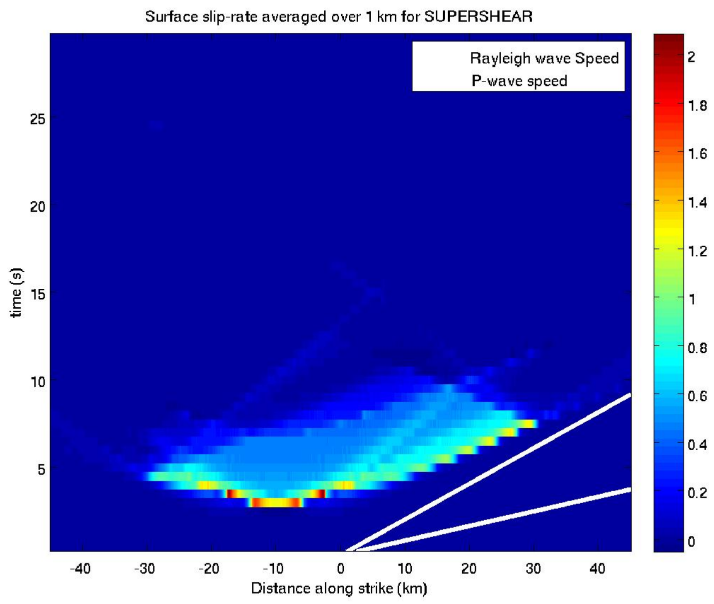
Super-shear

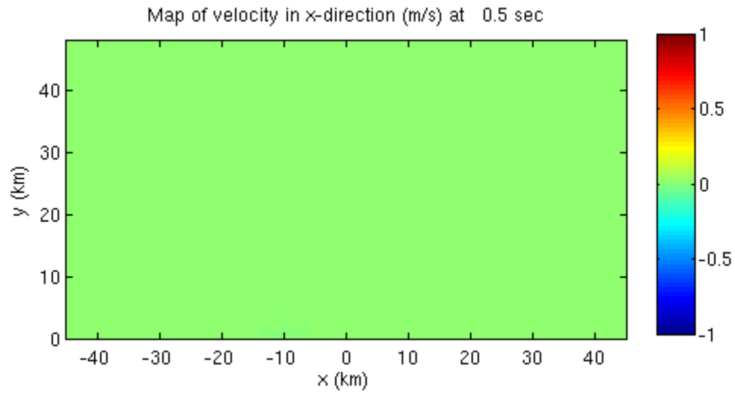


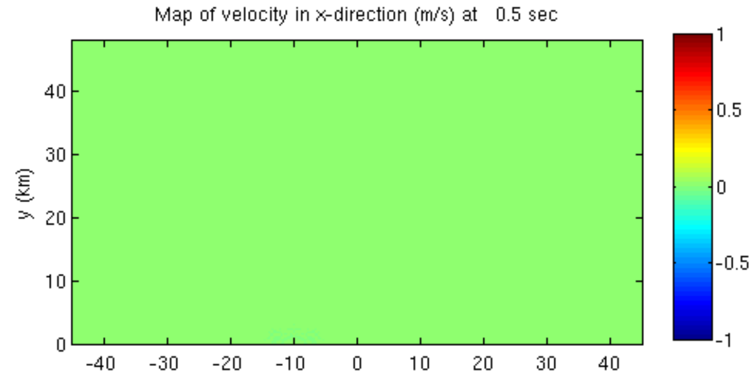
Direct estimate of surface slip velocity from satellite optical images

Sub-shear **Super-shear**



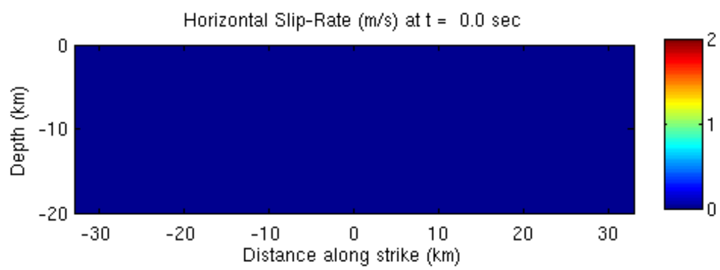


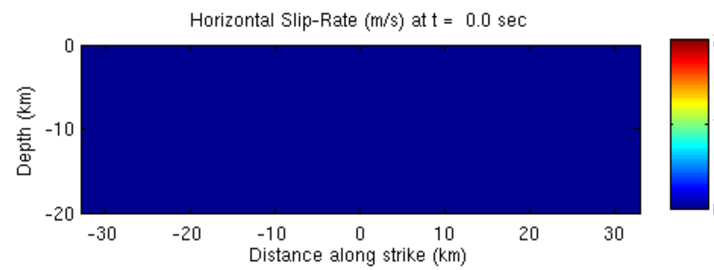


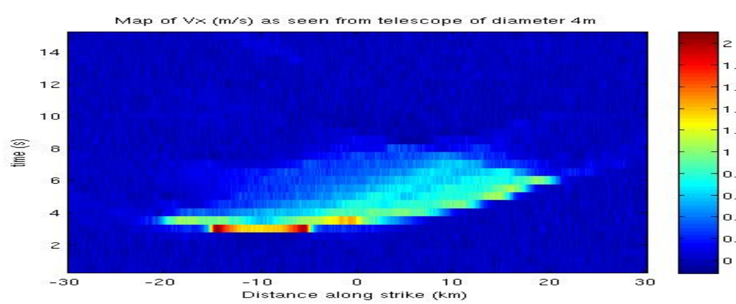


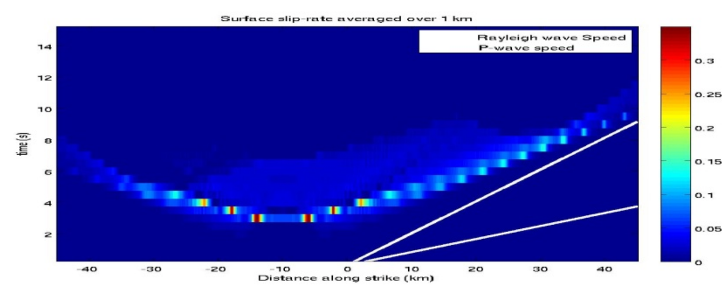
With surface rupture

Without surface rupture

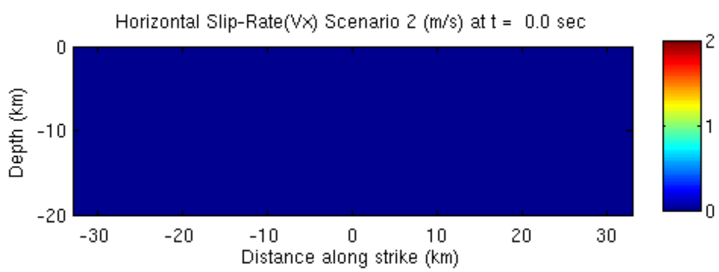


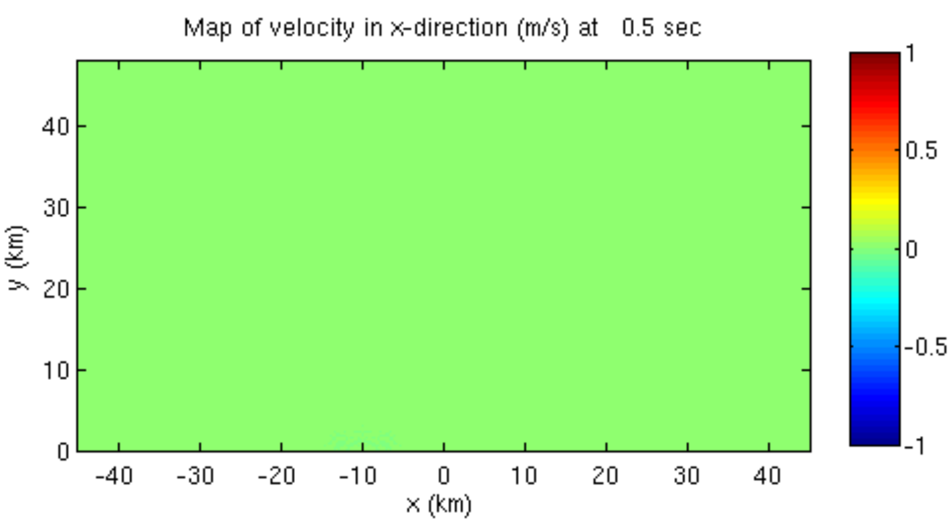


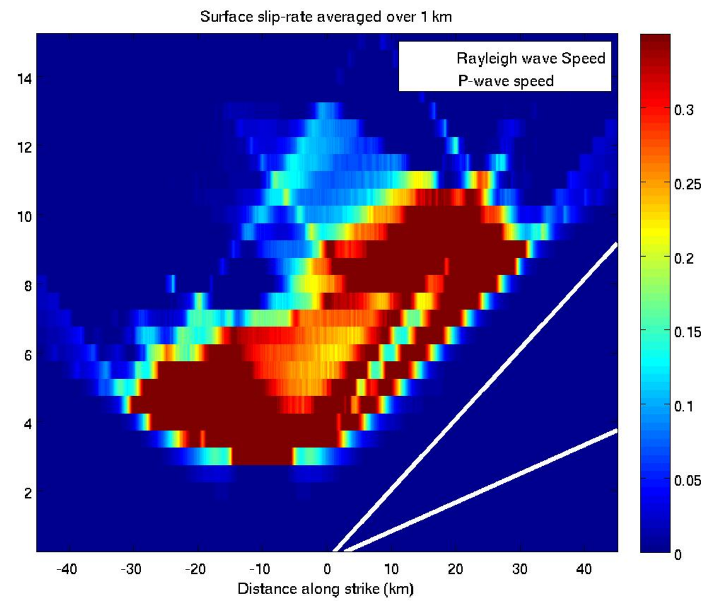




Imaging rupture complexity
Scenario with a second asperity







- J.-P.

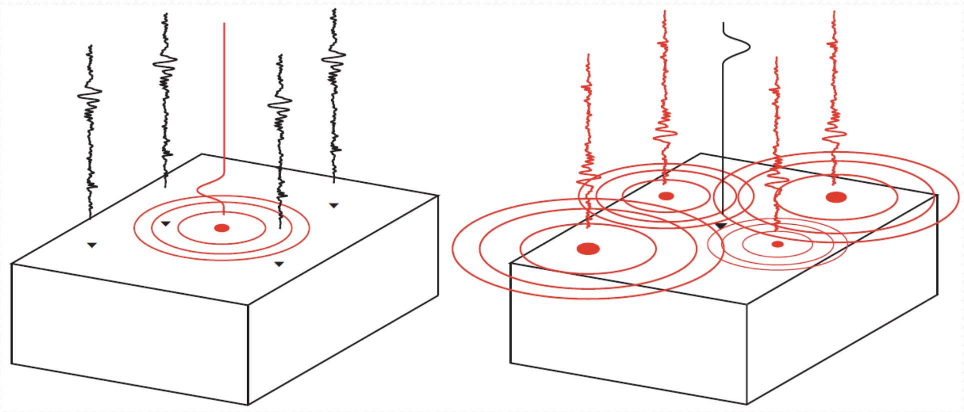
Source inversion

- **Task**: infer spatio-temporal fault slip distribution from recorded ground motions
- **Goal**: quantify the improvements on source imaging provided by the satellite-based system
- **Challenge**:
  - The satellite system would provide unprecedentedly dense sampling of ground motions: several million seismometers!
  - Classical source inversion approaches typically work with <20 stations and do not scale up to an immensely larger ($\times 10^5$) seismic network, several Terabytes of data, $>10^4$ unknown fault parameters.

  → Source inversion codes are just not ready for that.
- **Alternative**: We tried a more direct path, time-reversal imaging

Time-reversal source imaging: principles and limitations

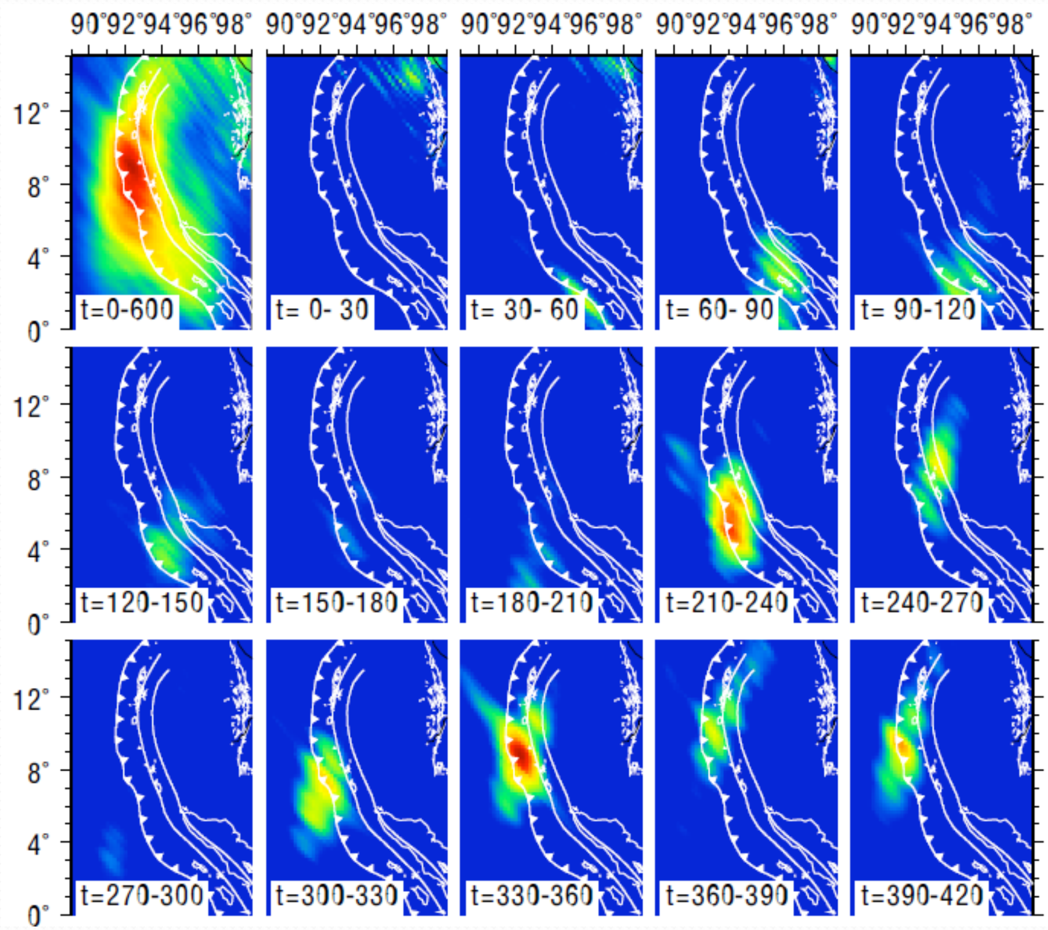
Forward wave propagation



Time-reversed wave propagation

Principle and properties:

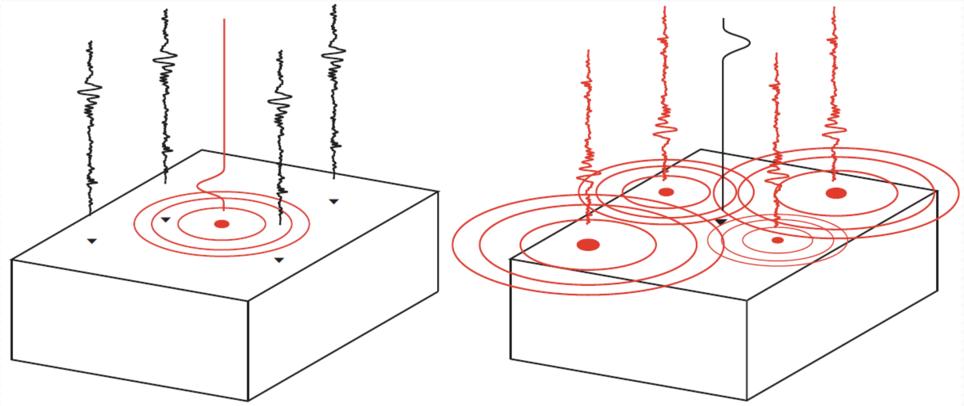
- Exploit the time-reversal symmetry of the wave equation and the reciprocity principle
- Recorded motions are time-reversed and applied as surface force sources. Waves back propagated (by simulation) focus on the original source.
- The spatial resolution of focusing is dictated by the sampling wavelength (= S wave speed / sampling frequency)
- Has been applied before for huge earthquakes (Sumatra 2004) with teleseismic data. Never been attempted with near-field data.



Source imaging of the 2004 Sumatra earthquake
by time reversal of teleseismic hi-f data (Hinet array, Japan)
(Hjorleifsdottir, 2007)

Time-reversal source imaging: principles and limitations

Forward wave propagation



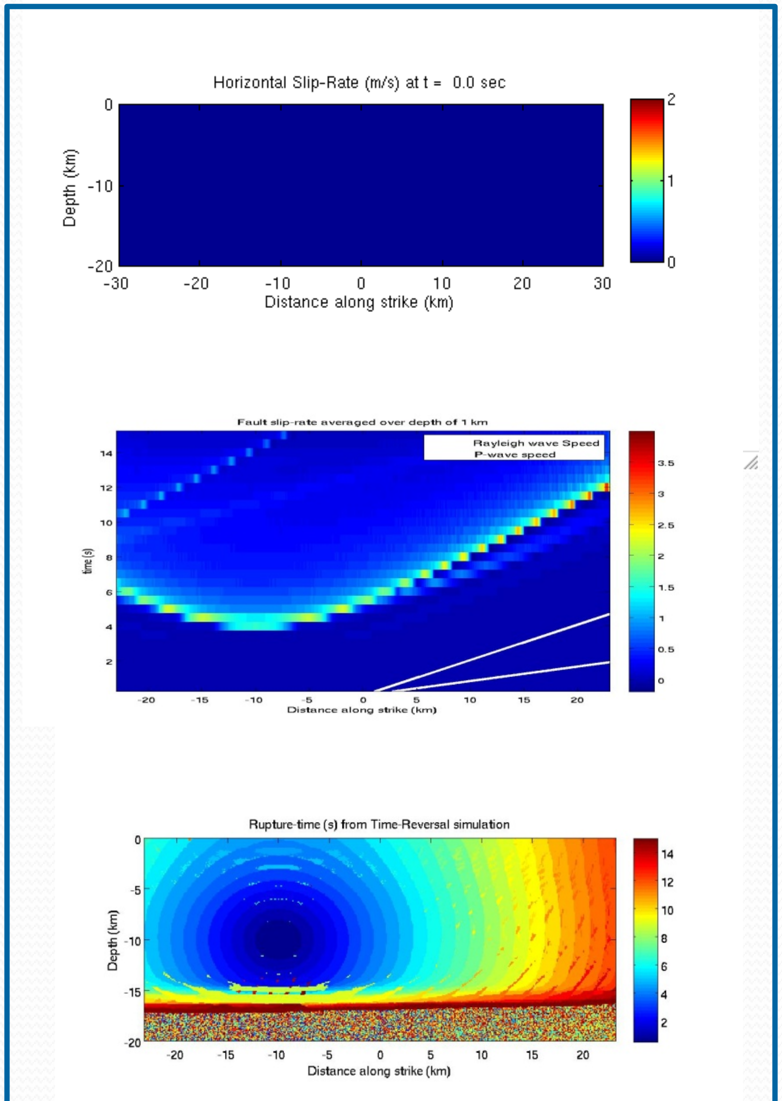
Time-reversed wave propagation

Limitations:

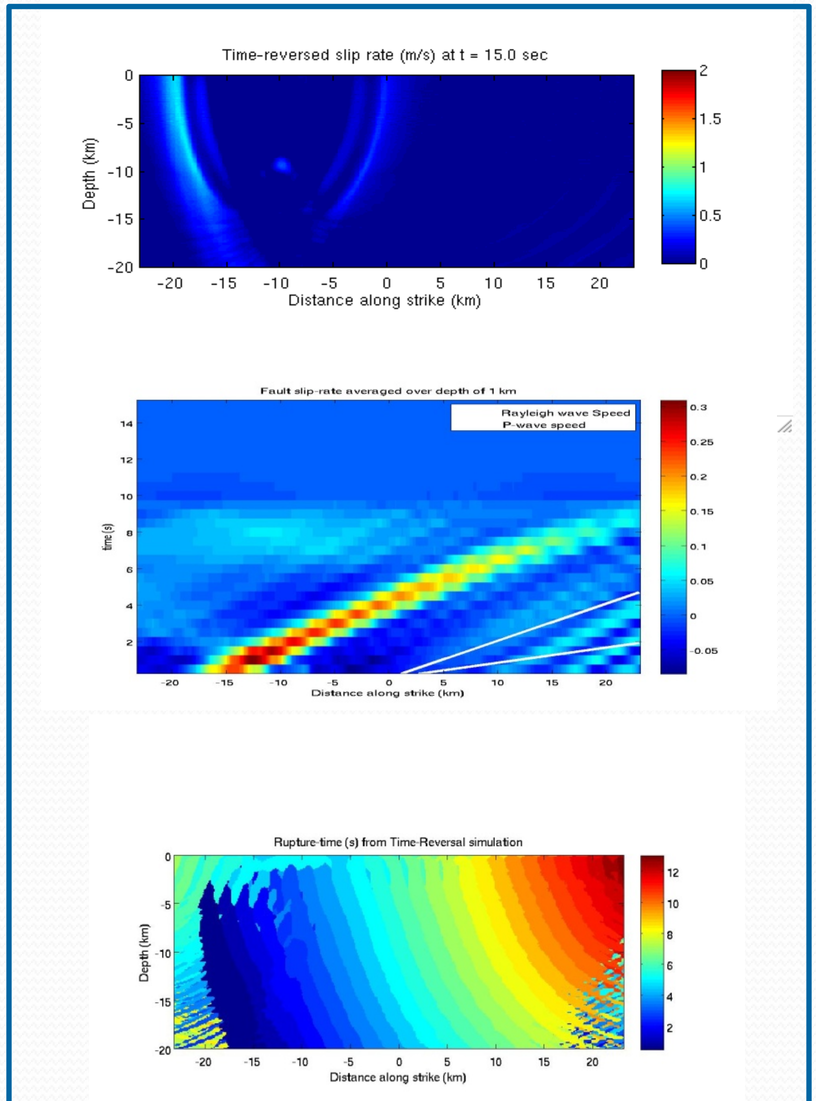
- Focusing requires recordings over a surface that completely surrounds the source. We have only recordings at the Earth's surface.
- → partial compensation (at low frequencies) based on teleseismic data
- Waves defocus right after focusing: serious interference problem when imaging the multiple delayed sources that constitute an extended source.

  → requires **iterative** time-reversal imaging, perhaps absorbing conditions

Forward scenario

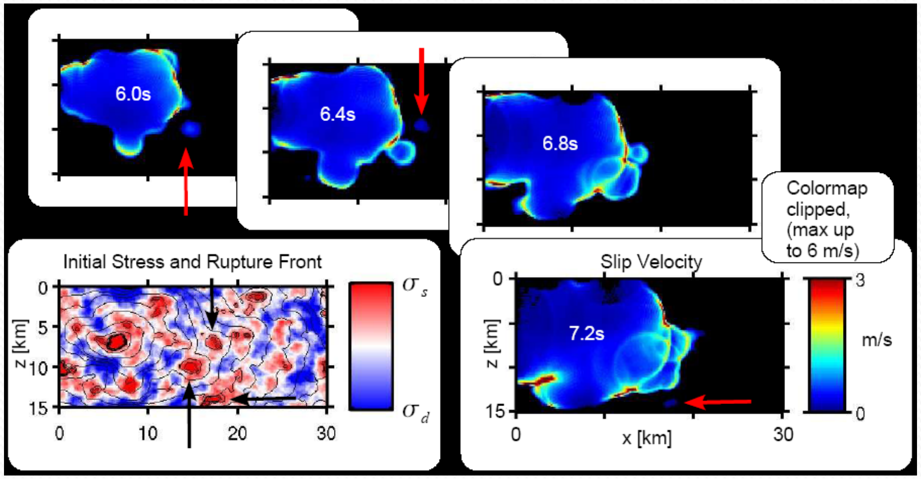


Time-reversal modeling



Summary

What can we learn about earthquake physics from 1Hz seismic waves adequate sampled by a satellite system ?



From direct observation:

- Distinguish between sub-shear and super-shear ruptures
- Complexity of surface rupture

From source inversion (expected): Complexity of sub-surface rupture at kilometric scale

In progress:

- iterative time-reversal source imaging, jointly with teleseismic data
- assess perturbations by site effects, scattering in the shallow crust

Not discussed: potential for seismic tomography and for quantification of site effects
+ exploiting smaller earthquakes → improved tomography → revisit past earthquakes

Time-reversal simulations