Università degli Studi di Bologna

EARTHQUAKES AND FAULT DYNAMICS: AN OVERVIEW

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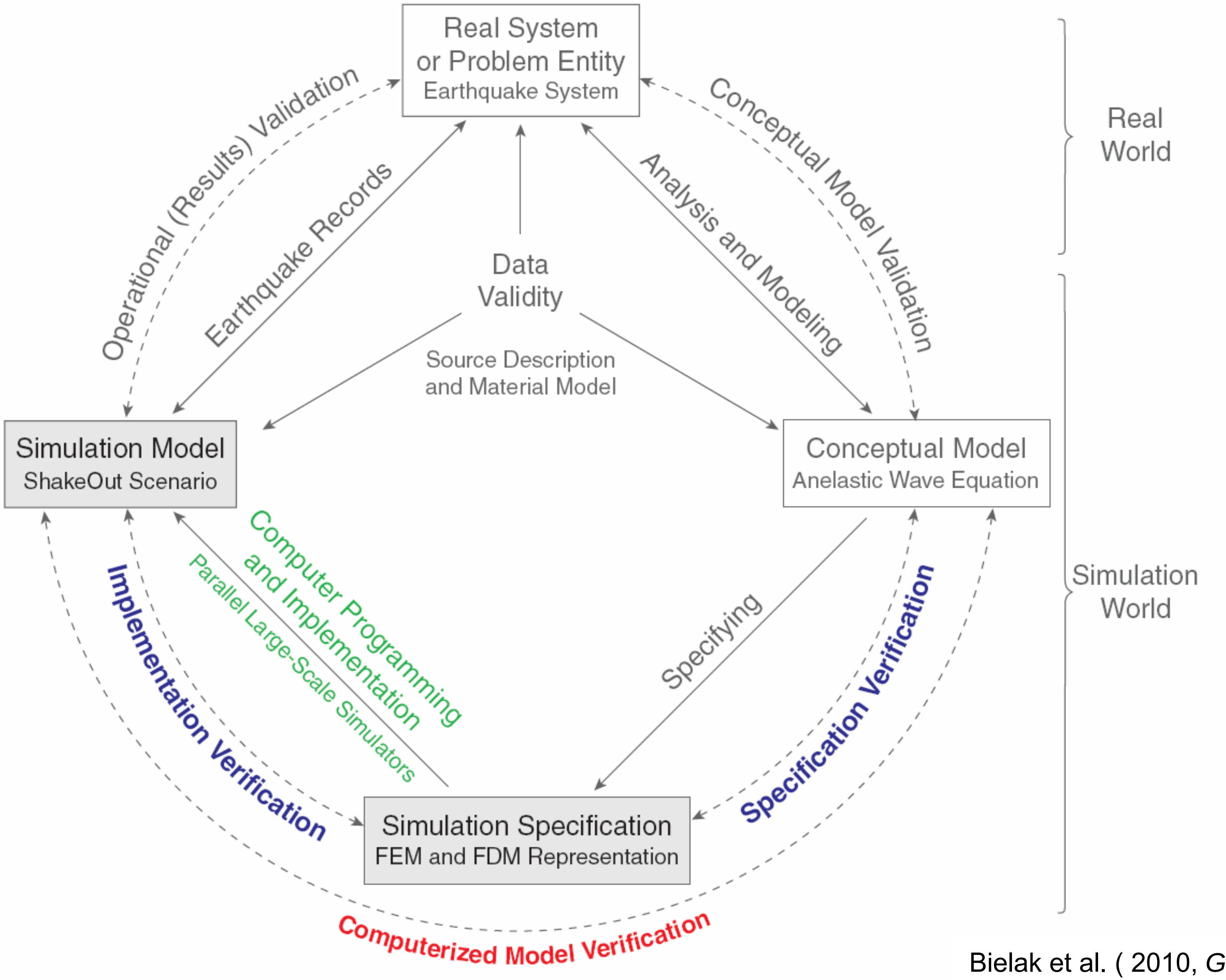
General overview

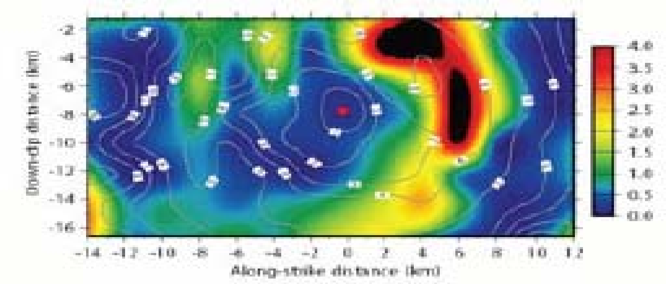


Bielak et al. (2010, *GJI*)

Seismologists need traction

- ✓ To apply fracture mechanics on mathematical planes representing the fault surfaces;

- ✓ To numerically simulate the spontaneous rupture nucleation, propagation, healing and arrest in dynamic earthquake models;



- ✓ To model seismic wave propagation in the surrounding medium;

- ✓ To predict ground shaking.

Stochastic or deterministic?

✓ Stochastic (or statistic) models: several aspects of the phenomenon under study are out of range, and they are replaced by unknowable, and hence random, processes, whose behavior cannot be predicted exactly but can be described in probability terms:

- Gutenberg–Richter law
- Omori law

✓ Deterministic (or physical) models: aim to understanding (and hence to predict) all the details of the considered phenomenon which does not include random components.

Central issues

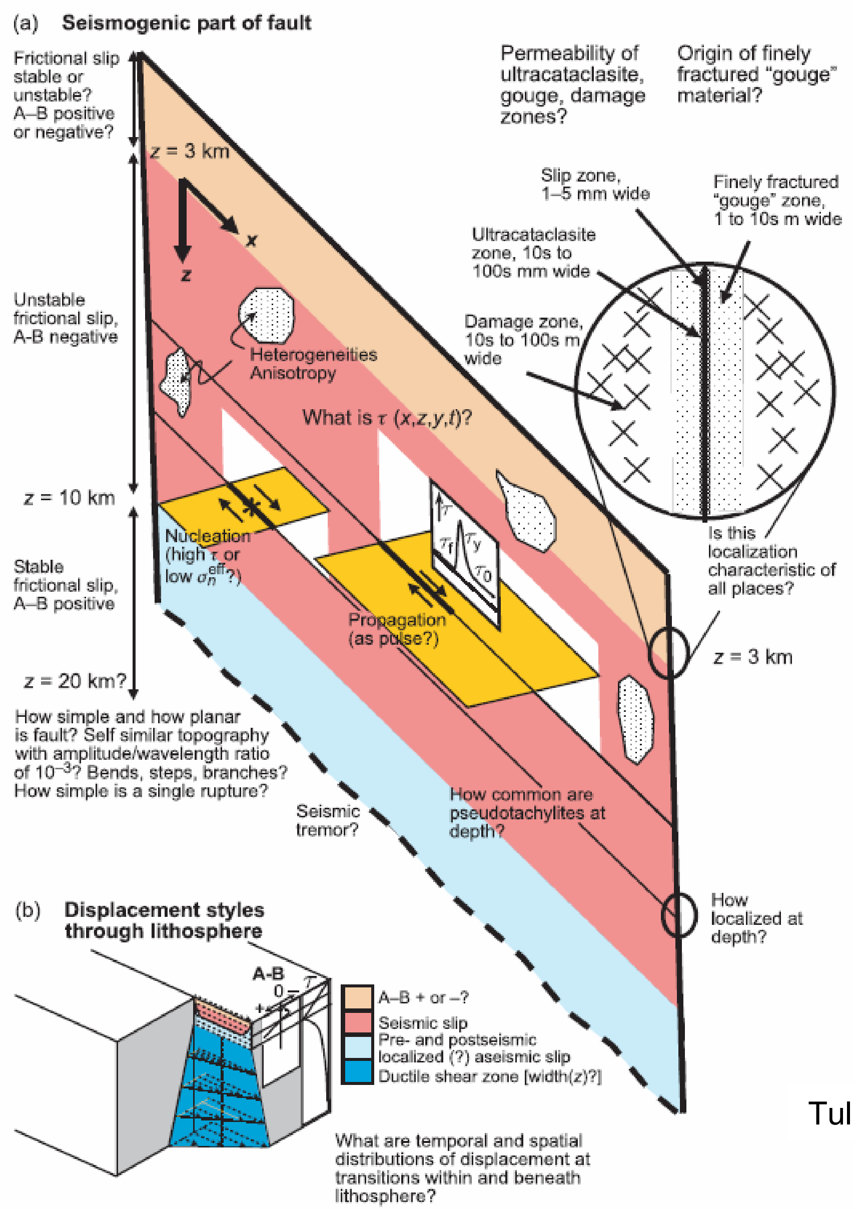
- ✓ Quantitative (instrumental) seismology is a relatively juvenile discipline

- ✓ Contrary to other fields of science, we can not plan natural (i.e., at real–world scale) experiments (like biology, chemistry, etc.)…

- ✓ … and we do know the PHYSICS, i.e., what are the exact equations which completely describe the complex fault systems (on the contrary, climatologists, e.g., know the equations to be solved through numerical experiments)…

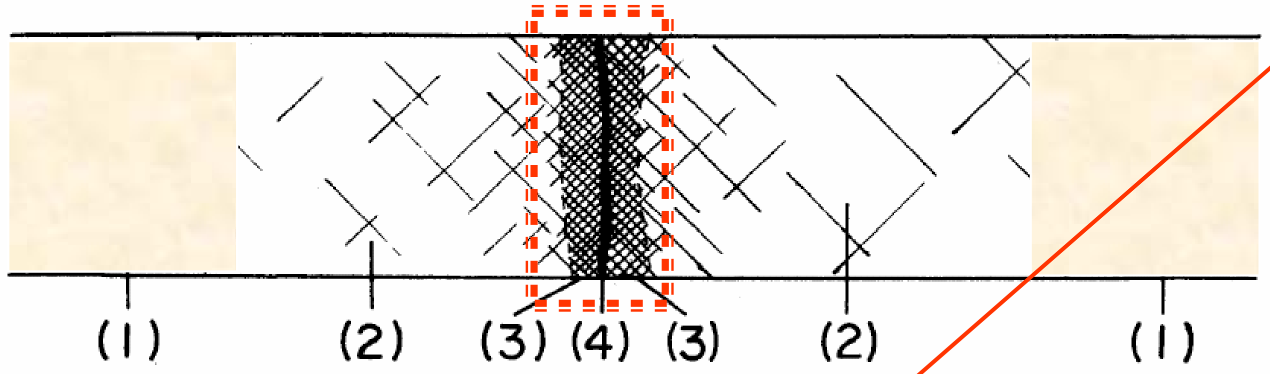
- ✓ … and we do not know the initial conditions.

Fault models



Tullis et al. (2007, *MIT Press*)

Internal Structure of Principal Faults of the North Branch San Gabriel Fault



1) Undeformed Host Rock

Fault Zone {
2) Damaged Host Rock
3) Foliated Zone
4) Central ultracataclasite layer } Fault Core

30 - 100 m (Damage ≈ *highly cracked rock*)

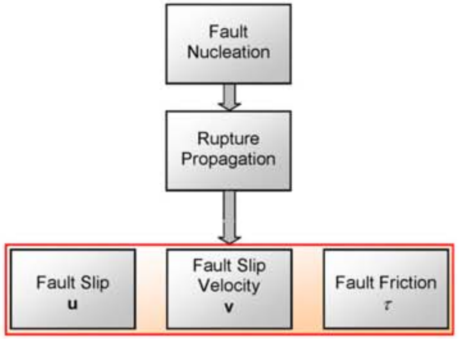
1 - 10 m (*foliated gouge* or *gouge*)

10s - 100s mm (containing the ***principal slipping zone***, *which* is *much thinner*, typically < 5 mm)

Fig. 2. Schematic section across the North Branch San Gabriel fault zone illustrating position of the structural zones of the fault. The diagram is not to scale.

Chester et al. (1993, *J. Geoph. Res.*)
Sibson (2003, *BSSA*)
Chester and Chester (2004, *SSA, SCEC meetings*)

Physical Phenomena in Faulting



Fault Nucleation

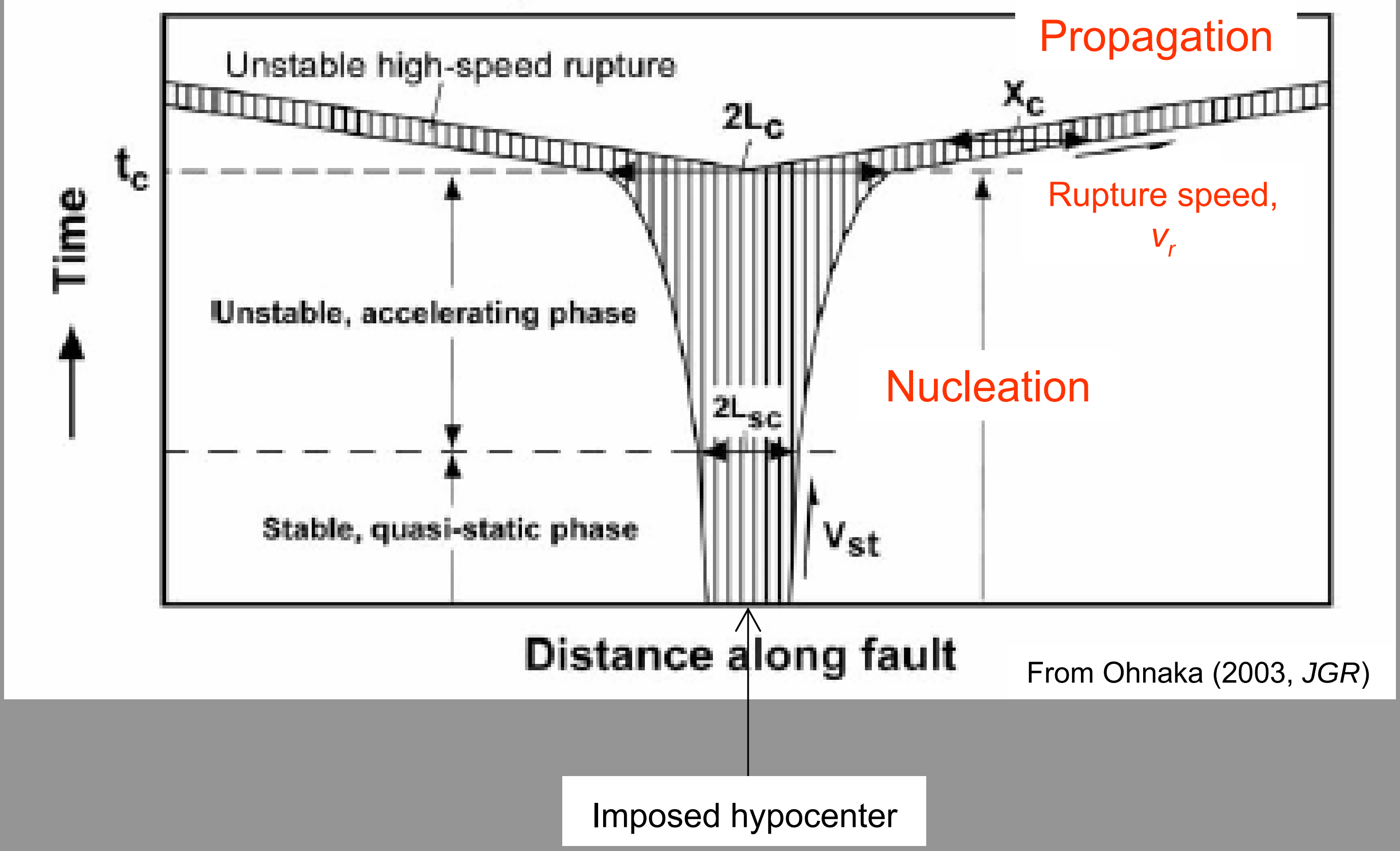
Rupture Propagation

Fault Slip **u**

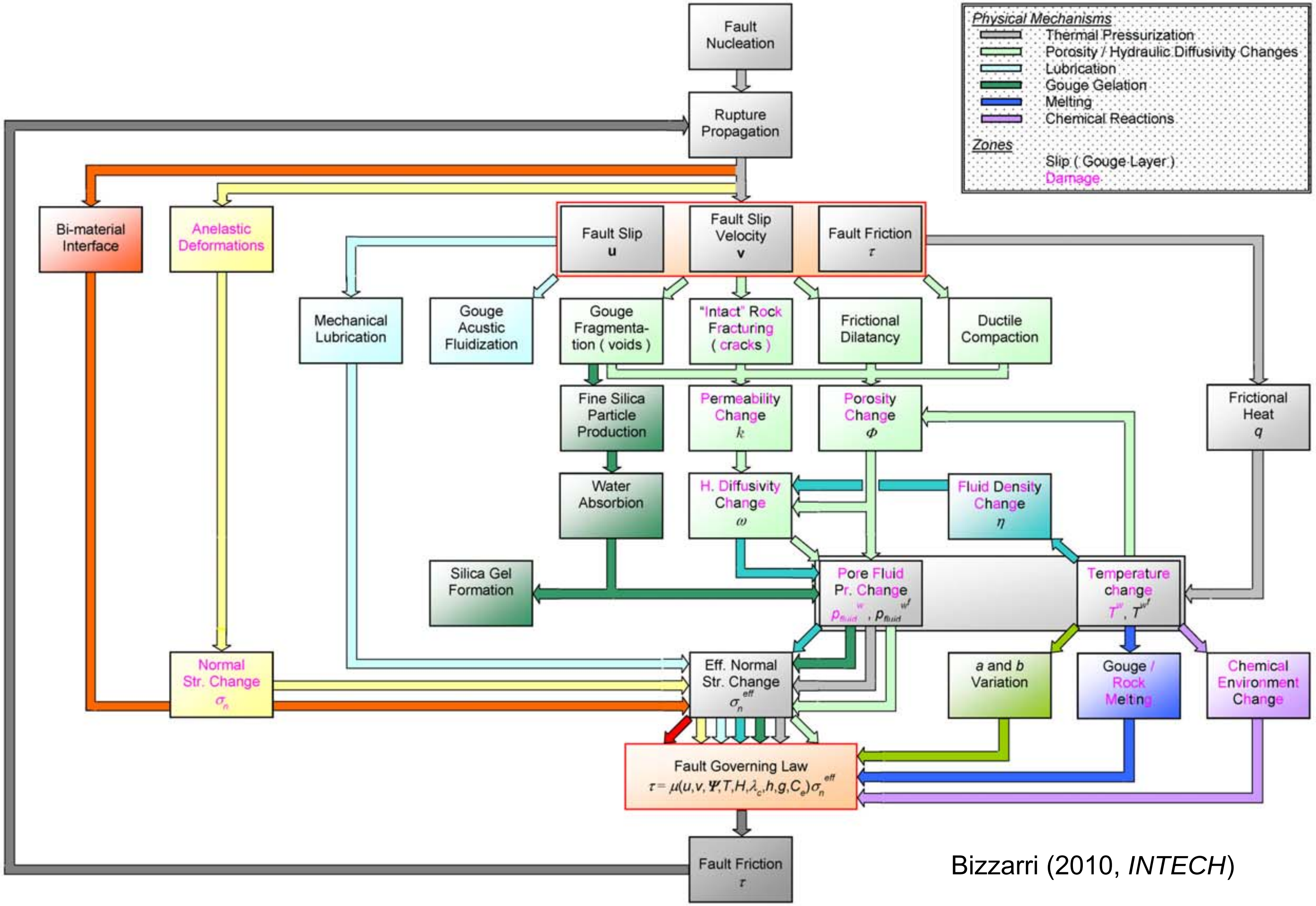
Fault Slip Velocity **v**

Fault Friction τ

Sketch of an expanding bilateral rupture



From Ohnaka (2003, *JGR*)



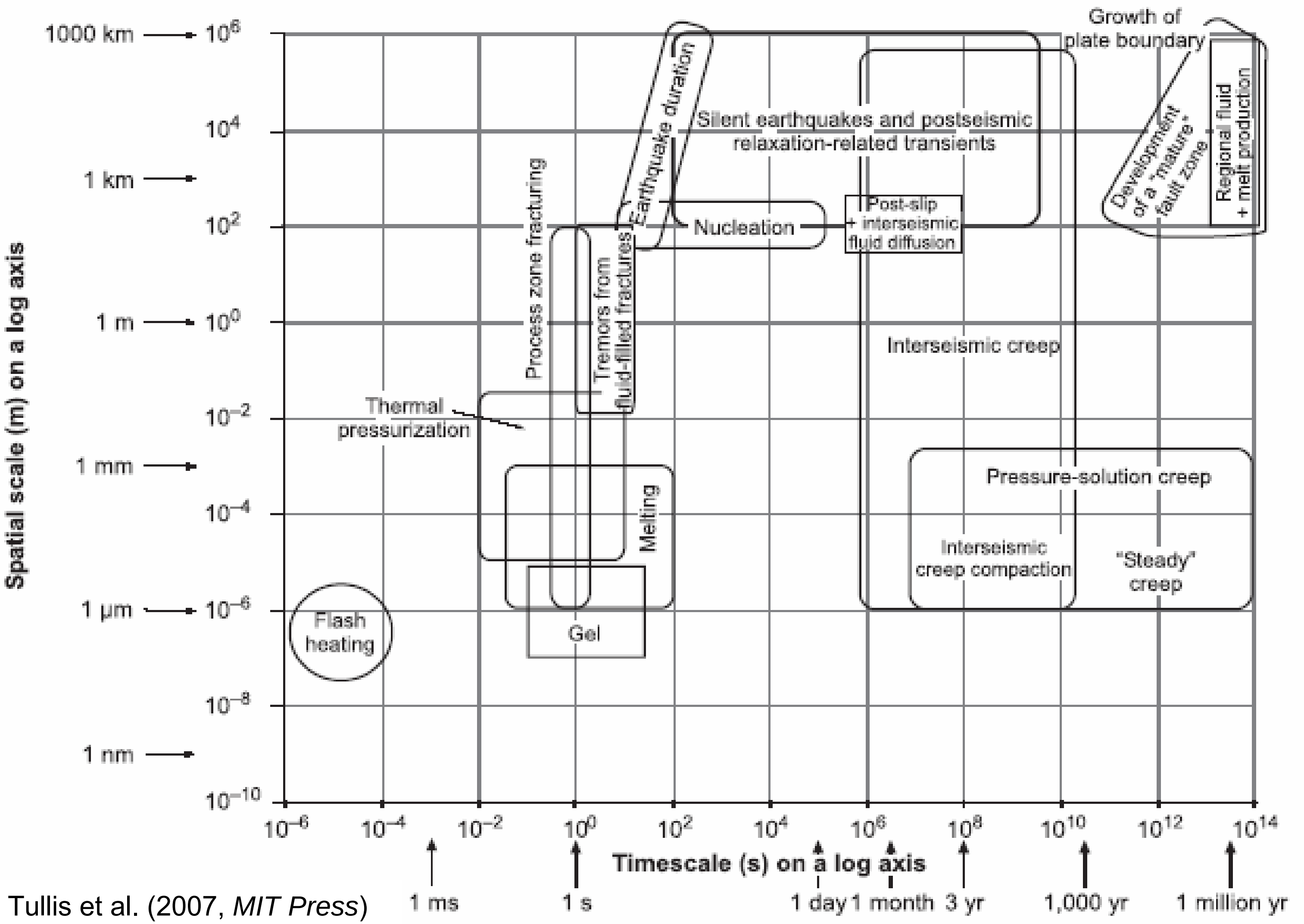
Bizzarri (2010, *INTECH*)

Occam's razor

- ✓ We follow the logical principle of simplicity (i.e., the Occam' s razor):

  The simplest way to describe the fault complexity is to **start from the beginning** (i.e., from the canonical formulations of the governing equations) and then **add** to the model **one by one** all additional phenomena until the empirical (instrumentally recorded) evidence can be explained.

Spatial and temporal scales



Tullis et al. (2007, *MIT Press*)

Rupture Description

Following *Scholz (1990)* the rupture can be described by using:

- ***CRACK MODELS***:

  The energy dissipation at crack edge (or crack tip) is paramount. Describe explicitely the crack propagation.

- ***FRICTION MODELS***:

  The effects at the edges are not explicitley considered. Explicitely allow for the calculation of the evolution of stress tensor components in terms of material properties of the fault.

Dislocation vs. Crack Models

DISLOCATION MODELS

- Study of **displacement discontinuity**
- **Slip** is assumed to be constant on the fault;
  The fault evolution is represented by unilateral or bilateral motion (rectangular dislocations: Haskell' s model)
- Kinematic description: it accounts for time evolution of rupture front and it neglects dynamics of faulting

⬆ **Long period** seismic waves modeling ($\lambda \geq L_{fault}$)

⬇ **constant dislocation** is **inadmissible**;
strain **energy** at crack tip is **unbounded**;
stress drop is **infinite**

CRACK MODELS

* Impose **finite energy flow** into the rupture

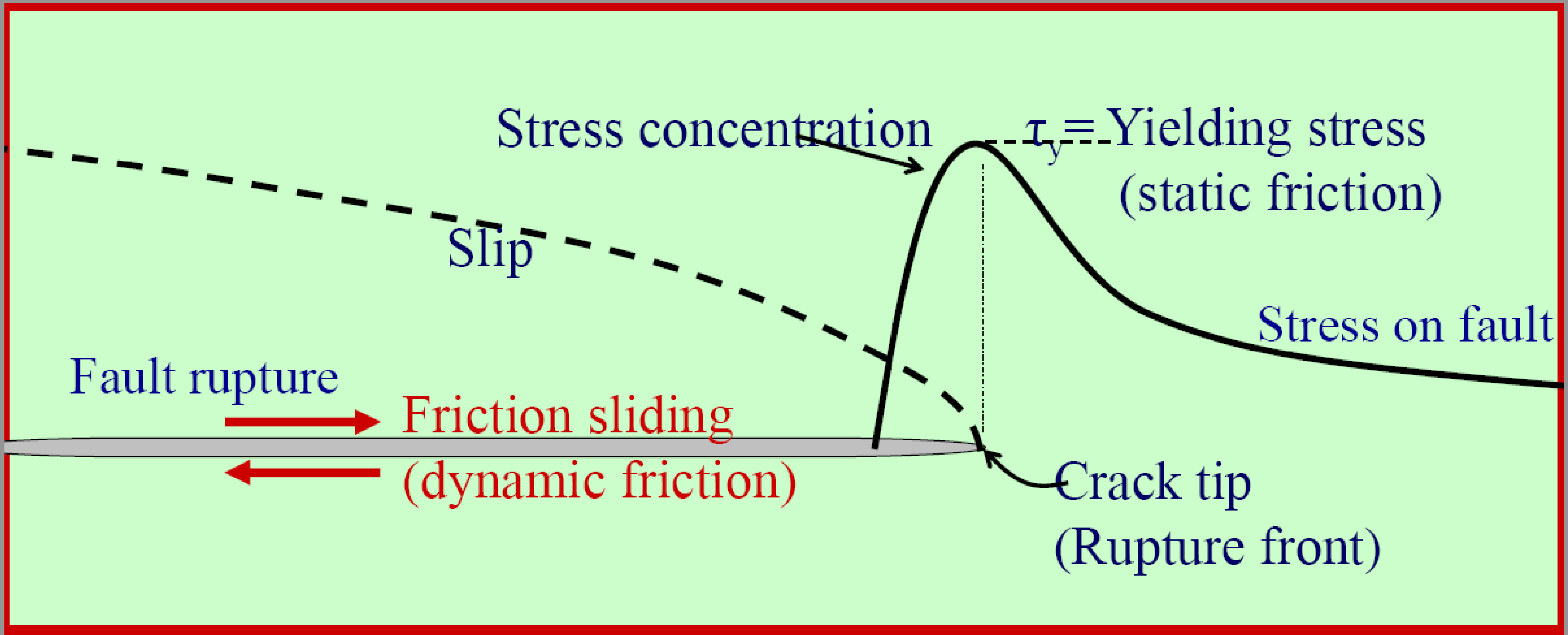
* **Slip** is **not prescribed**,
but it is calculated from the stres drop and from the fault strength S^{fault}

* Dynamic description: the shear stress drops inside the crack (after nucleation processes), increases the stress outiside the crack near the crack tip) and tends to facilitate further grow of the rupture

⇧ The motion is determined by fracture criterion (and eventually by the assumed constitutive law on the fault)

⇧ The problem is characterized by assuming the boundary conditions on the fault plane. It has mixed b. c.: slip assigned outside the crack tip and stress tensor components inside the crack tip

The concept of crack tip



Cracked portion of the surface (propagating rupture)	Locked portion of the surface

Rupture stages

1. Nucleation (quasi – static to dynamic evolution)

- *How can we simulate nucleation?*
- *How can we promote fault instability?*

2. Propagation

- *What is the fault constitutive equation (governing law)?*

3. Healing

- *What type of healing occurs?*
- *What controls fault healing?*

4. Rupture arrest

- *What is responsible of rupture arrest?*
- *How can we represent it? Earthquake energy balance?*

5. Fault re – strengthening

- *How can we model further instabilities episodes on the fault?*

Forward modeling scheme

1. Fault model:

- **Fault geometry** (orientation, planar or non – planar, …)
- **Fault system** (multiple segments, multiple faults, …)

2. Medium surrounding the fault surface (s)

- **Properties of the medium** surrounding the fault(s): cubic mass density structure, velocity structure, anisotropy, attenuation

3. Choice of the dimensionality d' of the problem (1 – D, 2 – D, 3 – D, 4 – D).
(d' = number of the independent variables in the solutions)

4. Choice of the representation

5. Choice of the numerical method

- (**FE**, **FD**, **BE**, **BIE**, **SE**, **hybrid**)

6. Specification of the Boundary Conditions

- **Domain** Boundaries Conditions (DBCs)
- **Fault** Boundary Condition (FBCs)
- **Auxiliary** Conditions (ACs)

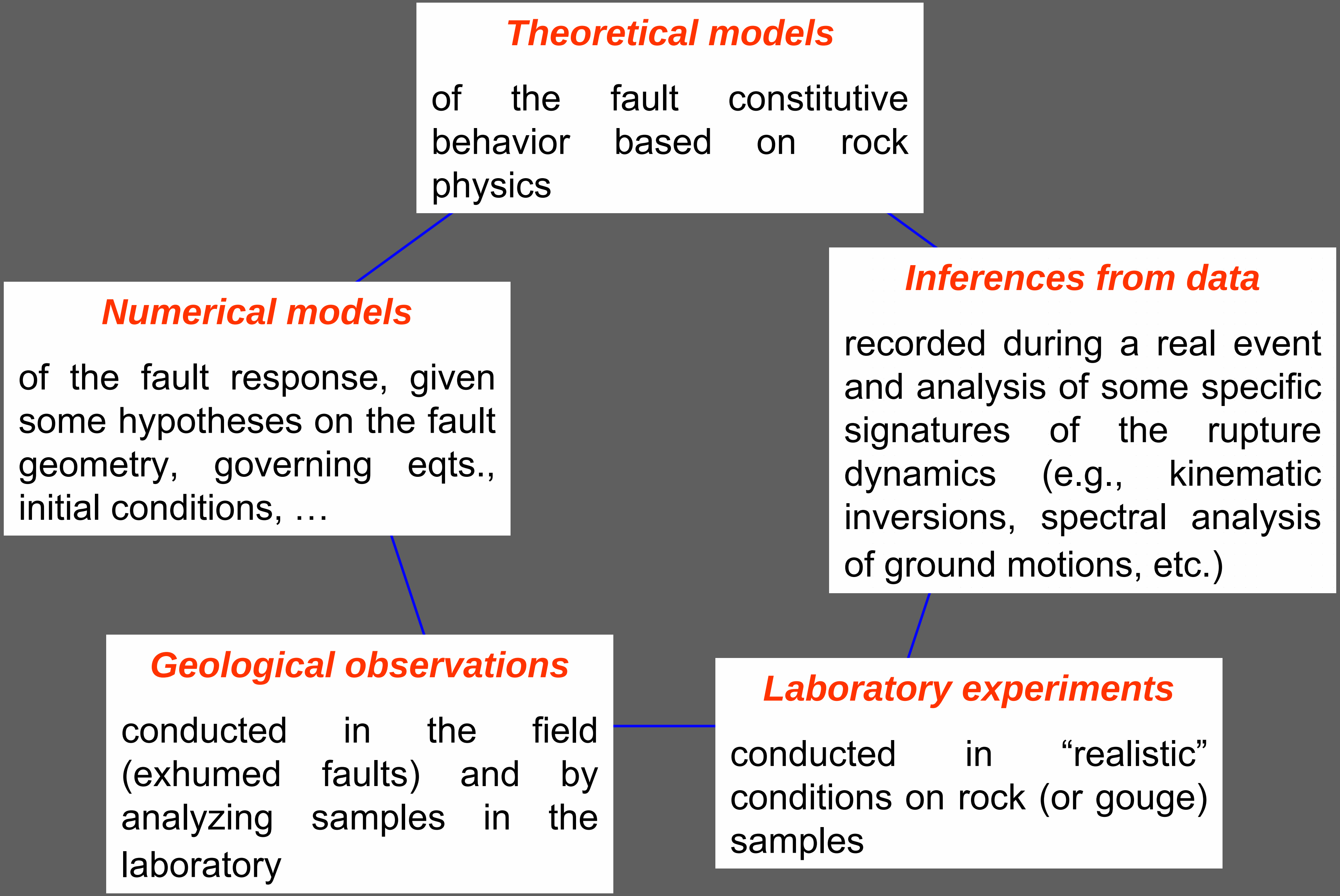
7. Specification of the Initial Conditions

- Initial conditions **on the fault**: (initial slip, slip velocity, state variable, pre – stress);
- Initial conditions **outside the fault**: (tectonic load, (state of neighbouring faults: the fault is not an isolated system))

8. Evaluation of the solutions

- Convergence analysis (**consistency** + **stability**)

A multidisciplinary approach



Theoretical models

of the fault constitutive behavior based on rock physics

Numerical models

of the fault response, given some hypotheses on the fault geometry, governing eqts., initial conditions, …

Inferences from data

recorded during a real event and analysis of some specific signatures of the rupture dynamics (e.g., kinematic inversions, spectral analysis of ground motions, etc.)

Geological observations

conducted in the field (exhumed faults) and by analyzing samples in the laboratory

Laboratory experiments

conducted in “realistic” conditions on rock (or gouge) samples

Thank you!

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Support Slides:
Parameters, Notes, etc.

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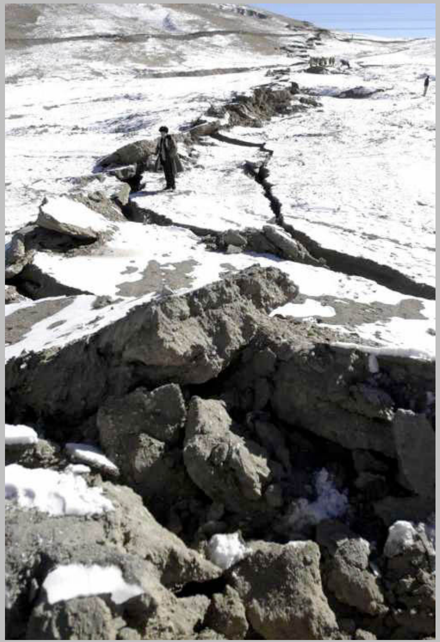
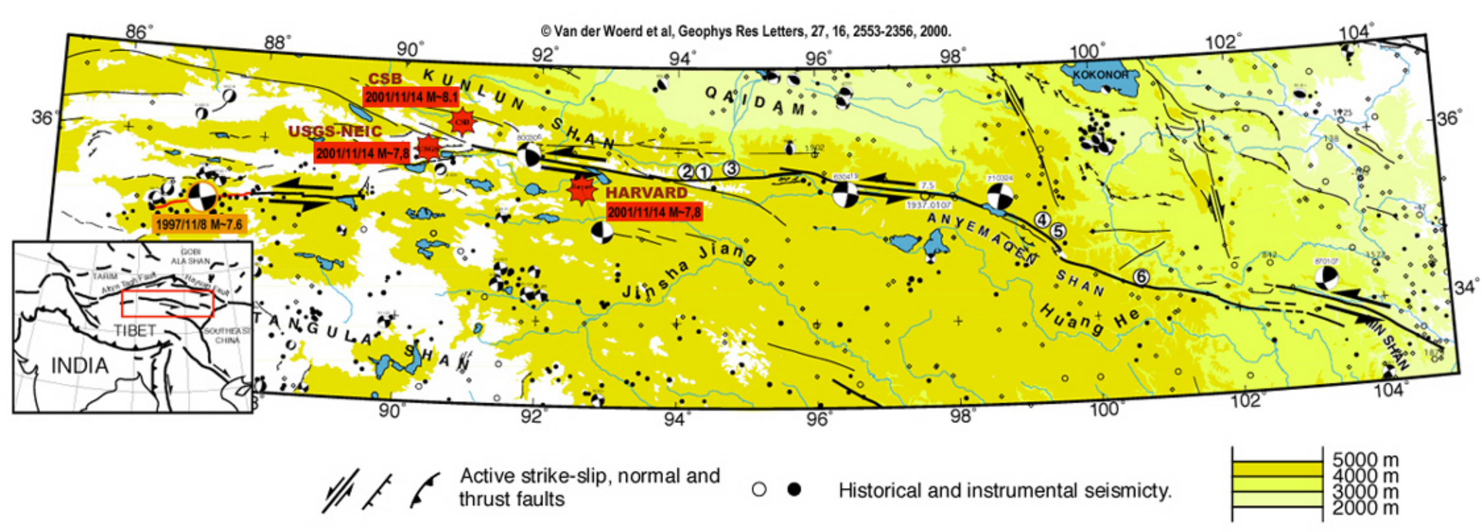
Geometrical complexity

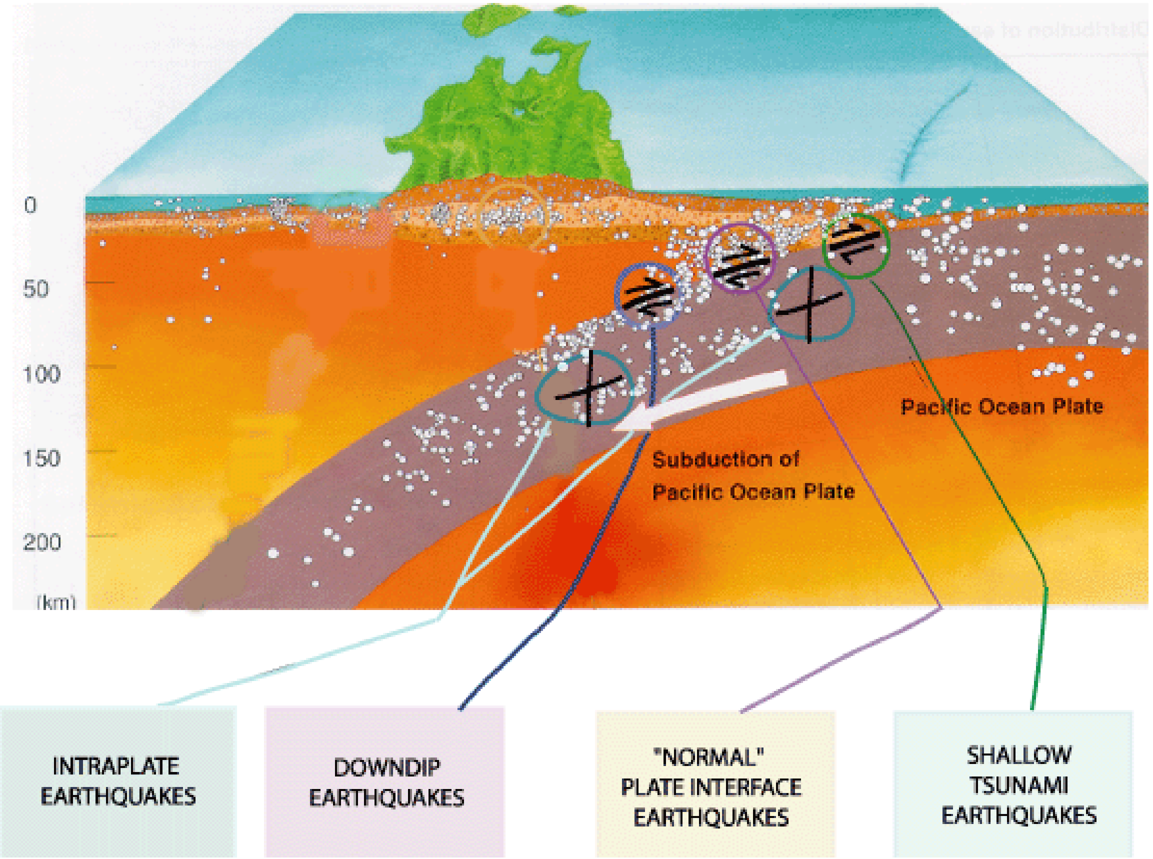


Kokoxili
M_w 7.9
earthquake
(Qinghai
Province,
China)


© Van der Woerd et al, Geophys Res Letters, 27, 16, 2553-2356, 2000.

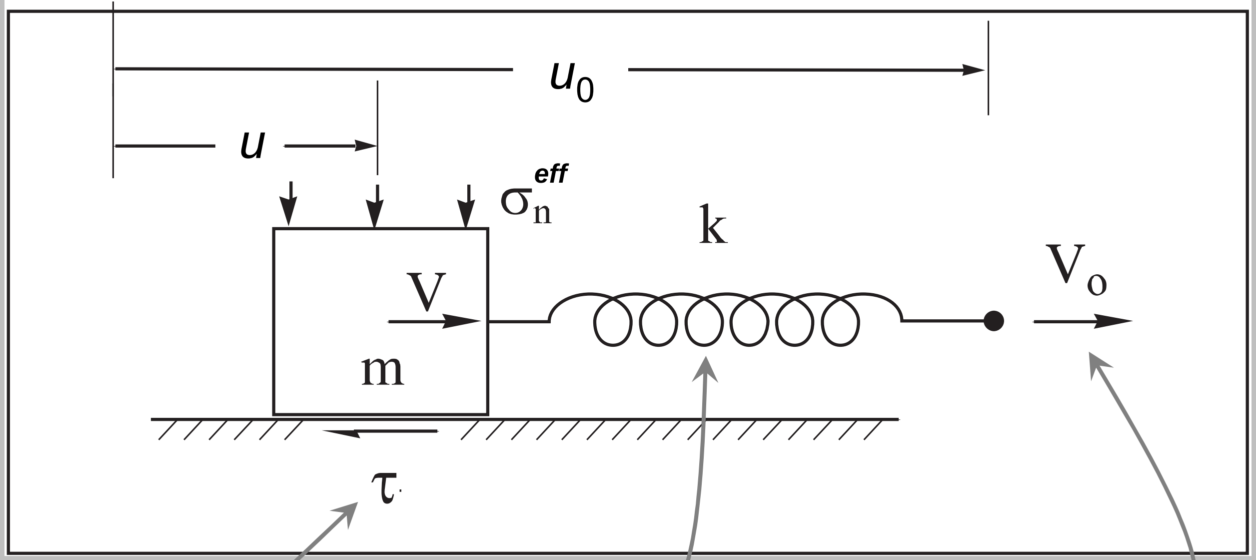
Different types of earthquakes

1. Interplate
2. Tsunami
3. Crustal
4. Downdip
5. Intraplate
6. Deep



Dimensionality *d'*

1 – D Sping – Slider (mass – spring) model



Frictional sliding

(↔ rheological properties)

Elastic behaviour

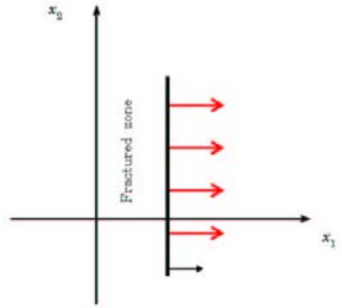
(↔ surrounding medium)

Loading velocity

(↔ tectonic load)

Shear rupture on a planar fault surface ($x_3 = 0$)
Snapshots at fixed time t

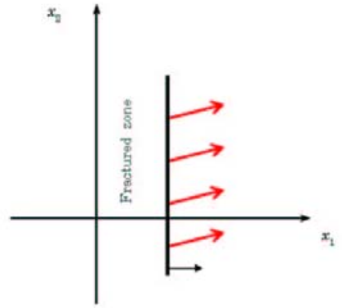
PURE MODE II



Dependence on x_1
Independence on x_2

$\Rightarrow u_1(x_1,t)$

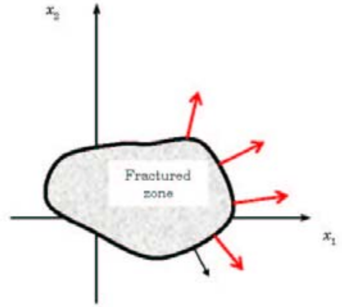
MIXED MODE



Dependence on x_1
Independence on x_2

$\Rightarrow u_1(x_1,t)$
$u_2(x_1,t)$

TRULY 3 – D



Dependence on x_1
Dependence on x_2

$\Rightarrow u_1(x_1,x_2,t)$
$u_2(x_1,x_2,t)$

━ Crack tip

→ Local displacement

→ Local crack enlargement direction