How can we connect the scales of laboratories and earthquakes?

Introduction of multi-hierarchy into earthquake rupture model.

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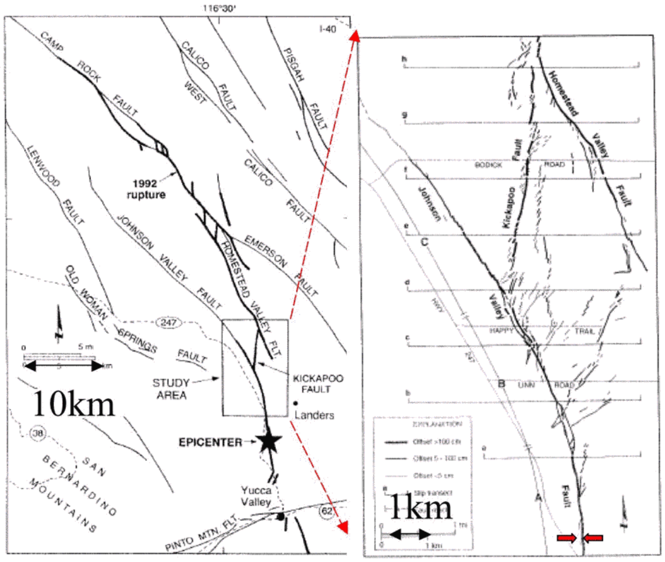
Purposes

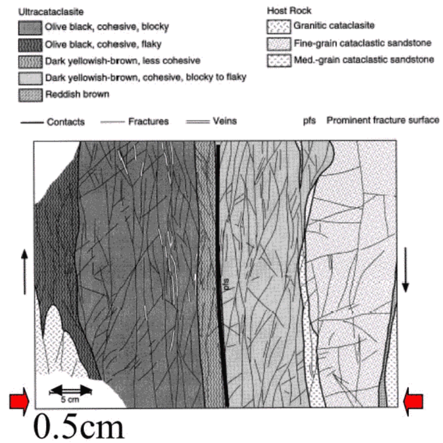
- Deriving fault constitutive law applicable to earthquakes from numerical models and laboratory-derived constitutive laws
- Understanding geometrical complexity of natural fault zones including formation processes and mechanical effects
- Proposing a conceptual framework into earthquake models regarding geometry and scales: Multi-hierarchy model consisting of micro, meso and macro-scales
- Examining the effectiveness and limitations of the constitutive modeling

Geologically observed hierarchy structures of natural fault geometry



Landers fault system, California

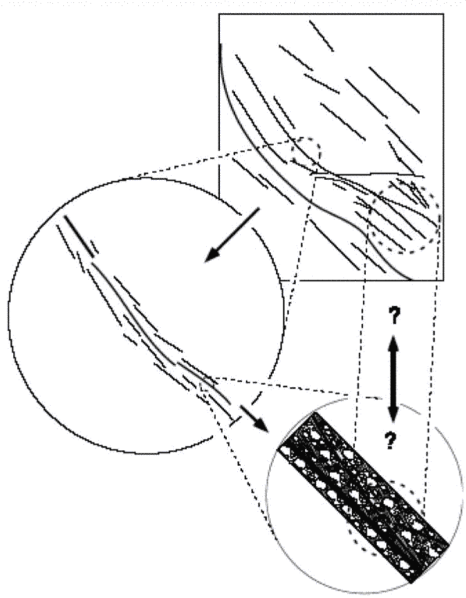
Sowers et al, 1994



Punchbowl fault, California

Chester & Chester, 1998

Hierarchy structures of fault geometry

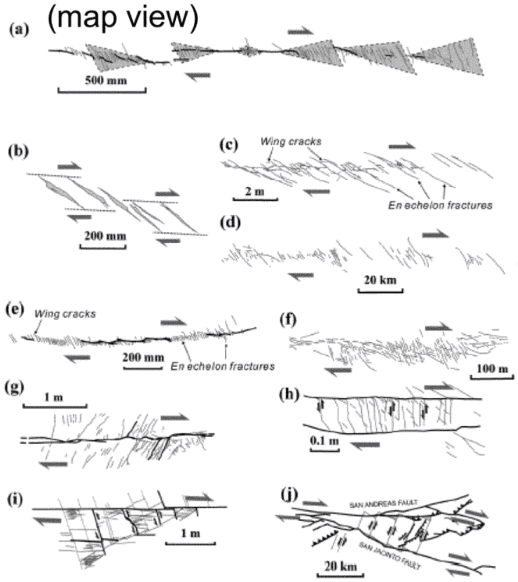


Ben-zion and Sammis [2003]

Geometrical characteristics of fault zones

Branches, steps, bends

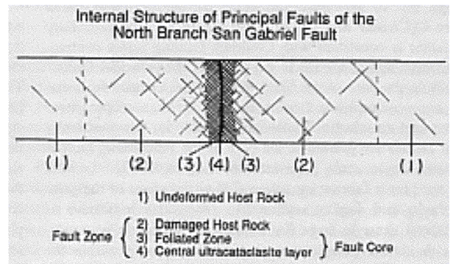
(map view)



Kim et al., 2004

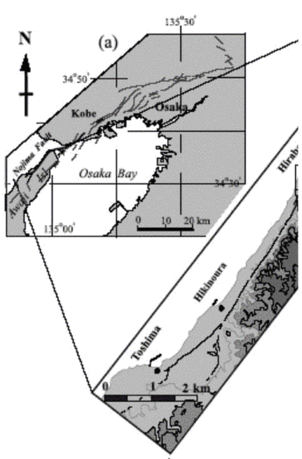
Off main-fault damage zone

(cross sectional view)

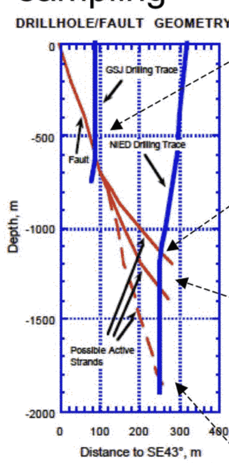


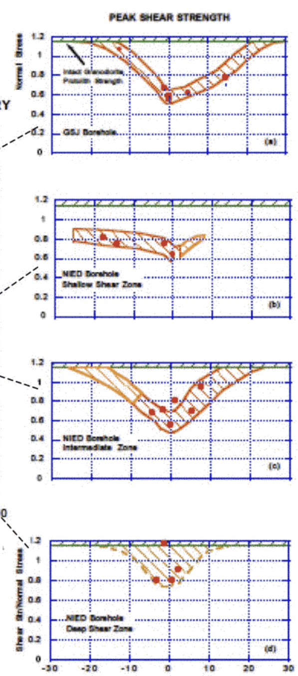
Chester et al, 1998

Characteristics of strength distribution inside fault zone



Position of sampling





Peak Shear strength/Normal stress

30m

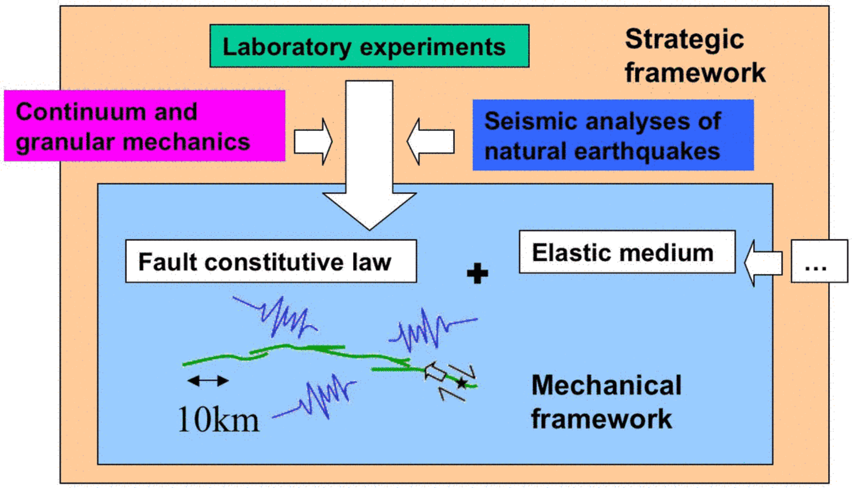
Horizontal distance from fault

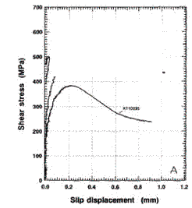
Nojima fault, Japan

Lockner et al., 2000

Low strength zone is widely distributed

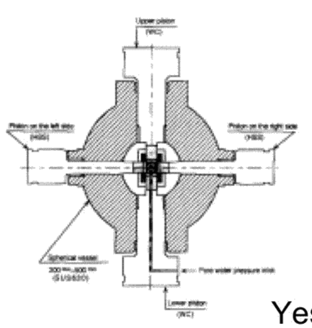
Fault zone was considered by currently most popular framework for seismologists?





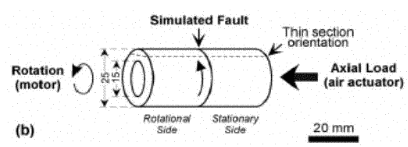
Shear sliding experiments

Tri-axial apparatus

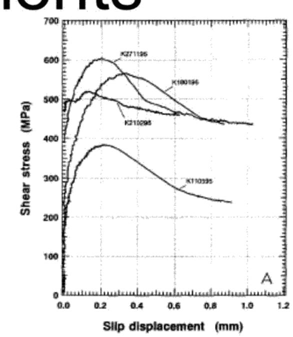


Ohnaka et al., 1997

Rotational apparatus



Hirose & Shimamoto, 2005



Yes? Some sandwich gouges (grains) between host rocks. [e.g. Marone and Kilgore, 1993]

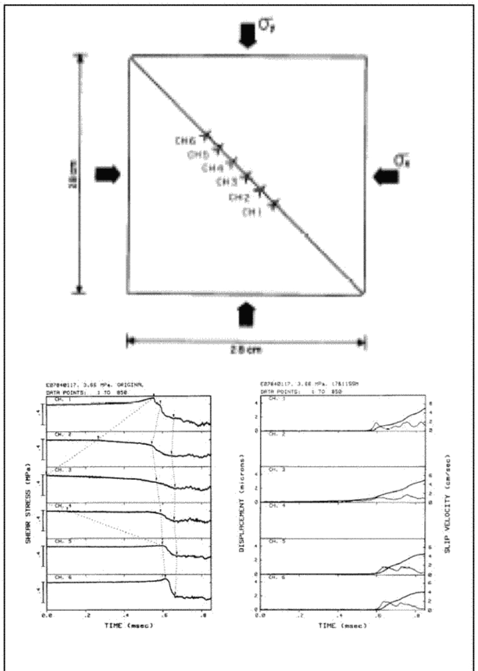
Problems:

•Sample scale <1m

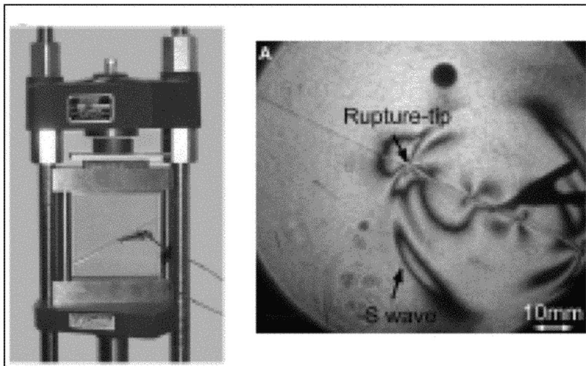
•Fault zone are not only gouge but also cohesive materials

•Axial monitoring: Impossible to monitor changes associated with rupture propagation

Shear rupture under spontaneous loading experiments



Ohnaka et al, 1990

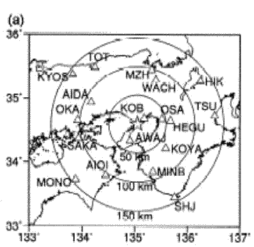


Xie, Rosakis and Kanamori, 2004

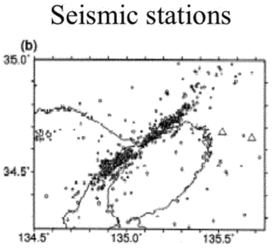
Problem

-Fault is a nominally flat precut surface
→Fault zones are hardly simulated.

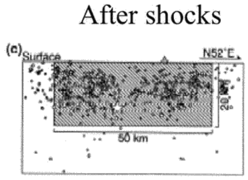
Seismic inversion



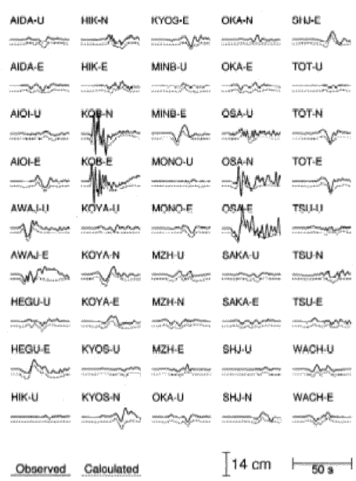
Seismic stations

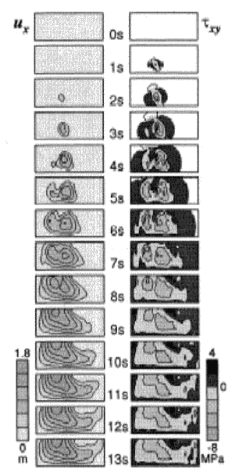


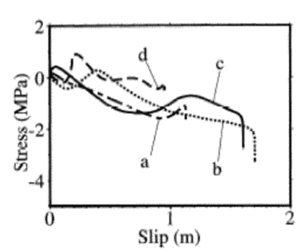
After shocks



Assumed fault geometry







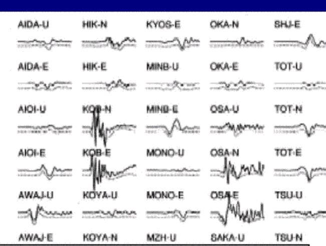
Problem: Spatial resolution >1km

Problems

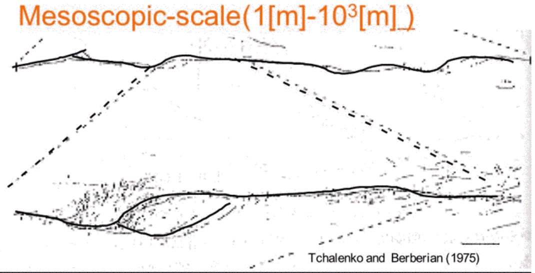
- Difference of scales (absence of information on rupture dynamics): 1m-10^3m
- Effects associated with rupture propagation in fault zone are hard to measure
- Laboratory-simulated fault zones only reproduce fault zone characteristics as a gouge layer

Introduction of mesoscopic scale: Multi-hierarchy model

Macro-scale(>>10^3[m])



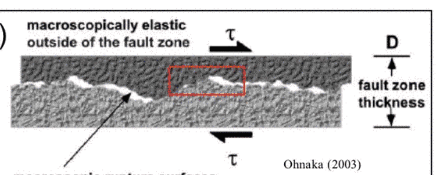
Mesoscopic-scale(1[m]-10^3[m])

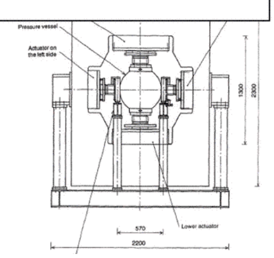


Mesoscopic scale

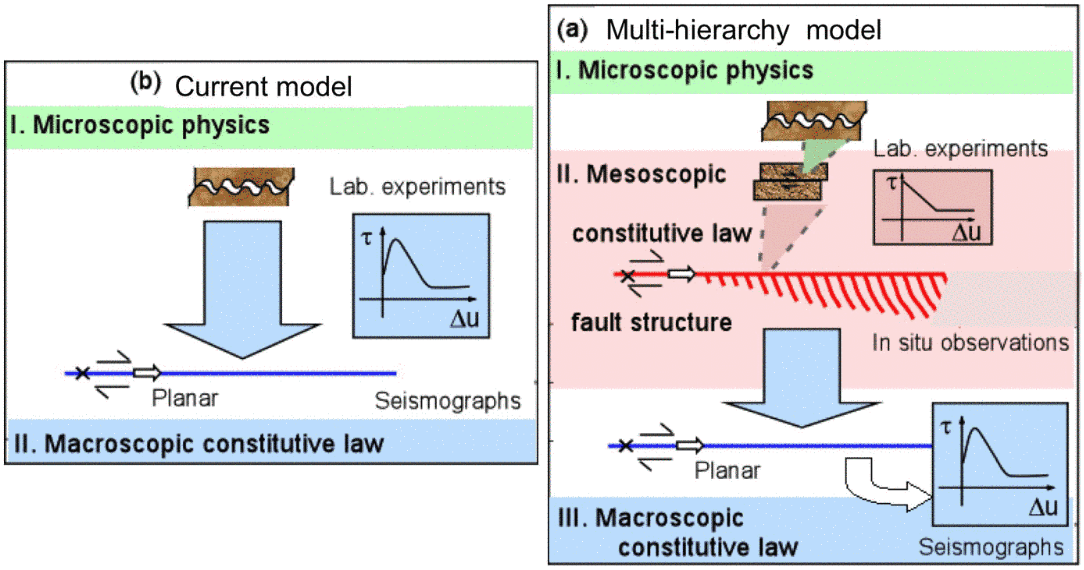
→ Scale of fault zones and numerically modeled

Micro-scale(<<1 [m])





Multi-hierarchy earthquake rupture model



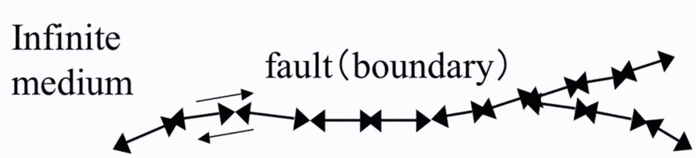
Method. Boundary integral equation method (BIEM)

BIE

$$T(\mathbf{r},t) = \mu/2\beta V(\mathbf{r},t) + T^o(\mathbf{r},t) + \iint K(\mathbf{r},t;\xi,\tau)V(\xi,\tau)d\xi d\tau$$

$T(\mathbf{r},t)$	Current traction
$V(\mathbf{r},t)$	current slip rate
$T^o(\mathbf{r},t)$	initial traction
$K(\mathbf{r},t;\xi,\tau)$	Green's function
$V(\xi,\tau)$	slip-rate
$\iint \ldots d\xi d\tau$	Spatio-temporal integration

Boundary condition $T(\mathbf{r},t) = f[S(\mathbf{r},t), V(\mathbf{r},t), etc.]$



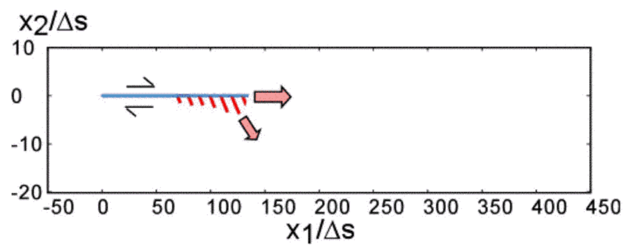
•2-D, in-plane (Mode II)

Advantages

- Accurately treat arbitrary geometry of **non-planar** faults
- Rupture path can be **self-chosen** (no need to be prescribed)

Cochard and Madariaga [1994], Tada and Yamashita [1997], Kame and Yamashita [1999], Ando et al. [2004]

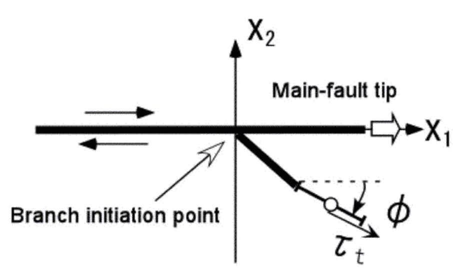
Multiple branches model

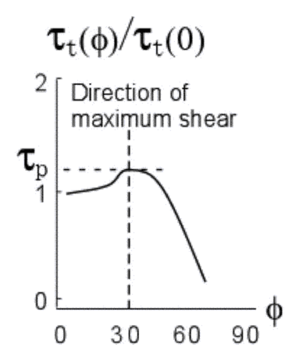


Modeled situation

- Main-fault:
  - Straight.
  - Bifurcation at equally spaced prescribed points (for simplification).
- Branch-faults:
  - Self-chosen rupture path obeying maximum hoop shear criterion (no secondary bifurcation)

Maximum hoop shear criterion for self-chosen rupture path



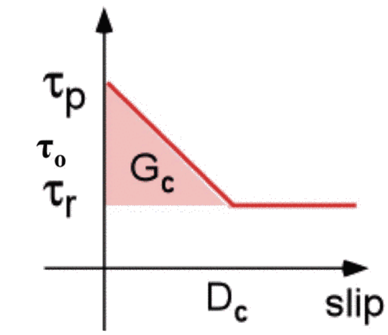


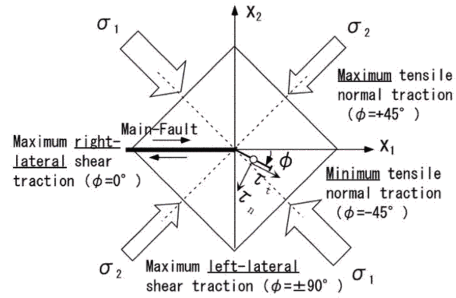
Criterion: A fault tip extends into the direction of maximum shear traction :

- Evaluate shear traction at a fault tip $0° < \varphi < 90°$
- Find the direction of maximum shear traction
- The tip extends if $\tau_t > \tau_p$

Mesoscopic fault constitutive law

Slip weakening law





$\tau_o = (\sigma_{max} - \tau_r)\cos(\cos 2\varphi)$

$\tau_r = 0$

The parameters are equivalent to:

$\sigma_{max} - \tau_r \sim 10\text{MPa}$, $\mu = \lambda \sim 10\text{GPa}$

$(\tau_p - \sigma_{max}) / (\sigma_{max} - \tau_r) = 1$

$Dc \sim 10^{-2}\text{m}$

Formation of branches

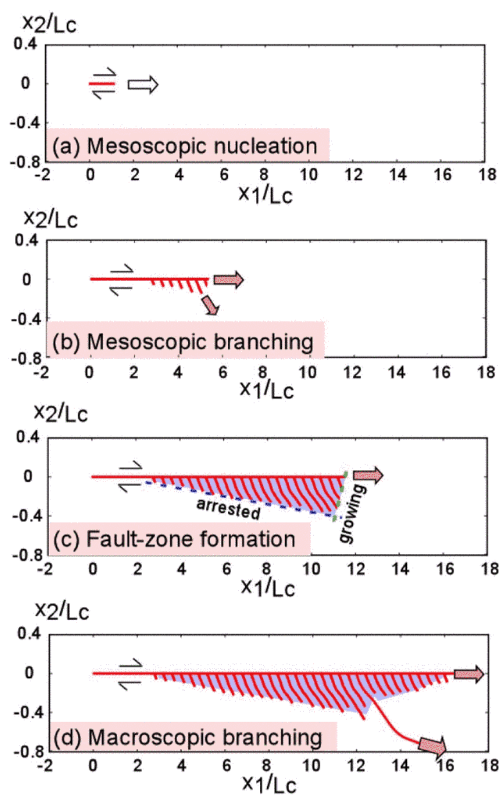
A snapshot

(a) Nucleation of rupture from a seed crack and unilateral propagation

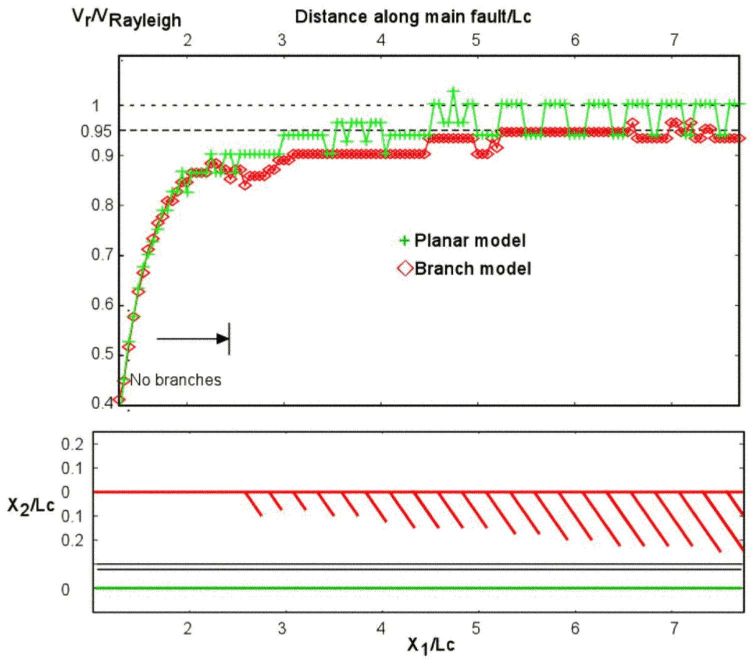
(b) Branching in mesoscopic scale from prescribed points

(c) Meso-branches are spontaneously arrested following a simple manner; considered as formation of fault zone

(d) A branch starts to extend unsteadily and growing into macroscopic scale



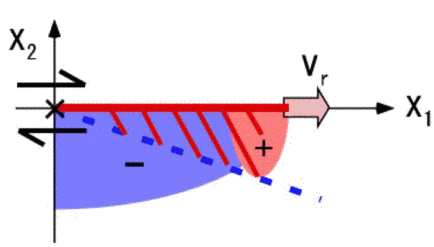
Rupture velocity of main-fault



φ is specified to 30º in the later

- Branches cause deceleration of rupture velocity
- $V_r \sim 95\% V_{Rayiegh}$

Why a fault zone becomes triangular ?



Stress field due to main-fault

+: stress increase

-: stress decrease

Explanations:

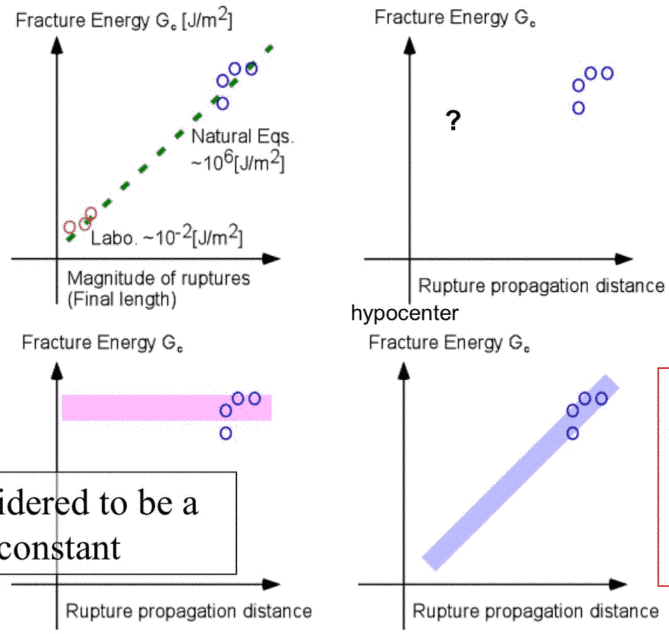
•Stress field around main-fault is proportional to the length of main-fault, due to

•Constant stress drop

•Constant Vr (steady state propagation)

→Large fault has large stress enhanced area where branches grow

Scale dependence of G_c



Gc: considered to be a material constant

Fundamental difference in rupture process

(~Earthquake prediction)

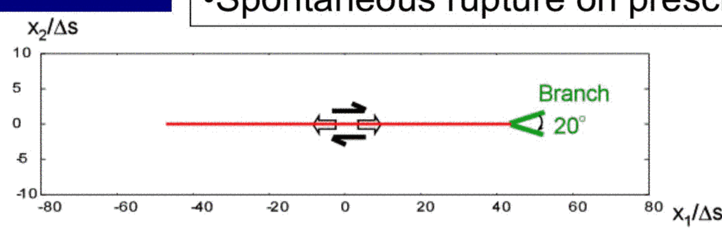
Purpose: We try to clarify what is theoretically expected using the multi-scale modeling.

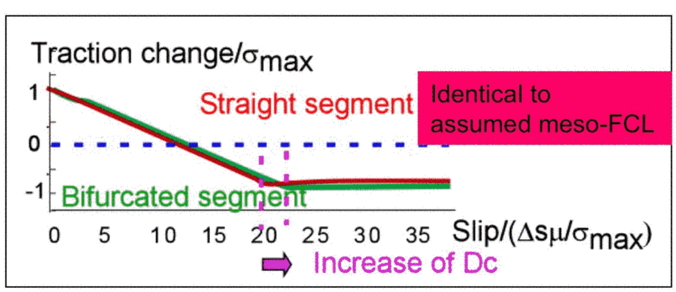
Effect of bifurcation

Configurations:

•Meso-param. $D_c, \tau_p \tau_r$: homogeneous

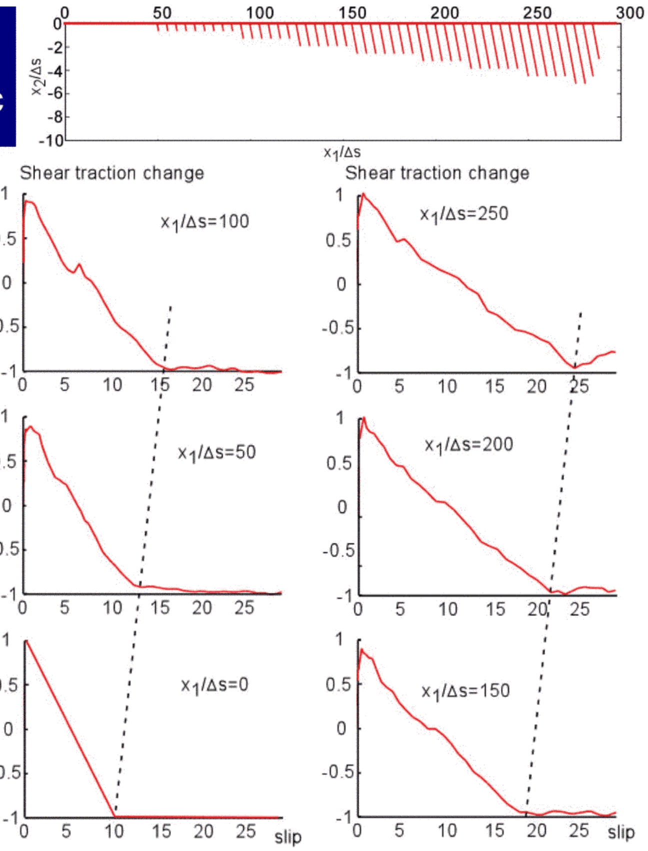
•Spontaneous rupture on prescribed fault





• D_c increases at bifurcation (Stress shadow effect)

Scaling law of G_c



Process zone size $\propto$ L

↓

Macroscopic fracture energy: proportional to L

$G_c \sim 1/2 D_c(\tau_p - \tau_r)$

$\propto$ L

Summary of fault zone formation

- We investigate formation processes of elemental fault structures such as fault bends, step-overs, branches and fault zones using dynamic rupture simulation.
- Two distinct branches exist
  - If main-fault length do not exceeds a critical length, mesoscopic branches passively grow and form a triangular (self-similar) fault zone.
  - If main-fault length exceeds a critical value, macroscopic branches grow unsteadily. Not reproduced by rheological constitutive model
- Rupture velocity of main-fault becomes constant $\sim 0.95 V_{Rayliegh}$

Summary of constitutive law

- Develop the multi-hierarchy model taking account of meso-scale fault structures (Branches)
- Investigate effects of the meso-structure on macroscopic fault constitutive law
- Macroscopic fracture energy G_c is
  - Off-main fault energy dissipation as one of factors (by meso-branches)
  - Depended on dynamic rupture processes
    →not a material constant
  - Proportional to distance of rupture propag

$$G_c = G_c(L) \propto L$$