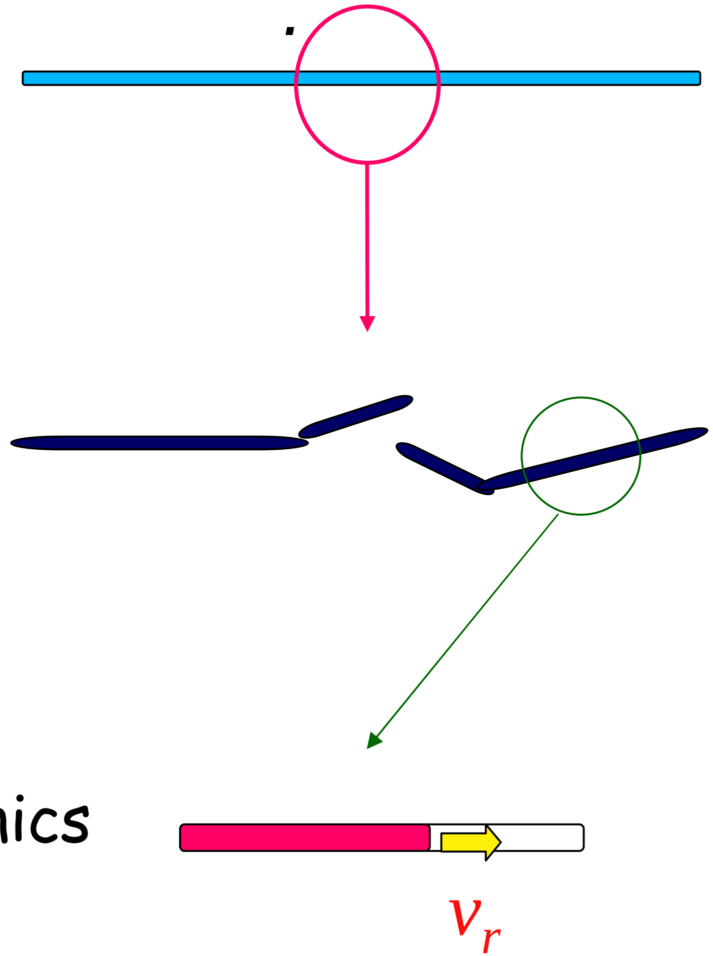
EARTHQUAKE DYNAMICS:
from rupture to seismic radiation

Keynote lecture delivered at IASPEI 2009
In Cape Town, South Africa

Raul Madariaga

Laboratoire de Géologie
CNRS
Ecole Normale Supérieure
Paris, France

Different scales in earthquake dynamics



BB Seismic waves

(< 0.3 Hz   λ> 5 km)

Macroscale

Hifi Seismic waves

(>0.5 Hz λ<2 km)

Mesoscale

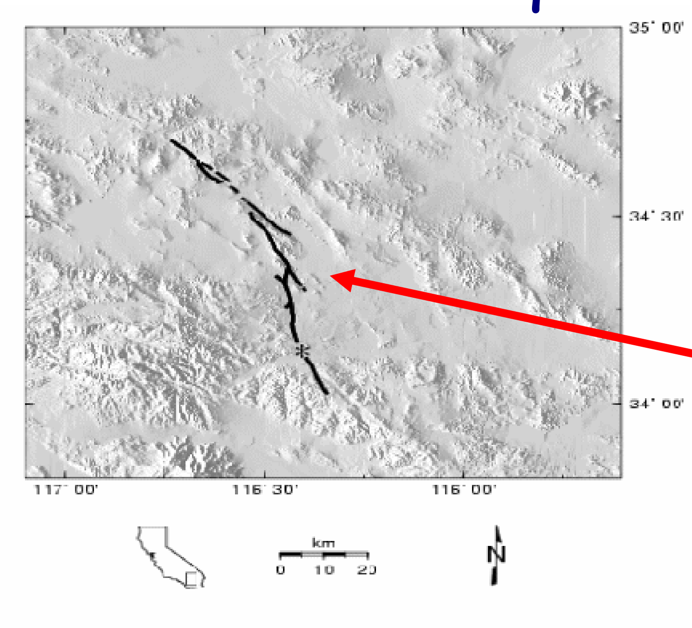
Steady state mechanics

(non-radiative)

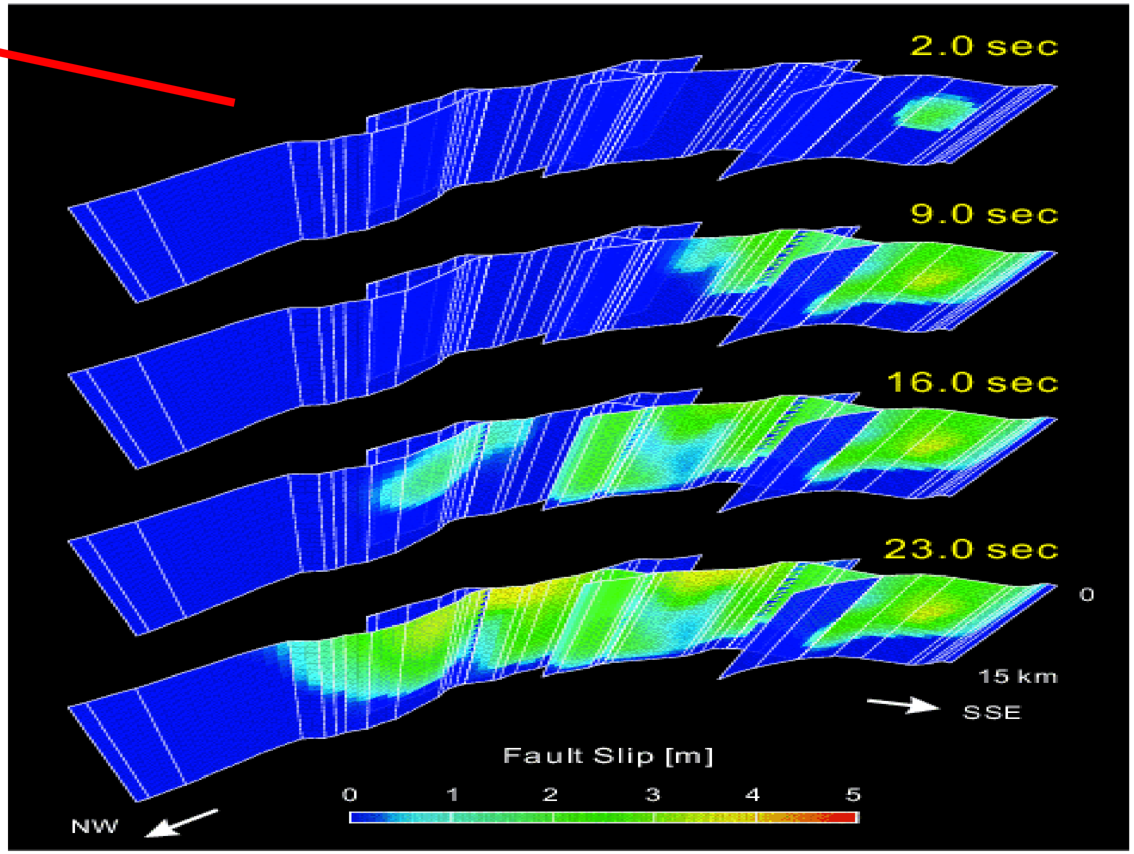
(λ~ 100 m)

Microscale

Earthquakes as dynamic shear ruptures



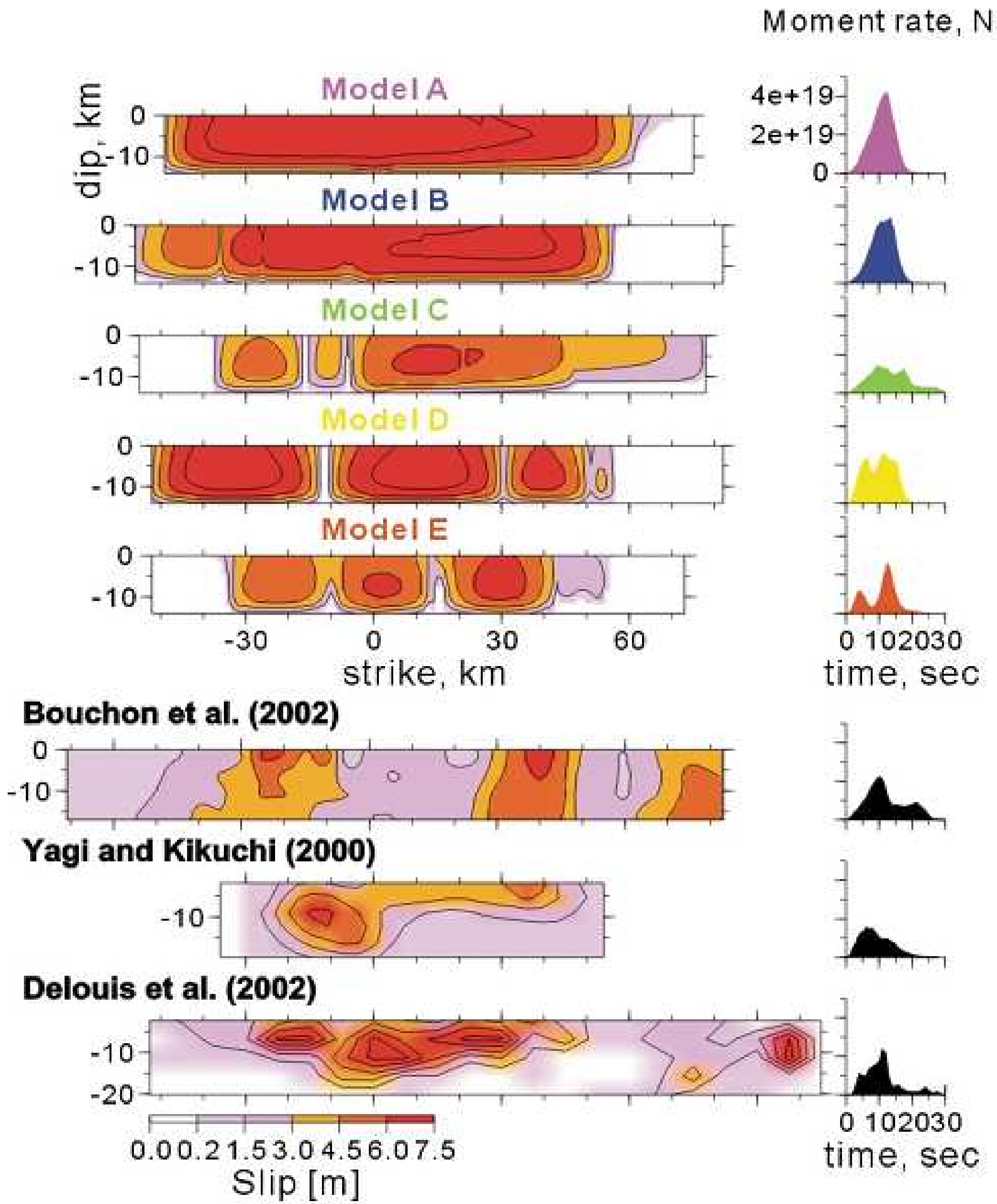
Preexisting Fault system
in the Mojave desert



Rupture modelled
on the complex fault
system determined
from Geology,
Geodesy and
Seismology

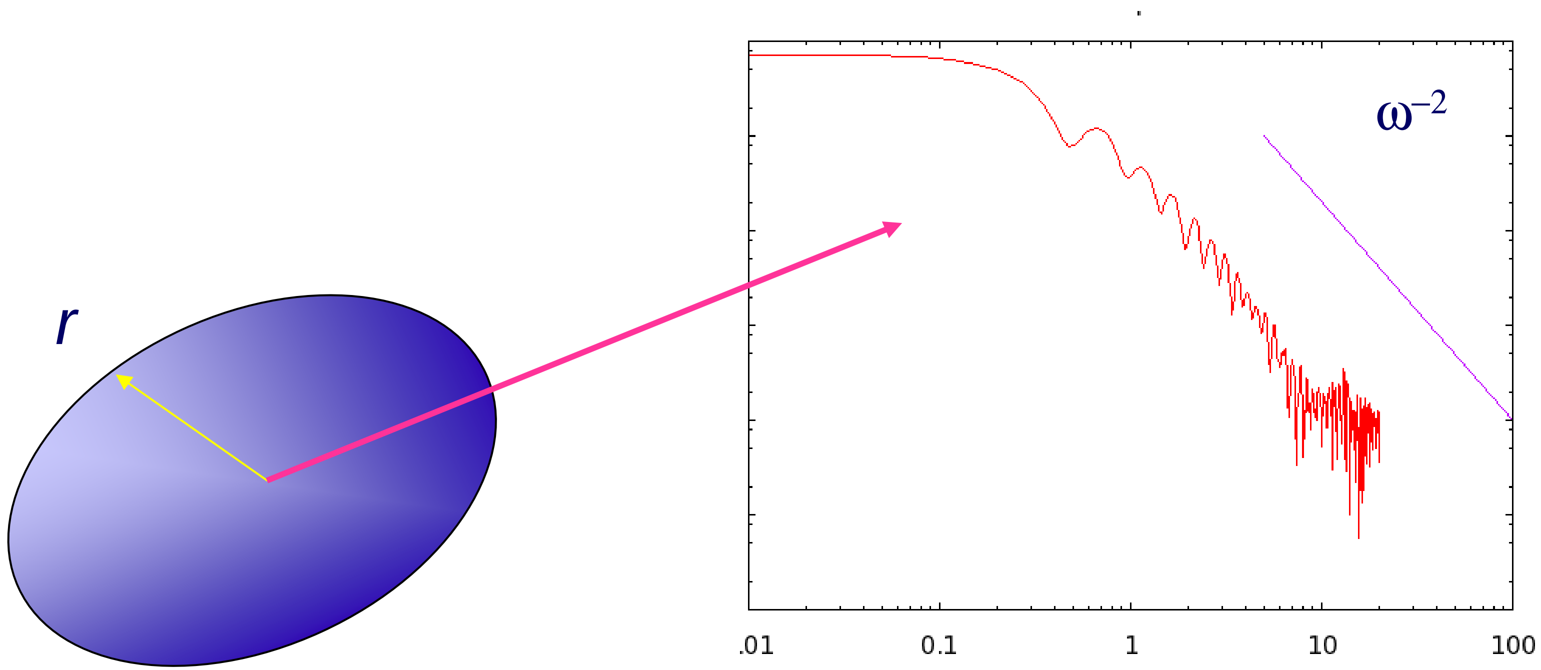
Aochi et al. 2003

Kinematic models of the Izmit Earthquake 1999



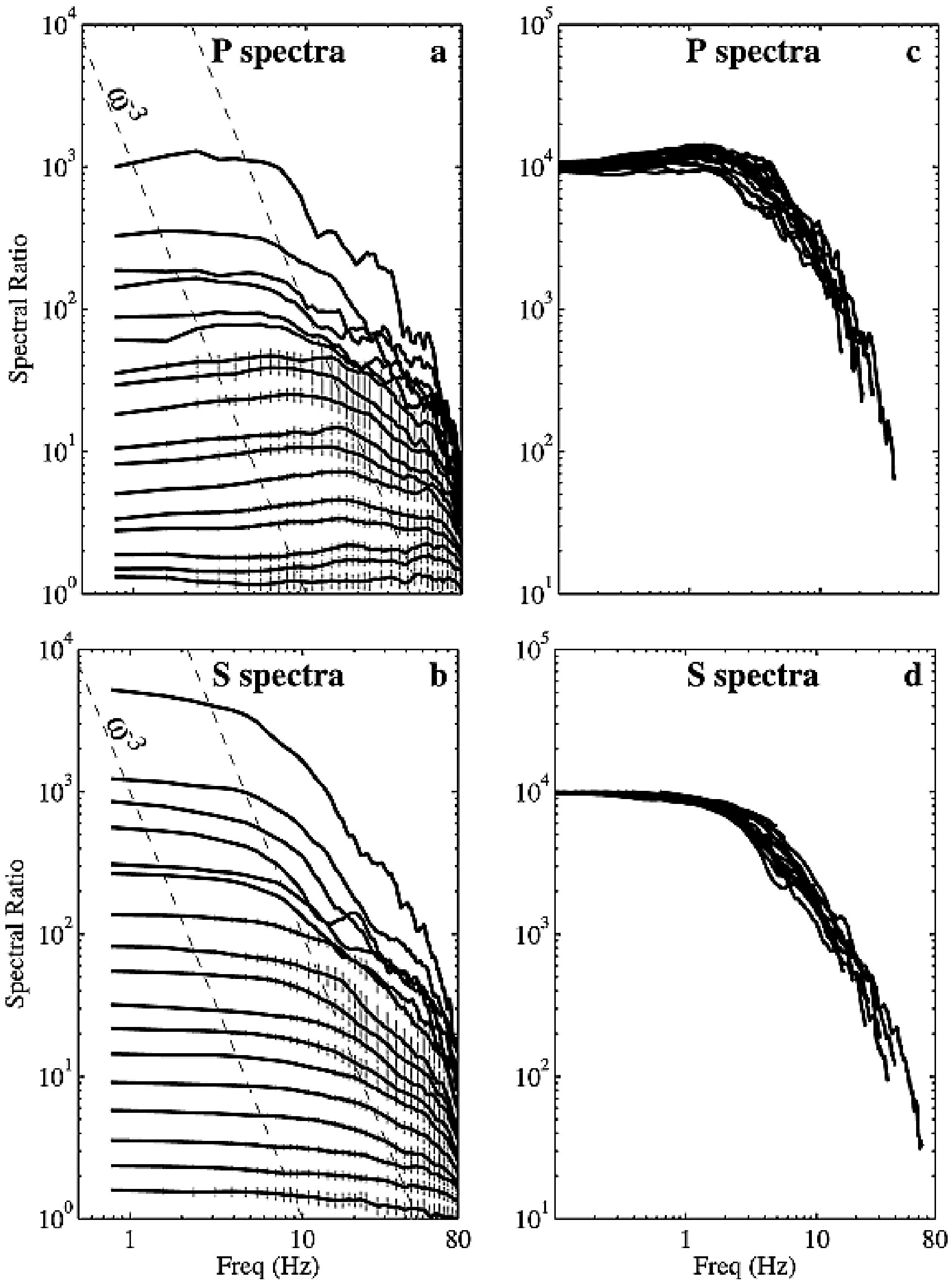
Yet kinematic inversions are often very non-unique.

The good old circular crack explains Brune's spectrum



$$\omega_c = 2.34\frac{\beta}{r}$$

$$\Omega(\omega) = \frac{1}{1+\omega^2/\omega_c^2}$$



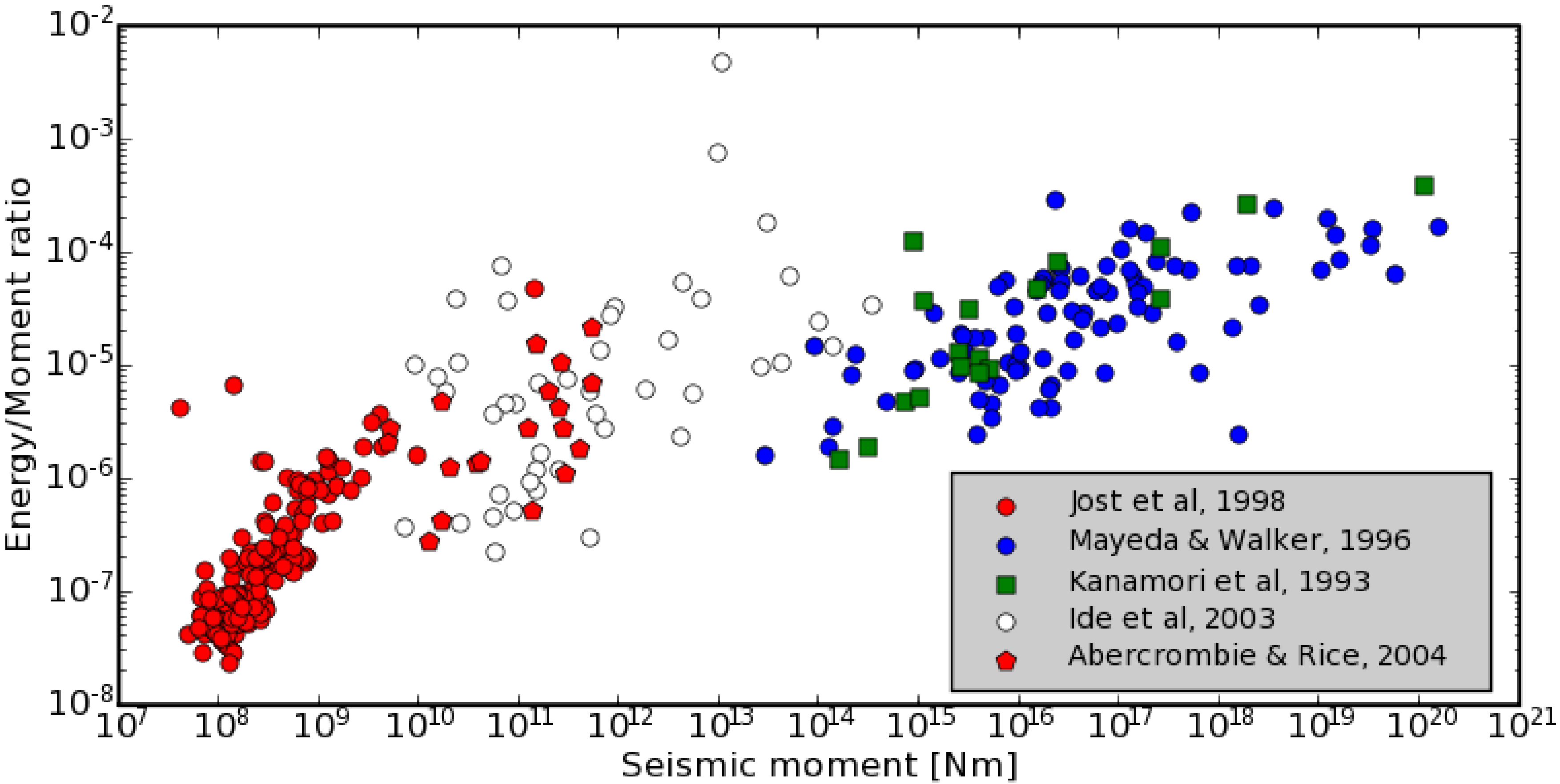
Spectral stack from Prieto et al. , 2004

From these spectra we can compute

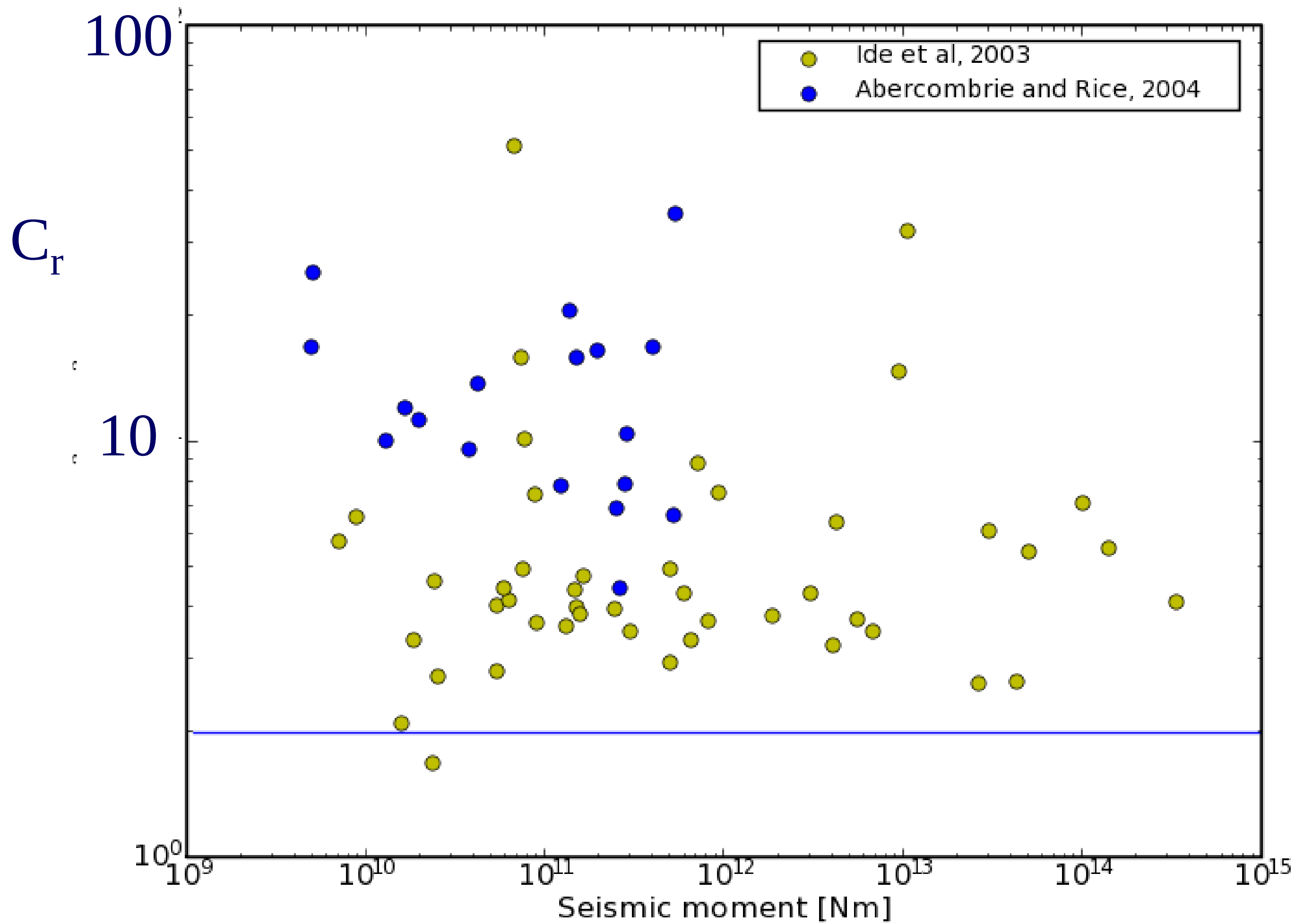
the damping coefficient

$$C_r = \frac{\mu E_r}{M_o^2} \frac{\beta^3}{f_0^3} = \sigma_a \frac{\beta^3}{M_O f_0^3}$$

The usual view of this variation



Deviation of self-similarity over 6 orders of magnitude



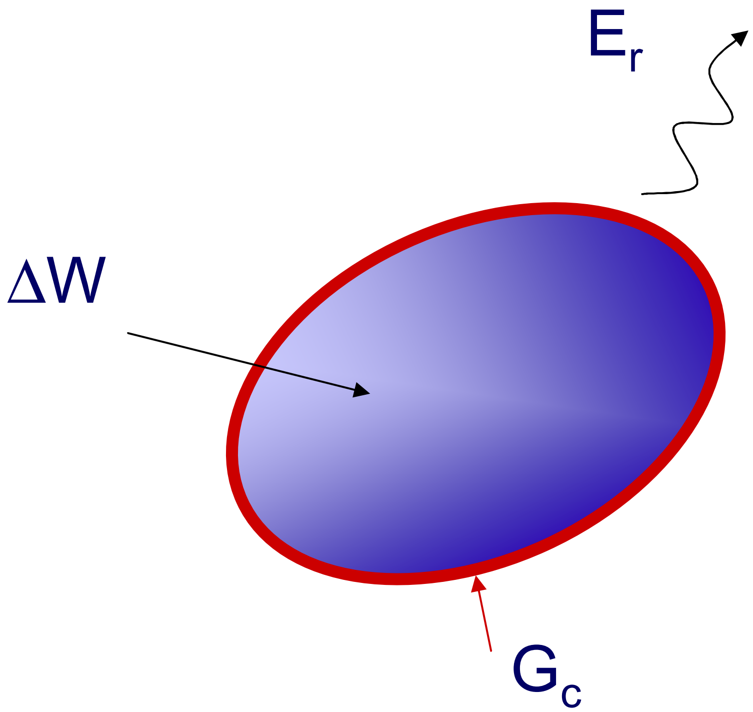
$$C_r = \frac{\mu E_r}{M_o^2} \frac{\beta^3}{f_0^3}$$

Decreasing damping

Boatwright's

Brune spectrum

Scaling of energy with earthquake size



$$\Delta W = E_r + G_c S$$

For Brune's model

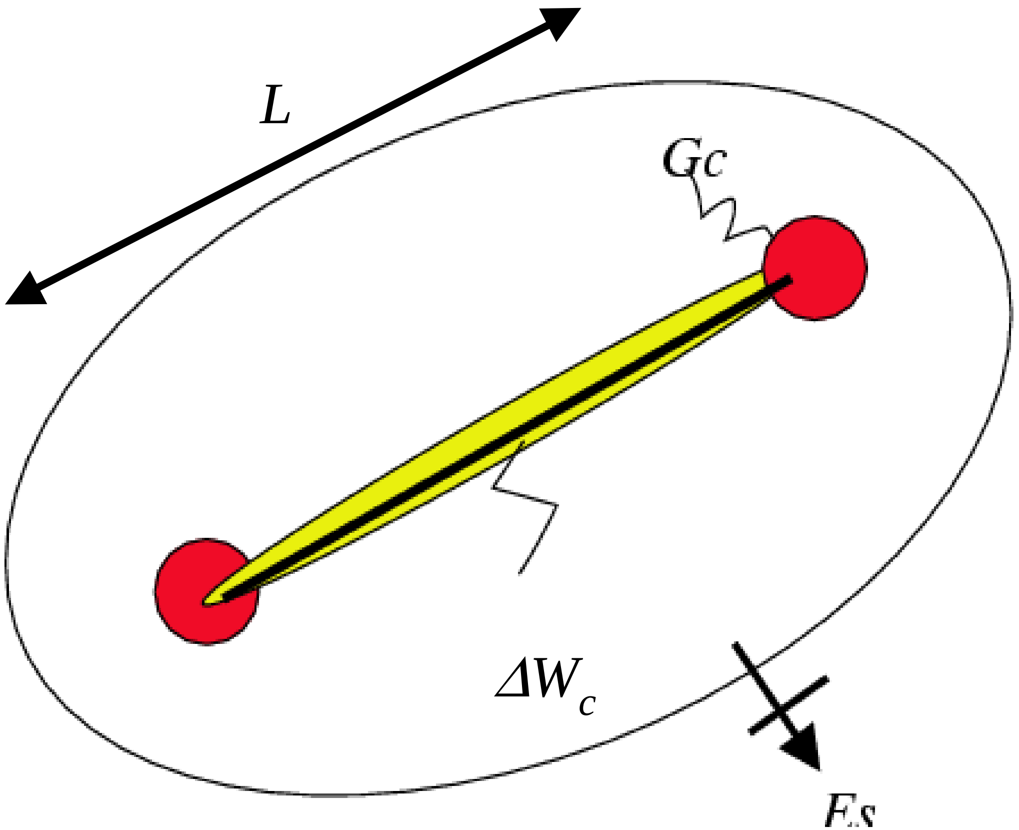
$$\frac{E_r}{\Delta W} = \frac{32}{7} C_r \frac{r^3 f_0^3}{\beta^3}$$

Brune used

$$f_0 = 0.3724 \frac{\beta}{r}$$

$$\frac{E_r}{\Delta W} = 0.466$$

Global Energy Balance



$$E_r = \Delta W_c - G_c\, S$$

S = fault surface

E_r = radiated energy

ΔW_c = avail. strain energy

G_c = surface energy

Fracture energy grows with earthquake size

It is not a material property

This must be included in earthquake models designed to predict seismicity

Circular crack dynamics

Fully spontaneous rupture propagation under slip weakening friction

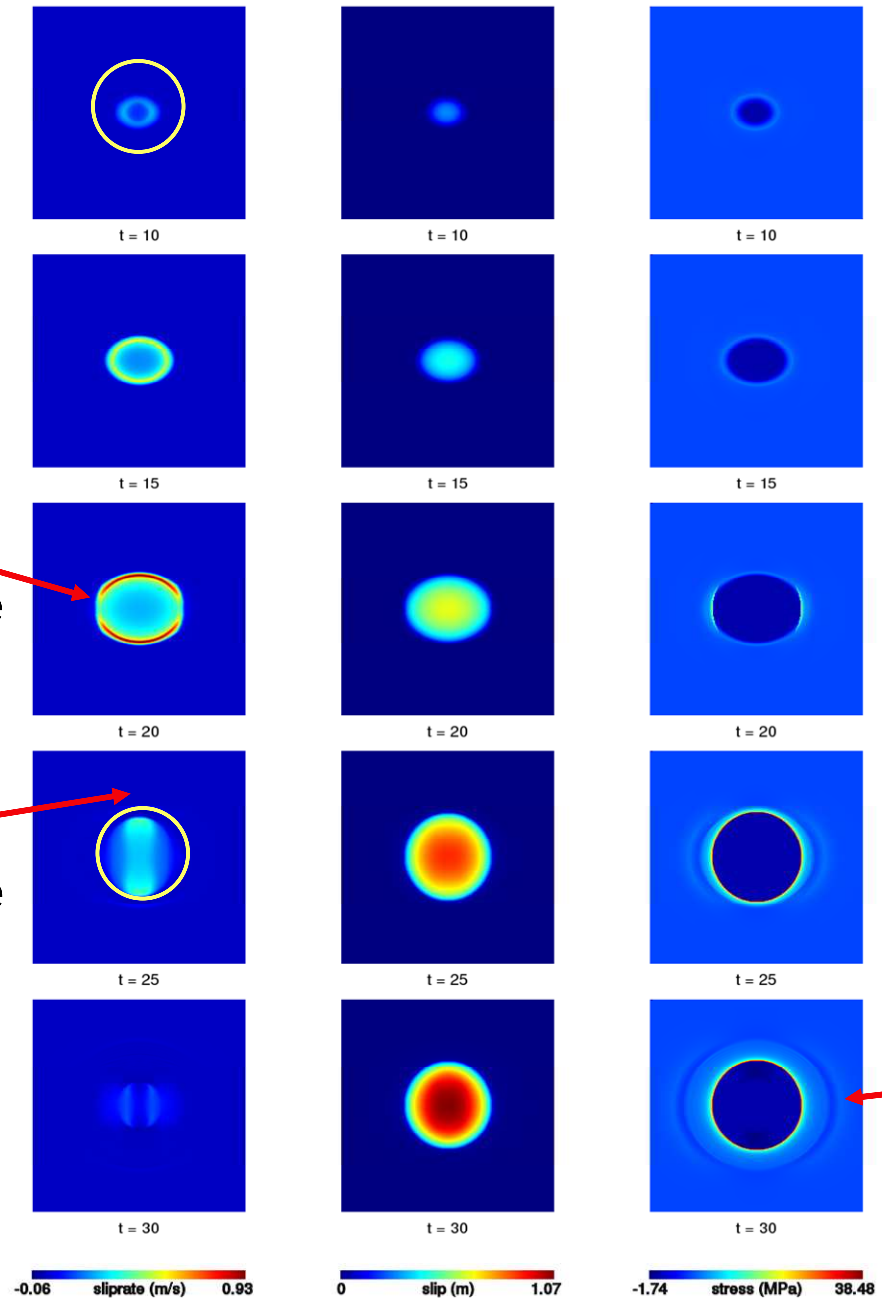
Slip rate | Slip | Stress change

Starts from Initial patch

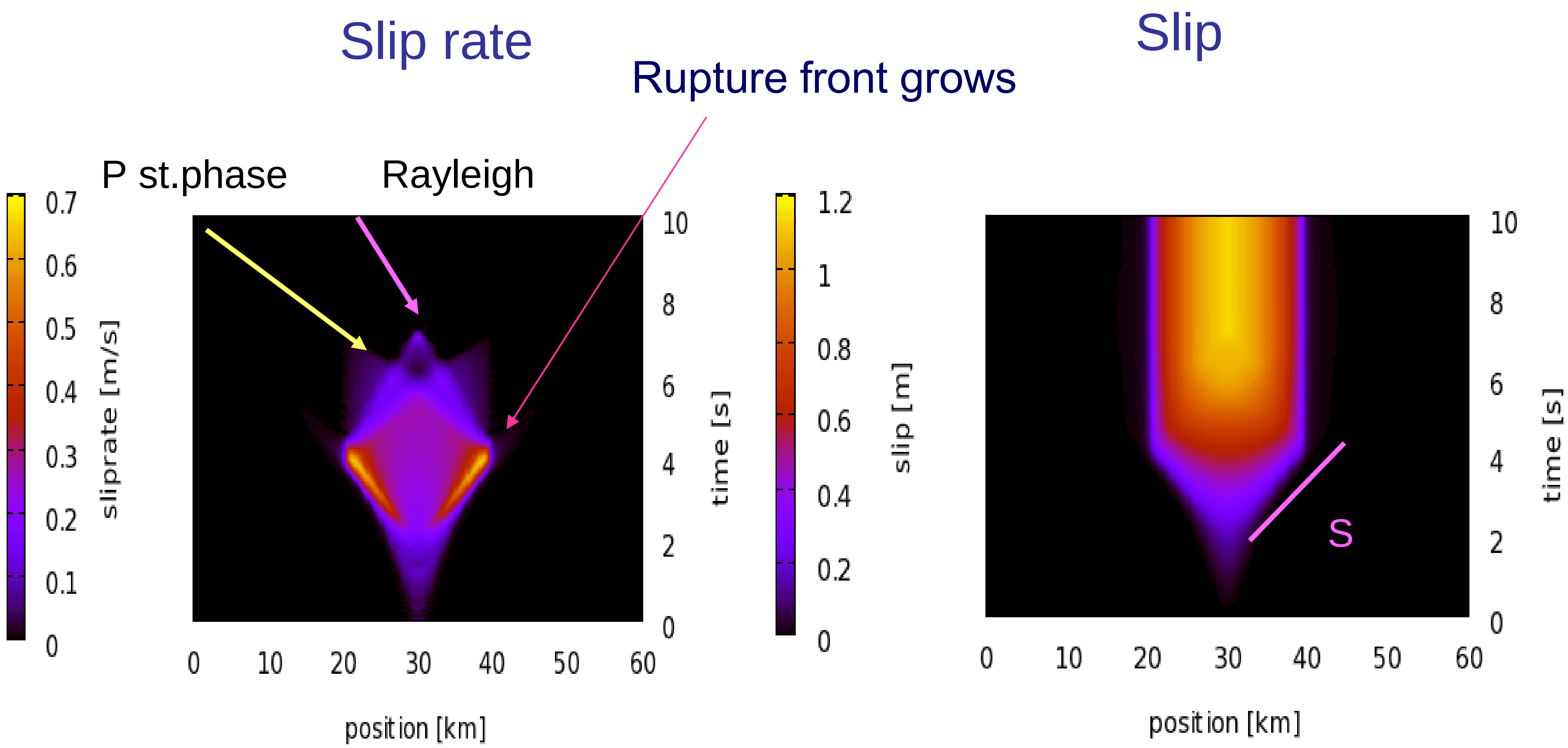
Longitudinal stopping phase

Transverse stopping phase

Stopping phase (S wave)

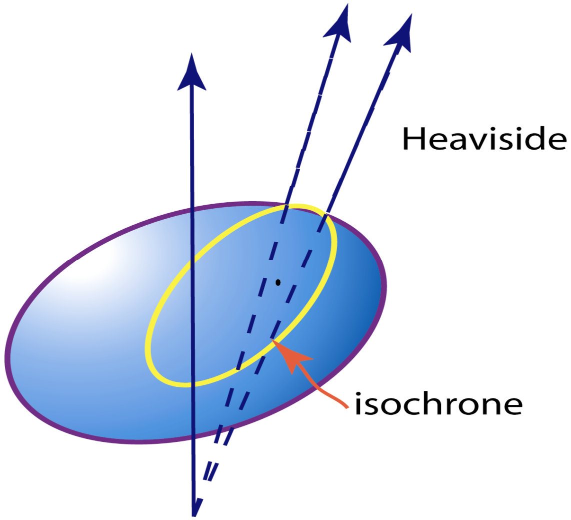


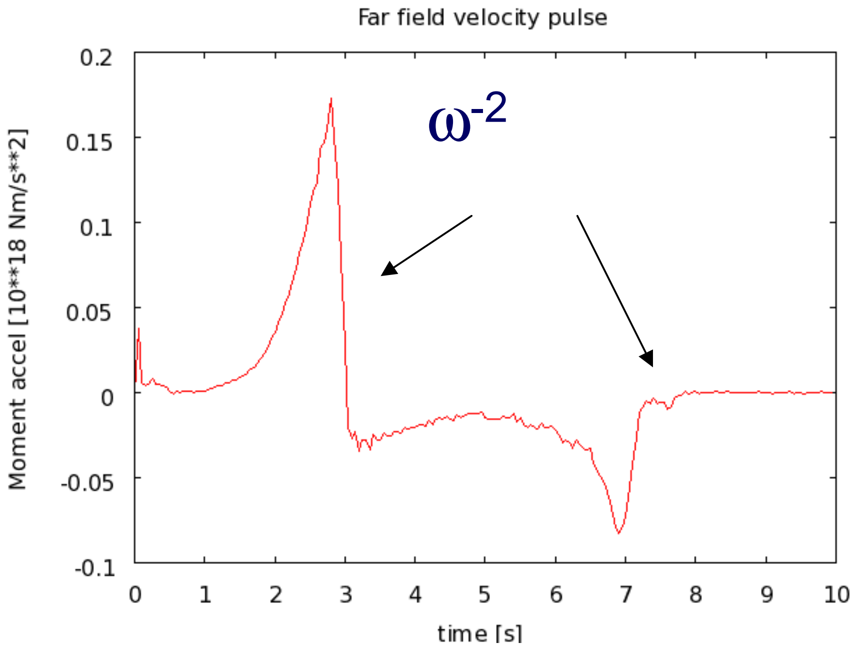
Rupture process for a circular crack

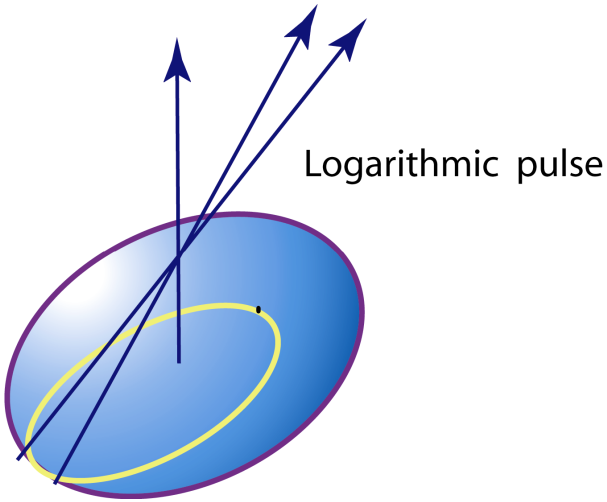


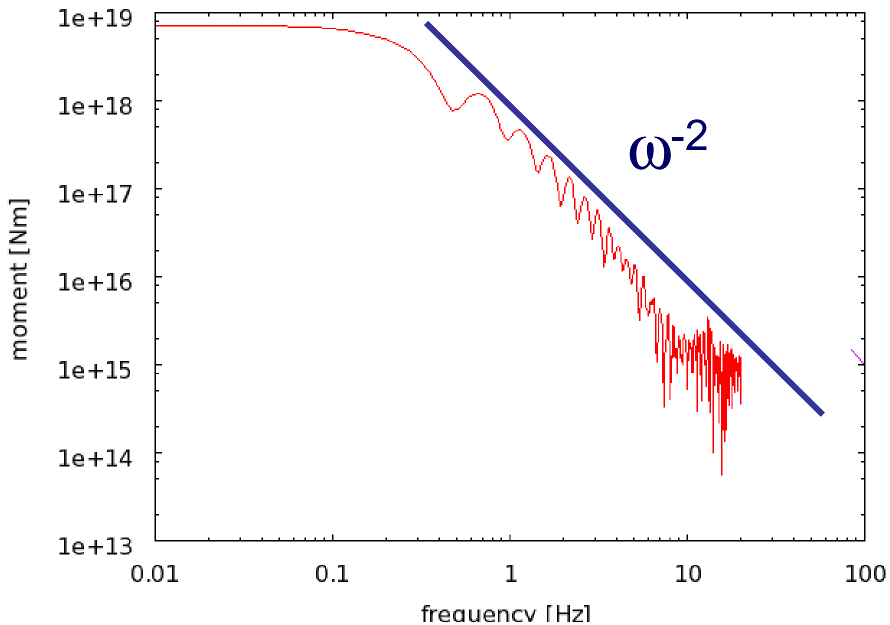
Radiation is controlled by wave propagation inside the fault!

Far field radiation from circular crack





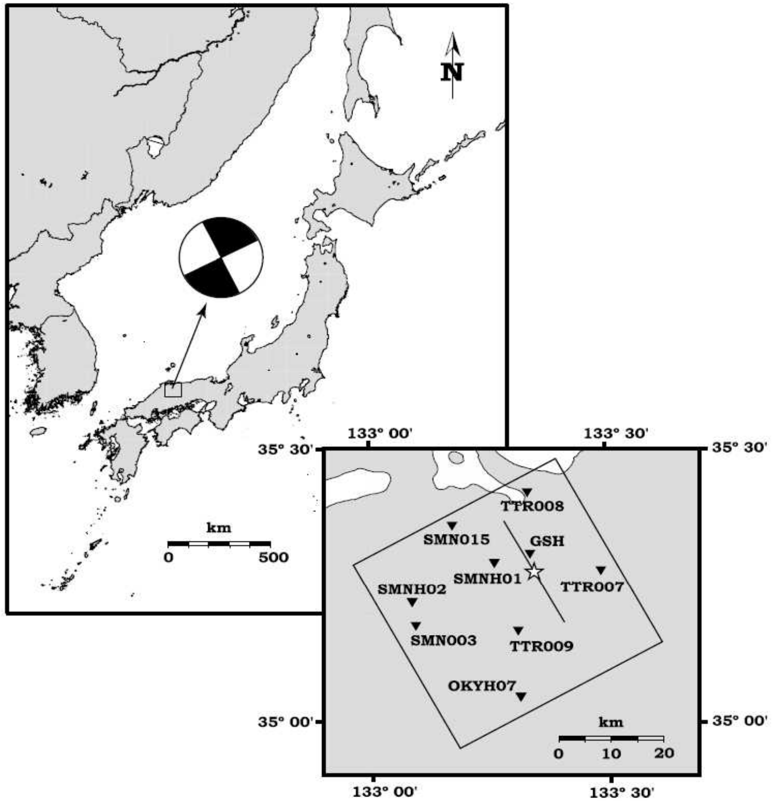




Can devise the equivalent of Brune's model for near field data ?

Work done in collaboration with
Sara DiCarli (ENS Paris)
Caroline Holden-François (New Zealand)
and Sophie Peyrat (IPG Paris)

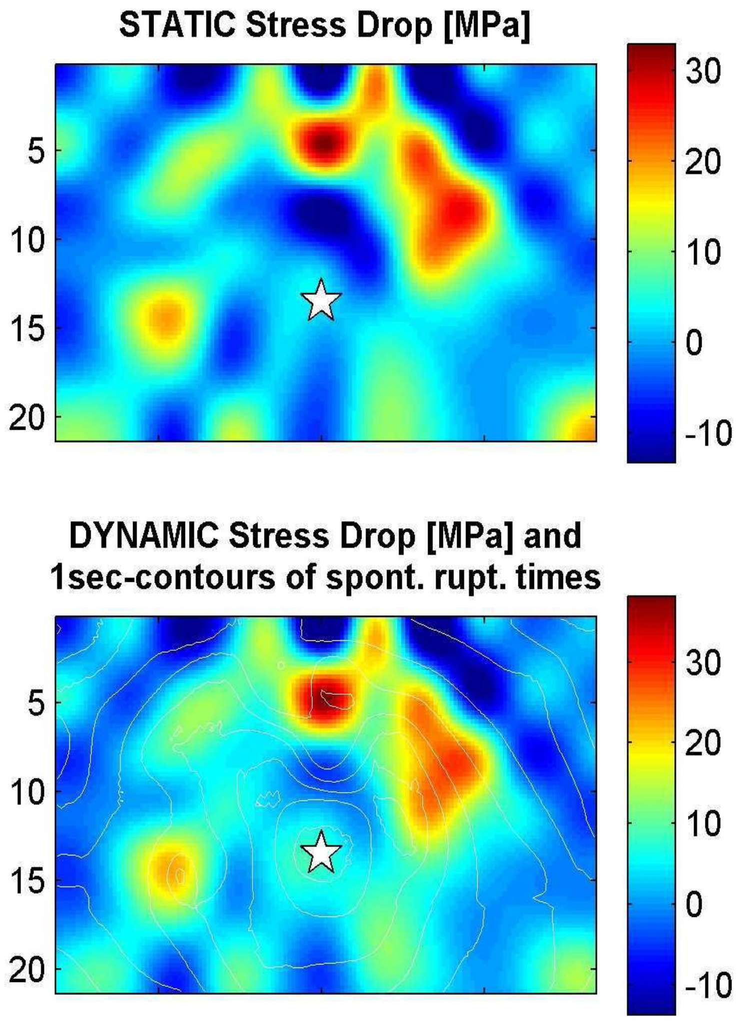
The 2000 Western Tottori earthquake



- Tottori accelerograms have absolute time
- Hypocentre determined directly from raw records

- **No surface rupture observation**
- **M_w 6.6~6.8**
- **Pure left-lateral strike slip event**

Classical Dynamic inversion



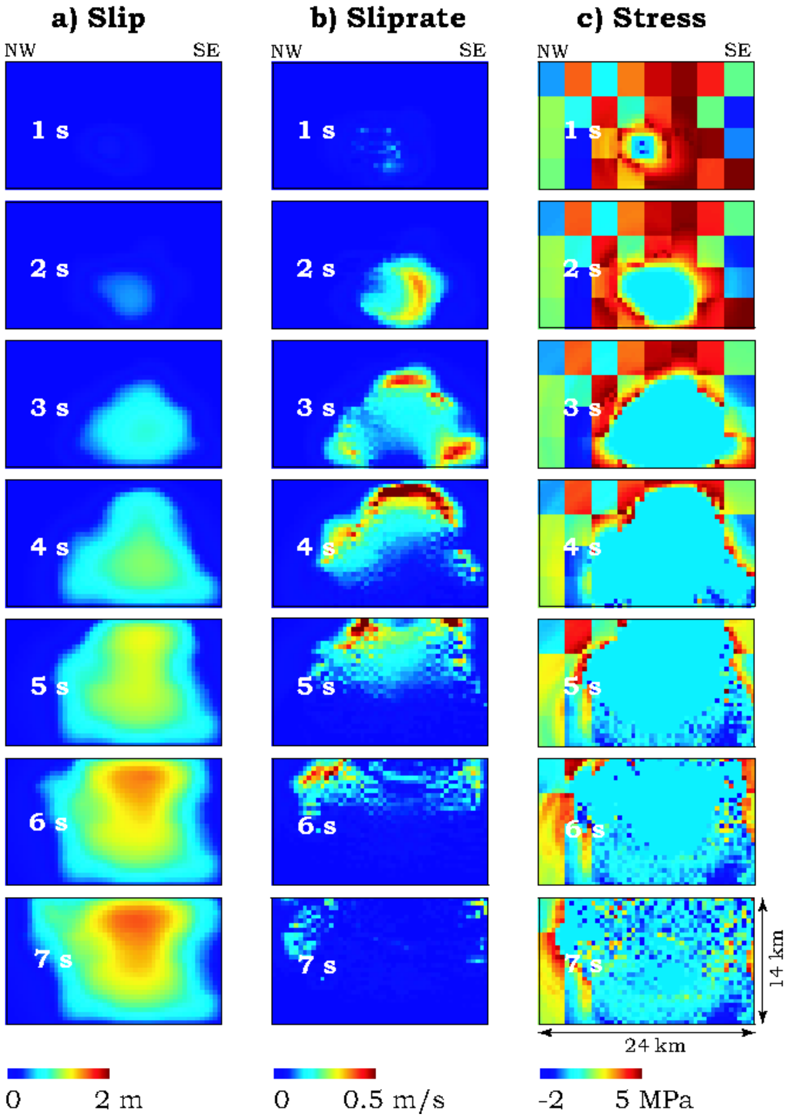
Classical approach:

convert kinematic model into a dynamic model

compute stress change from slip history.
(Bouchon, Ide and Takeo, etc.)

Example from Dalguer et al (2002)

Tottori earthquake: first true dynamic inversion by Peyrat and Olsen (2003)



Inversion followed the grid pattern of classical kinematic inversions.

Used 32 patches of initial stress

Rupture resistance was uniform,

Two problems :

How to handle discontinuous stress patches

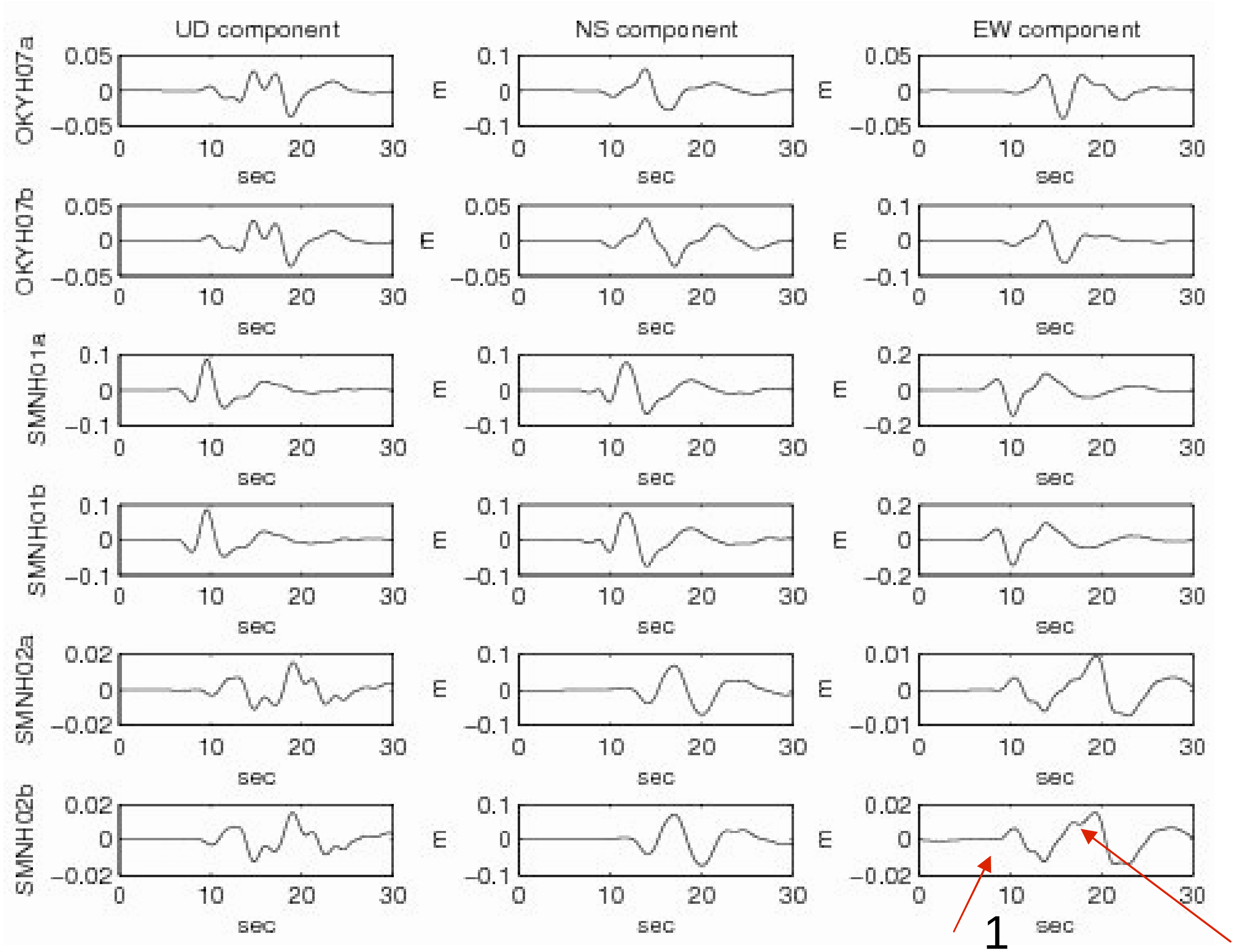
And how to stop rupture?

Tottori earthquake June 2000:

Data: 8 3-component displacement records integrated from KiK-net and K-net stations
filtered with *causal* Buttersworth filter between 0.1 and 0.5 Hz

depth

shallow



:

KiK-net stations

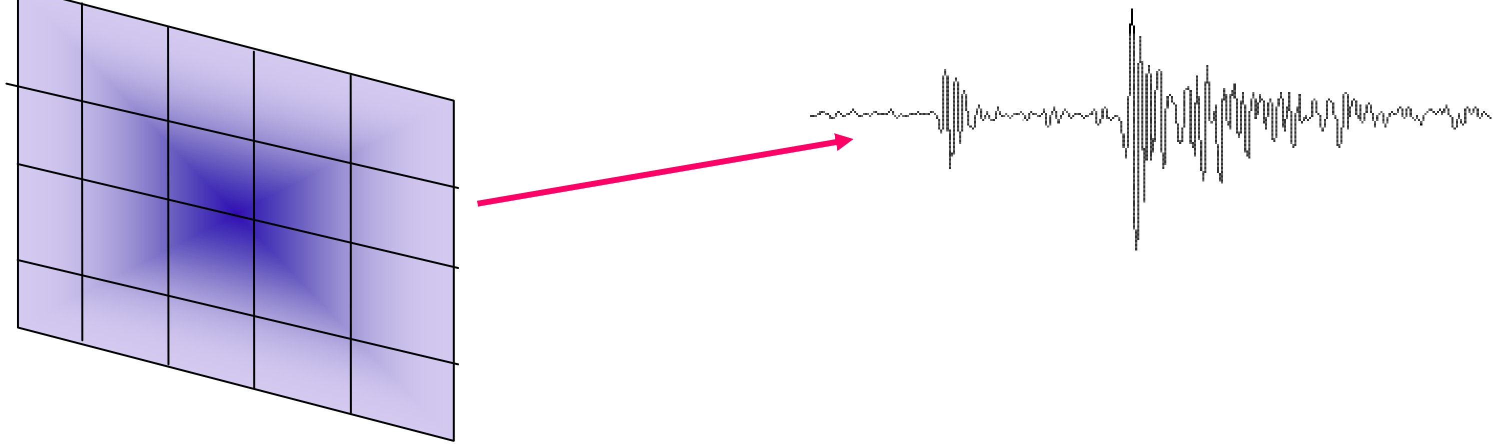
2 subevents

1

2

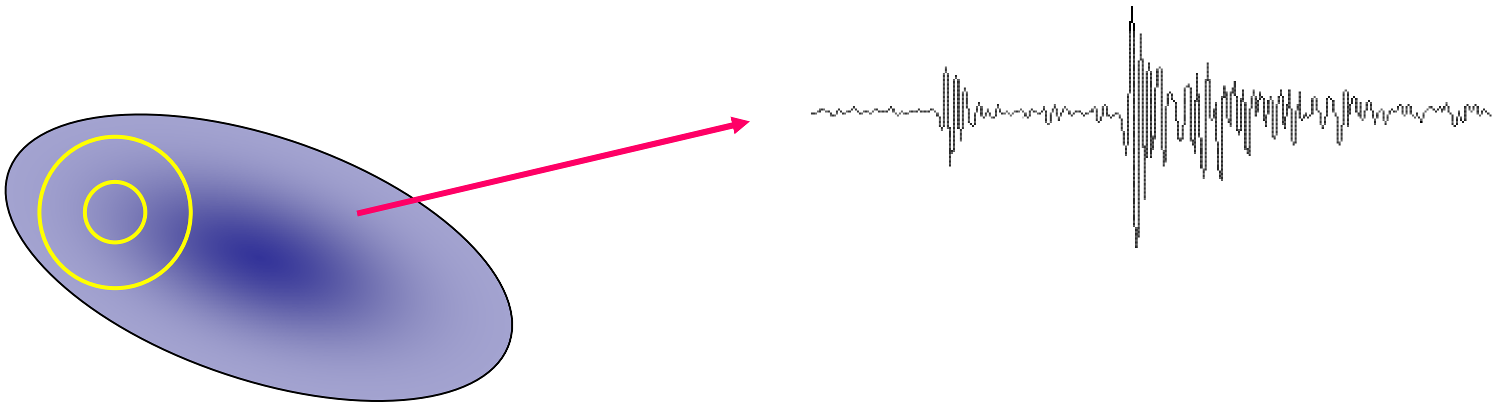
Inverse Kinematic Problem

Traditional approach is to use a discontinuous grid.



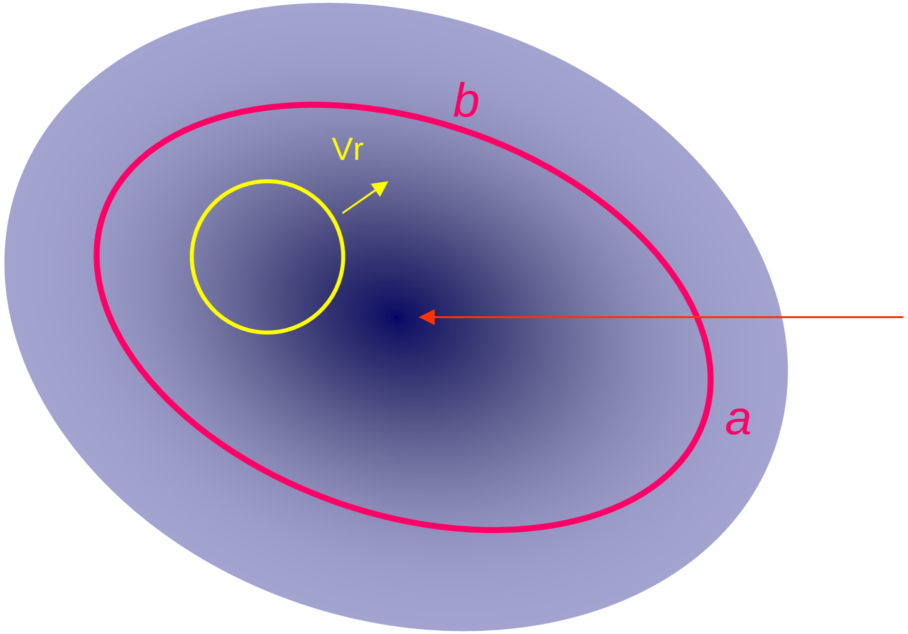
Suggestion:

Let us look only at low frequencies using Moments of slip distribution:



An alternative approach to the Inverse Kinematic Problem

We use a Gaussian slip distribution



This slip distribution has 8 parameters:

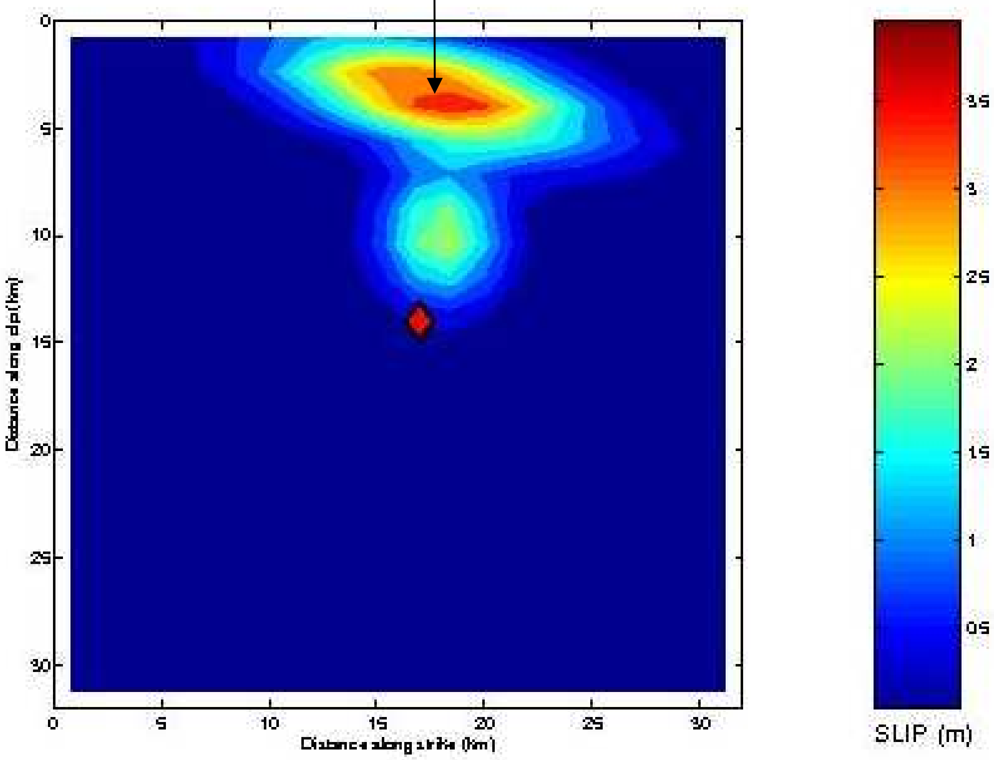
(x_o , y_0) centroid
(a, b, ϕ) semiaxes and angle
D_0 maximum slip
v_r rupture speed
τ rise time of STF

See also Bukchin et al, McGuire and Jordan, Vallée and Bouchon

Tottori earthquake June 2000:

Kinematic inversion with 2 ellipses

Peak slip ~ 3 m



Objective function:

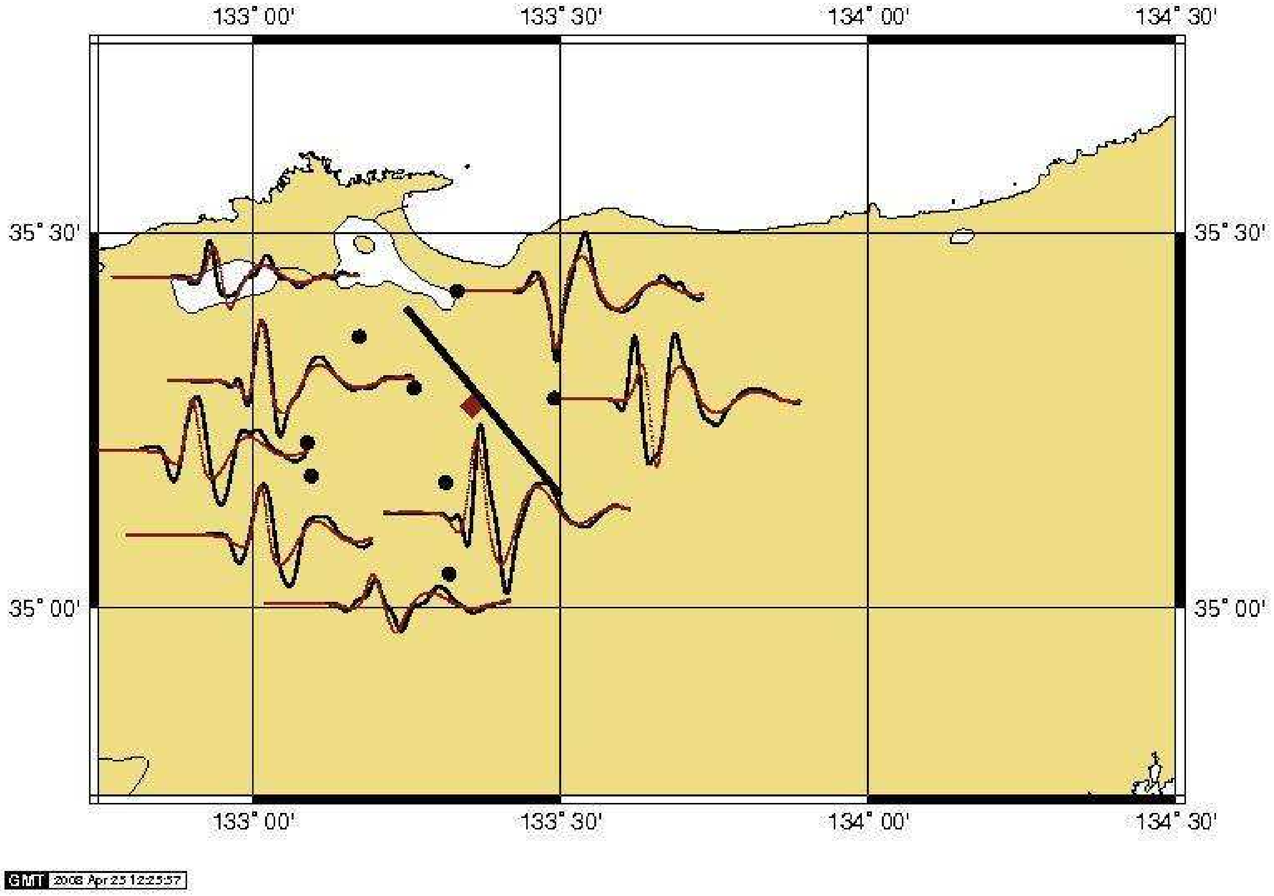
$\mathbb{L}^2$ norm

$$\chi^2 = \frac{\sum (obs - calc)^2}{\sum obs^2}$$

$M_0 = 1.19\ 10^{19}$ Nm Mw=6.7

Tottori earthquake June 2000:

Comparison of observed and kinematically modelled records

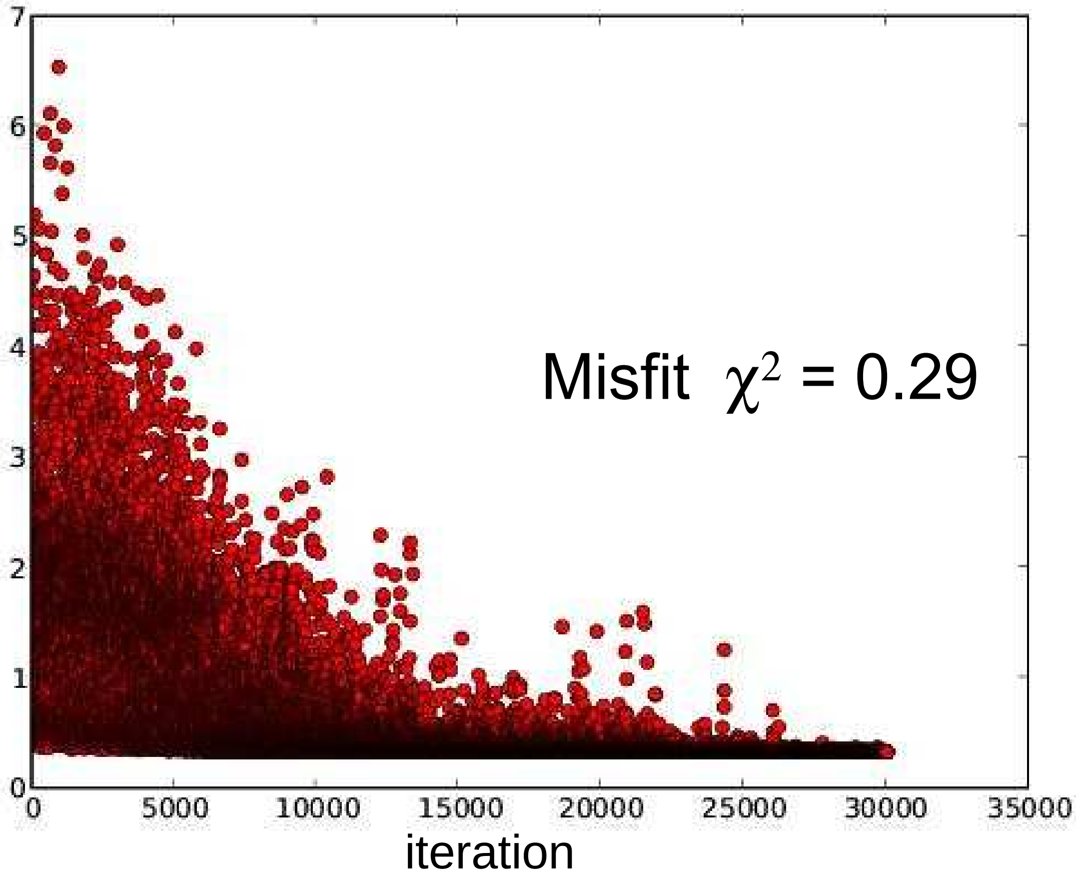


Misfit $\chi^2 = 0.29$

It is as good as many more detailed models.

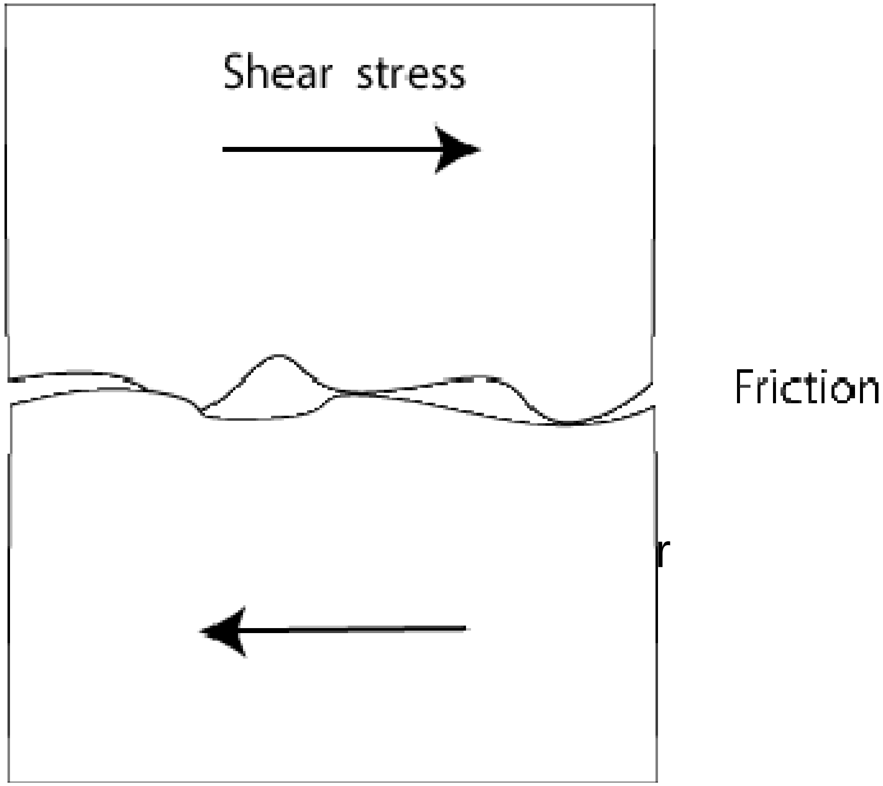
Convergence of the NA algorithm

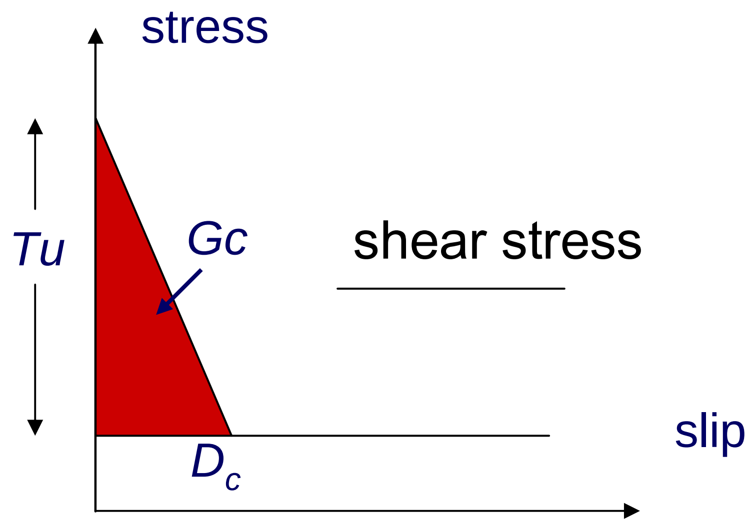
14 parameters



30000 iterations

Dynamic inversion





Problem: radiation does not know about absolute stress value

The most important feature:
The dynamic problem is fundamentally ill-posed

we can either invert a **Barrier** or an ***Asperity*** model

Asperity: variable initial stress, homogenous rupture resistance (Kanamori, Stewart, Ruff, Lay, …)

Barrier: initial stress is homogenous, rupture resistance is variable and stops rupture (Das, Aki)

Seismic waves can not distinguish asperities and barriers

Dynamic modeling

Numerical simulation by staggered grid Finite Differences

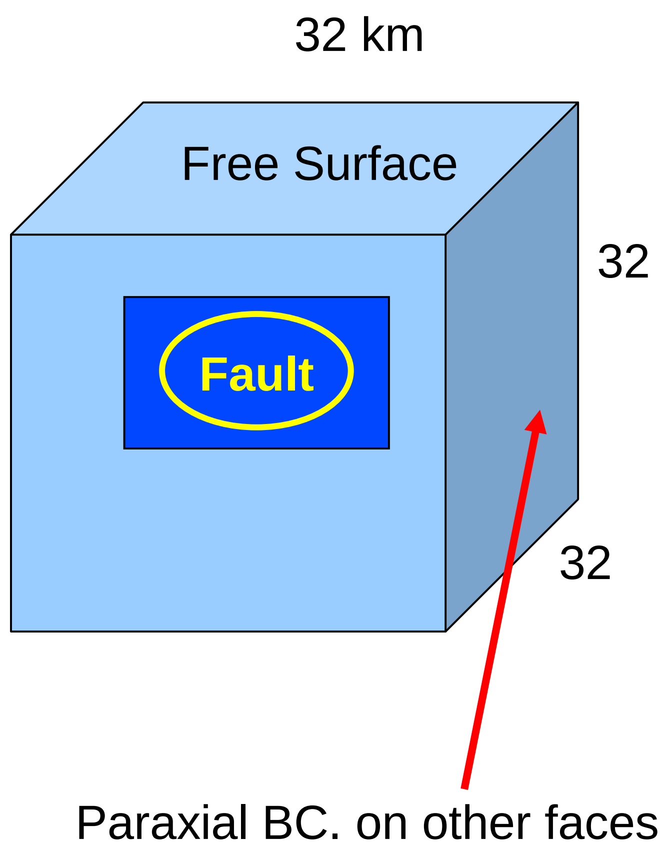
Cube 80×80×80 points,
Δx = 400 m
Δt = 0.02 s

Thin boundary conditions (no split nodes)

Friction law: slip weakening

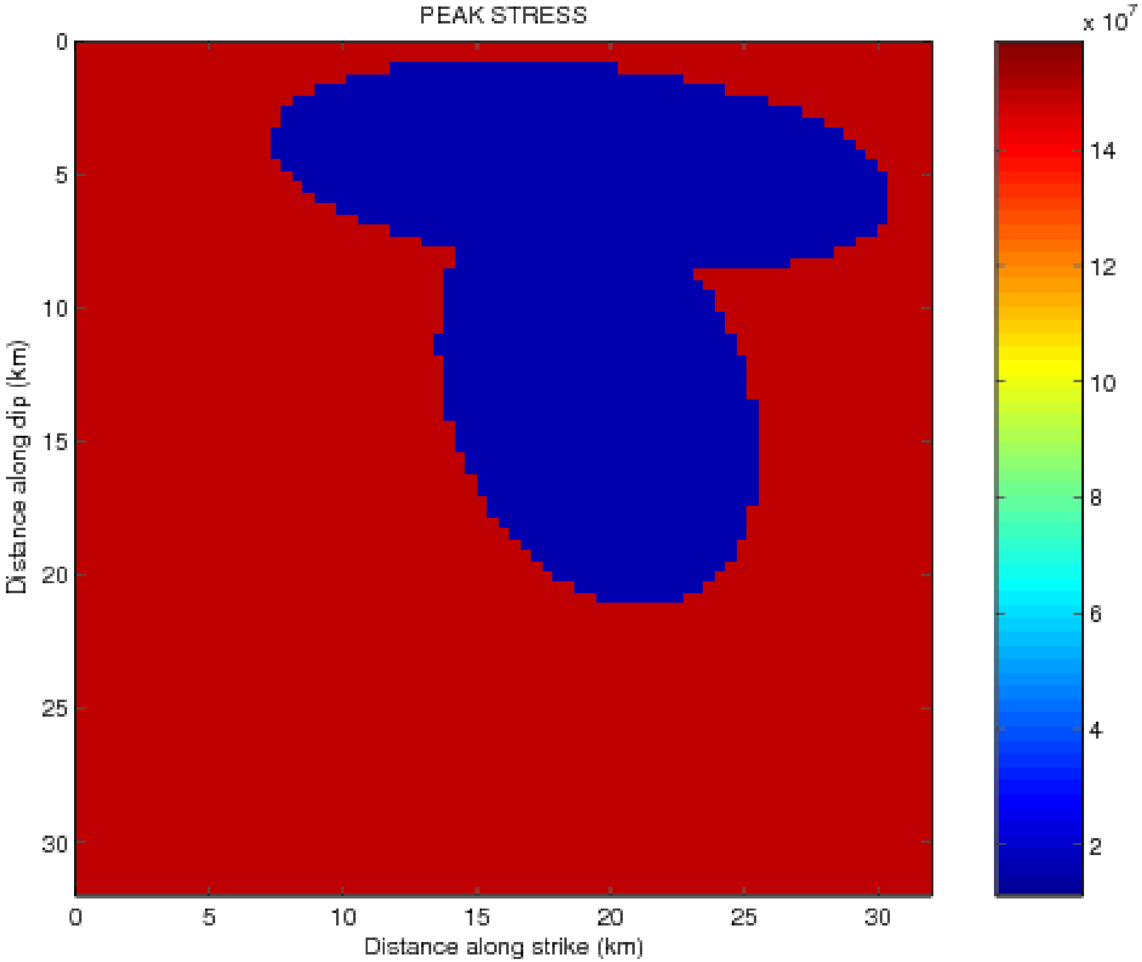
Propagation with Axitra (spectral method)

1 mn per model



Dynamic inversion of Tottori earthquake

Distribution of barrier: blue breakable
red unbreakable



Slip weakening model:

Dc = 0.5 m

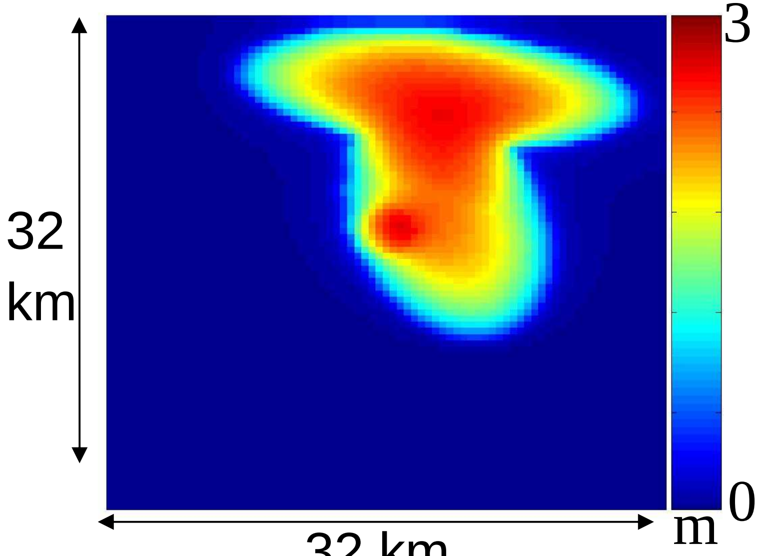
Peak stress

blue=15 MPa
red = 150 MPa

Initial stress model
Te
Fixed = 12 MPa

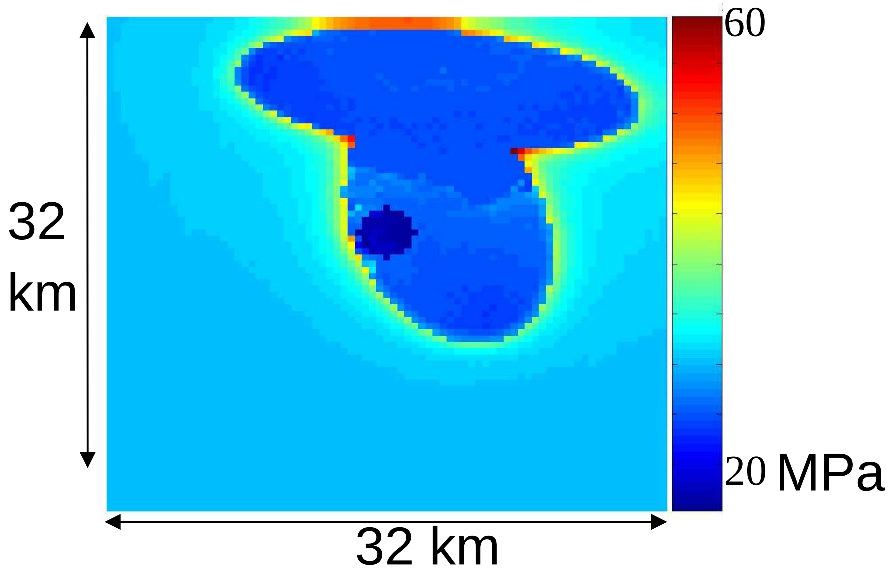
Dynamic inversion of Tottori earthquake

slip distribution



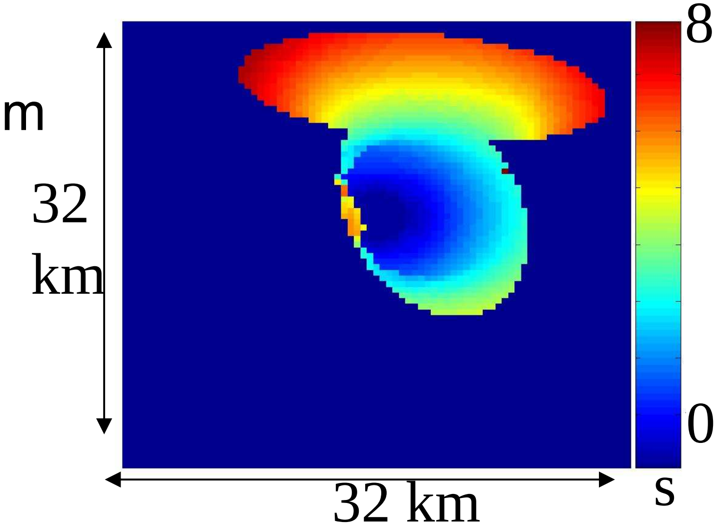
Maximum slip : ~ 2.5 m

Stress drop



stress drop: ~ 10 MPa

Rupture time



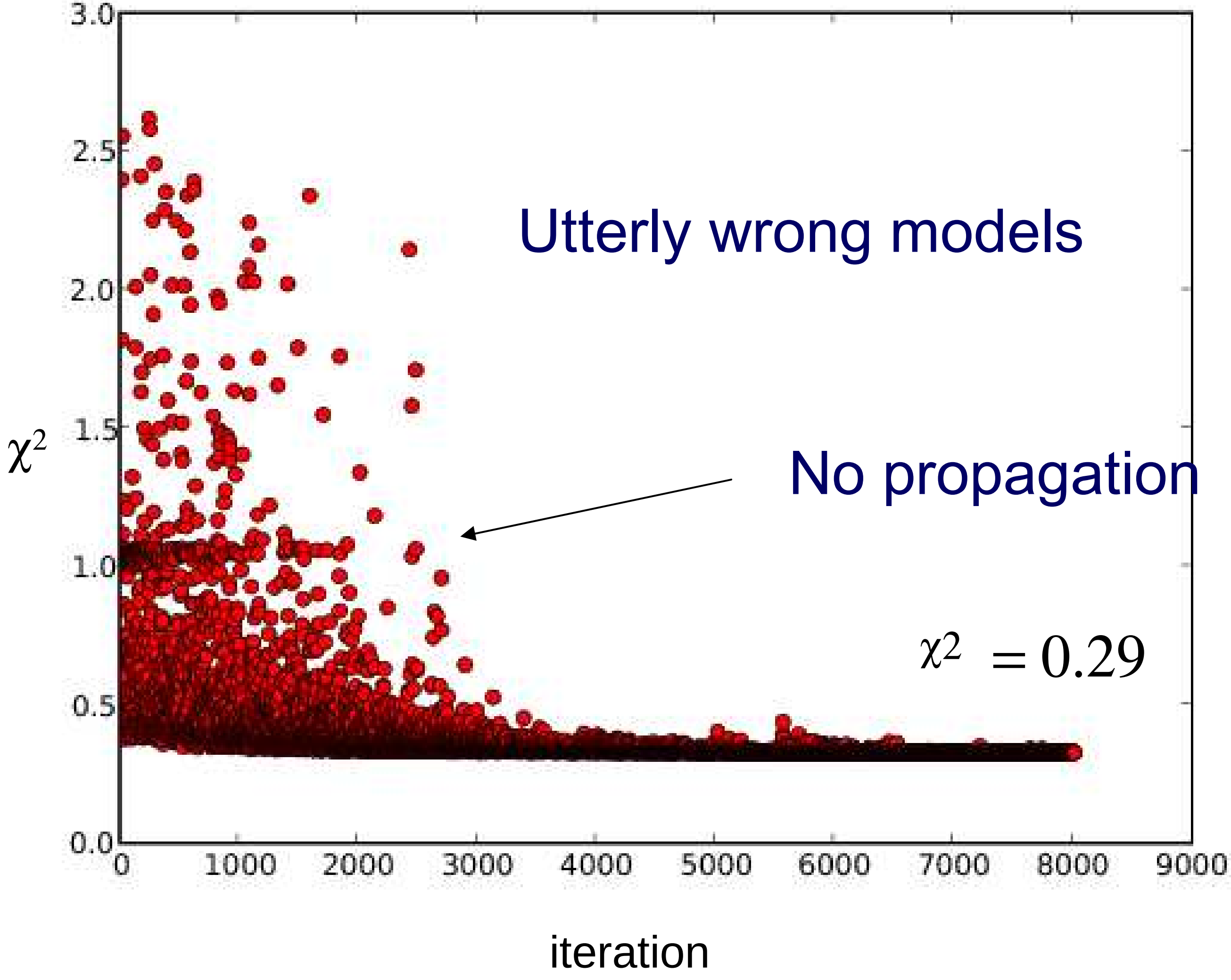
M_o = 1.19 10^{19} Nm

Mw=6.7

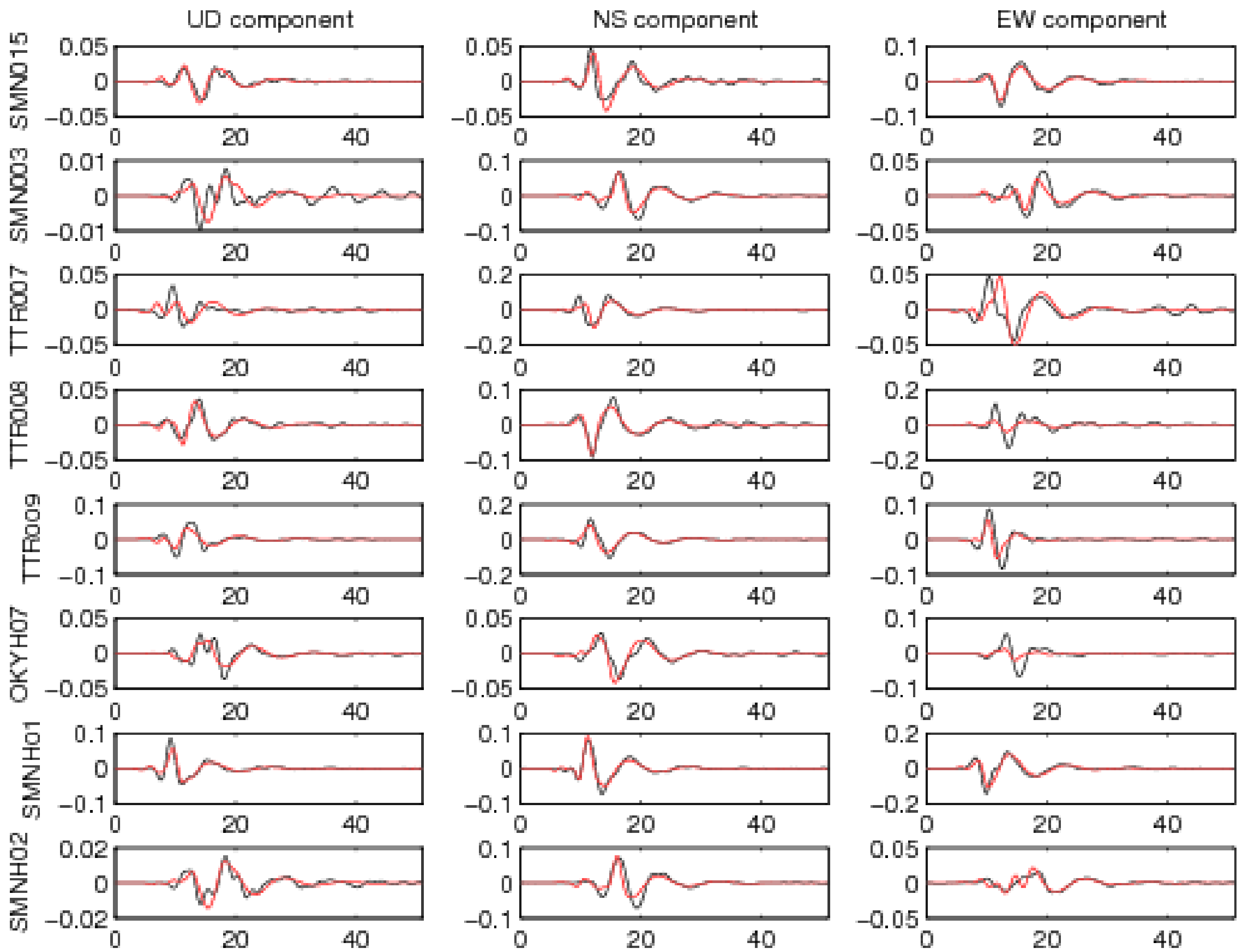
Duration ~ 8 s

Convergence of dynamic inversion algorithm

Only 12 parameters were inverted



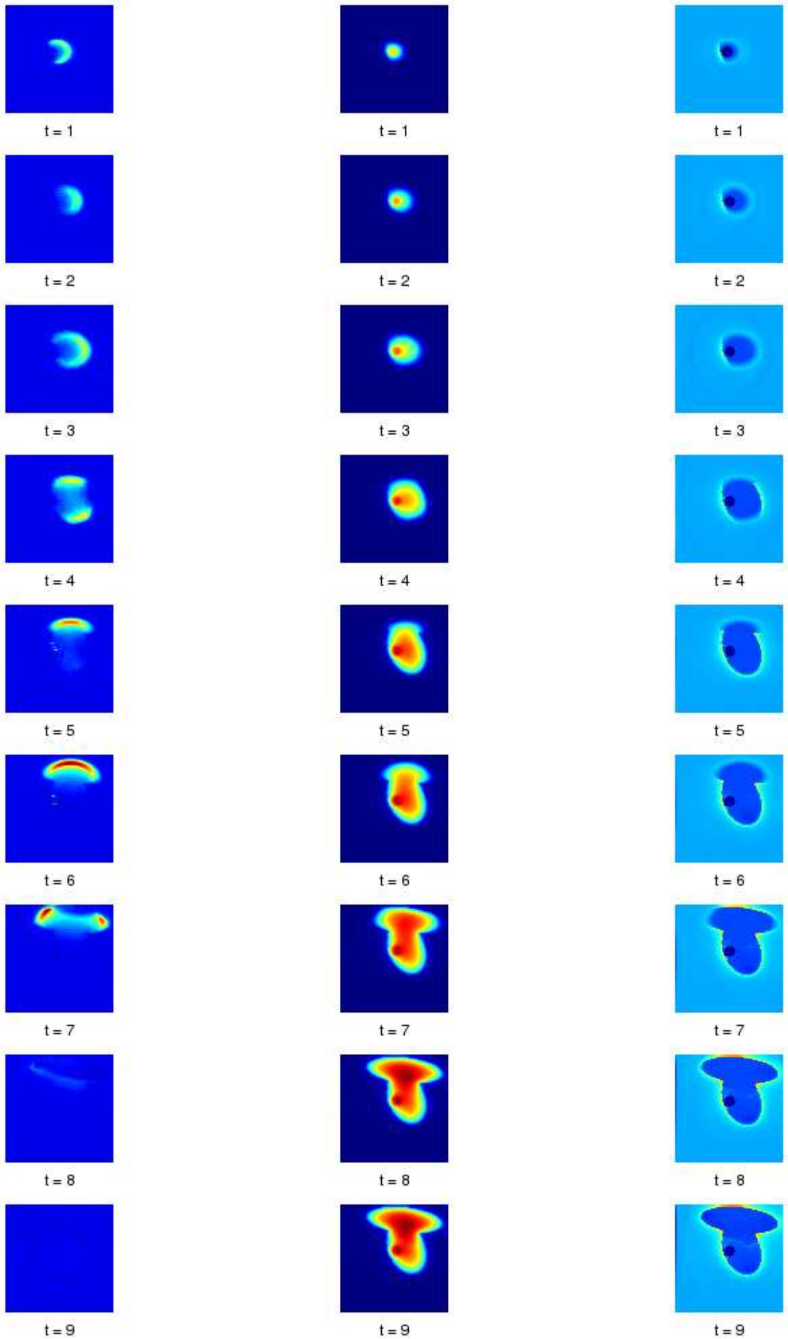
Comparison of observed and dynamically modelled records



Misfit $\chi 2 = 0.29$

Kinematic was 0.29

Rate slip Stress change

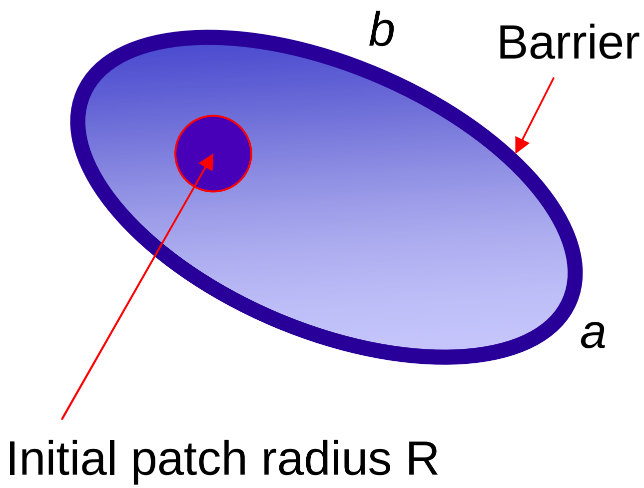


time

Tottori earthquake

Rupture process of best model

Dynamic parameters are not independent



$$\kappa_{asp} = \frac{T_u}{\mu}\frac{R}{D_c} \approx 1$$

From kinematics

Stres drop *fault size*

$$\kappa = \frac{T_e^2}{\mu}\frac{b}{G_c}$$

G_c: choosen so that

rupture ocurs and is subshear
(iff $1<\kappa<1.2$)

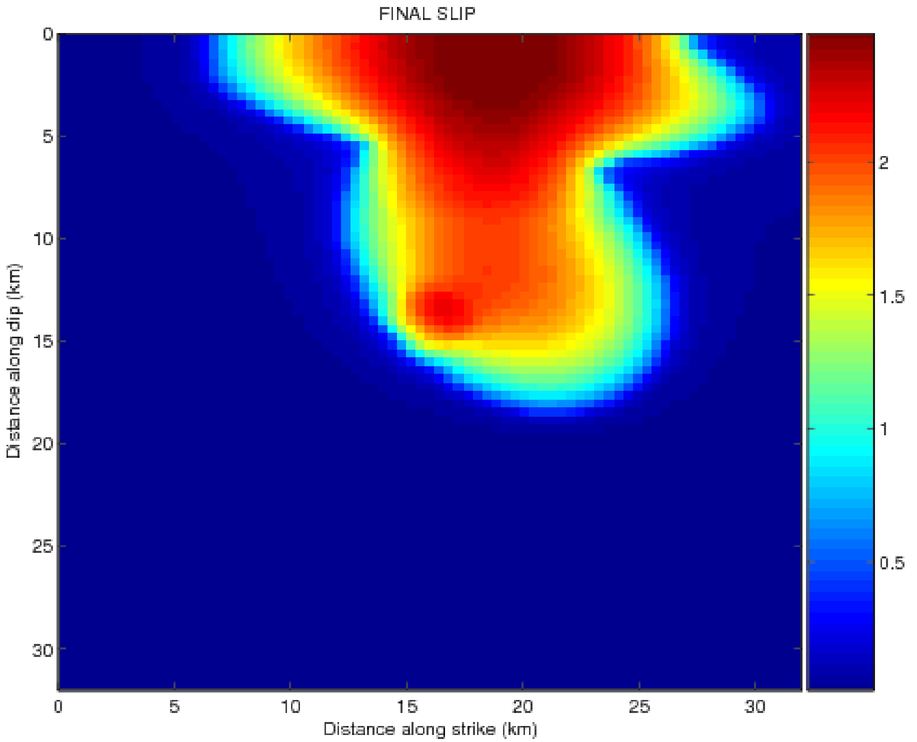
Non-uniqueness due to limited resolution

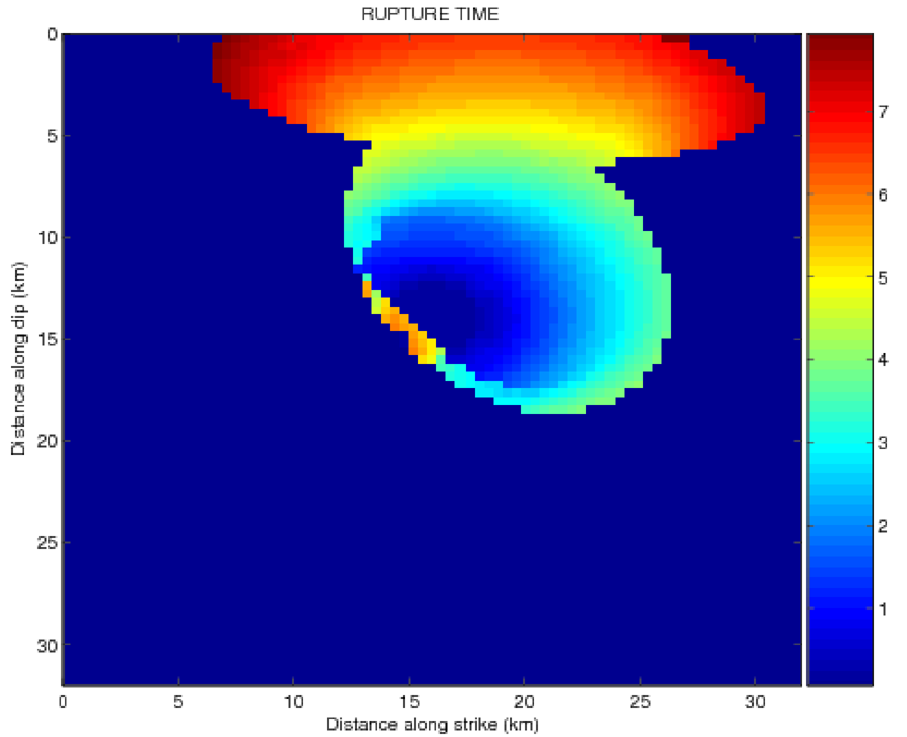
Alternative model of Tottori earthquake

Inverted model that
Rupture the free surface

Misfit

χ^2 = 0.295





Conclusions

Dynamic inversion is possible

Like Brune's model, inversion is dominated by stopping phases

Dynamic parameters (stress and Gc) are connected by k.

Dynamic inversion is non-unique

Dynamic inversion is dominated by geometry

We need more power to study a posteriori PDFs