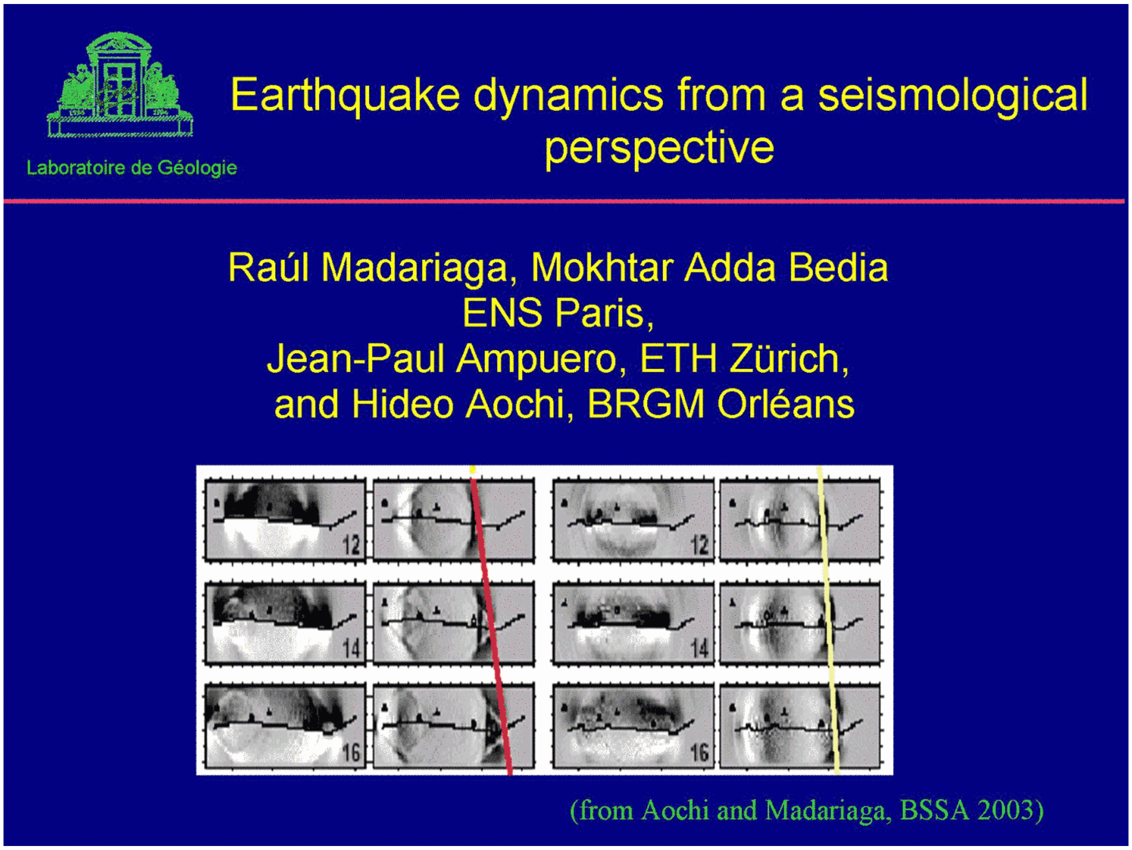
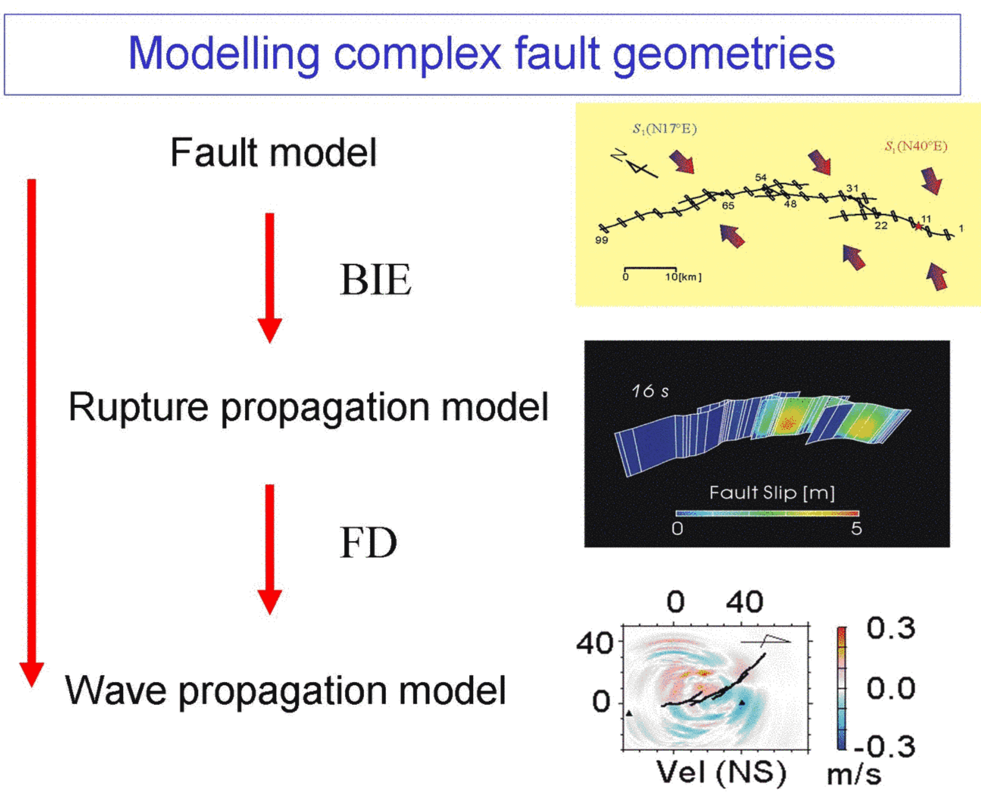
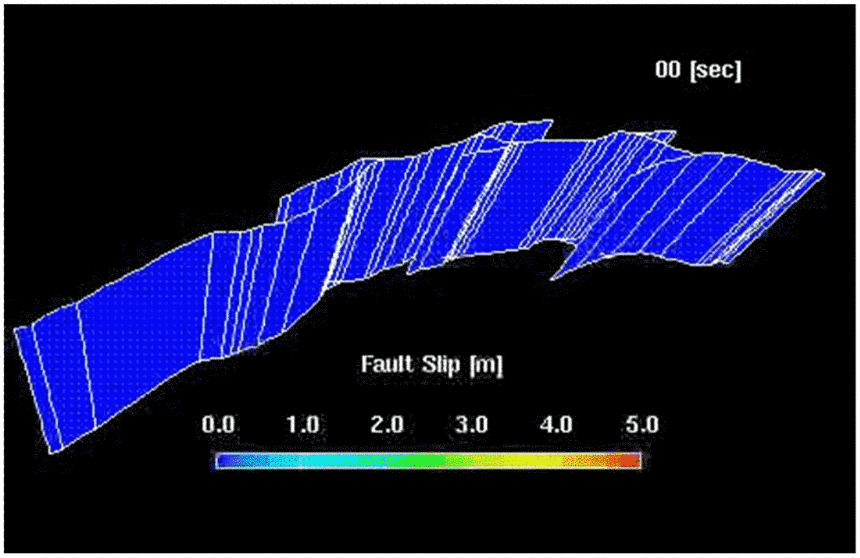

Laboratoire de Géologie
Earthquake dynamics from a seismological perspective
Raúl Madariaga, Mokhtar Adda Bedia
ENS Paris,
Jean-Paul Ampuero, ETH Zürich,
and Hideo Aochi, BRGM Orléans
12
14
16
(from Aochi and Madariaga, BSSA 2003)

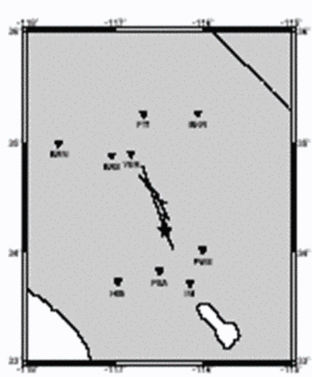

Modelling complex fault geometries
Fault model
BIE
Rupture propagation model
FD
Wave propagation model
S_1(N17°E)
S_1(N40°E)
99
65
54
48
31
22
11
1
0
10[km]
16 s
Fault Slip [m]
0
5
0
40
40
0
0.3
0.0
-0.3
Vel (NS)
m/s

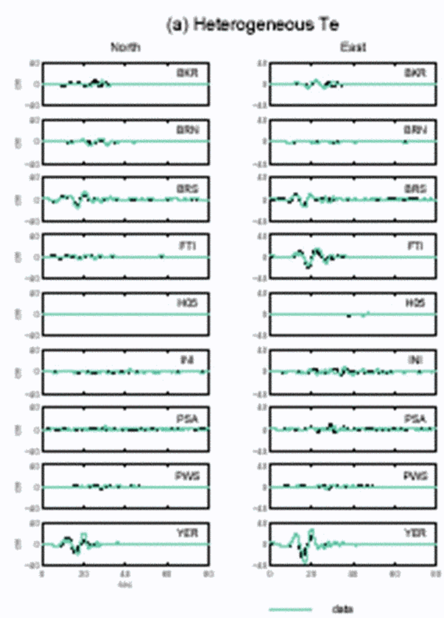
Example of dynamic inversion:
The Landers earthquake of 1992



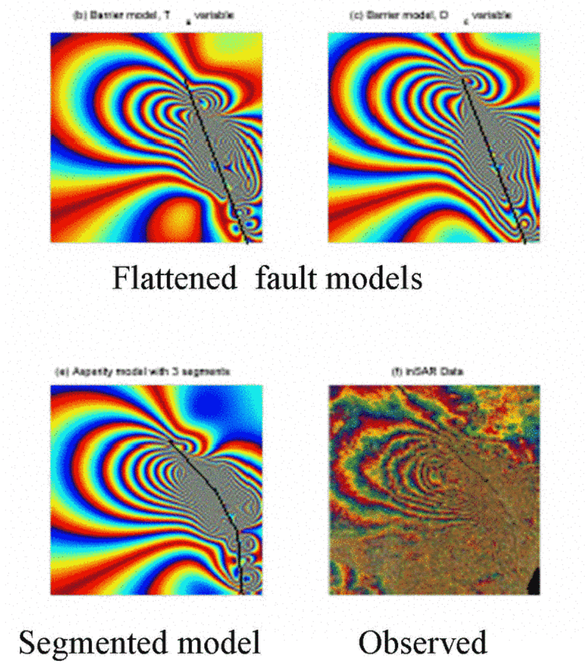
Aochi et al, 2003 following Peyrat et al, 2001

Integrated, filtered accelerograms





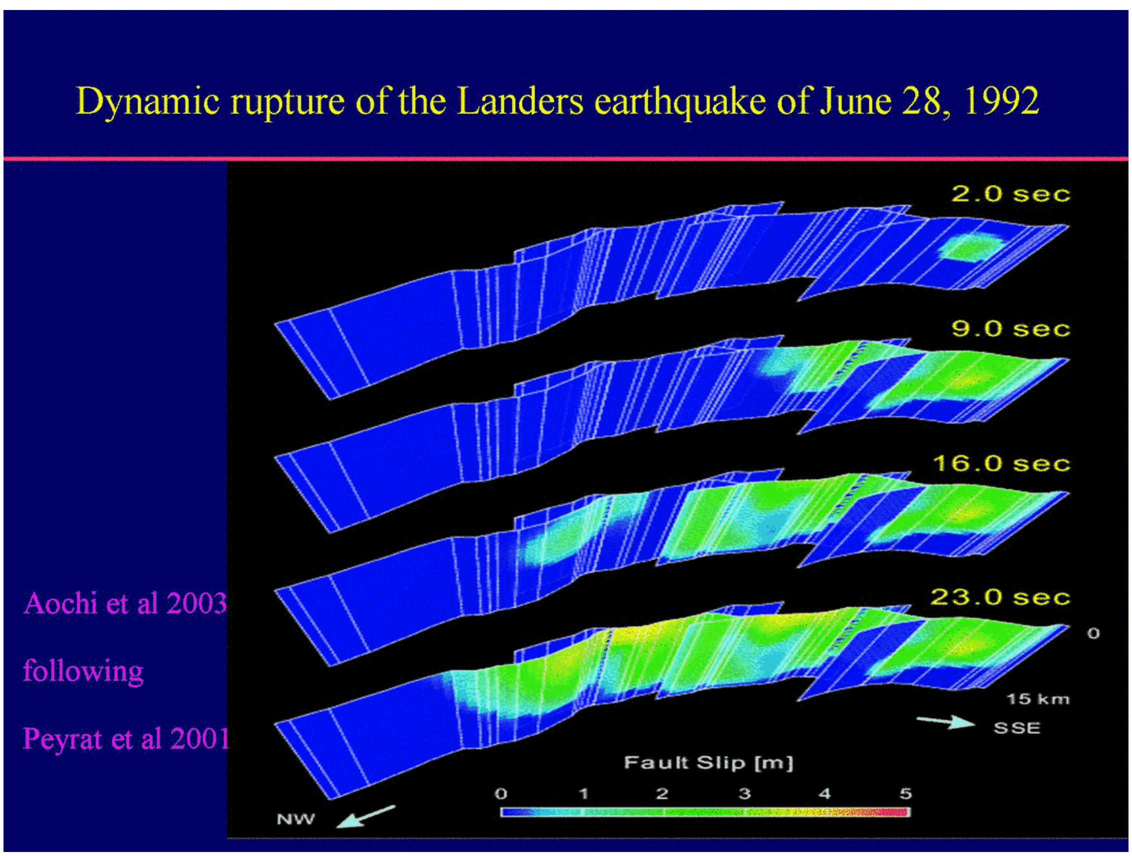
Geodetic Observations : SAR interferometry



Inversions by
Peyrat, Olsen, Madariaga 2001

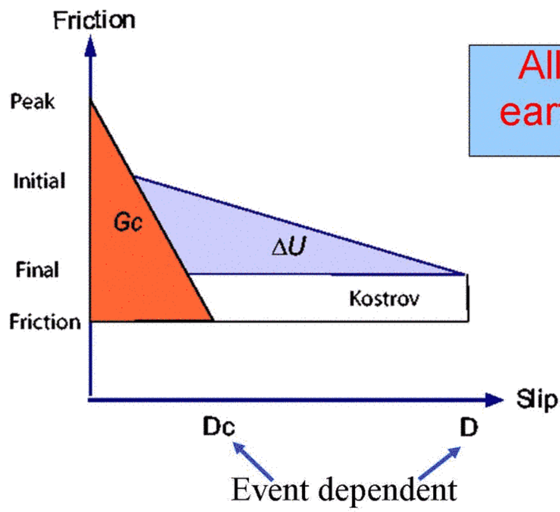
Aochi, Fukuyama, Madariaga, 2003

Peyrat, Madariaga, Olsen, 2003



Slip weakening model with healing

$Es = \Delta U - Gc +/- K$



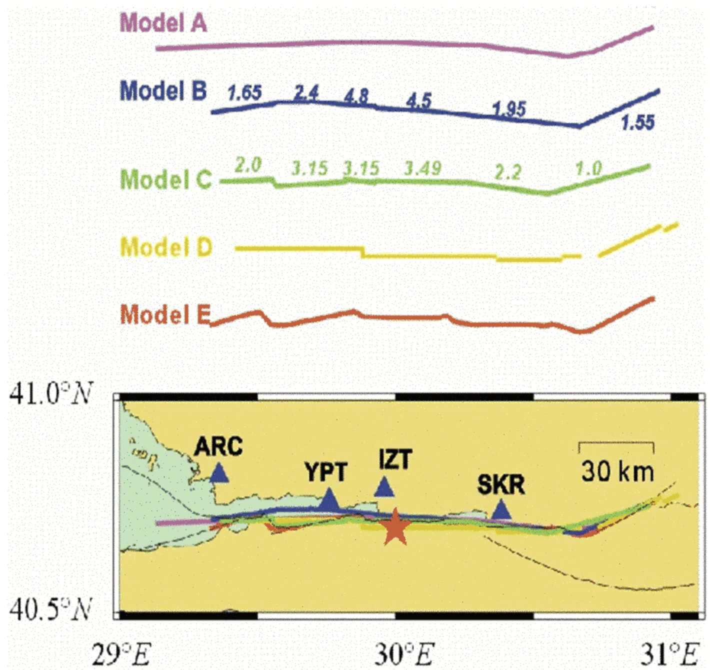
All the lengths scale with earthquake size (Aki, 1967)

This is an average
global model
not necessarily a local model

Some inferred properties of seismic ruptures

1. Slip distributions and ruptures are complex at all scales.
2. Very large variations of stress change.
3. Slip weakening is a substantial fraction of static slip
4. Self-healing rupture (Heaton pulses) is the rule.
5. Local control of rupture
6. How about Energy and High frequencies?

Possible rupture scenarios for the Izmit Earthquake

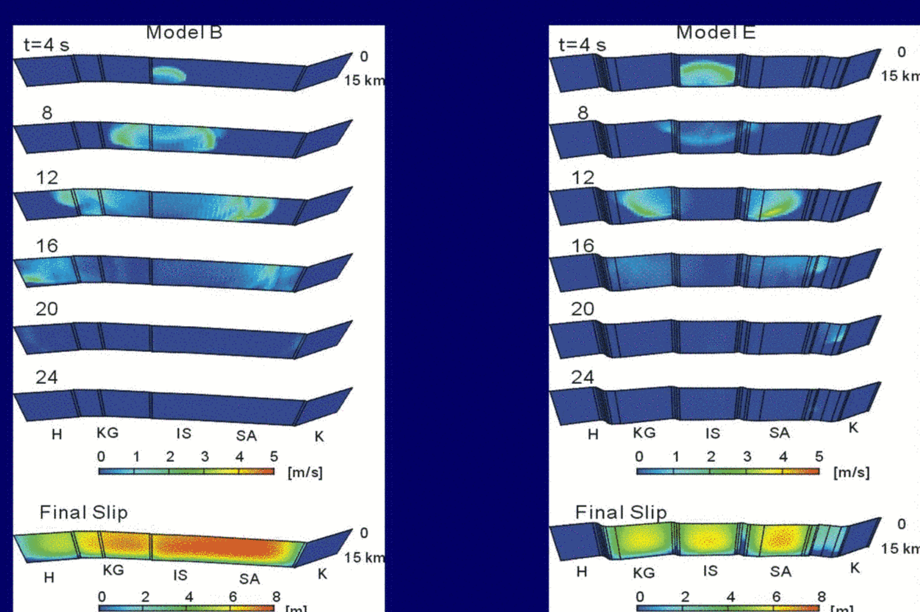


Possible models
A seismic (Bouchon)
B GPS (Wright)
C Spot Images
D FDM Harris
E Aochi Madariaga

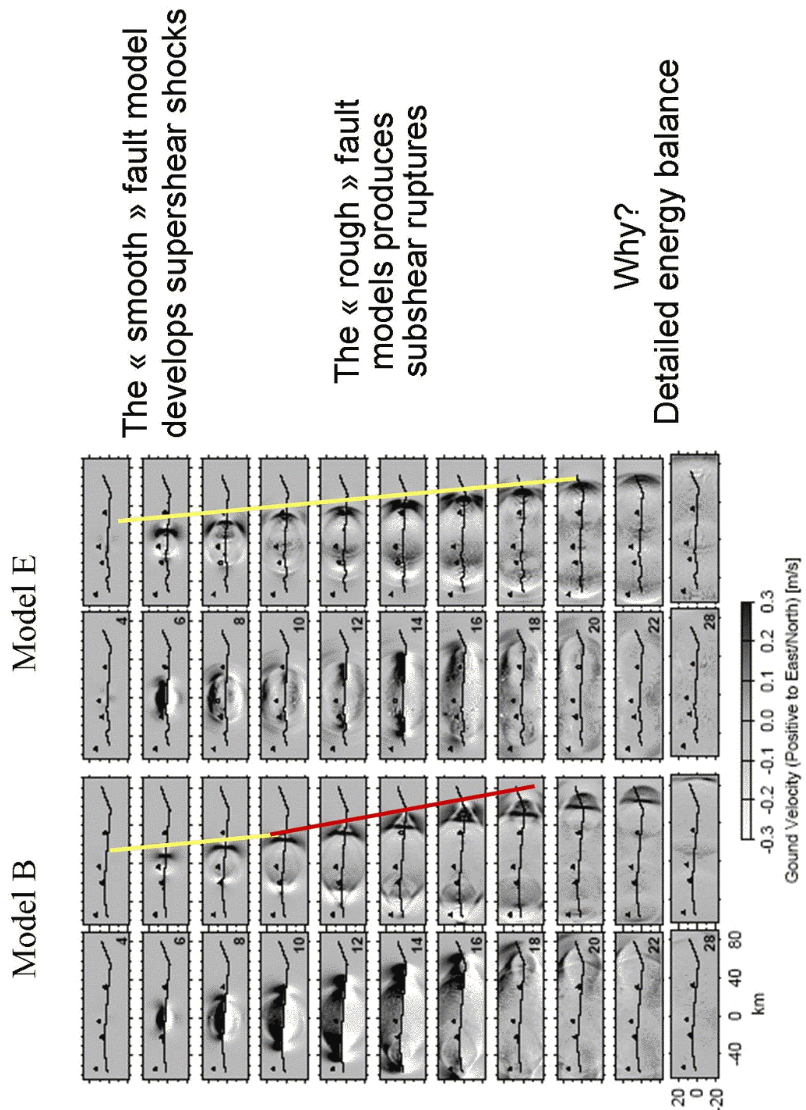
Two reasonable models of the Izmit earthquake

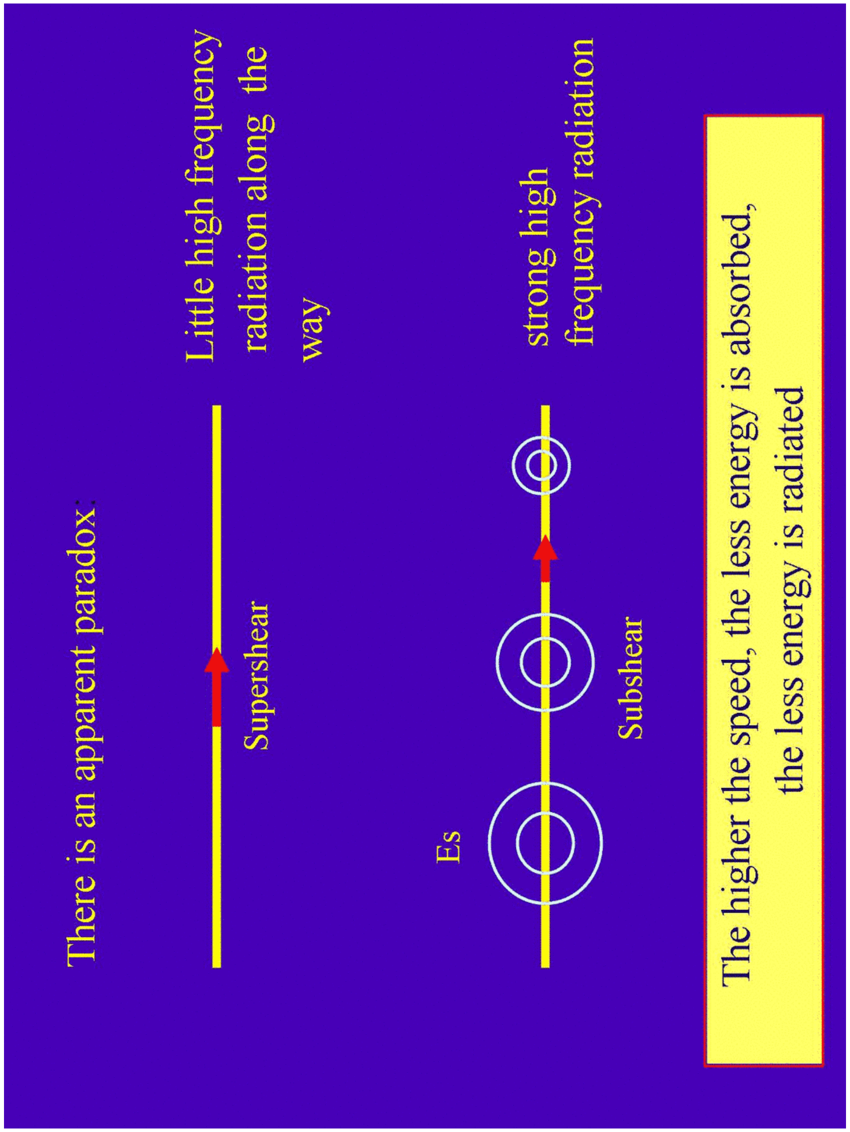
Bouchon like « smooth » model

Harris-like « rough» model



After Aochi and Madariaga (2003)

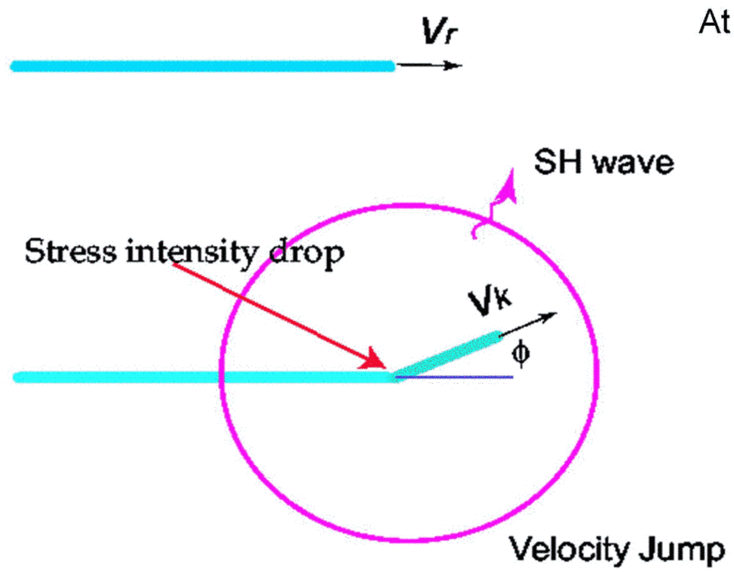

Model B
Model E
The « smooth » fault model develops supershear shocks
The « rough » fault models produces subshear ruptures
Why?
Detailed energy balance
Gound Velocity (Positive to East/North) [m/s]
km


There is an apparent paradox:
Little high frequency radiation along the way
Supershear
Es
Subshear
strong high frequency radiation
The higher the speed, the less energy is absorbed, the less energy is radiated

Seismic radiation from a kink in an antiplane fault

(Adda-Bedia et al, 2003-2005)

At $t = t_c$ the crack kinks



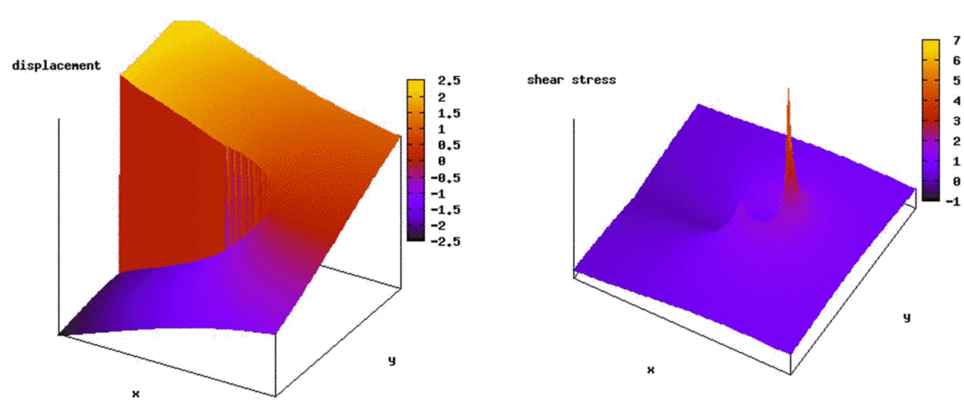
Emits a strong high frequency wave of ω^{-2} type

(Jump in velocity)

Radiation from an antiplane crack moving along a kink

Displacement

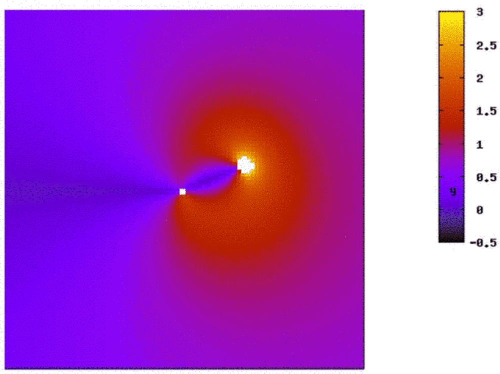
Shear stress



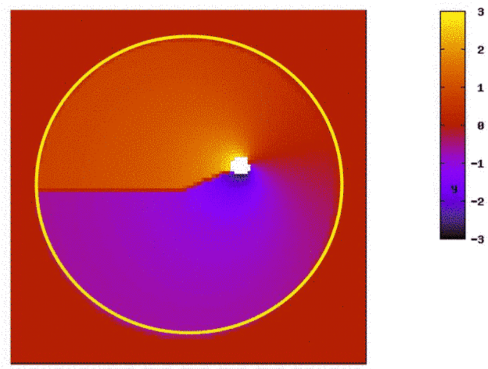
Analytical solution from Adda-Bedia et al (2003-2005)

Radiation from an antiplane crack moving along a kink

Shear stress (zϕ)



Particle velocity (z)



From Adda Bedia & Madariaga, in preparation

Energy balance

(Kostrov, Husseini, Freund, etc)

If rupture propagates very slowly there is no seismic radiation

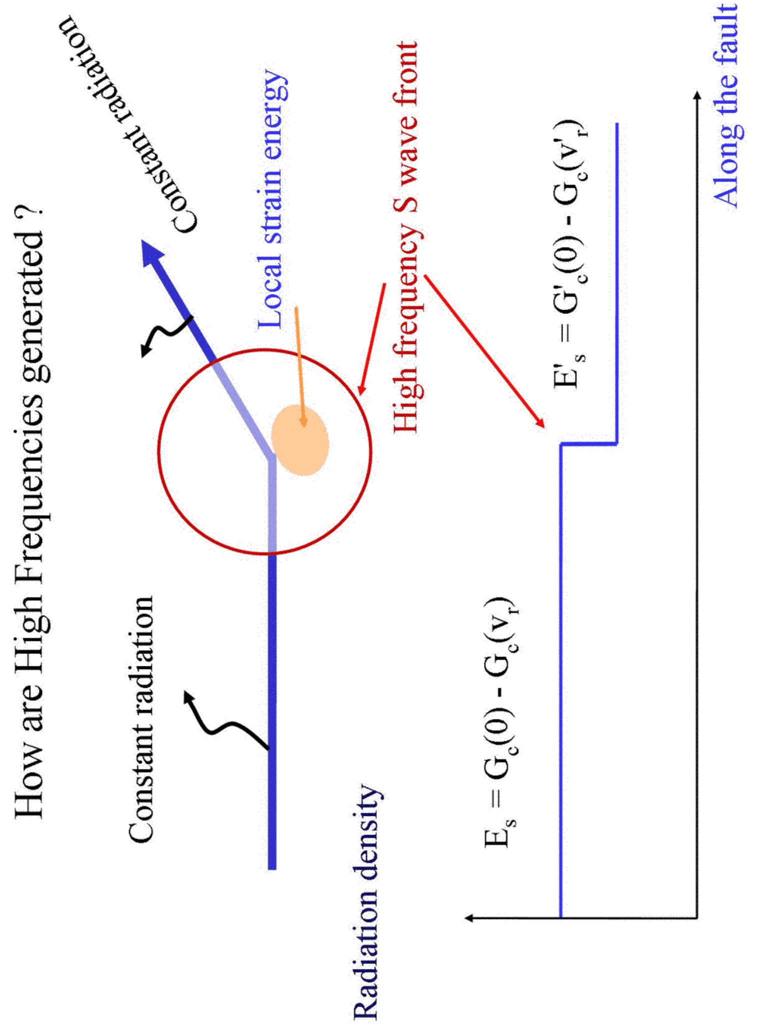
$$\Delta U = \underbrace{\frac{1}{2}\int_\Sigma -\Delta T \cdot \Delta u \, dS}_{\text{Strain Energy}} = \underbrace{\int_\Sigma G_c(0)\, dS}_{\text{Quasistatic Fracture energy}}$$

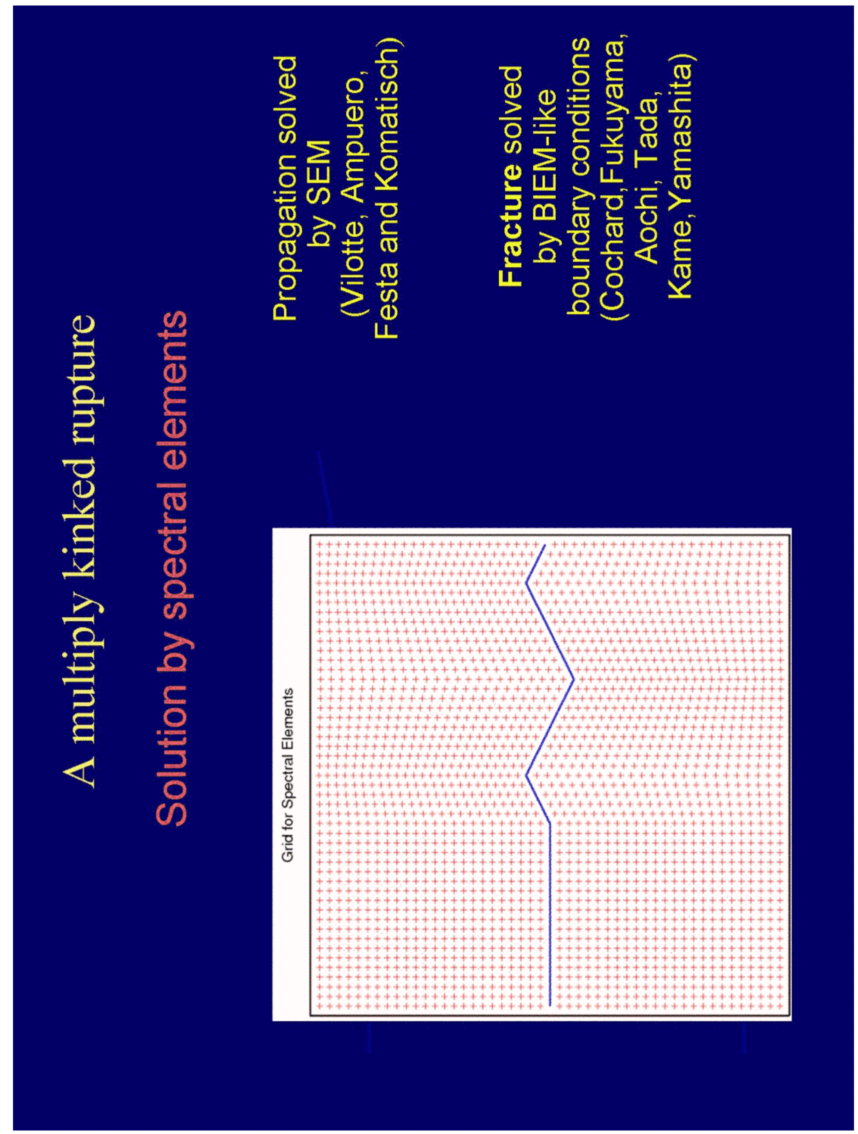
If rupture does not absorb available strain energy,
it accelerates and radiates.

$$E_s = \underbrace{\int_\Sigma G_c(0)\, dS}_{\text{Quasistatic Fracture energy}} - \underbrace{\int_\Sigma G_c(v_r)\, dS}_{\text{Fracture energy at speed } v_r}$$

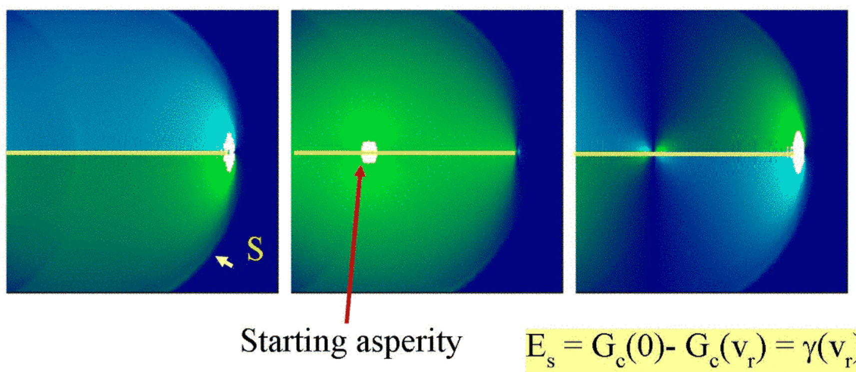
quasistatic dynamic

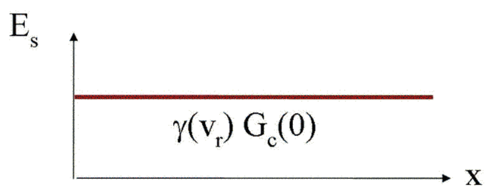
(Neglecting Kostrov's term)


How are High Frequencies generated ?
Constant radiation
Constant radiation
Local strain energy
High frequency S wave front
Radiation density
$E_s = G_c(0) - G_c(v_r)$
$E'_s = G'_c(0) - G_c(v'_r)$
Along the fault


A multiply kinked rupture
Solution by spectral elements
Propagation solved by SEM (Vilotte, Ampuero, Festa and Komatisch)
Fracture solved by BIEM-like boundary conditions (Cochard, Fukuyama, Aochi, Tada, Kame, Yamashita)
Grid for Spectral Elements

A simple antiplane crack running at almost shear wave speed

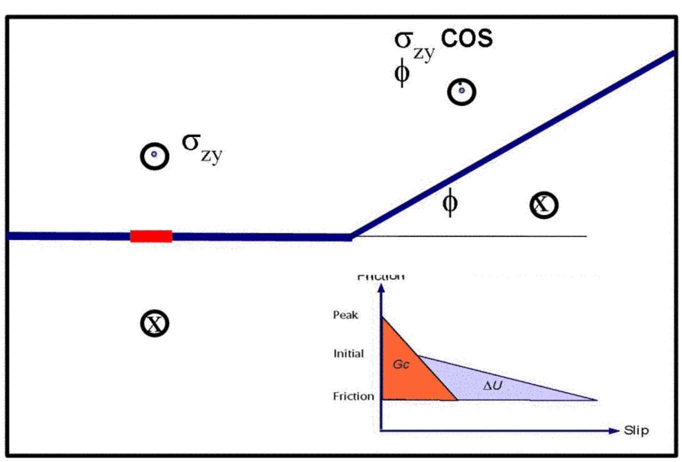




$$E_s = G_c(0) - G_c(v_r) = \gamma(v_r)\, G_c(0)$$

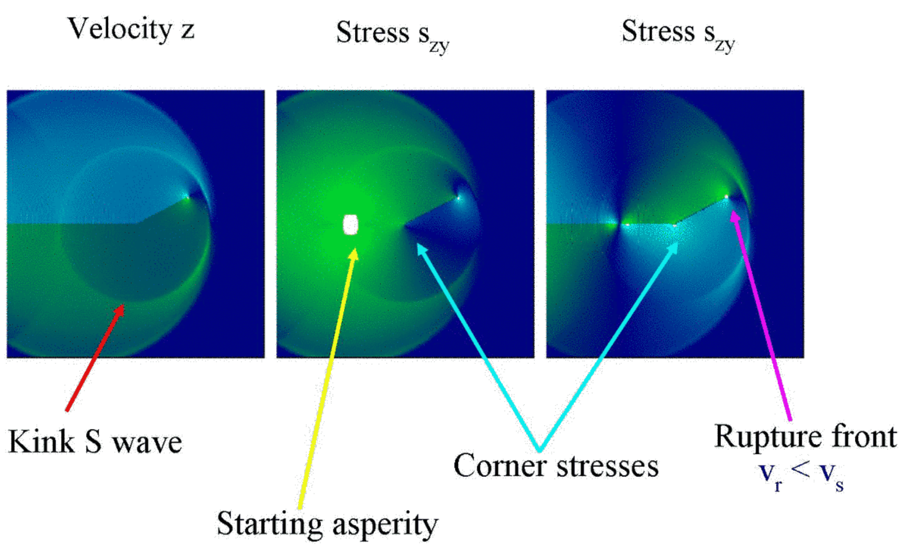
$\gamma(v_r) = 0$ $v_r \sim 0$ (no radiation)
$\gamma(v_r) = 1$ $v_r \sim v_s$ (no friction)

Model of a kink in mode III

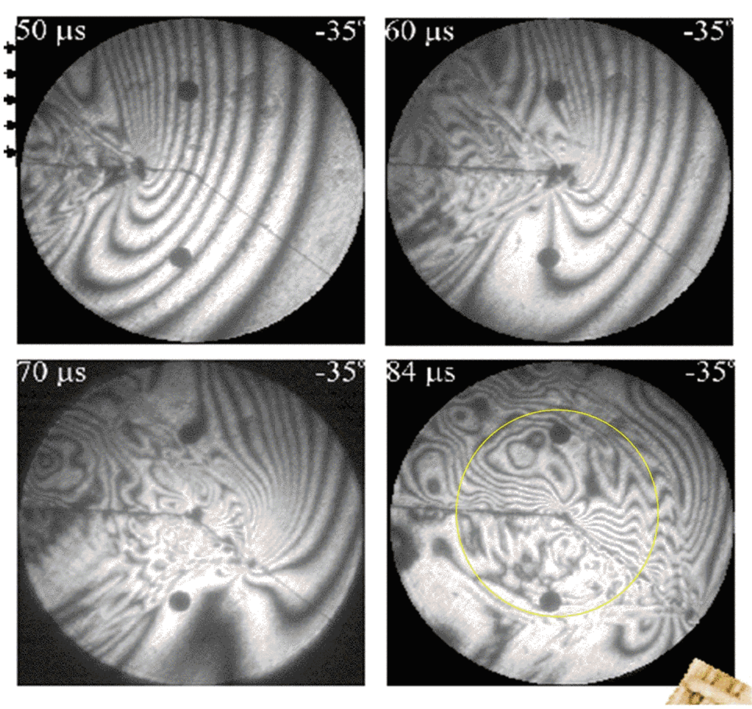


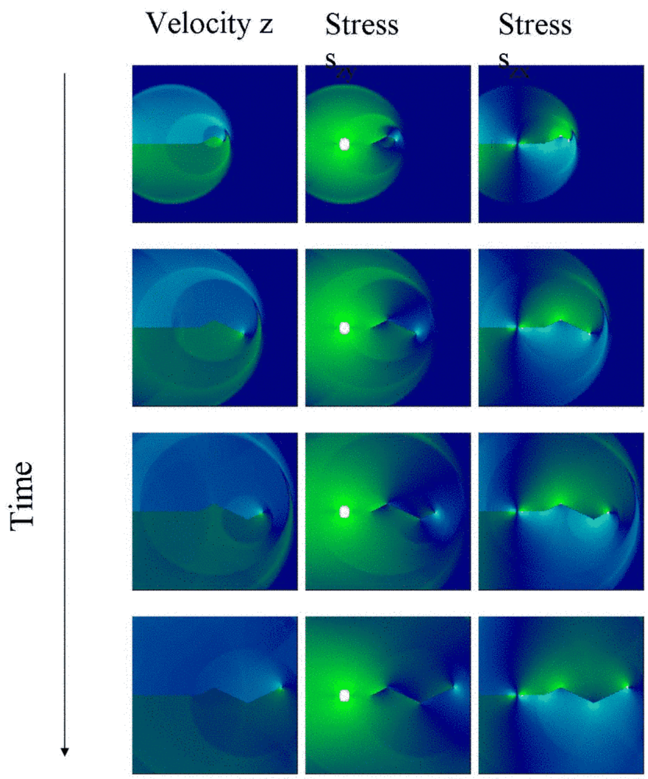
- Uniform slip weakening friction
- Homogeneous elastic medium (SCEC test case)
- Spontaneous rupture propagation

Radiation from an antiplane crack with a kink



Kink waves in the experiments by Rousseau and Rosakis

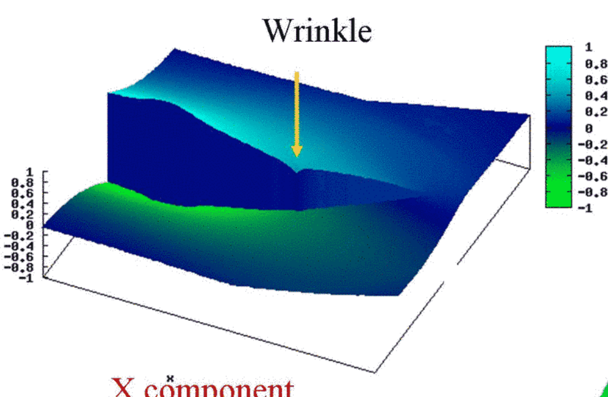


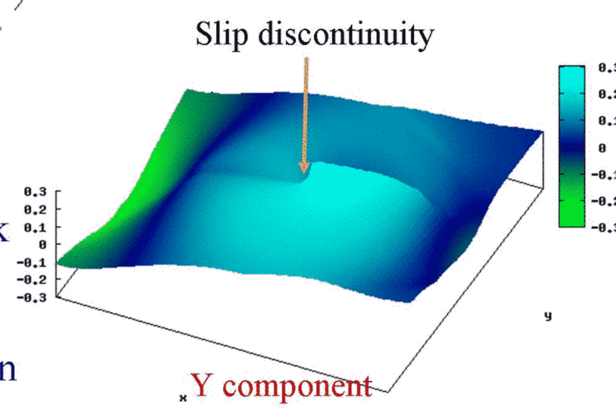


A complex antiplane (Mode III) crack

- Multiple kink phases
- Diffraction
- Residual stresses
- Low rupture speeds

Displacement field for a rupture moving along a kink



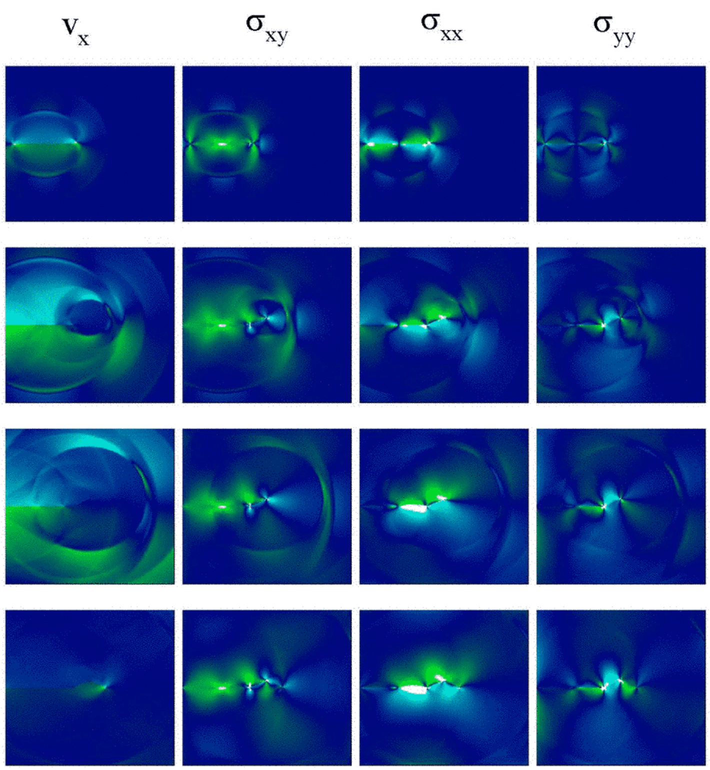


Slip is frustrated by the kink

Residual stress concentration

(Williams, 1952)

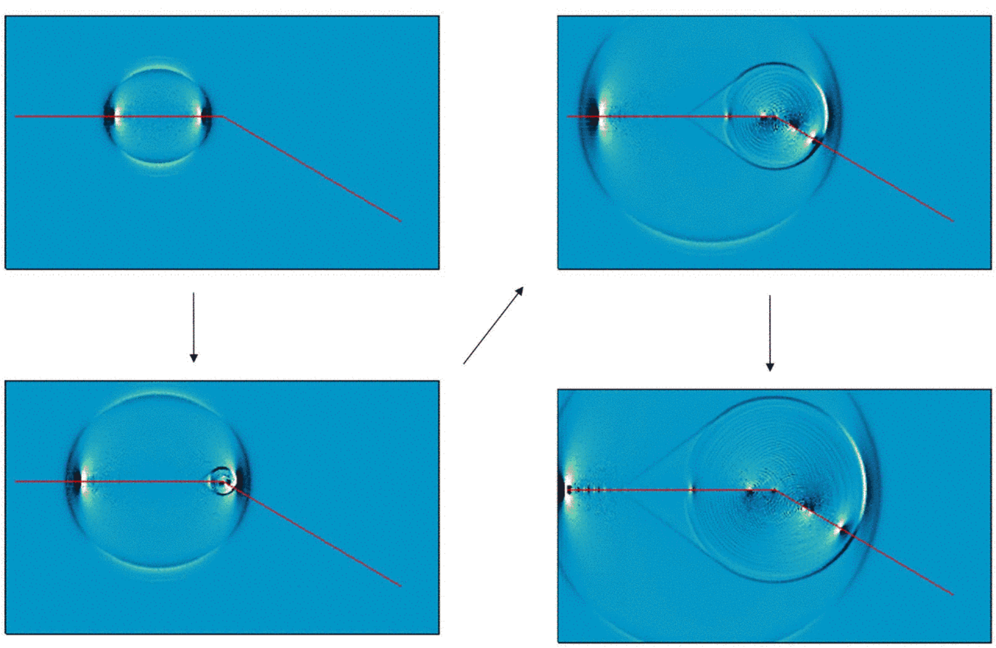
(King, Yamashita, Kame, Polyakov, etc)



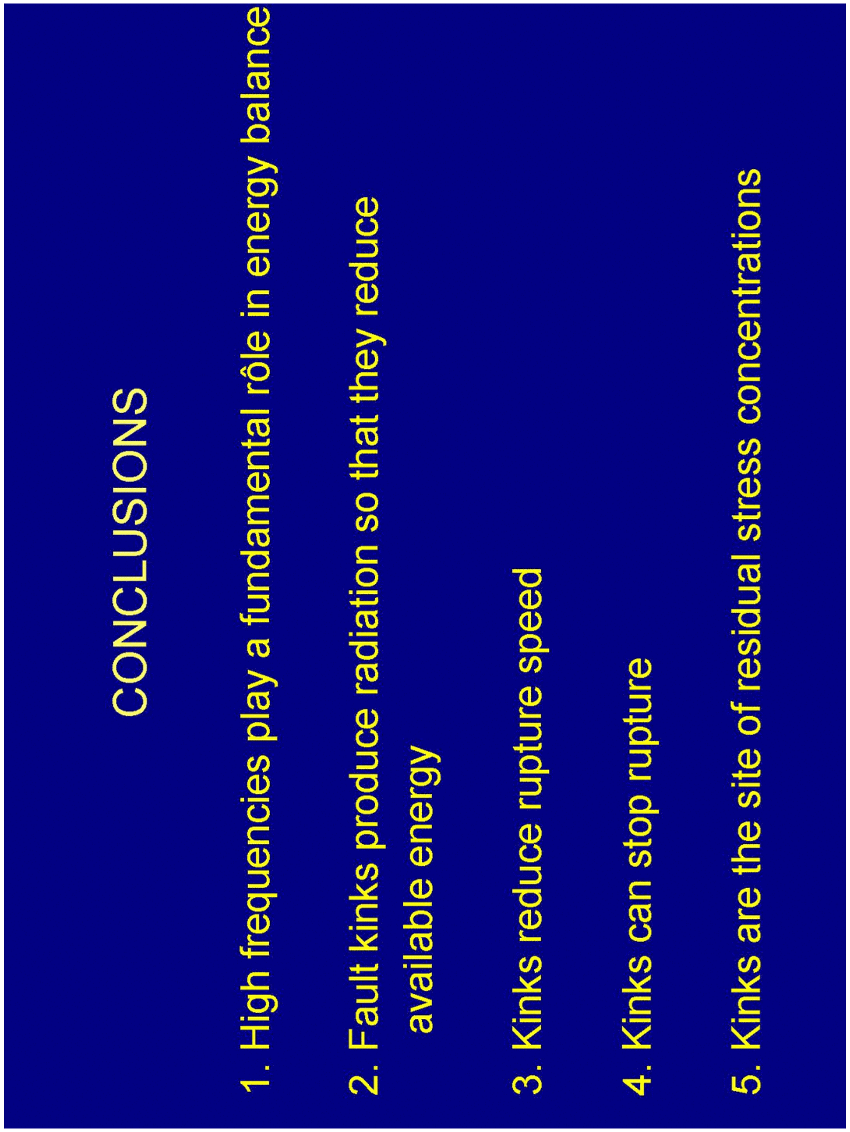
A complex shear (Mode II) fault

- Multiple kink phases
- Diffraction
- Residual stresses
- Stop and restart
- Low rupture speed

Vorticity of the particle velocity field



Computed by Festa and Vilotte April 2005


CONCLUSIONS
1. High frequencies play a fundamental rôle in energy balance
2. Fault kinks produce radiation so that they reduce available energy
3. Kinks reduce rupture speed
4. Kinks can stop rupture
5. Kinks are the site of residual stress concentrations