Challenges in earthquake physics and source imaging

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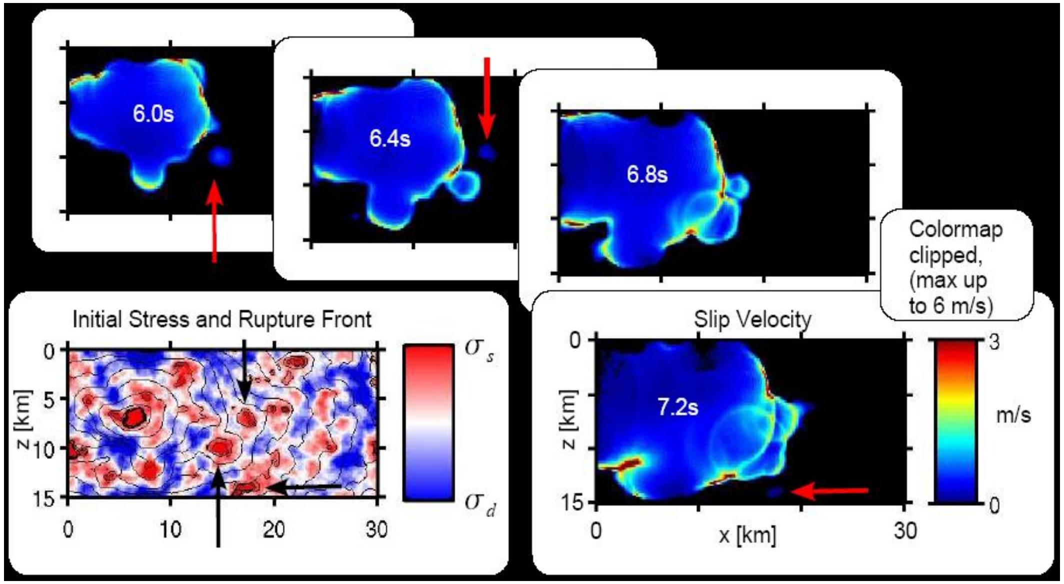
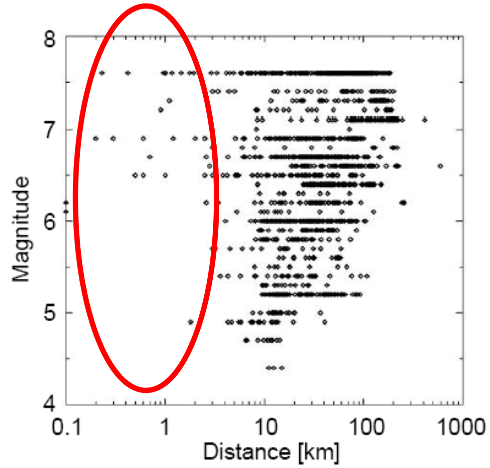


- Main goals and current issues in earthquake dynamics
- The source imaging inverse problem
- Parallels with laboratory experiments
- Interaction of earthquakes and slow slip

Goals of earthquake source dynamics studies

- **Earthquake engineering**: hazard assessment including **source**, path and site effects.
  - Amplitude and spatial variability of ground motions
  - Tall buildings and lifelines ~ secs
  - Short structures < sec
- **Fundamental questions**: understanding earthquake physics. Requires slip velocity v(x,z,t) on scales:
  - Rise time ~ secs, kms
  - Process zone << sec,km
  - Rupture complexity: multi-scale

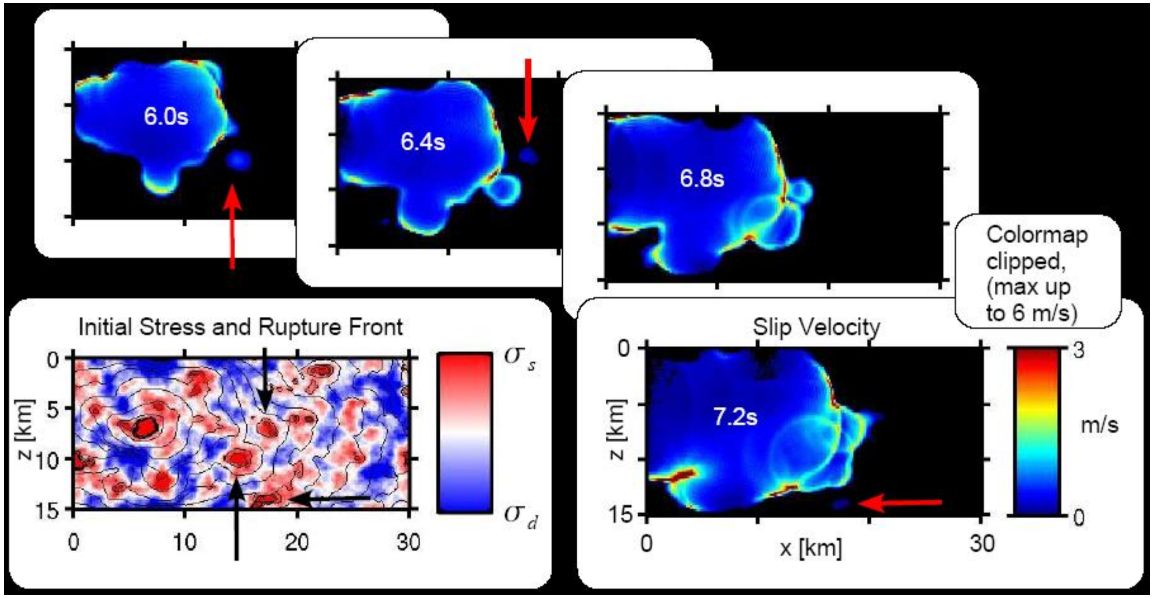


Modified after Stewart et al. (2002)

Each dot is an available recording

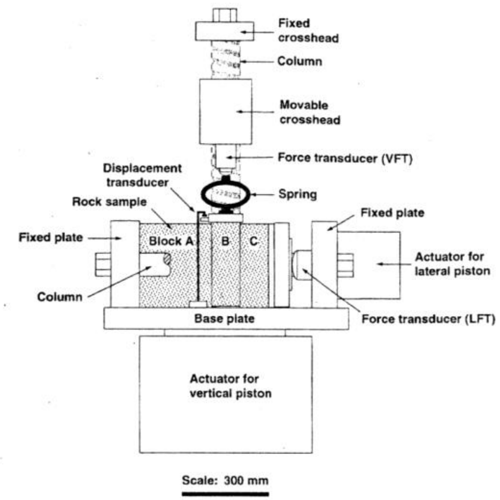
Scientific questions about the earthquake source

- 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?
- Fault rheology: which weakening mechanisms are dominant in real faults?



Fault rheology: poorly known earthquake physics

Laboratory friction experiments



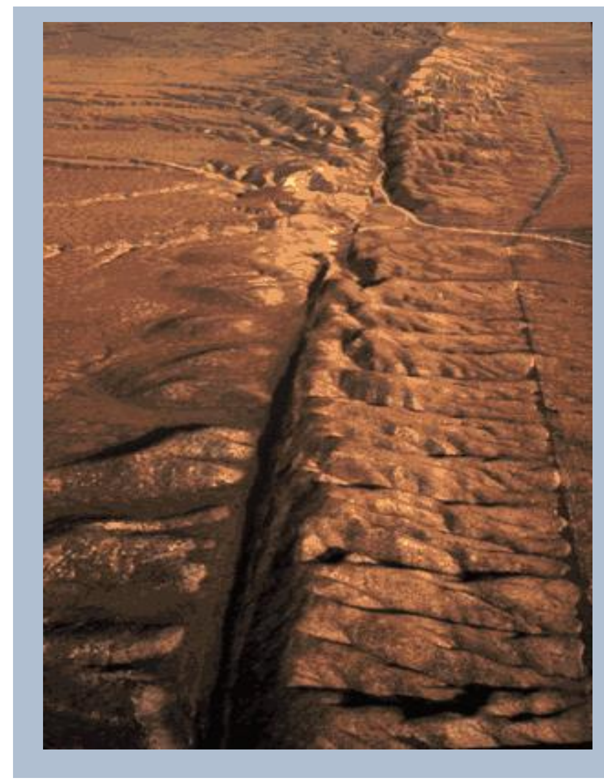
Two Axial Testing Apparatus (Ohnaka)

Missing fault constitutive law !

+ Scaling problem

?

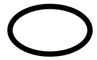
San Andreas fault



Which physical processes are dominant?

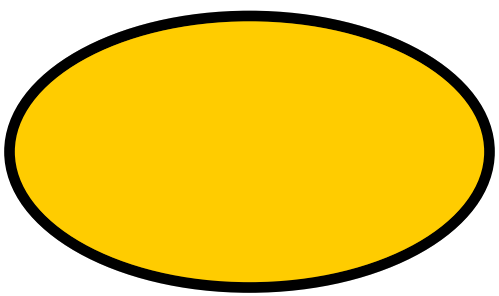
- Friction
- Dynamic damage around the fault
- Thermal pressurization of fault zone fluids
- Dilatancy of the fault gouge
- Flash heating, melting, lubrication
- …

Cracks vs. pulses (definition)

Looking at slip velocity on the fault plane
Thick ellipse  = barrier (will stop rupture)
Colored zone = actively slipping region at a given time

Rise time = duration of slip at a given point on the fault

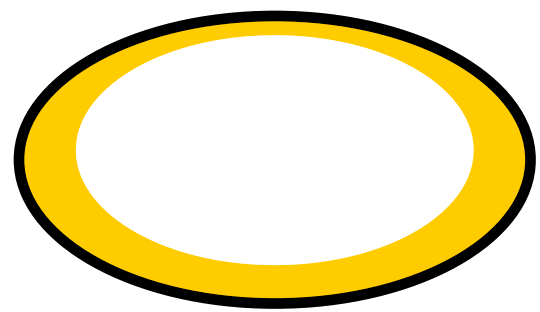
Crack



Long rise time

≈ final size / rupture speed

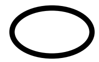
Pulse



Short rise time

Cracks vs. pulses (definition)

Looking at slip velocity on the fault plane

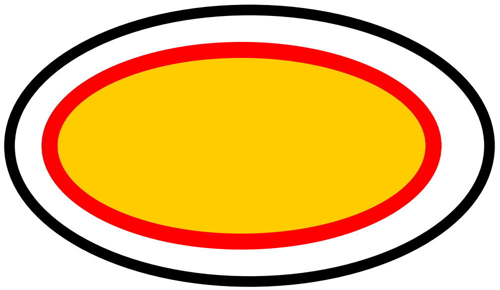
Thick ellipse  = barrier (will stop rupture)

Colored zone = actively slipping region at a given time

Rise time = duration of slip at a given point on the fault

Process zone = 

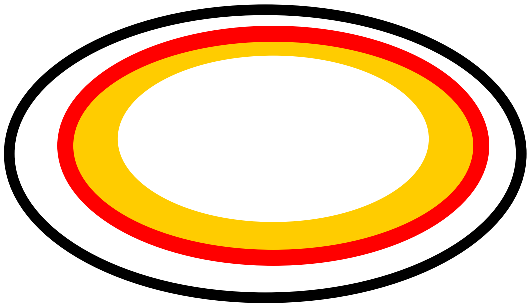
Crack



Long rise time

≈ final size / rupture speed

Pulse



Short rise time

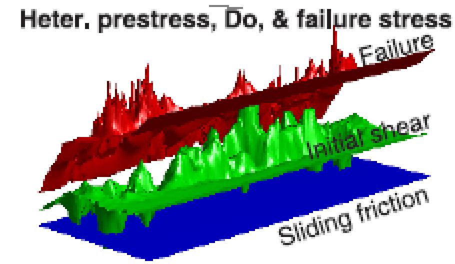
Possible origins of pulse-like rupture (short rise times)

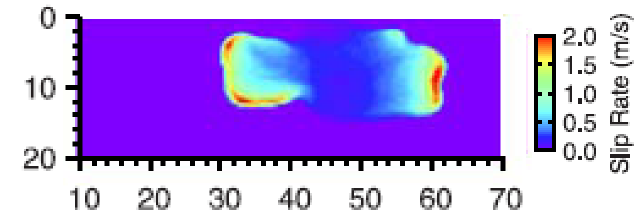
- In homogeneous faults, at low stress, self-healing pulses appear under **velocity-weakening friction** (e.g. thermal weakening)
  Perrin, Rice and Zheng (1995); Zheng and Rice (1998); Nielsen and Carlson (2000)

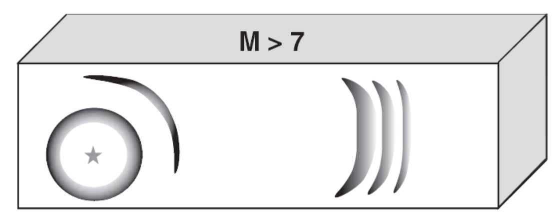
- Pulses (healing fronts) generated by heterogeneities
  Mikumo and Beroza (1994); Oglesby and Day (2002); Aagaard and Heaton (2009)

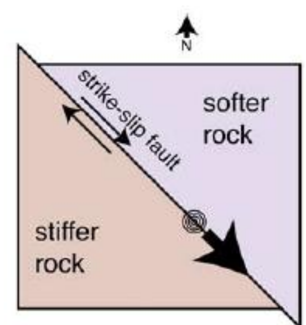
- Pulses controlled by geometry
  Day (1983); Johnson (1992)

- Pulses in bimaterial faults
  Weertman (1980), Adams (1995), Andrews and Ben-Zion (1997), Cochard and Rice (2000)



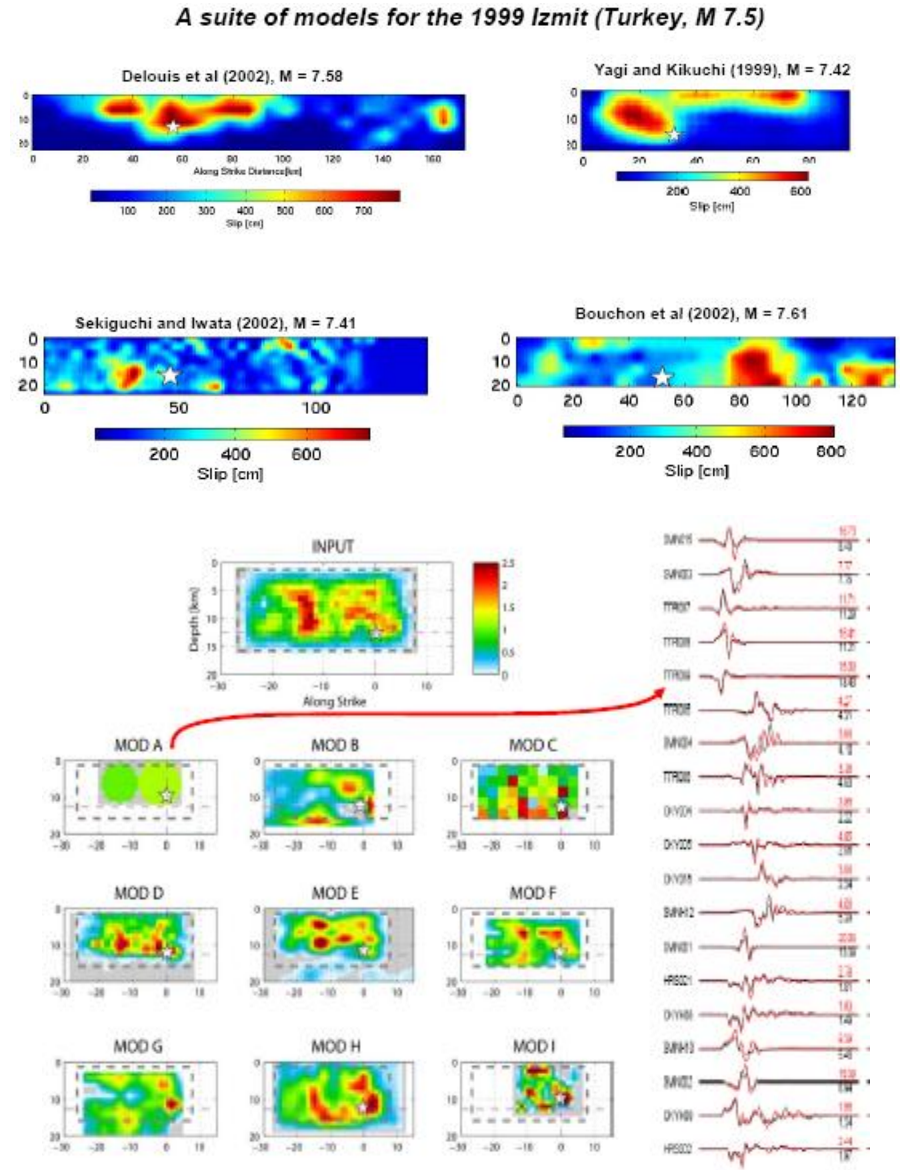


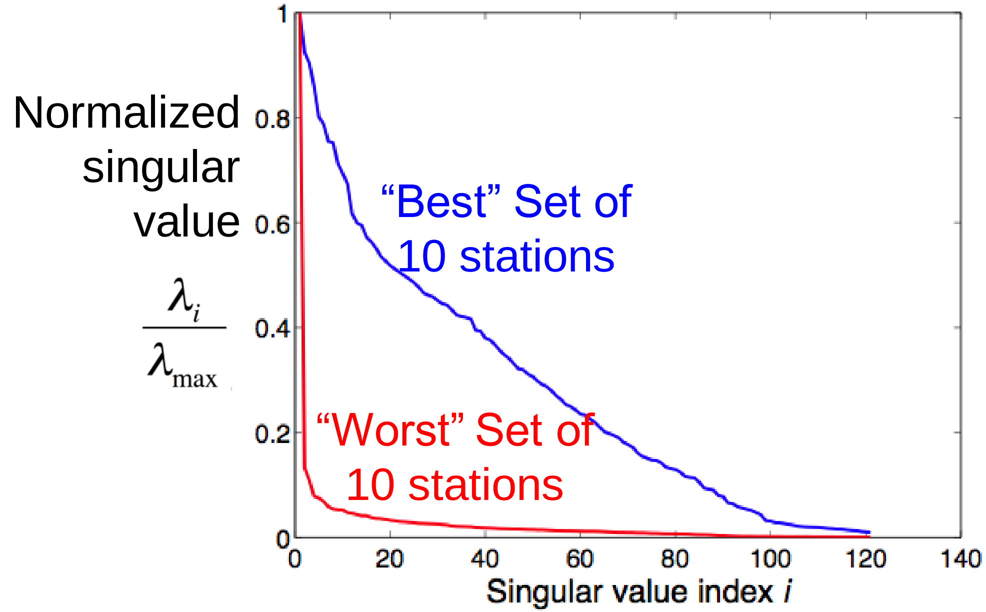




Source imaging today

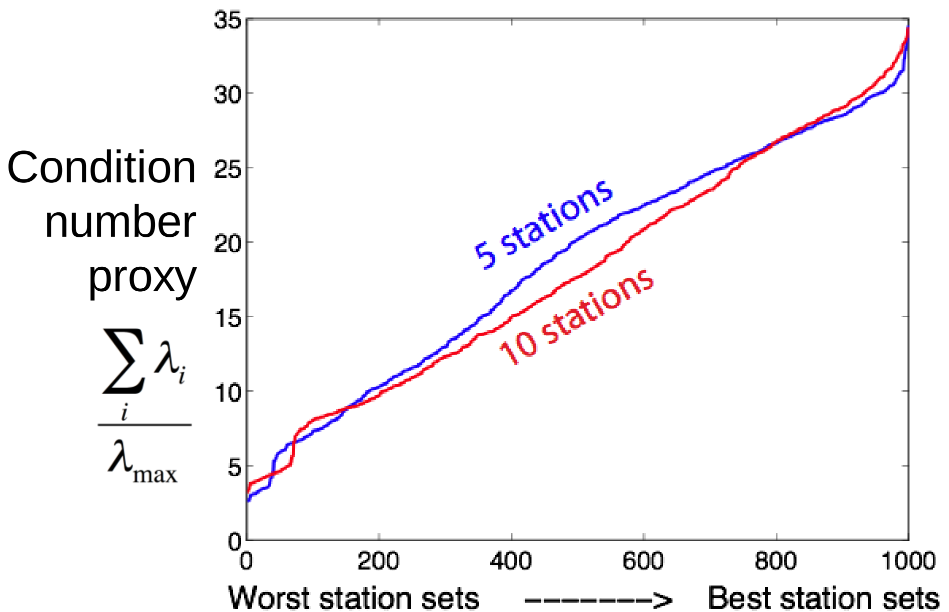
- **Source imaging inverse problem:** retrieve the space-time distribution of fault slip from seismological, geodetic and field data
- Resulting slip models are notoriously heterogeneous (large spatial variability)
- There are **intrinsic limitations**:
  - Ill-posed inverse problem: very sensitive to regularization, data selection, model parameterization.
  - Limited frequency band < 1Hz: poor resolution on the fault >5km, no detail about the friction law can be retrieved
  - Surface observations: lower resolution at depth, contamination by shallow site effects
  - Imaging resolution improves slowly as function of station density





Seismic inversions are well-conditioned when the singular values fall off slowly (when the condition number, which bounds the model error, is low)

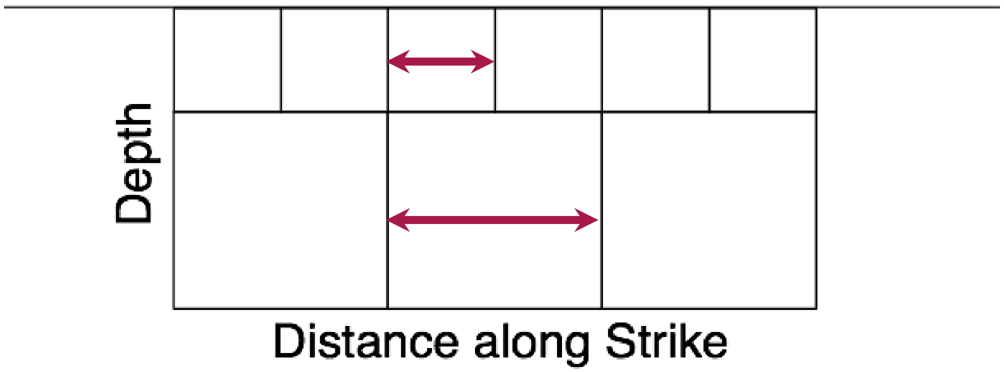
However, the condition number is stable with respect to the number of stations!



M. T. Page (*in progress*)

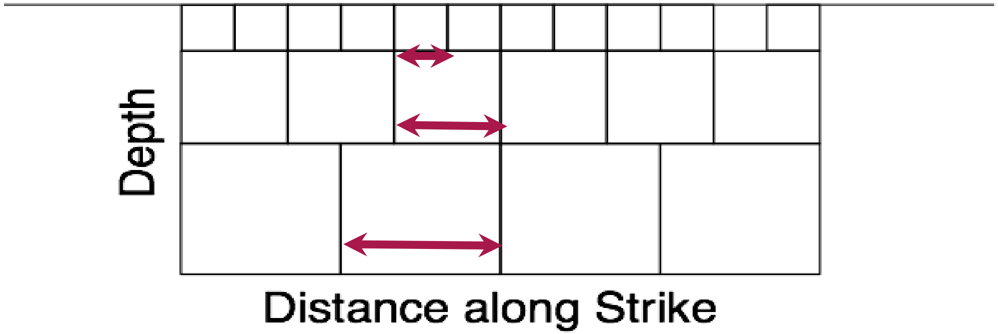
Adding more stations decreases resolution length...
but proportionally with depth

Fewer stations



The majority of the data variance can always be explained by small-scale structure near the surface

More stations



This explains why the inversion is poorly conditioned regardless of the number of surface stations

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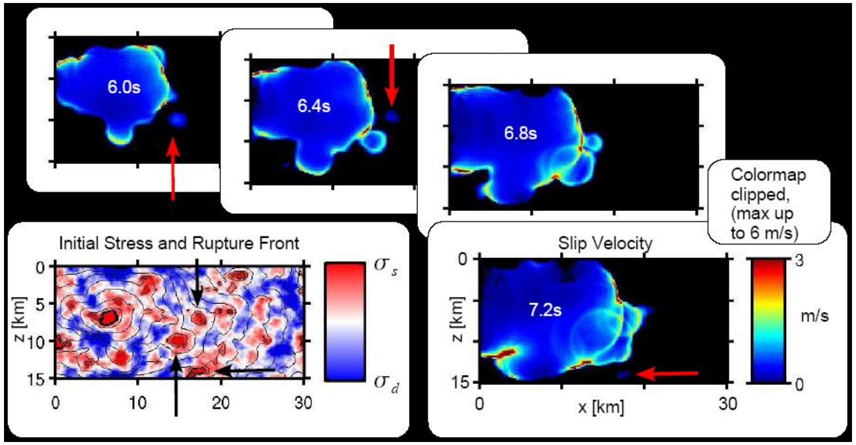
Partial summary



- Wish list: infer fault slip velocity v(x,z,t) from near-fault ground motions on the following resolution scales:
  - Rise time ≈ secs, kms
  - Process zone << sec,km
  - Rupture complexity: multi-scale
  - Large earthquakes: displacement, velocity resolution < cm, cm/s
- Can space techniques yield these dense, high rate observations?
- Strategies: regional vs. global monitoring ?