Current challenges in computational earthquake dynamics

Jean-Paul Ampuero

Caltech Seismolab

Collaborations: Martin Mai and Johannes Ripperger (ETH Zurich),
Yehuda Ben-Zion (USC)
Josep De La Puente (LMU Munich)

Overview

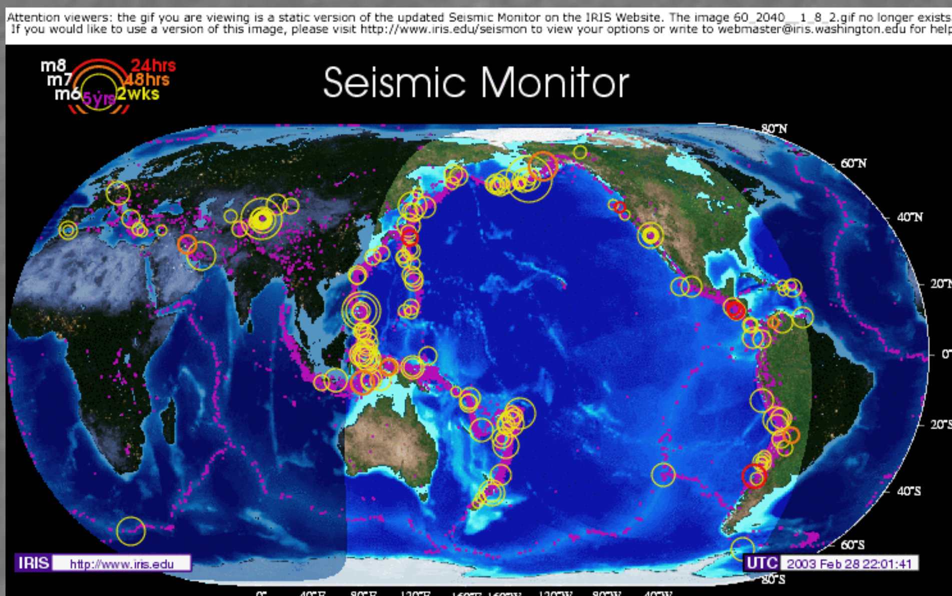
- Basic phenomenology and standard modeling assumptions
- Typical questions in computational earthquake dynamics:
  - Understanding earthquake physics
  - Inferring dynamic fault properties from observations
  - Predicting seismic ground motions
- Current numerical methods and computational challenges

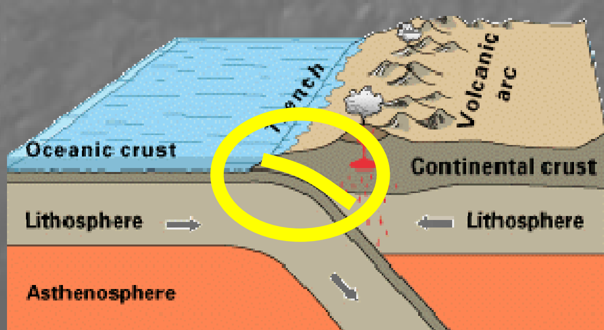
Plate tectonics, faults and earthquakes (101)

Faults are weak planes in the Earth crust, where displacement discontinuities (**slip**) may occur.

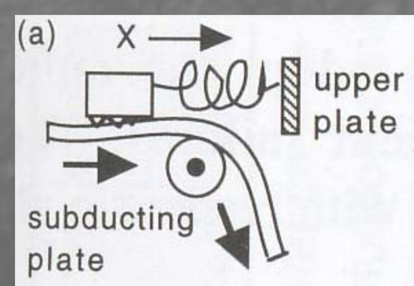
Faults typically lie at the contact between the tectonic plates that divide the crust.

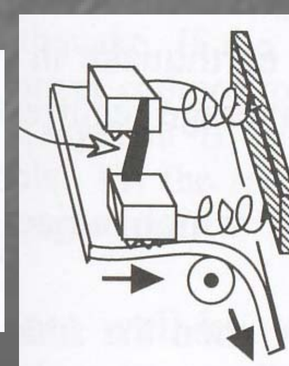
Earthquakes are sudden episodes of slip along faults that release the elastic energy stored by the long term tectonic motions.



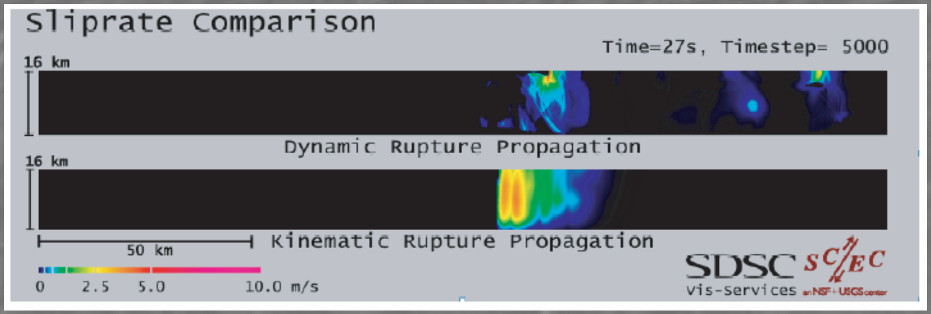


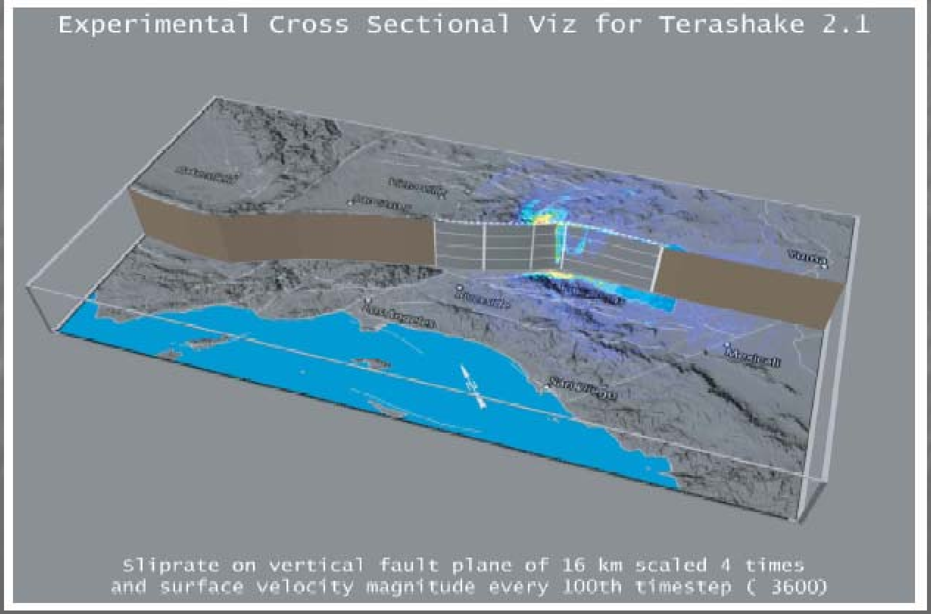
A subduction zone



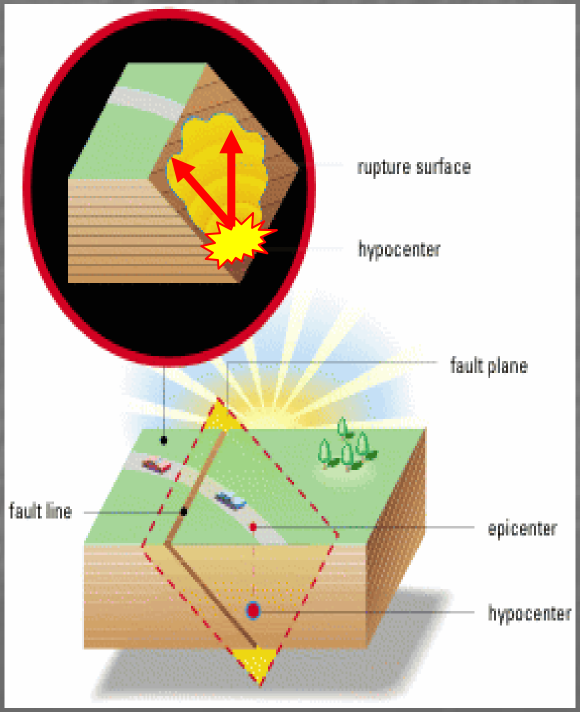


The earthquake dynamics time-scale

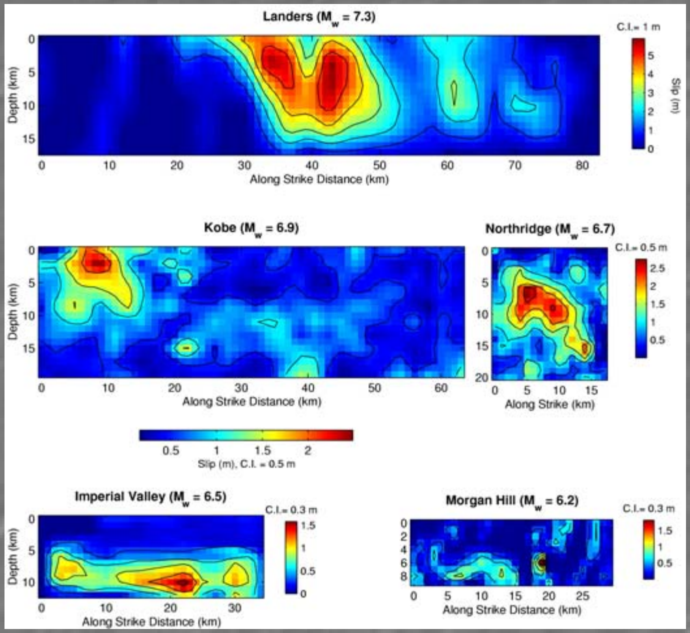




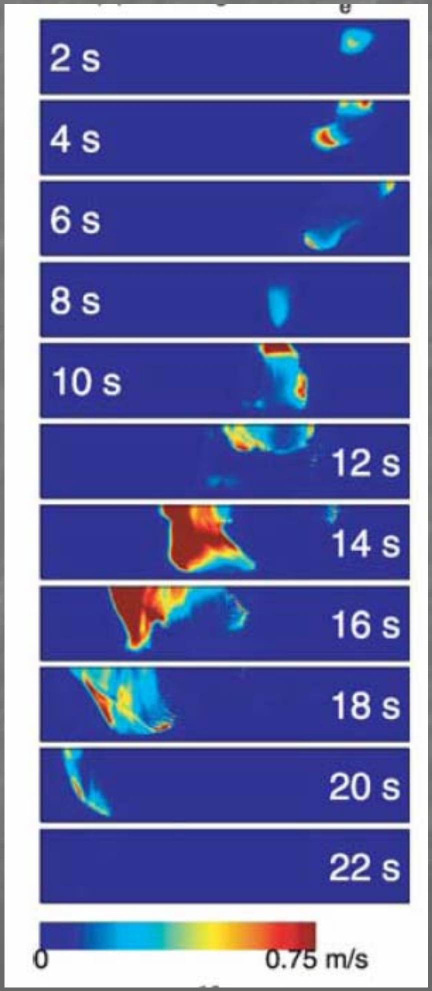
Earthquake slip nucleates, propagates and stops over timescales of seconds to minutes



The spatio-temporal complexity of earthquakes



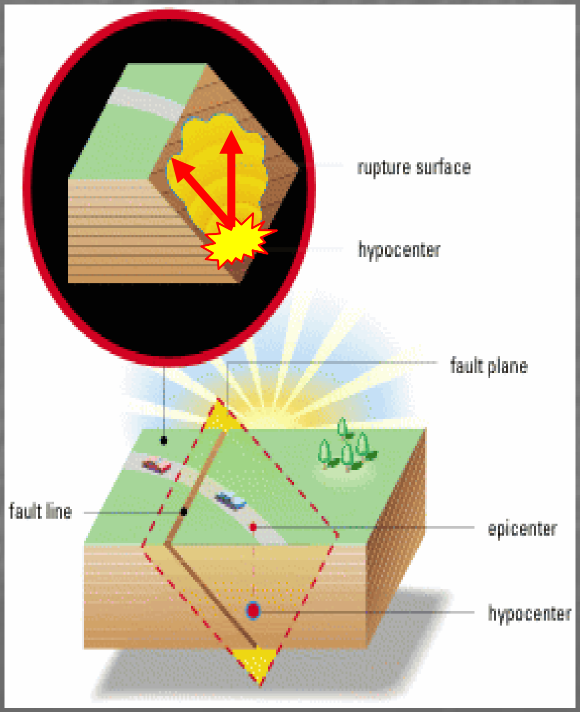
Earthquake slip distributions inferred from seismological and geodetic observations (M. Mai)



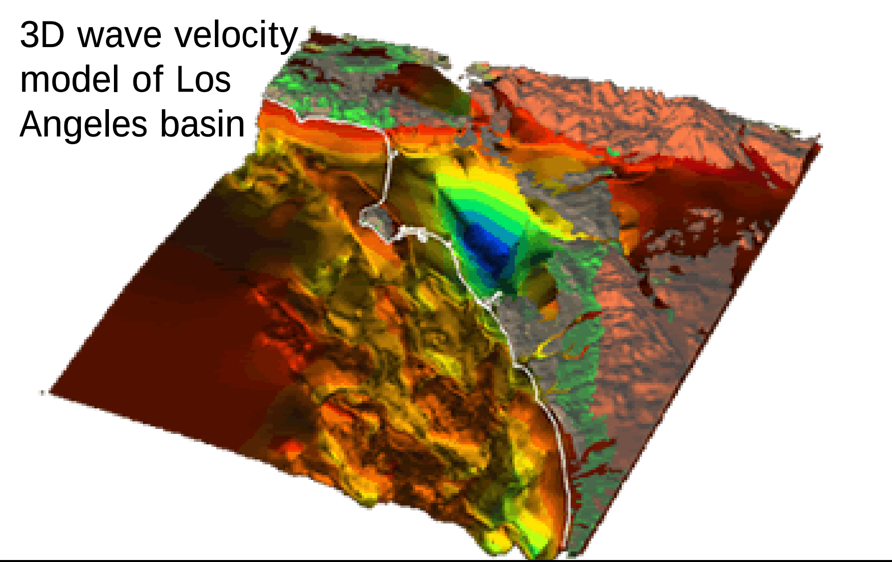
Slip rate history in 3 dynamic models of the Landers earthquake (Peyrat et al 2004)

Earthquake slip is notoriously heterogeneous

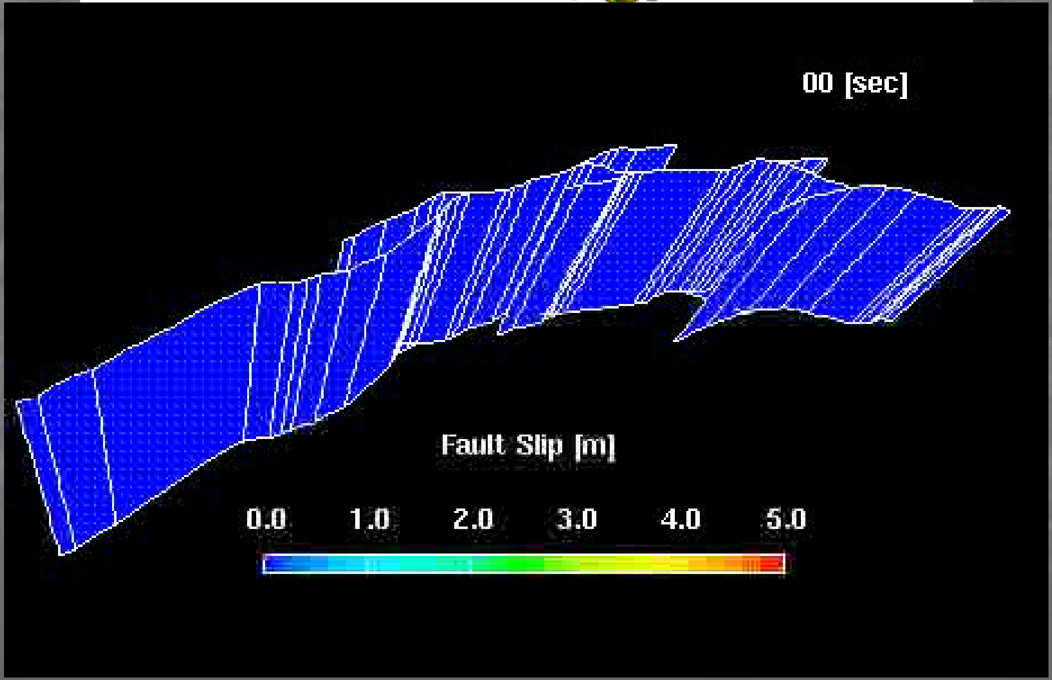
Earthquake rupture is notoriously complex



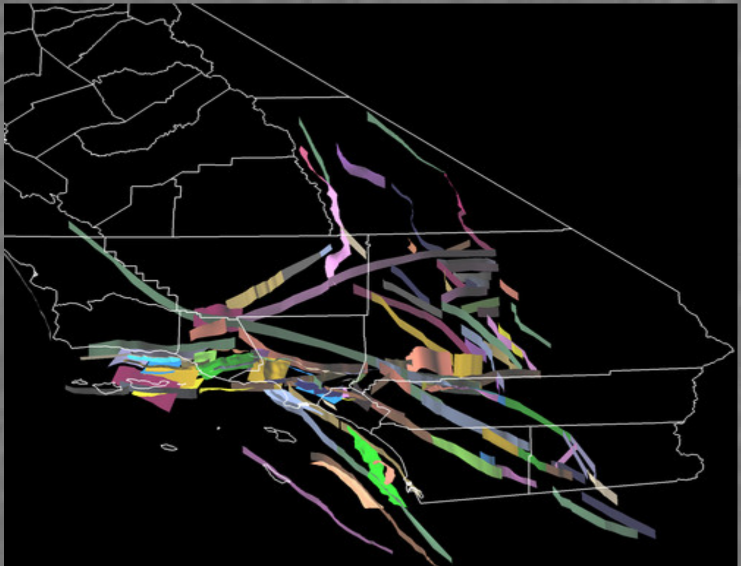
Structural and geometrical complexity



3D wave velocity model of Los Angeles basin



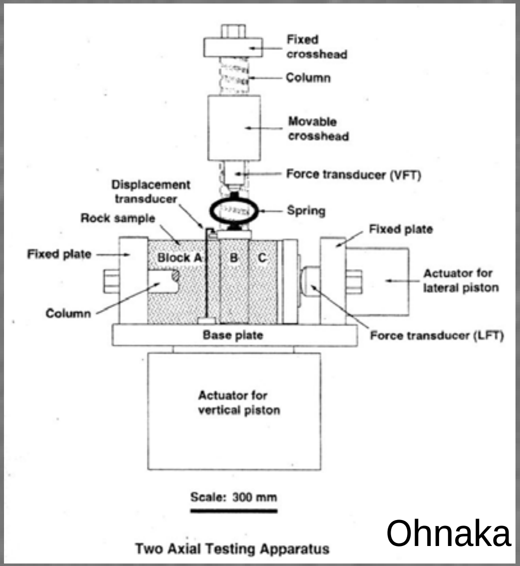
BIEM dynamic model of the Landers earthquake (Aochi et al)



3D model of the fault systems of Southern California

Poorly known physics

Laboratory friction experiments

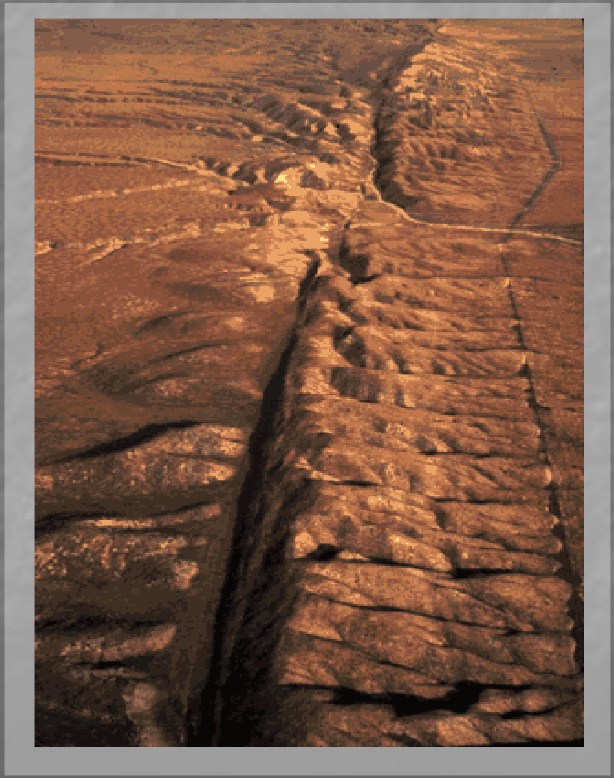


Missing fault constitutive law !

+Scaling problem

?

San Andreas fault

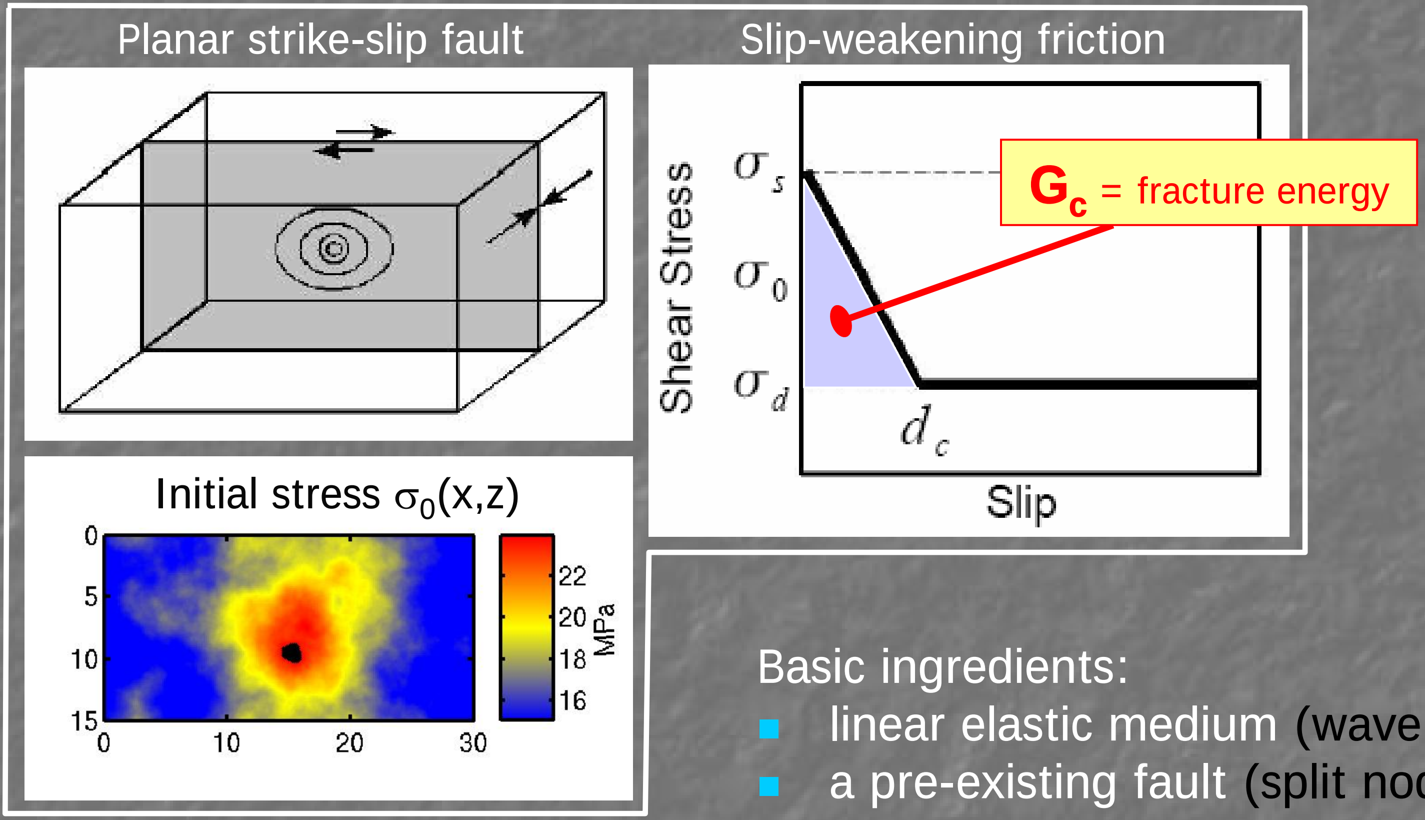


Possible physical processes:

- Friction
- Dynamic damage around the fault
- Fluids in the fault zone
- Dilatancy of the fault gouge
- Melting and lubrication

Which are the most relevant ?

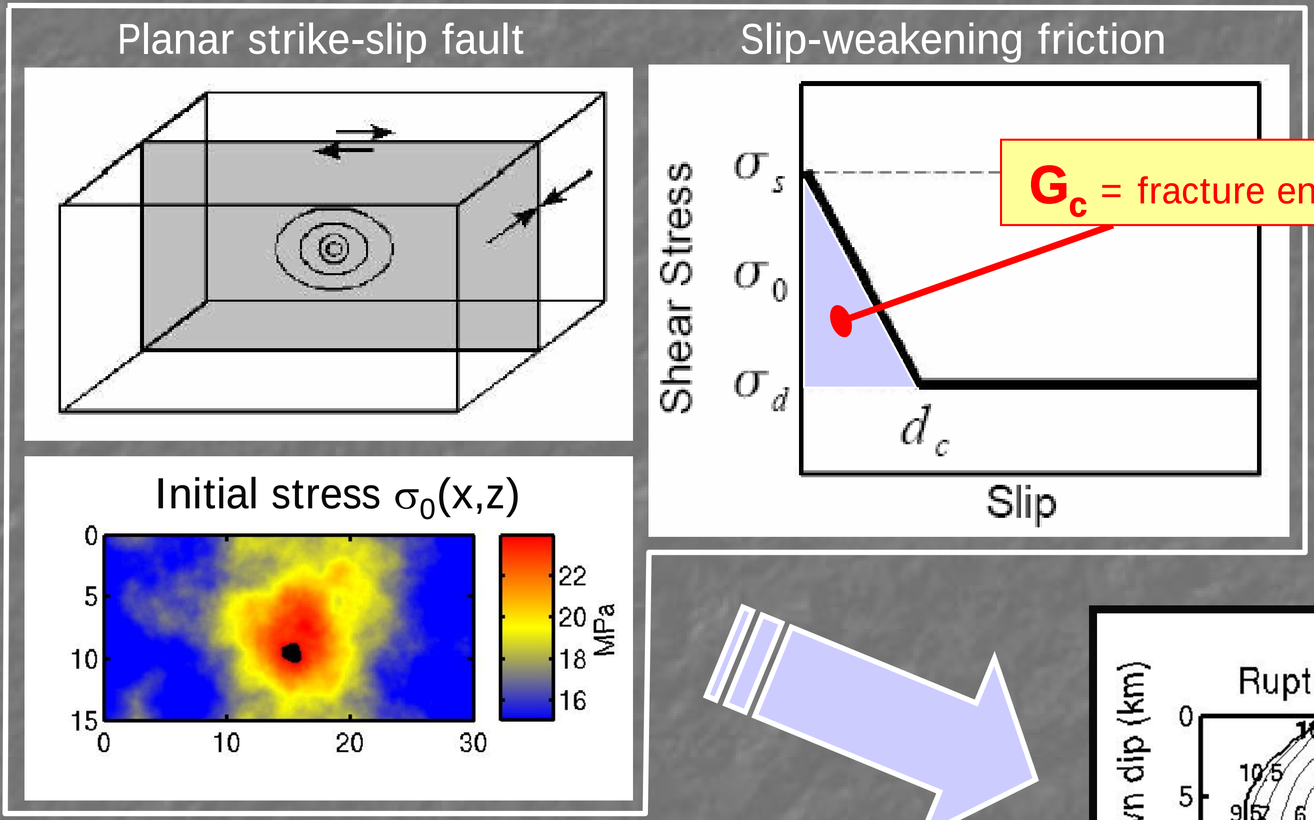
The “standard” dynamic rupture problem

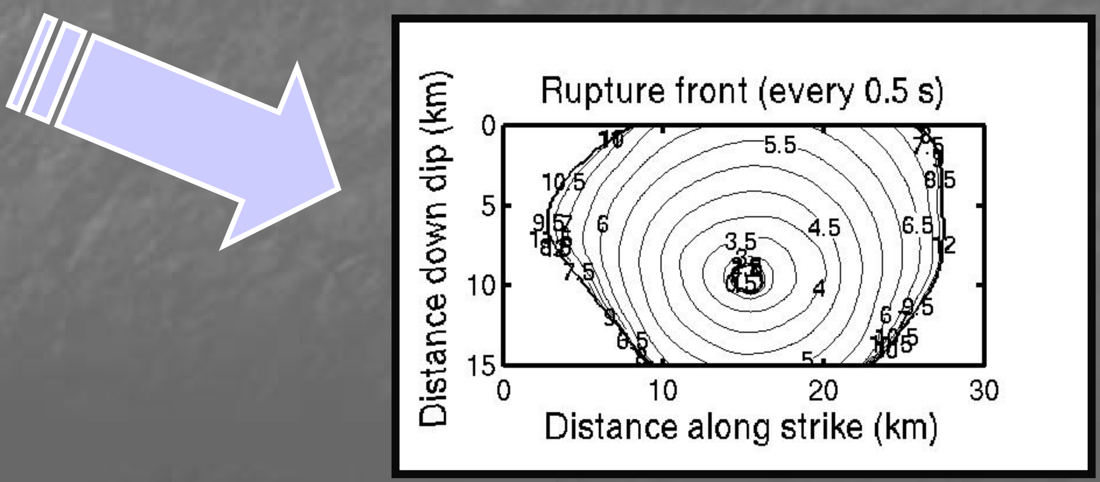


Basic ingredients:

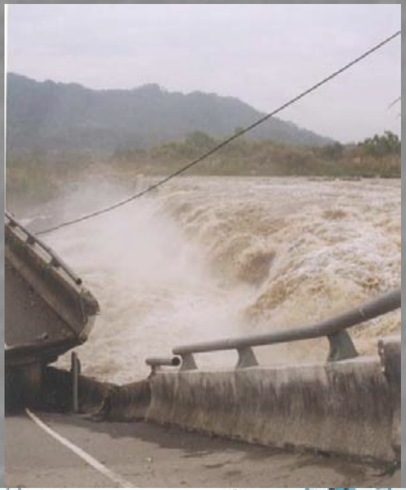
- linear elastic medium (wave equation)
- a pre-existing fault (split nodes)
- **Friction**: a non linear relation between fault stress and slip (a mixed boundary condition)
- initial conditions (stress)

The “standard” dynamic rupture problem





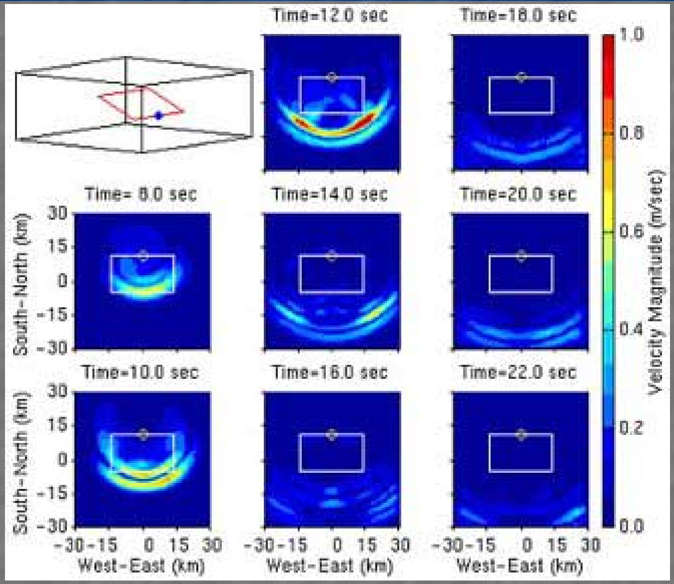
Goals of computational earthquake dynamics: seismic hazard assessment



Damaged bridge and new waterfall during the 1999 Chi-Chi (Taiwan) earthquake

Building collapse during the 1985 Mexico earthquake

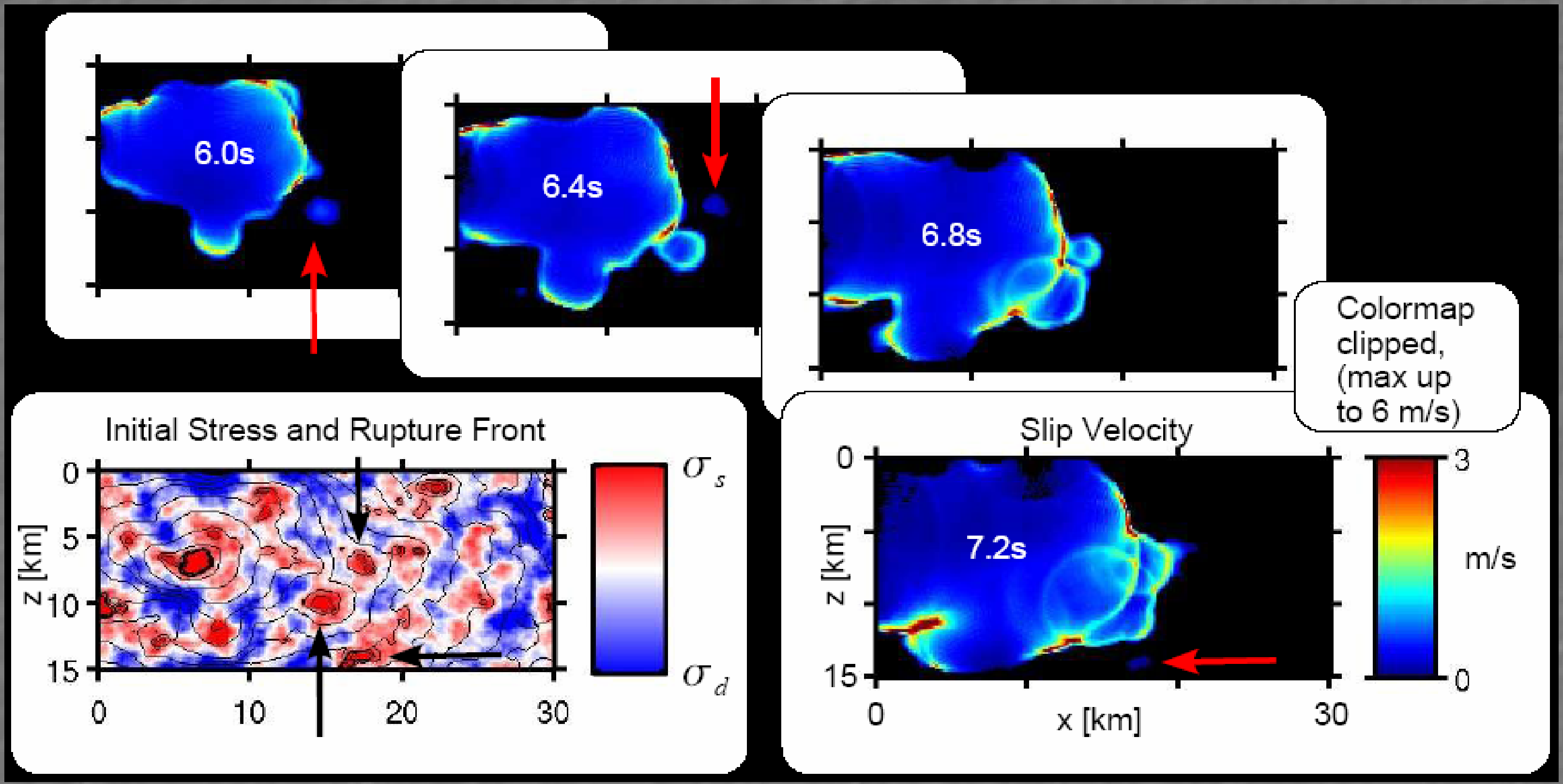
Compute ground motion for possible earthquake scenarios



FEM simulation of a hypothetical M6.8 earthquake (B. Aagaard)

Where empirical data is missing (very close to active faults), physics-based approaches (dynamic source and wave propagation modeling) complement traditional empirical approaches for strong ground motion evaluation

Example: effect of stochastic initial stress fields



SBIEM simulations by J. Ripperger (ETHZ)

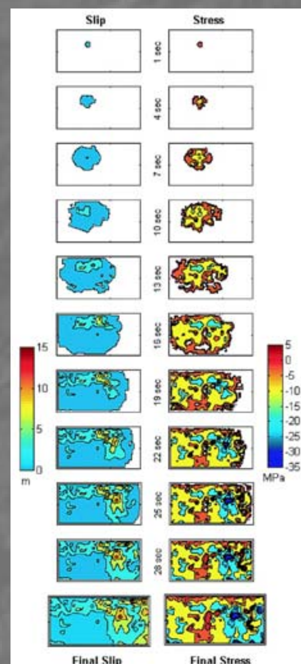
→ Statistical relations between spatial heterogeneities of initial stress and the variability of ground motions

Goals of computational earthquake dynamics: the inverse problem

Infer dynamic fault properties from recorded ground motions

How?

Kinematic source inversion of the Chi-Chi earthquake, from near-field seismograms



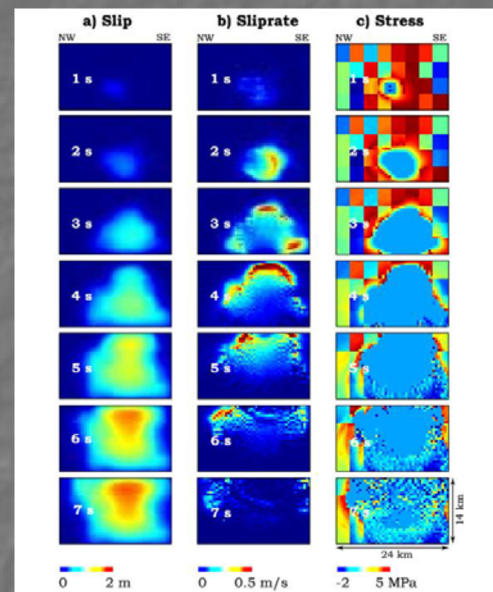


Figure 2. 7 second histories of slip, sliprate, and stress for the dynamic model generating synthetics with the best fit to 12 near-fault strong motion records.

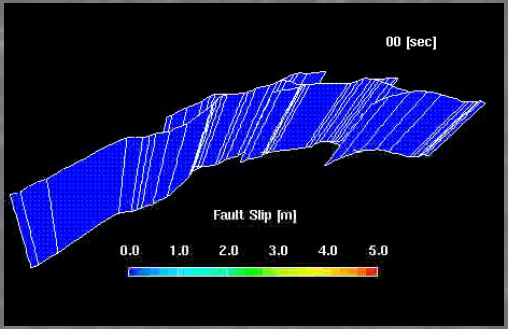
Why?

Dynamic source inversion of the Tottori earthquake (Peyrat and Olsen 2004)

Required 60000 forward simulations

Anatomy of the null-space of such a non-linear, ill-posed problem?
Optimal experiment design? (optimizing the recording network geometry)
Extracting information from high-frequency wavefield?

Goals of computational earthquake dynamics: Investigate the physics of earthquakes



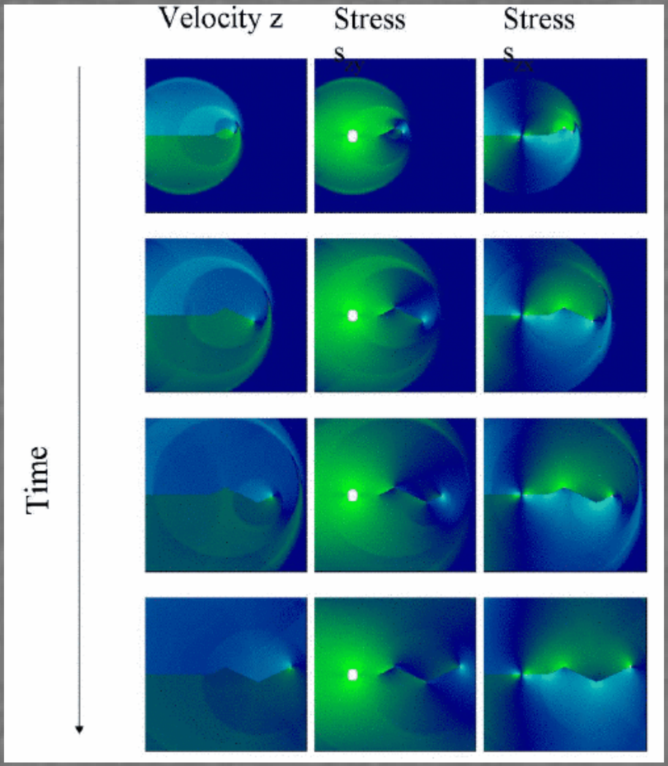
- What controls :
  - High frequency radiation ?
  - Rupture speed ?
  - Rupture directivity ?
  - Probability of breaking multiple faults ?

  → Effects of geometry, initial conditions, friction and multi-physics

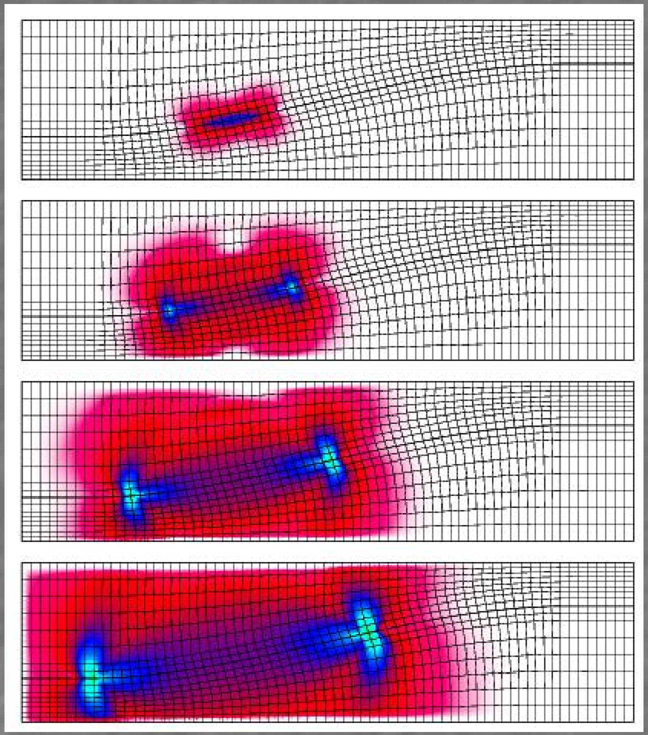
- Scaling: do small and large earthquakes share the same physics?

- Link to earthquake cycle simulations (time scale > 50 years):
  - effect of seismicity patterns on the initial conditions of large earthquakes
  - Interactions between seismic slip and aseismic transients

Example: rupture on non-planar faults

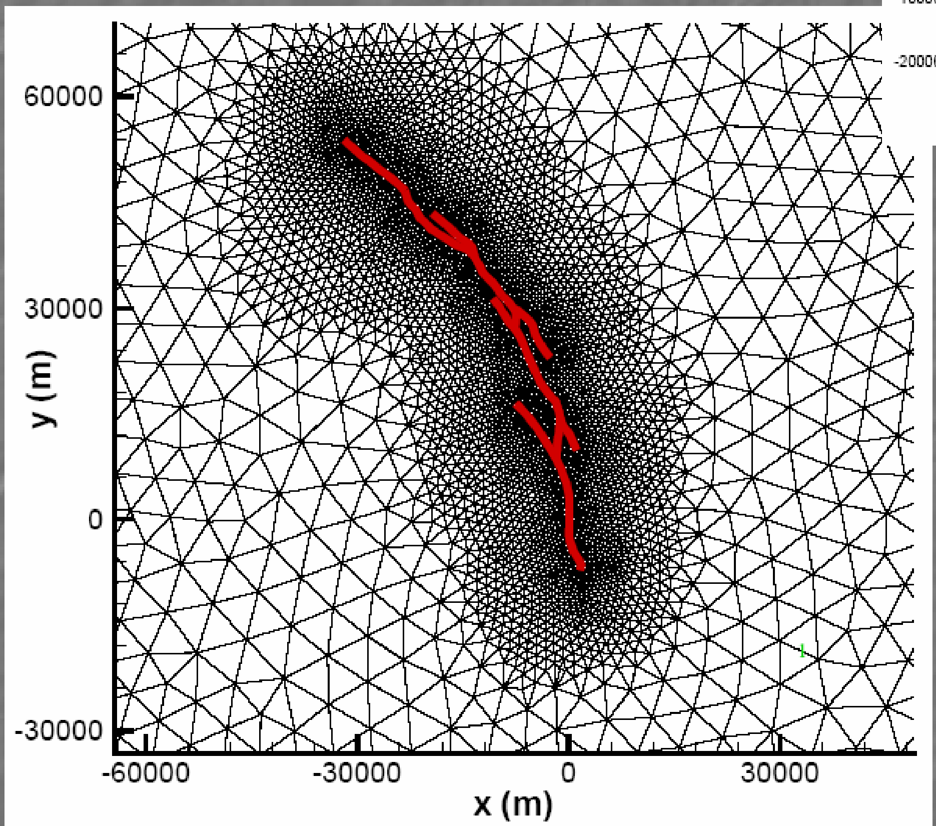


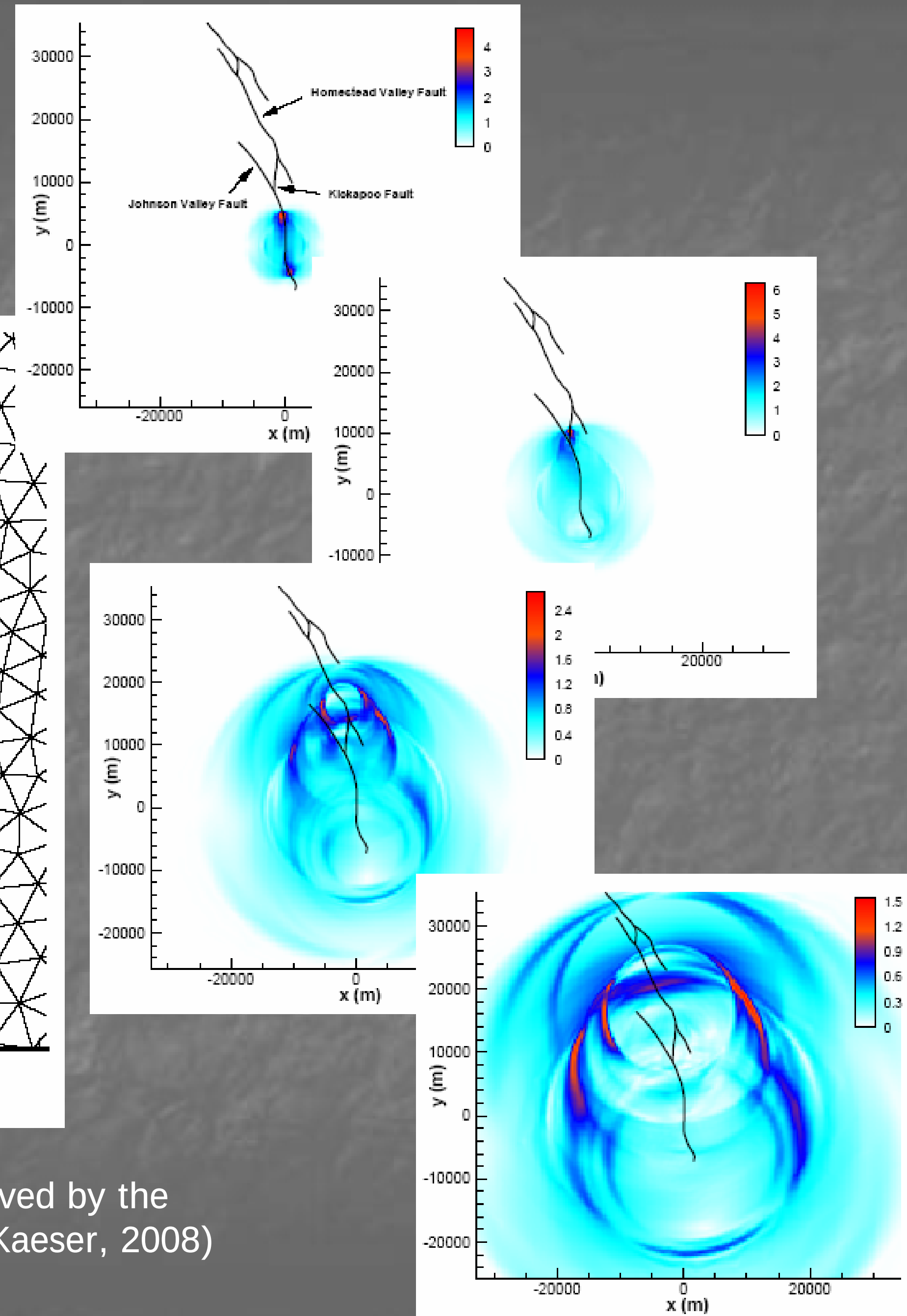
2D rupture on a kinked fault (SEM, R. Madariaga)
Snapshots of velocity and stress outside the fault



2D rupture on non-planar faults (SEM, G. Festa)
Snapshots of particle velocity outside the fault

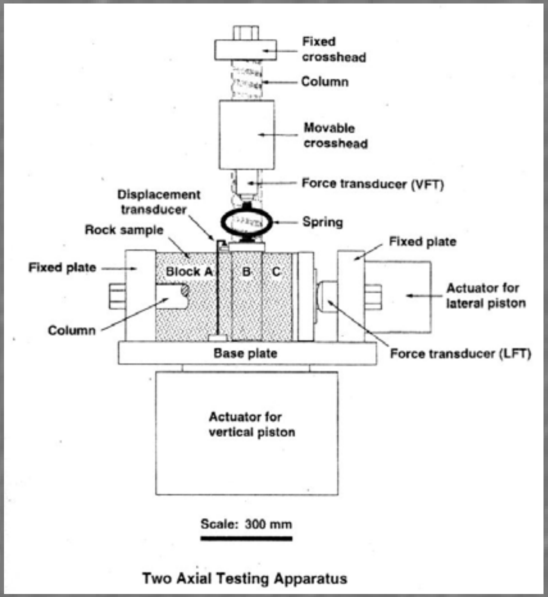
Example: rupture on non-planar faults



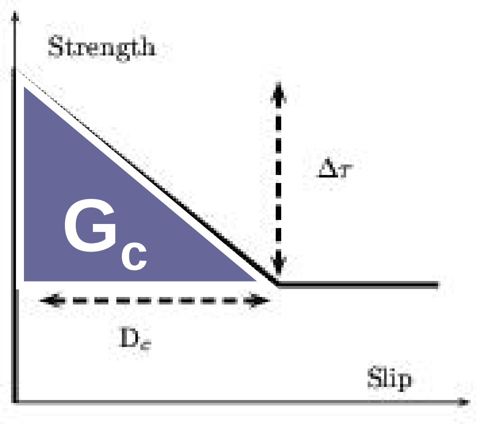


Dynamic model of the Landers earthquake solved by the ADER-DG method (De La Puente, Ampuero and Kaeser, 2008)

Apparent scale dependency of G_c requires evolution beyond the "standard" model



Fracture energy



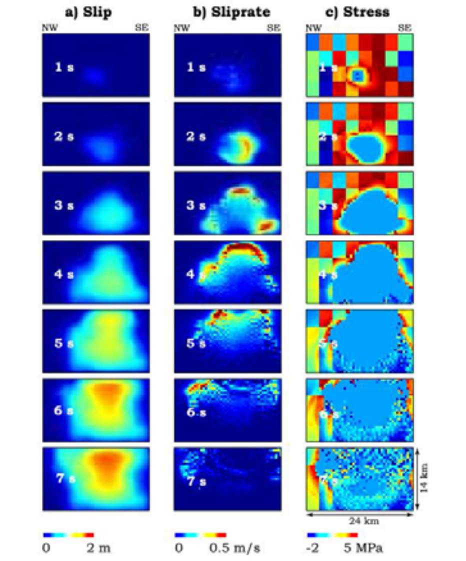


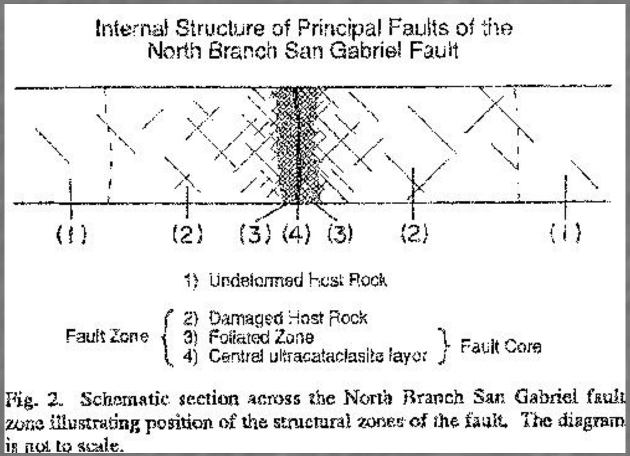
Figure 2. 7 second histories of slip, sliprate, and stress for the dynamic model generating synthetics with the best fit to 12 near-fault strong motion records.

?

In the lab: G_c=100 J/m^2

For large earthquakes: G_c=10^6 J/m^2

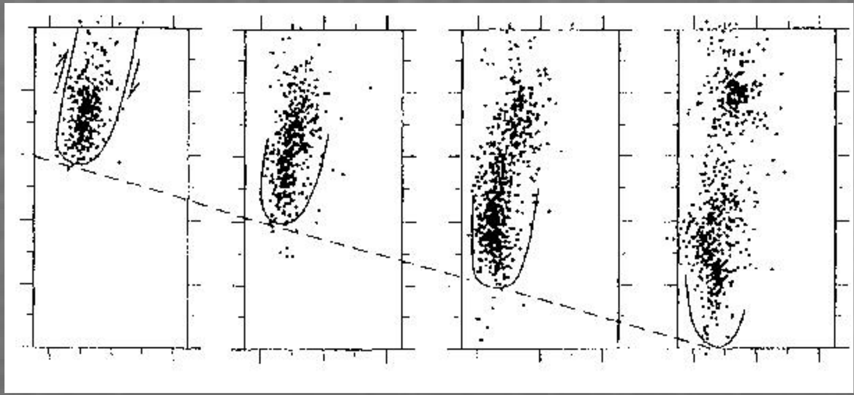
Off-fault dissipation



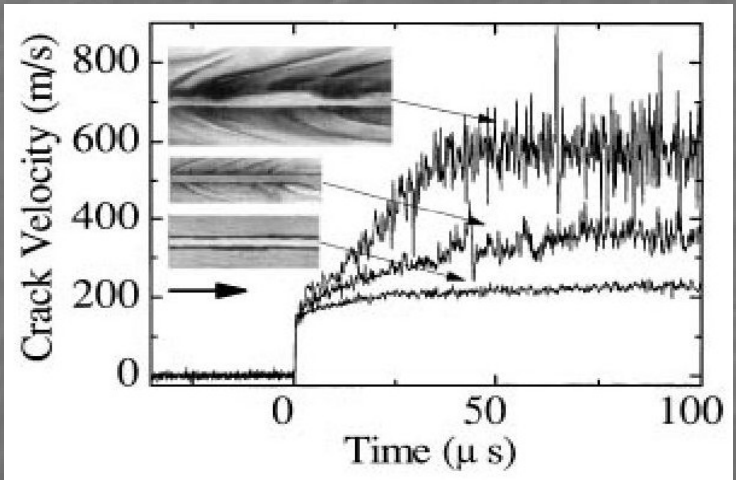
Chester et al

Real faults are not a simple contact planes

The hierarchical architecture of fault zones reveals off-fault dynamic damage



Monitoring the process zone by acoustic emissions in laboratory experiments (Zang et al 2000)

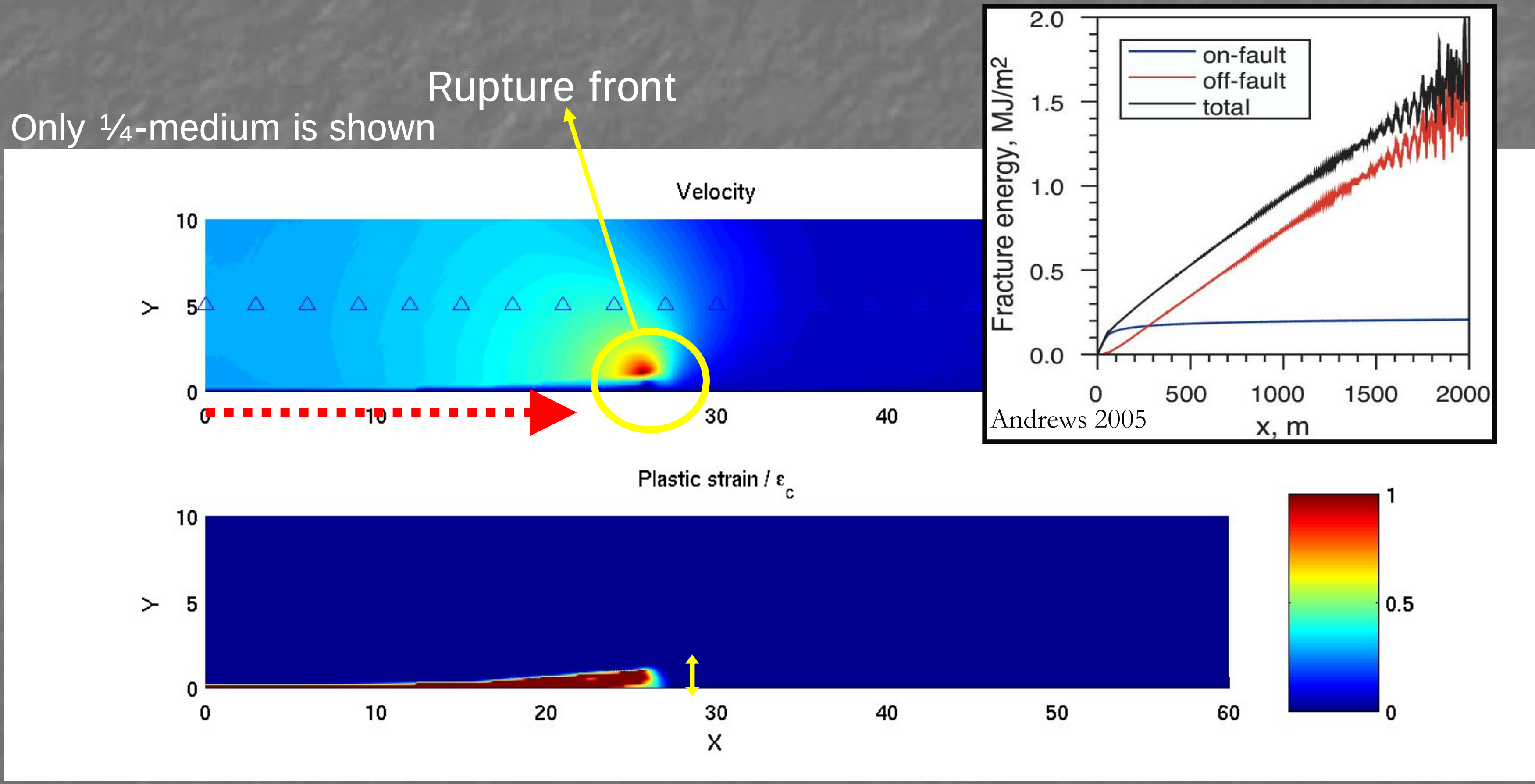


Secondary branching increases total dissipation (Sharon et al 1996)

Strain weakening visco-plasticity outside the fault plane (solved with SEM)

Rupture front

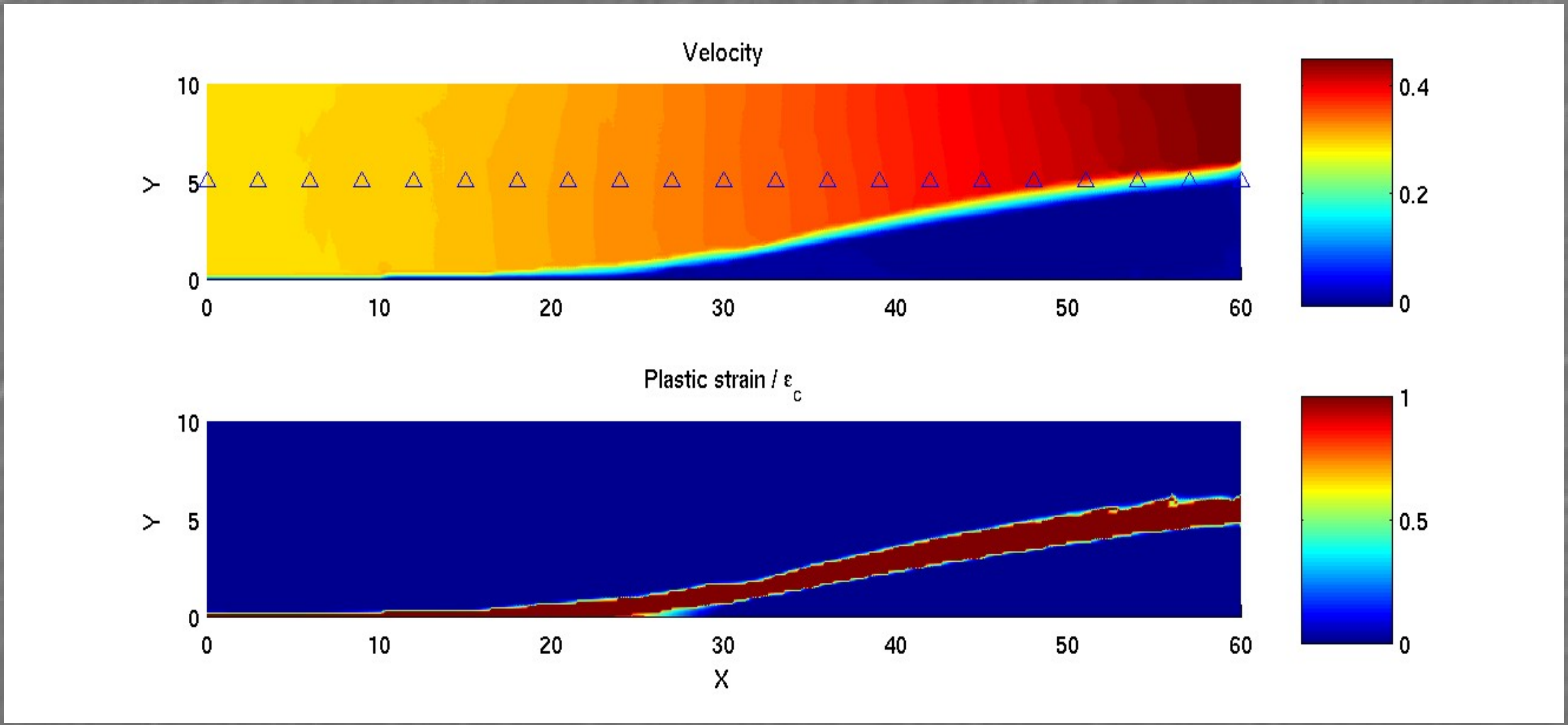
Only ¼-medium is shown



The thickness of the dissipation zone increases as the rupture propagates

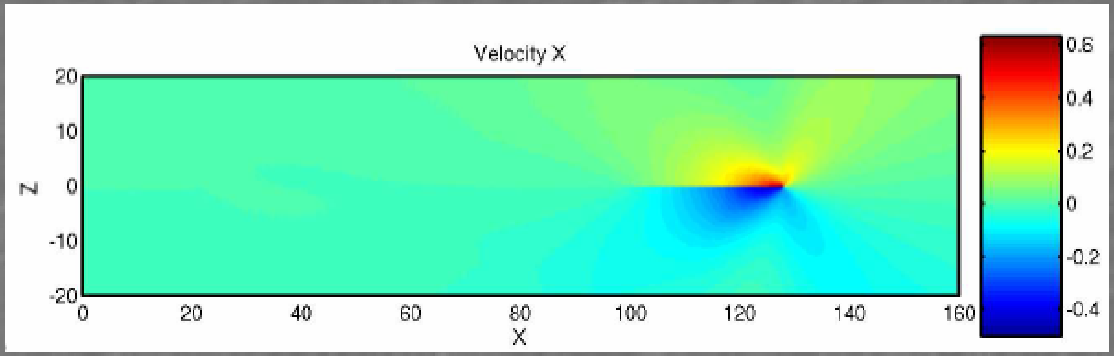
→ the “apparent” fracture energy increases with rupture length

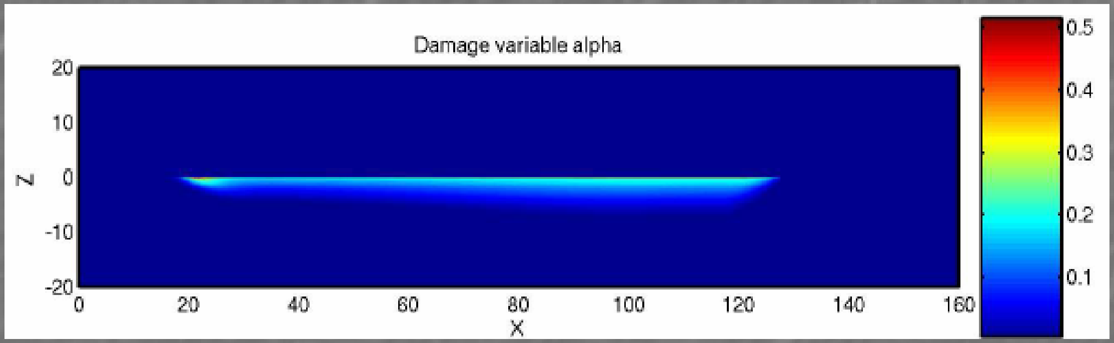
Strain weakening visco-plasticity outside the fault plane (solved with SEM)

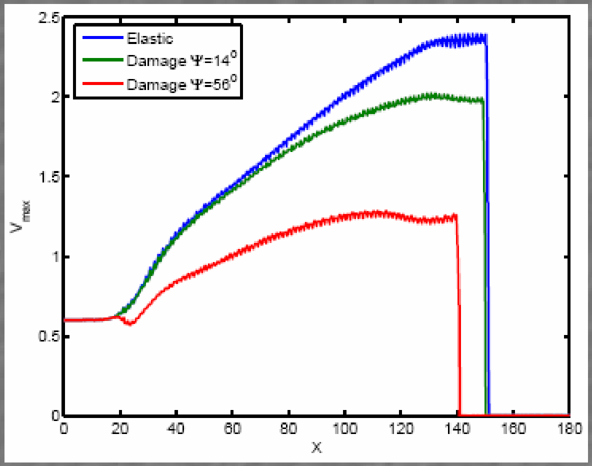


If not guided by a weak fault plane, the rupture **branches** out spontaneously

Continuum damage outside the fault







Effect of off-fault rock damage on peak ground motions and energy balance?
(Ampuero et al, 2008)

Numerical methods for earthquake dynamics

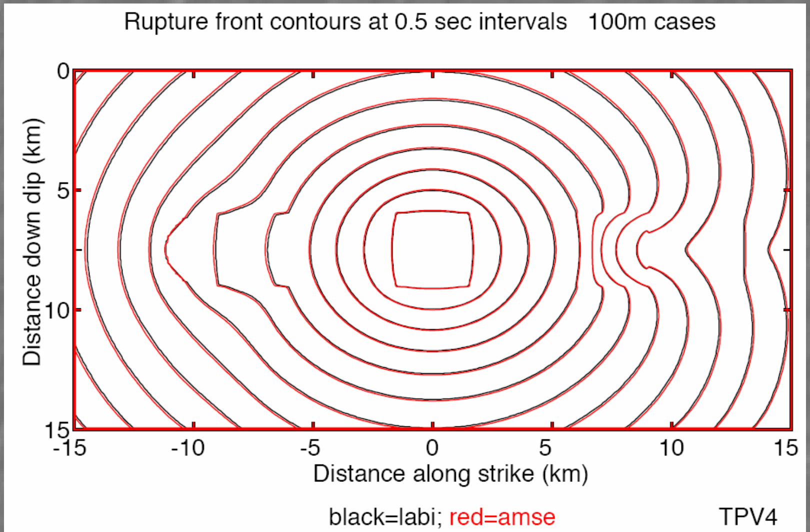
Method	Maturity	Main problem
Finite differences	since 70s	geometry
Boundary elements	since 80s	free surface, elastic
Finite elements	80s, few	low order
Spectral elements	recent	hex meshing
Discont. Galerkin	very recent	cost

First cross-validation effort started 3 years ago (SCEC). Quite qualitative so far (missing objective validation metrics).

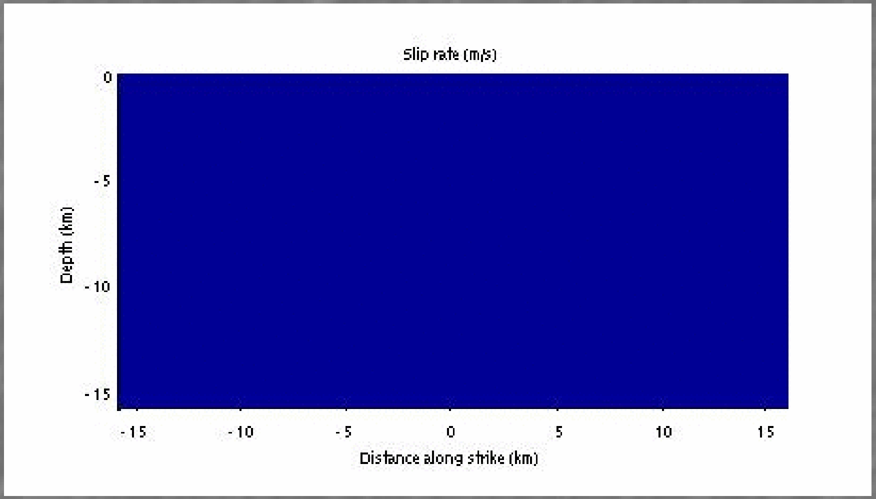
Large scale 3D simulations require Teraflop to Petaflop resources

All methods apply time domain explicit solvers, and are not adaptive

Spectral elements for earthquake dynamics

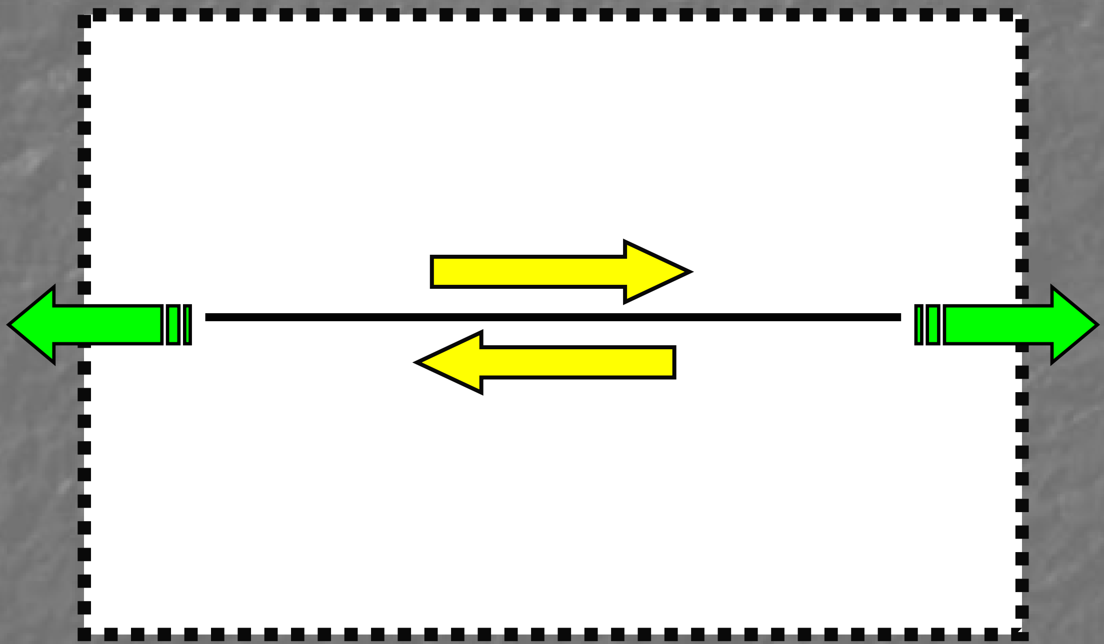


3D rupture with SPECFEM3D (Ampuero)
Rupture front snapshots compared to
SBIEM by N. Lapusta

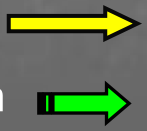


3D rupture with SPECFEM3D (Ampuero)
Slip velocity on the fault plane

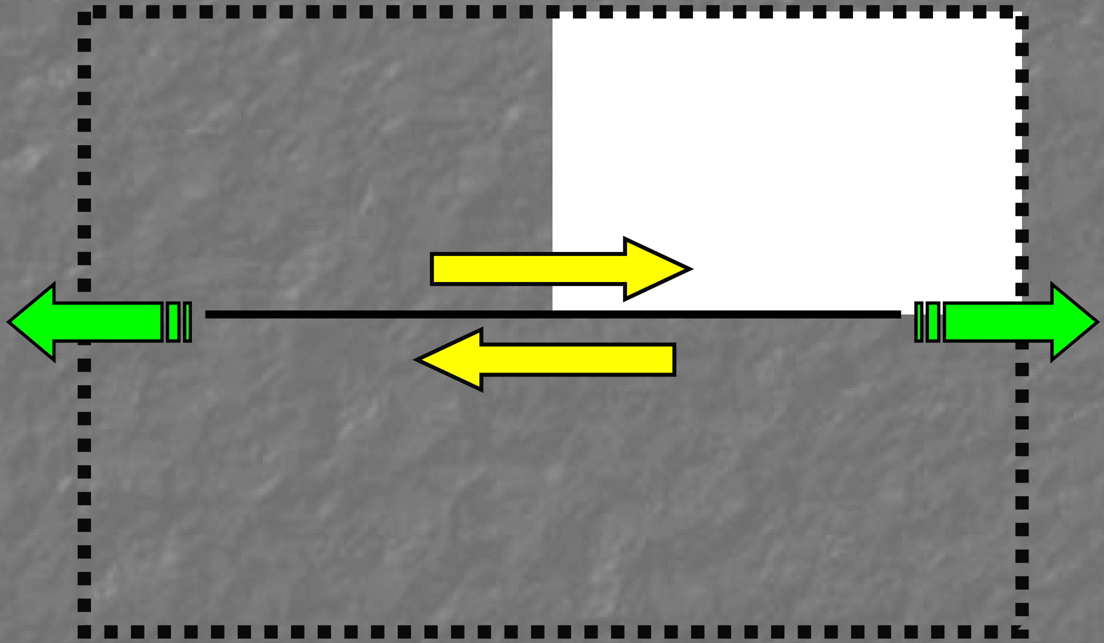
Scale contraction issue in the simplest problem



Displacement
Rupture growth



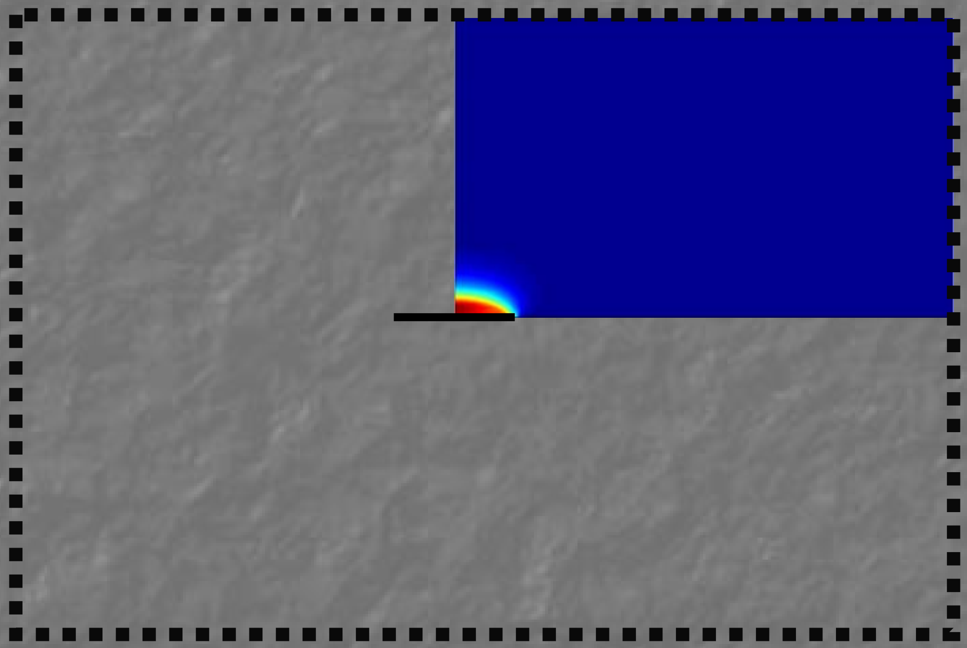
Scale contraction issue in the simplest problem



Displacement

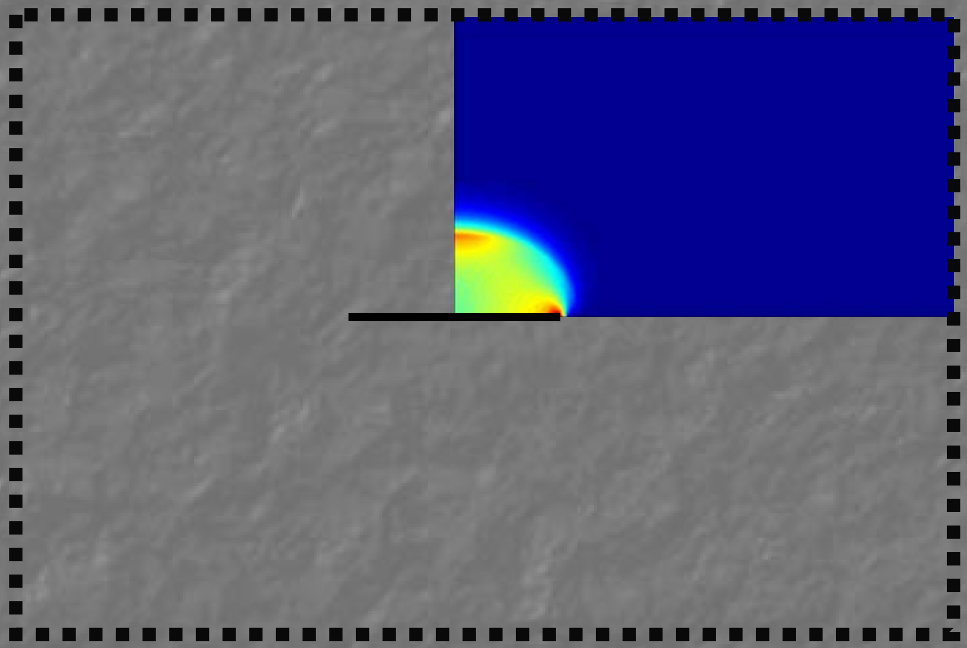
Rupture growth

Scale contraction issue in the simplest problem



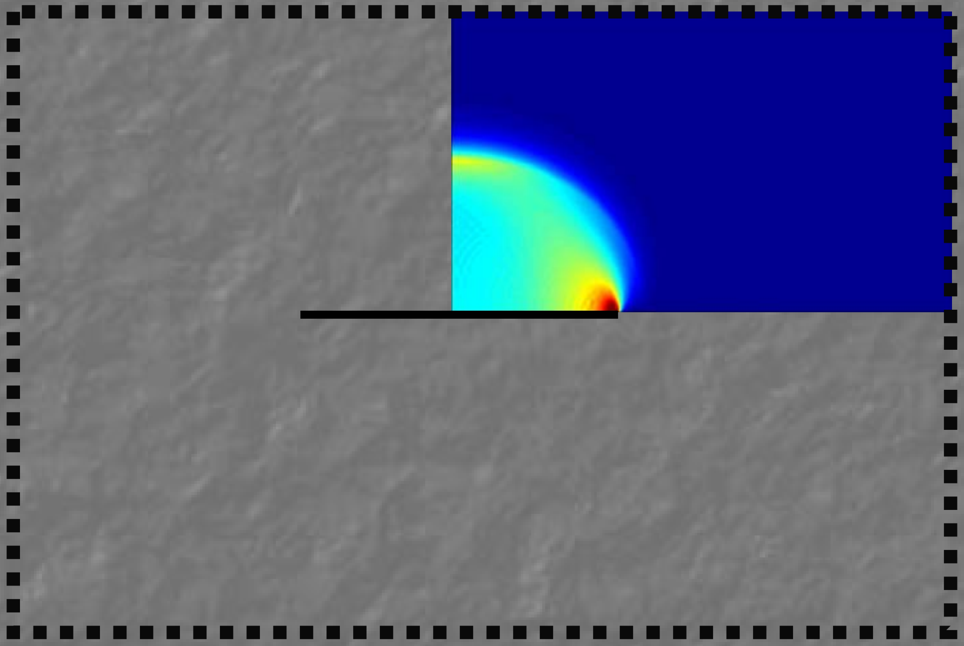
Particle velocity
snapshot

Scale contraction issue in the simplest problem



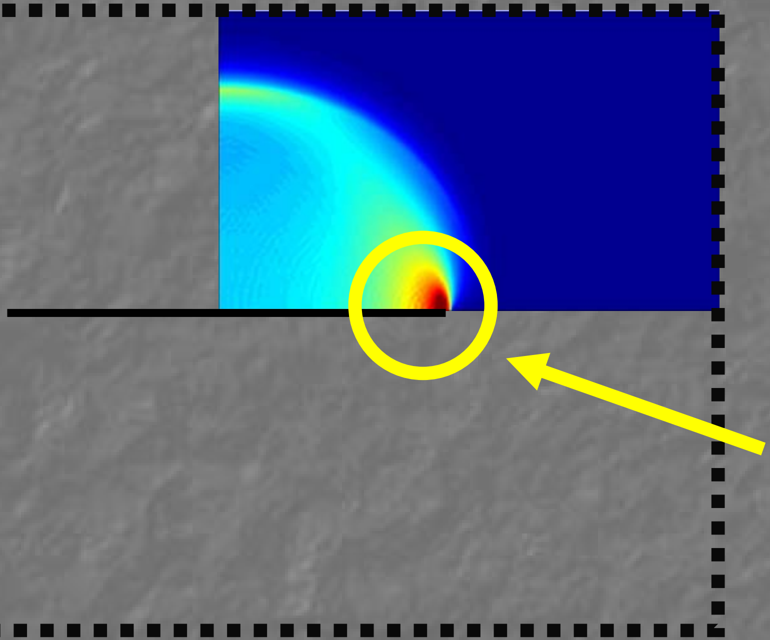
Particle velocity
snapshot

Scale contraction issue in the simplest problem



Particle velocity
snapshot

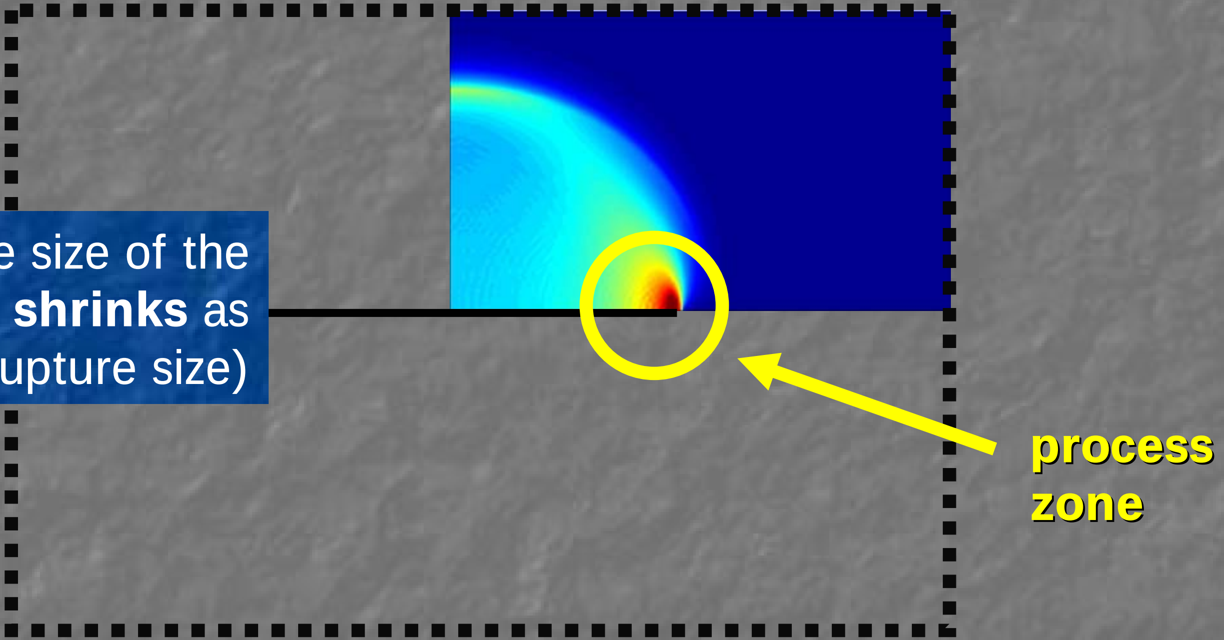
Scale contraction issue in the simplest problem



Energy dissipation and **high gradients** are concentrated in the **process zone**

Particle velocity snapshot

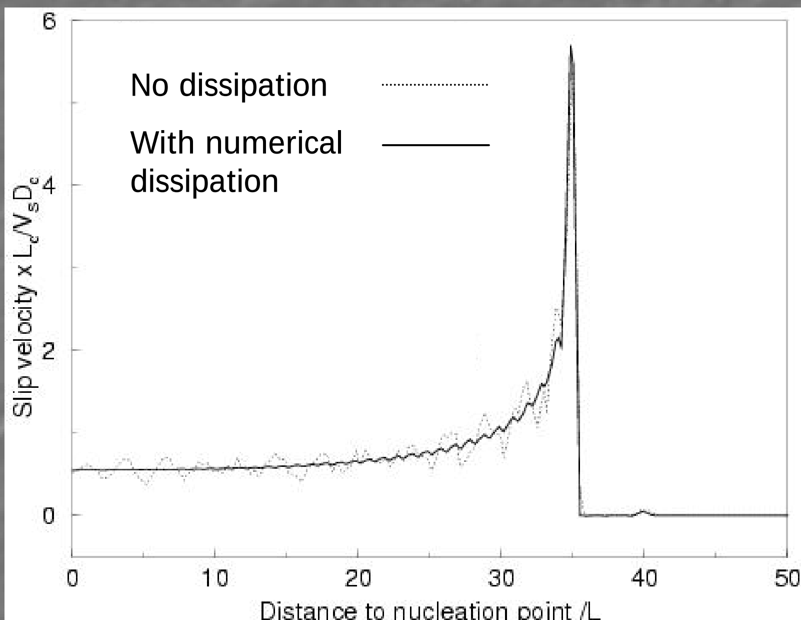
Scale contraction issue in the simplest problem



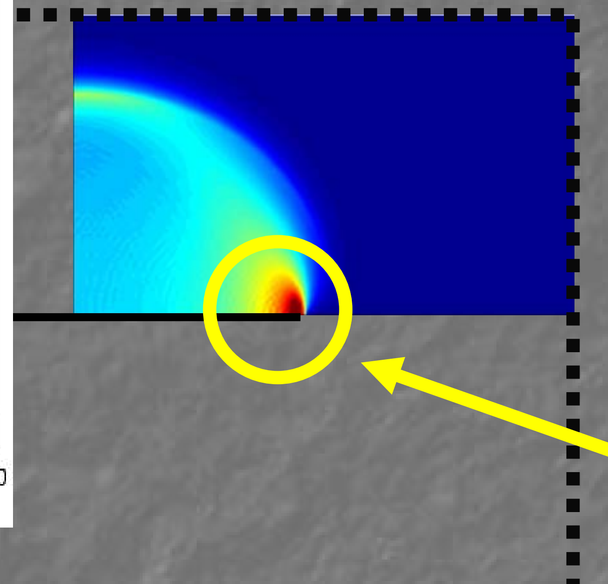
PROBLEM: the size of the process zone **shrinks** as 1/(rupture size)

Particle velocity snapshot

Scale contraction issue in the simplest problem



Slip velocity snapshot



process zone

PROBLEM: the process zone **shrinkage** excites high-frequency numerical noise

High-frequency numerical artifacts

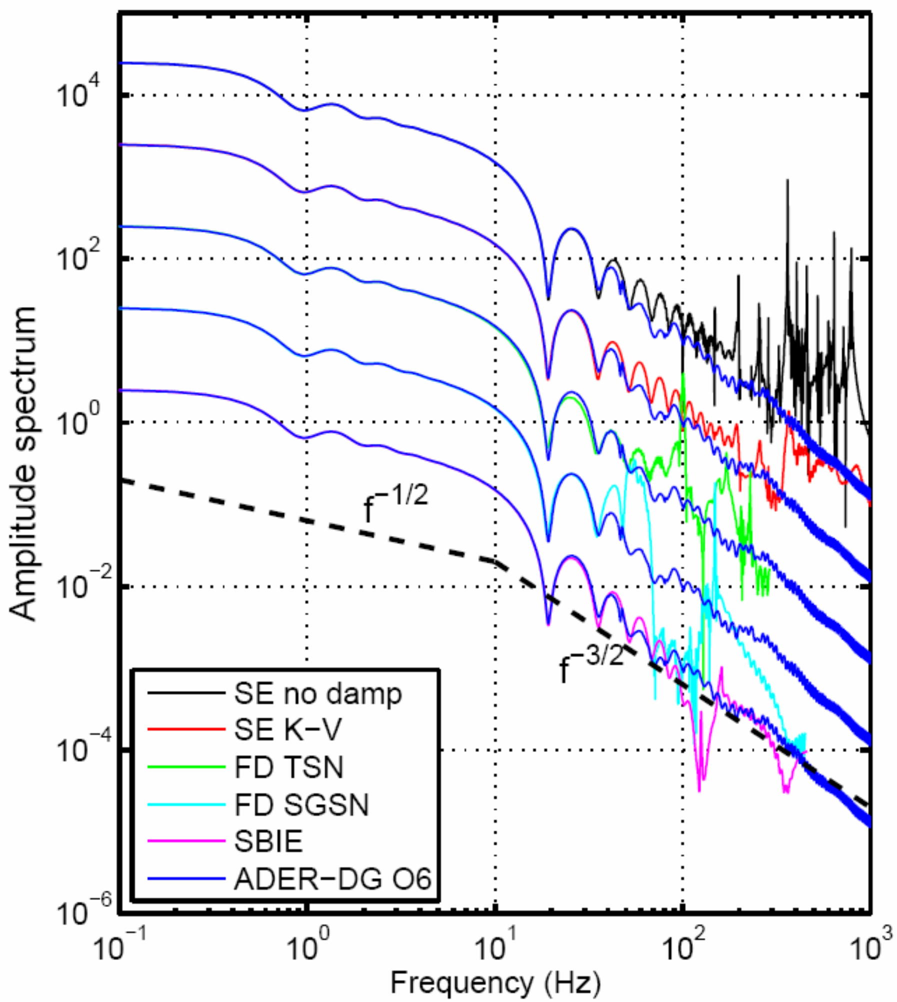


Figure 6. Spectra of the tapered slip rate at $x = 12.5$ km for the SCEC test problem solved with several methods. Dashed lines indicate theoretical expectations, $f^{-1/2}$ at frequencies lower than 20 Hz and $f^{-3/2}$ at higher frequencies.

Comparison of different numerical methods

(De La Puente, Ampuero and Kaeser; 2008)

Length scales involved

Earthquake rupture (like fluid turbulence) is a non linear process controlled by small scale features.

Small scales :

- Frequency for inversion < 1 Hz → λ>3 km
- Frequency for engineering < 10 Hz → λ>300 m
- Process zone <100m
- Other fault zone physical processes << 100 m ... ?

Large scales :

- Fault length > 30 km
- Distance to stations/city >>10 km

→ The typical scale ratio is >> 10^3

Computational time grows as (scale ratio)^4

Some possible next steps

Dynamically space-time adaptive methods?

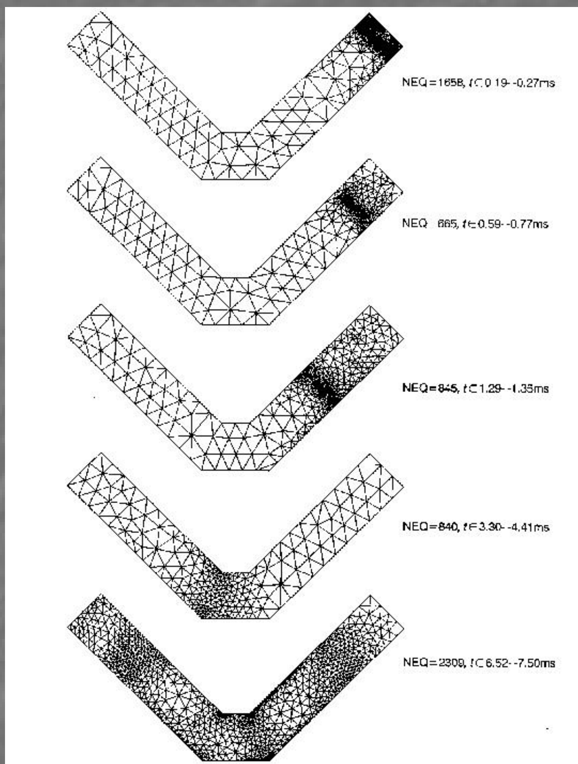
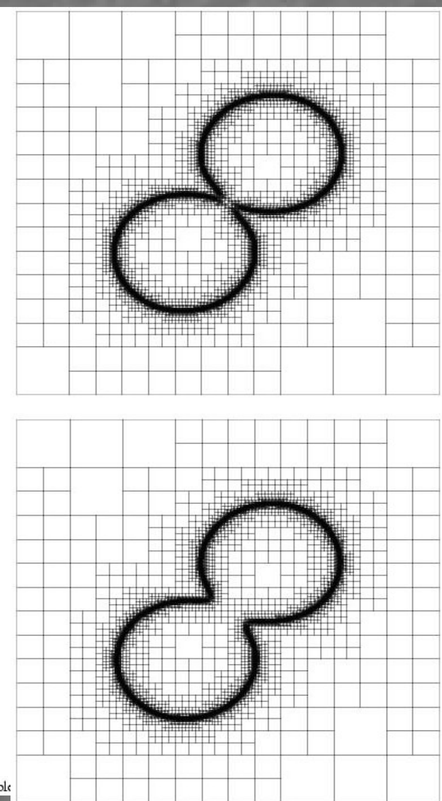


Figure 16. Some meshes used in the adaptive analysis for the 2-D wave propagation probl

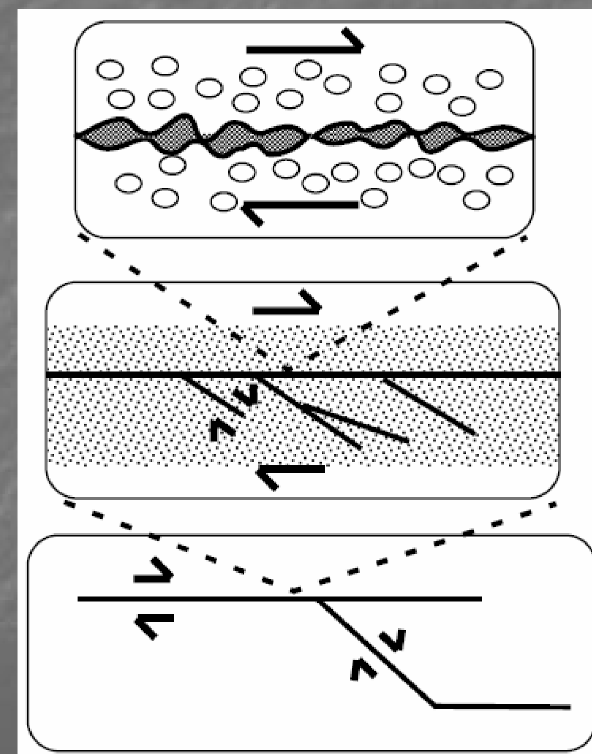
Implicit adaptive DGM for elastodynamics

(Wiberg and Li 1999)



Space-time adaptive SEM for multi-phase fluid dynamics (Barosan 2003)

Homogeneization?
Equivalent meso-scale representation of micro-scale physics, analogous to “Reynolds stresses” in fluid turbulence (e.g. large eddy simulations).



Computational earthquake dynamics Summary

- Poorly known physics
- Poorly known initial conditions
- Complex fault geometries
- Involving intensive computation:
  - even the simplest problem leads to scale contraction
  - effect of stochastic parameters,
  - Non-linear ill-posed inverse problems,
  - multi-physics/multi-scale problems

→ require novel, more efficient numerical methods