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"Seventh Workshop on Non-Linear Dynamics and Earthquake Prediction"

29 September - 11 October 2003

Earthquake Occurrence

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EARTHQUAKE OCCURRENCE (the seismic catalog)

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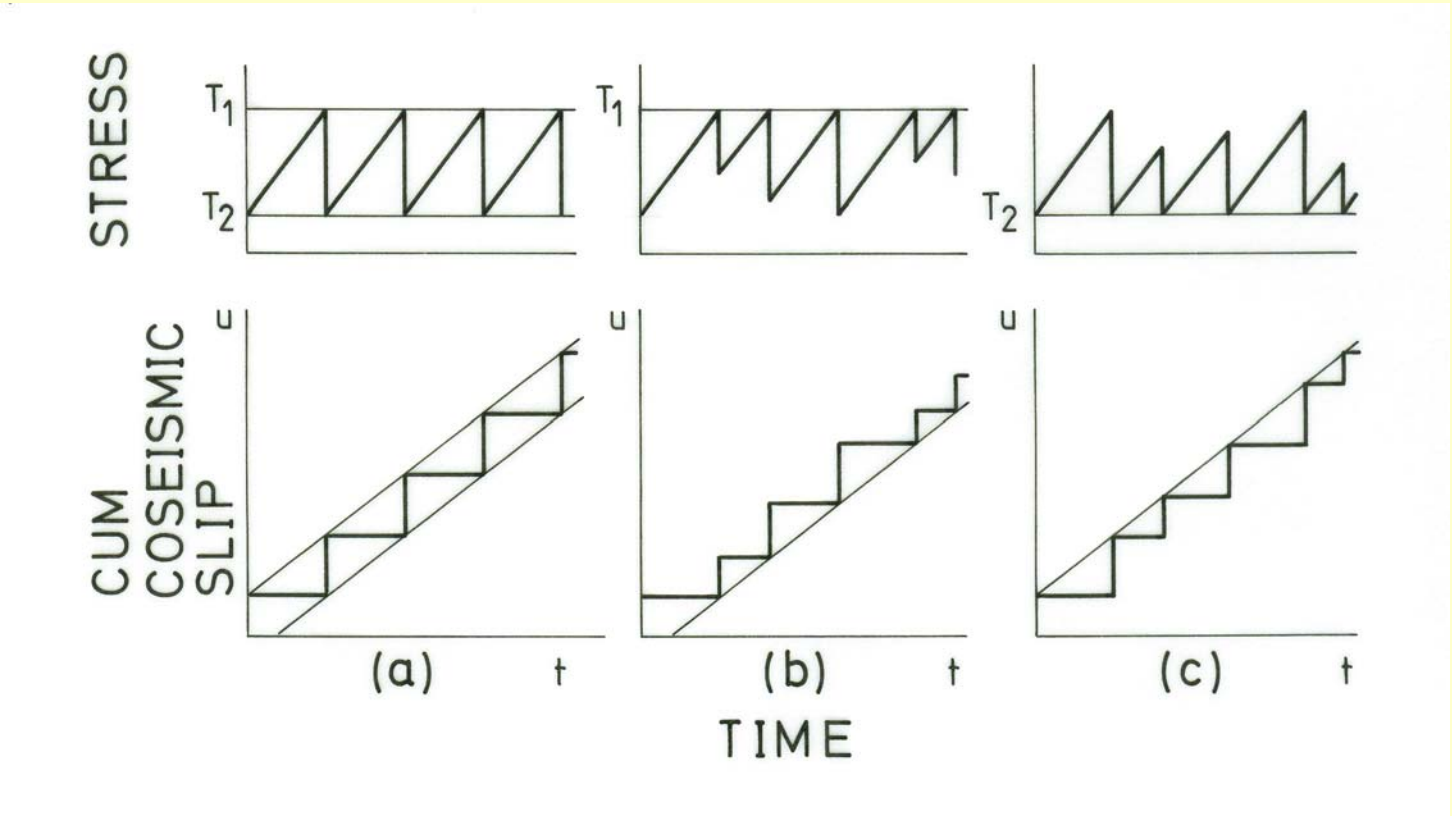
SEQUENCE OF EARTHQUAKES

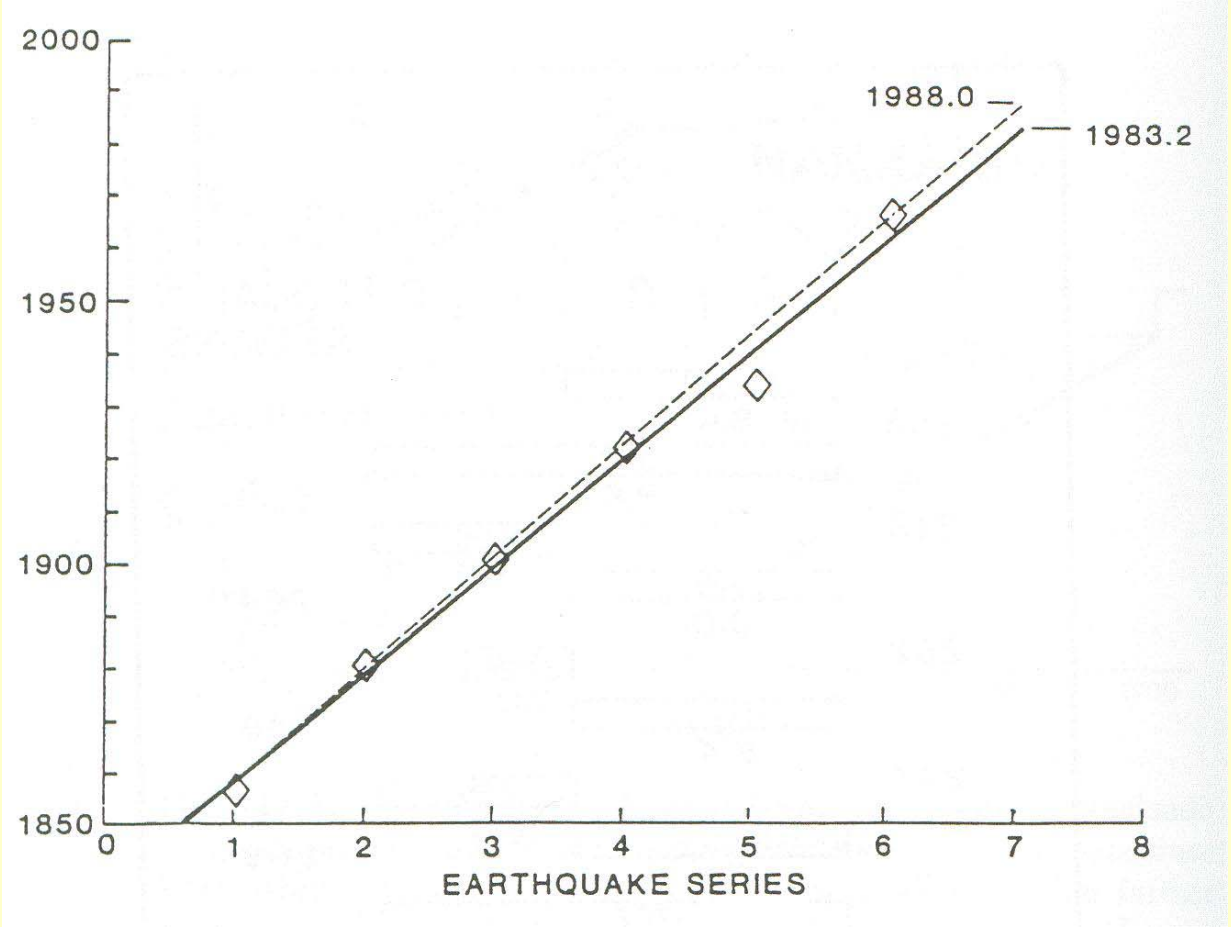
- It is a well established fact that earthquakes, recurrently, occur at the same places, on preexisting faults.
- Due to friction, the fault is locked and accumulates strain at both sides until the tangential component of the stress exceeds the forces of friction, leading the fault to rupture.
- Tectonic stress may be assumed to be *stationary*, so that the accumulated stress will also be stationary.
- If the above hypothesis apply, earthquakes will occur at regular intervals of time, known as **recurrence intervals**.

SHIMAZAKI & NAKADA'S PREDICTION MODEL



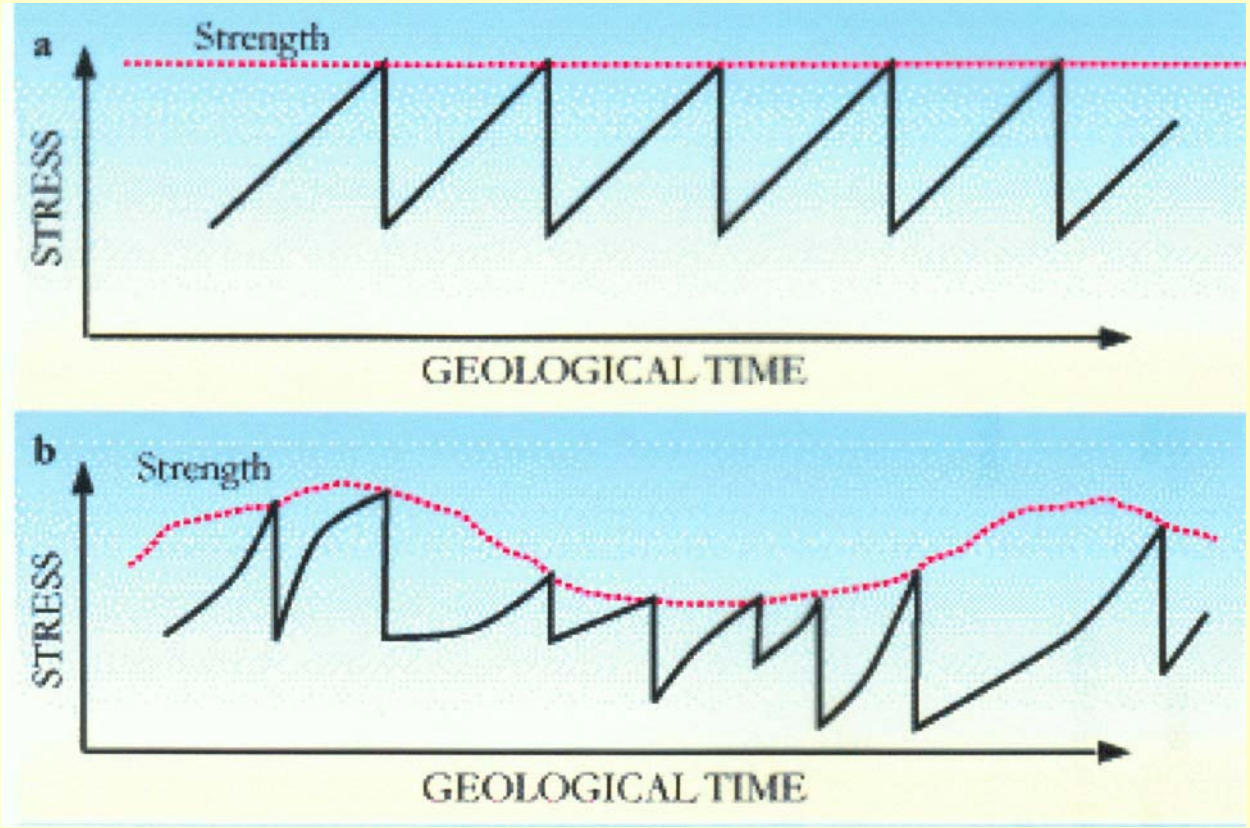
(a): Reid's model, (b): time-predictable, (c): slip-predictable

PARKFIELD SERIES OF EARTHQUAKES

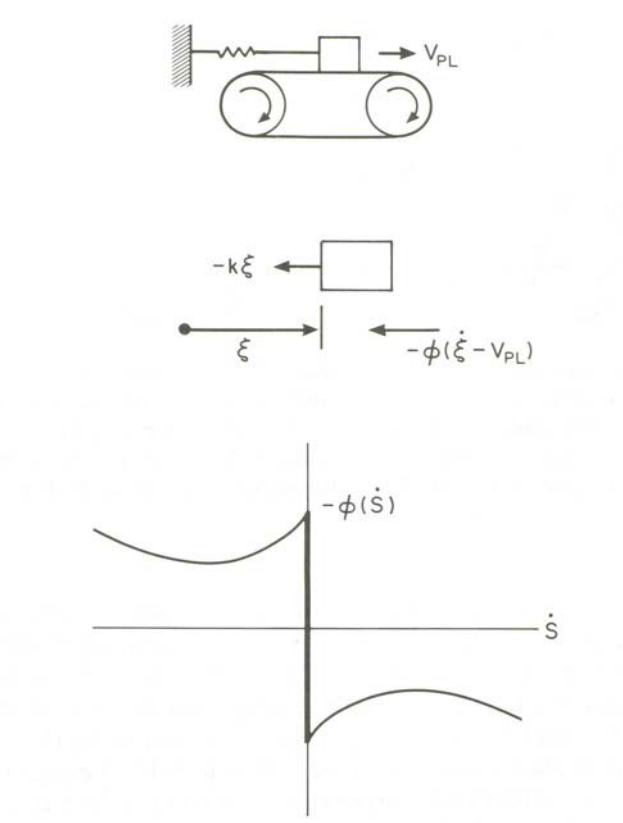


Recurrence time: ~ 22 years → **seismic cycle**

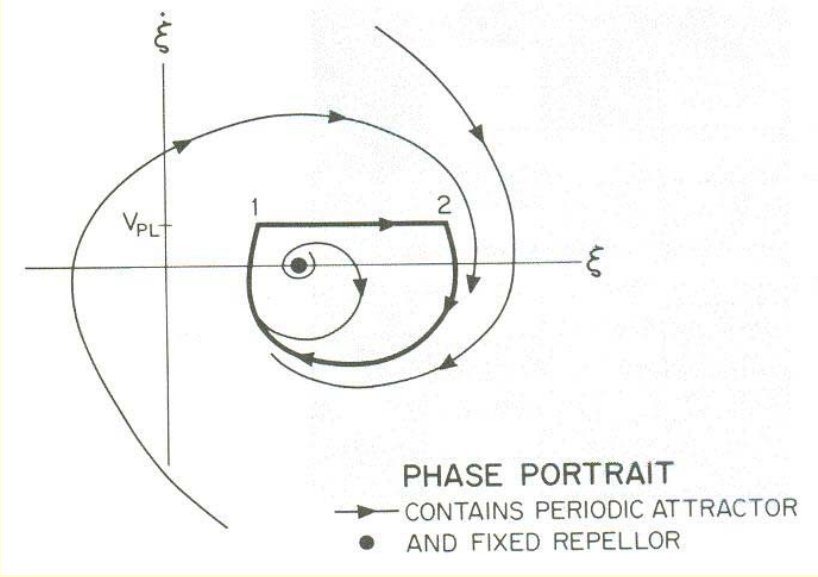
RECURRENCE TIMES



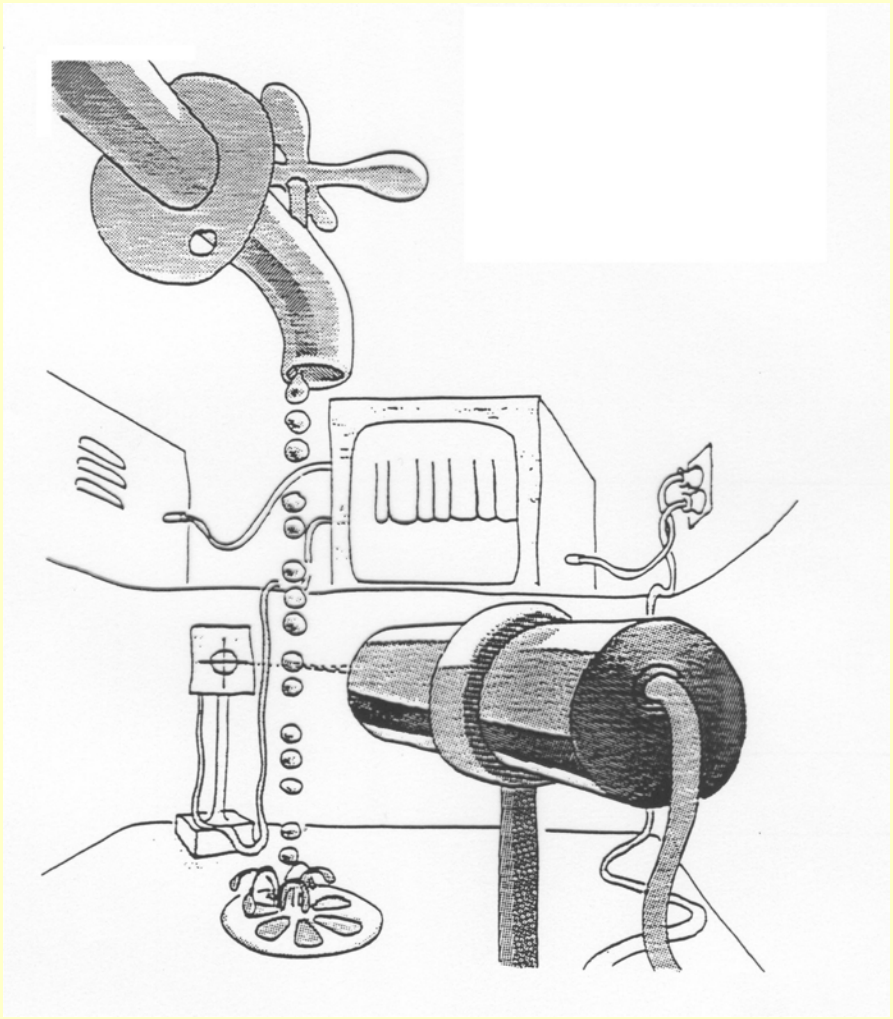
MASS-SPRING-SLIDER MODEL



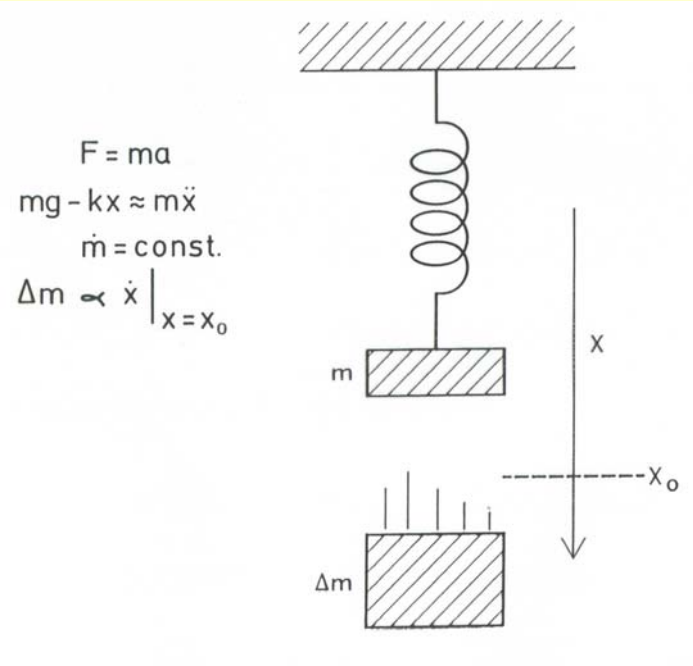
$$m\ddot{\xi} + \Phi\left(\dot{\xi} - v_{pl}\right) + k\xi = 0$$



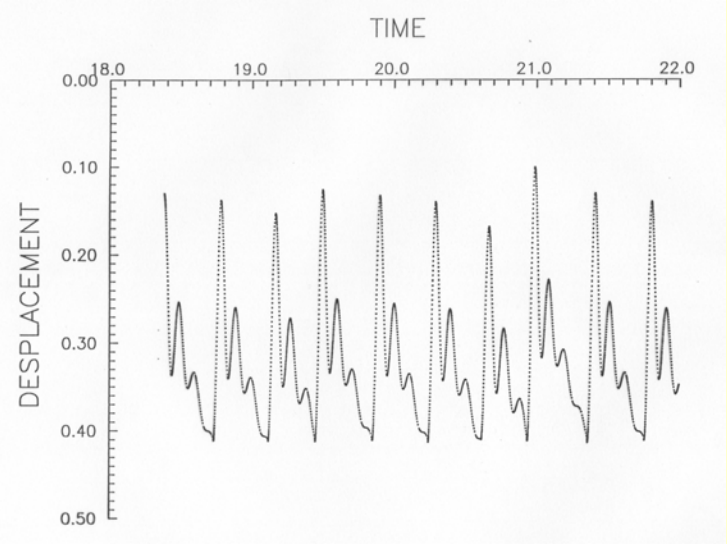
DRIPPING FAUCET MODEL. 1

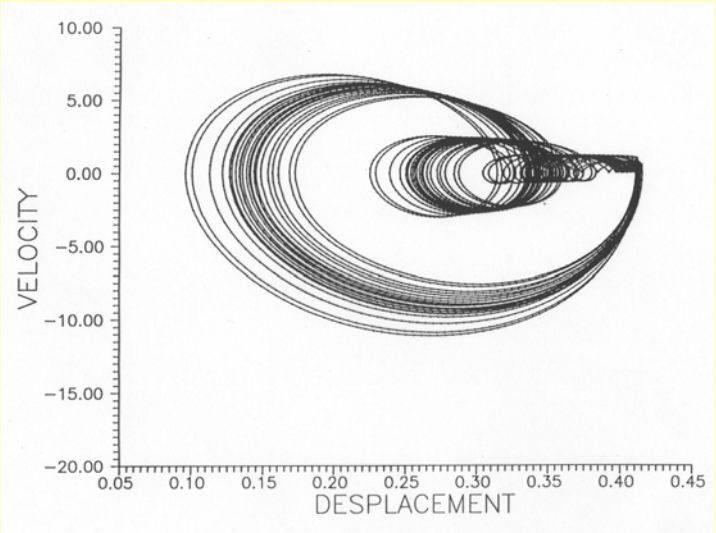


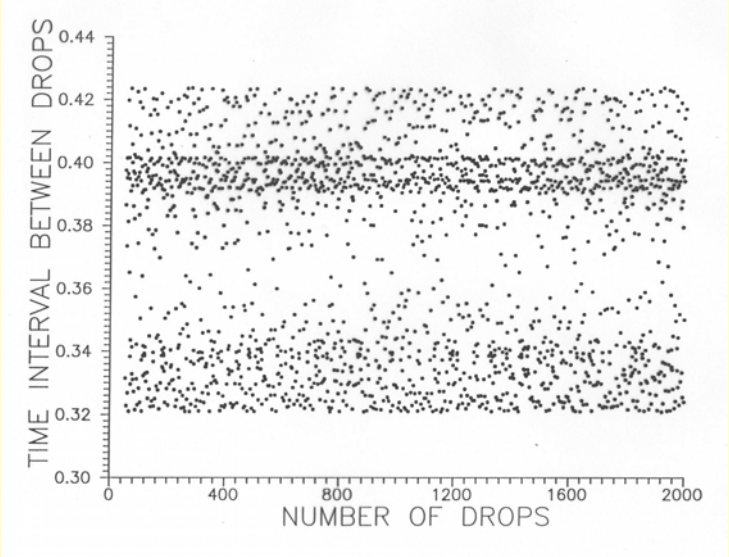
$$F = ma$$
$$mg - kx \approx m\ddot{x}$$
$$\dot{m} = \text{const.}$$
$$\Delta m \propto \dot{x}\Big|_{x=x_0}$$



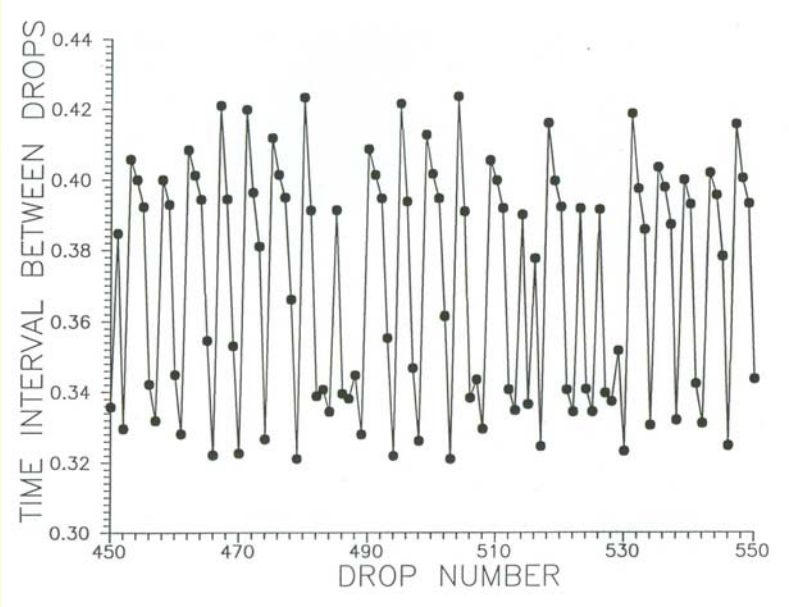
DRIPPING FAUCET MODEL. 2

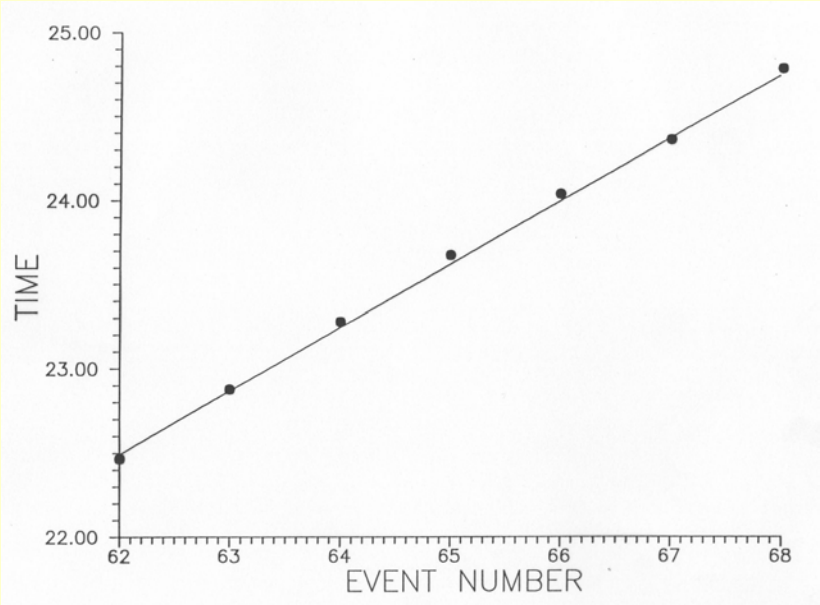






DRIPPING FAUCET MODEL. 3





MAIN CHARACTERISTICS OF REGIONAL SEISMICITY. 1

- Earthquake population in diverse tectonic zones exhibit spatial variability, clustering and intermittency.
- Frequency magnitude statistics follows a power-law, the *Gutenberg-Richter law*: the cumulative number of earthquakes per unit time $\acute{N}_{CE}$ of magnitude greater than *m* is given by

$$\log \dot{N}_{CE} = -bm + a$$

- Earthquakes have aftershock sequences (and some times also foreshock sequences) that decay (grow) with time at a rate R(t) determined by Omori's law:

$$R(t) = \frac{R_0}{(t + t_0)^p}$$

where p is a power law index and R_0 and t_0 are constants.

MAIN CHARACTERISTICS OF REGIONAL SEISMICITY. 2

- Earthquakes have a relatively constant and relatively small stress drop (~ 3 MPa) over a wide range of scales, compared to tectonic stress (~ 10 -100 MPa).
- Seismicity can be induced by stress perturbations smaller than the stress drop in individual events. That is, **earthquakes can be triggered**.

EARTHQUAKE OCCURRENCE AS A CRITICAL PHENOMENON

- The distribution of almost all properties of earthquakes are **self-similar**, *i.e.*, follow a **power law**.
- There exist action at a distance.
- These are the characteristics of critical phenomena that occur at continuous phase transitions order/disorder.
- Caution has to be taken not to confuse these phenomenological phase transitions with those that appear in statistical mechanics, defined in terms of a Hamiltonian and equipartition functions. The equivalence is only through observations (at lest at the present time.

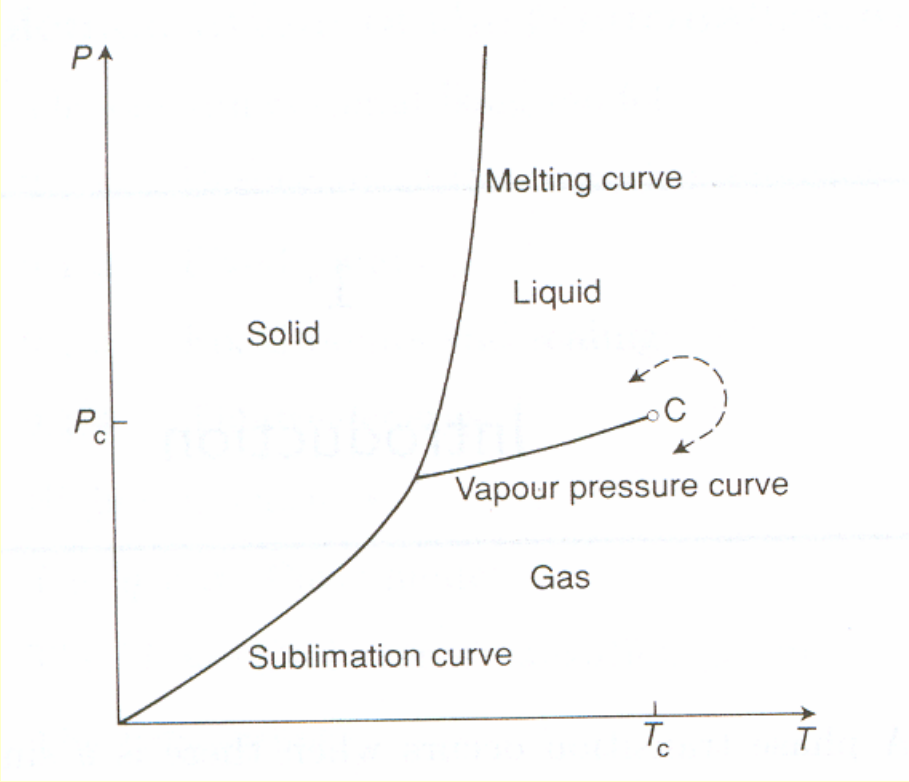
PHASE TRANSITION

-- LIQUID WATER/VAPOUR PHASE TRANSITION (2nd order or continuous phase transition)

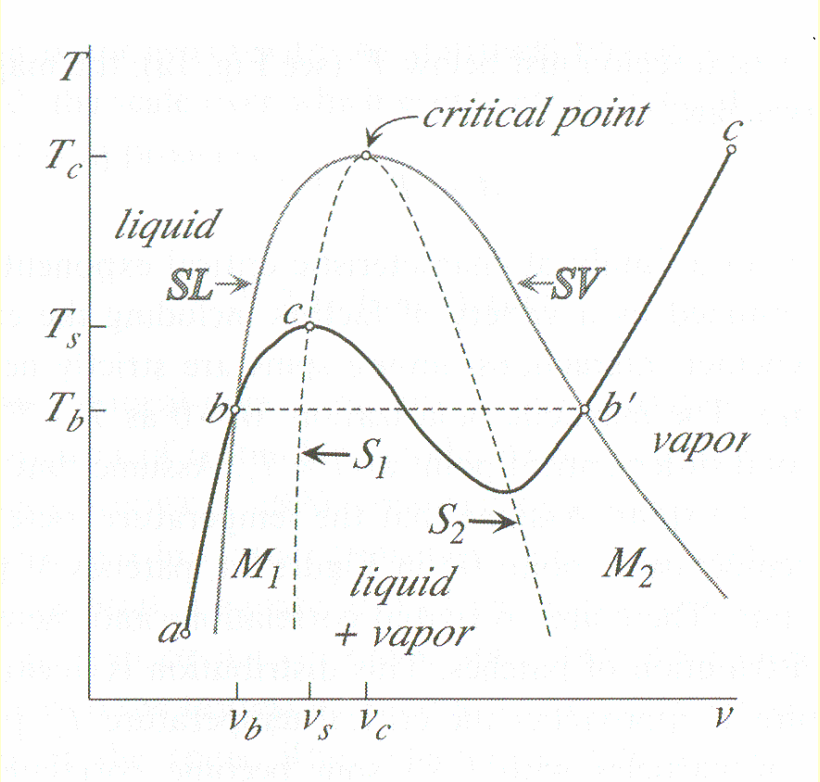
-- METASTABILITY → geometrical instability

CRITICAL PHENOMENA

2nd. order phase transition



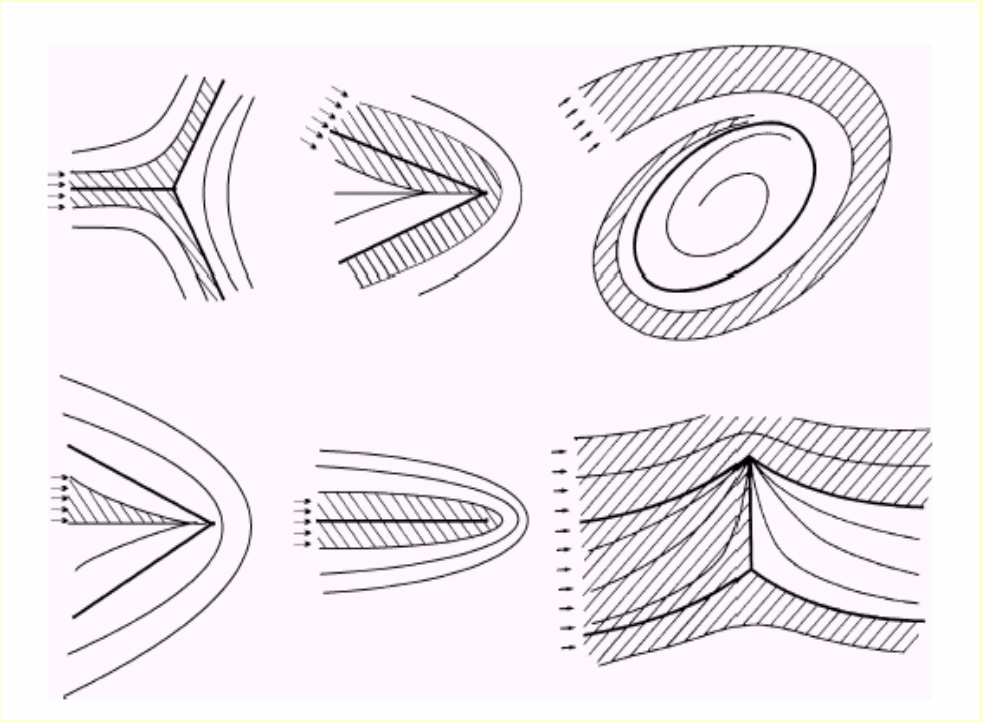
metastability



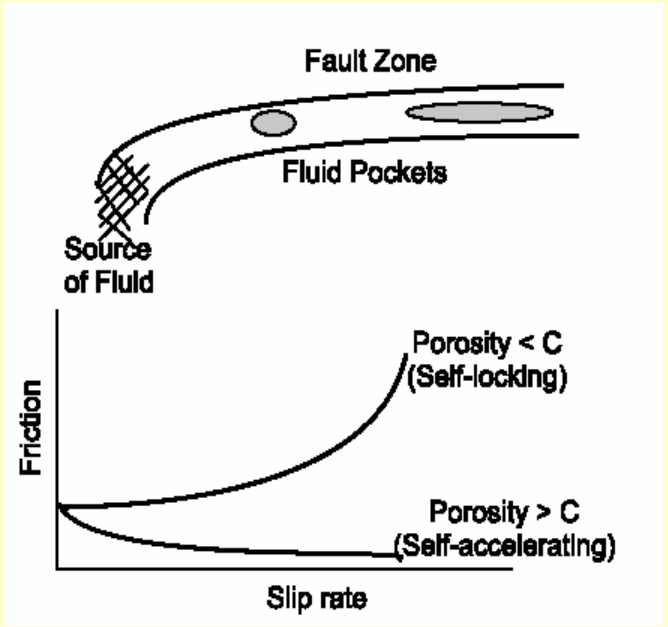
METASTABILITY

- Physical instabilities:
  - Stress corrosion
  - Infiltration of a lubricating fluid
- Geometrical incompatibilities:
  - Geometrical incompatibility
  - Kinematical incompatibility

PHYSICAL INSTABILITIES

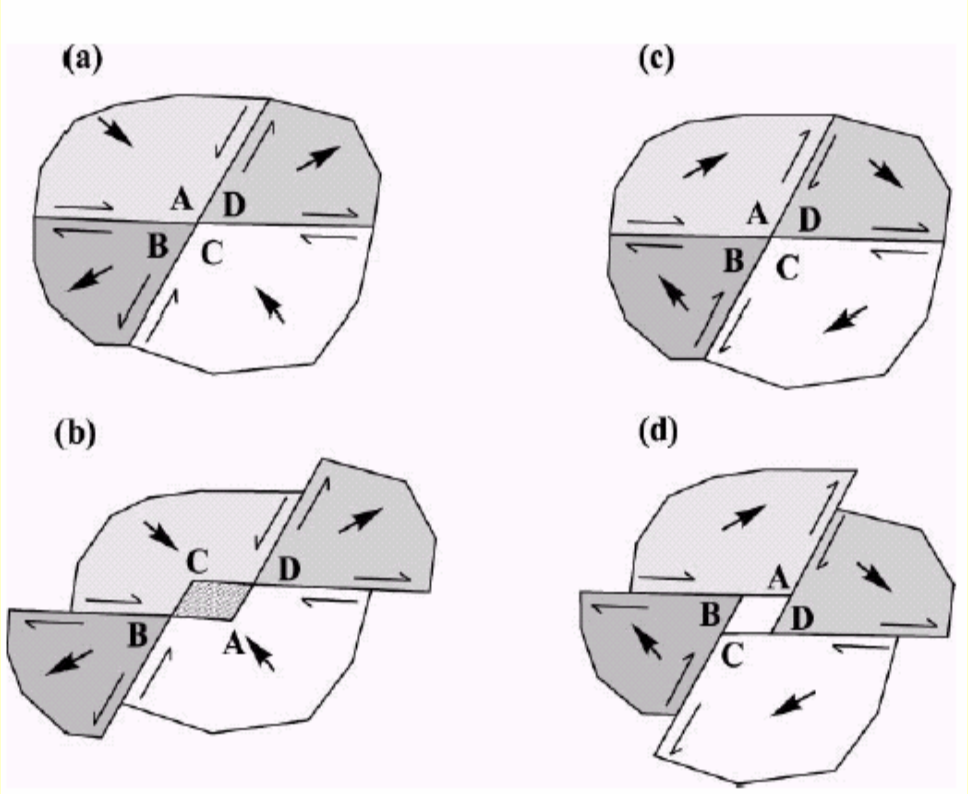


Instability caused by stress corrosion



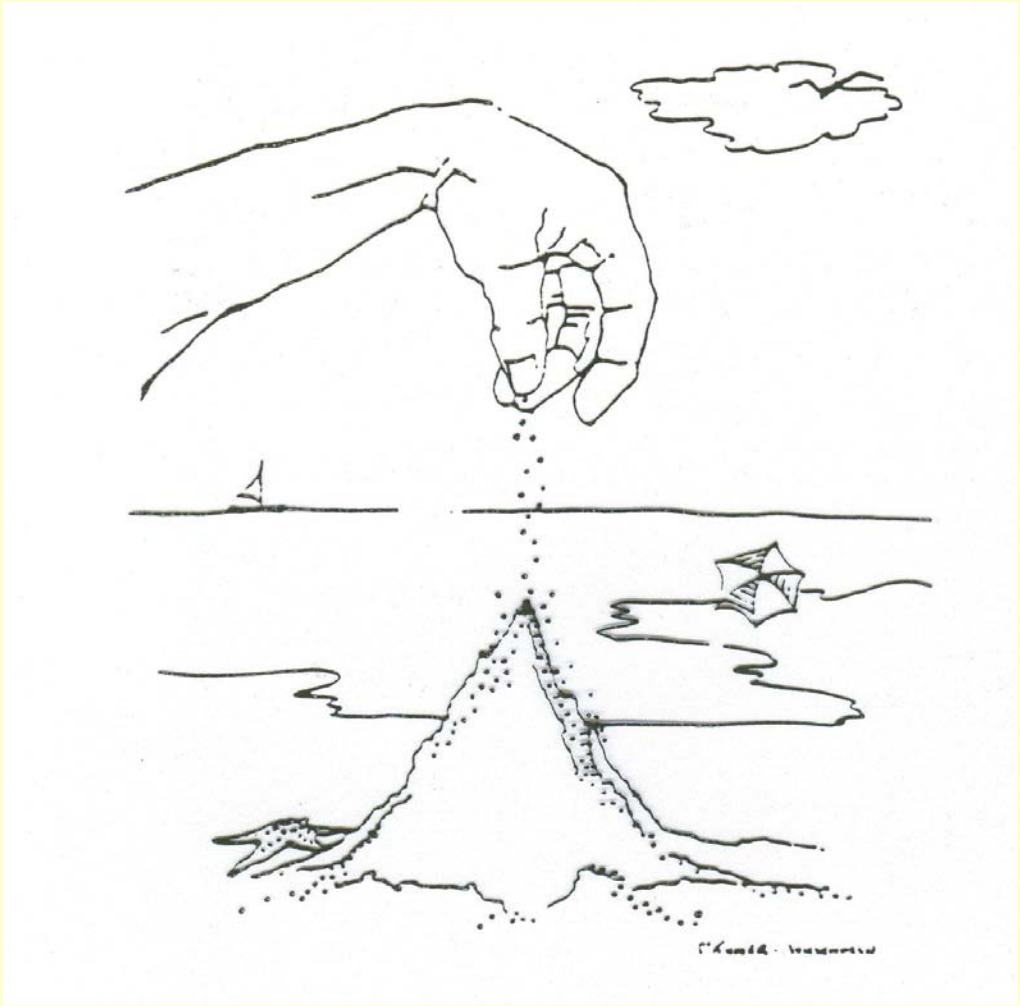
Instability caused by the infiltration of a lubricating fluid

GEOMETRICAL INCOMPATIBILITIES



BAK'S (SAND-PILE) MODEL:

SELF-ORGANIZED CRITICALLITY

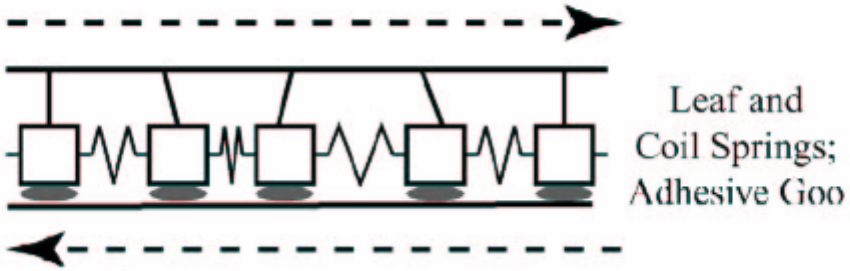


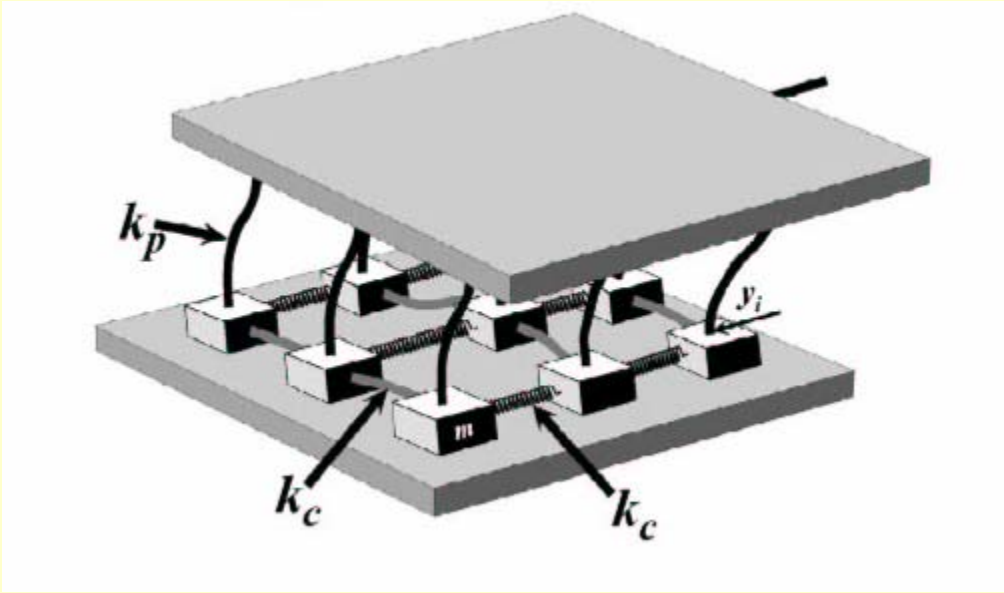
$$Z_i \longrightarrow Z_i - Z_c$$

$$Z_{nn} \longrightarrow +Y_i$$

BURRIDGE-KNOPOFF'S (MASS-SPRING) MODEL

$$m\ddot{u}_i = k\left(u_{i+1} - 2u_i + u_{i-1}\right) - \beta\left(u_i - u_{i0}\right) - \alpha\dot{u}_i + f_i$$





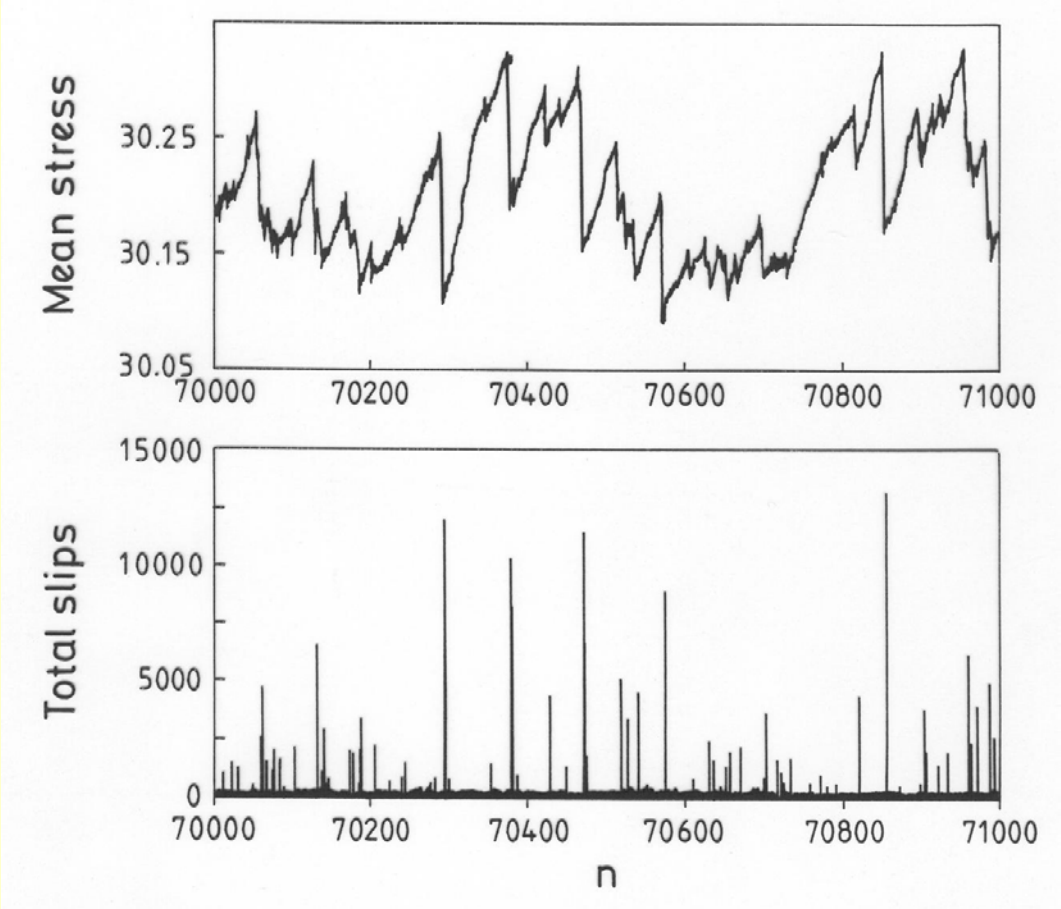
ACTUAL SEISMICITY MODELS

- Forest fire
- Inverse cascade (hierarchical model)
- Percolation
- Block-and-fault systems
- Thermodynamic (statistical mechanics)
- Mass transfer
- Minimalist

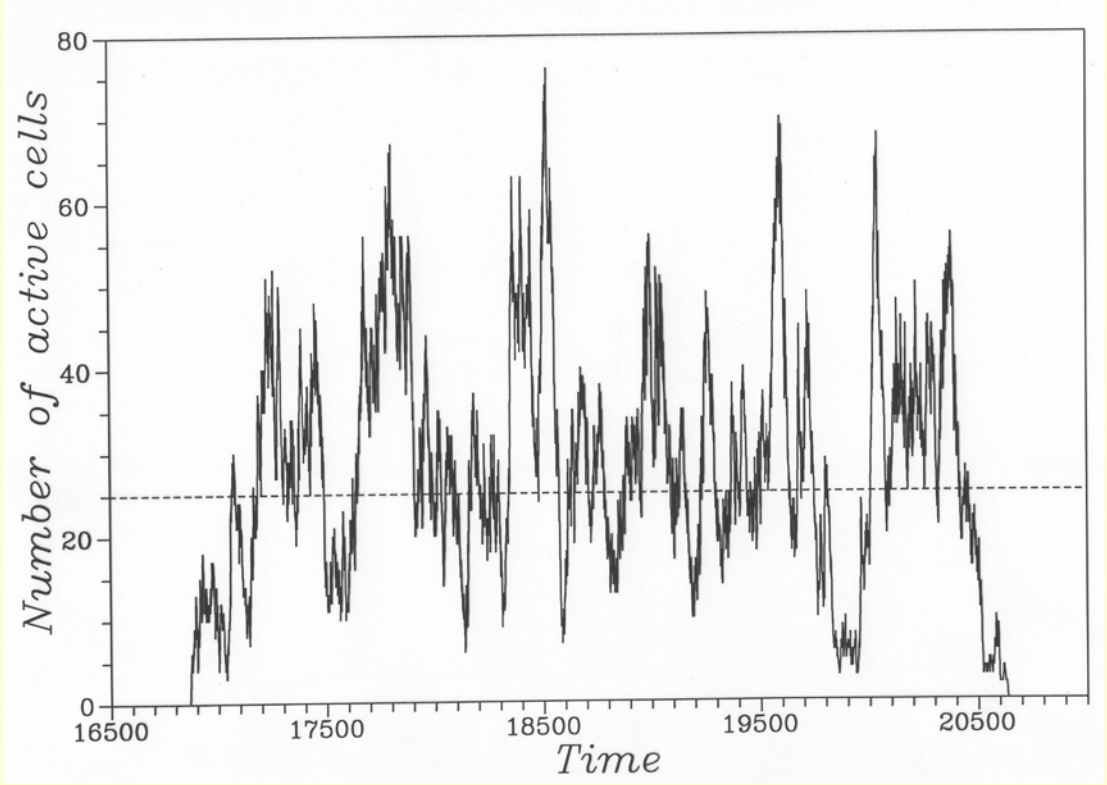
HALLMARKS OF SELF-ORGANIZED CRITICALLITY

Feature	*Sandpiles*	*Earthquakes*
Boundary condition	constant "grain" rate	constant strain rate
Critical parameter	repose angle θ_c	tectonic stress σ_c
Dynamic fluctuation	Small fluctuations in angle $\Delta\theta_c << \theta_c$	small stress drop $\Delta\sigma_c << \sigma_c$
Power law distribution	Avalanche volume or energy	Source length, seismic moment, or energy (Gutenberg-Richter law)

MODEL PREDICTION



EVENT DETECTOR



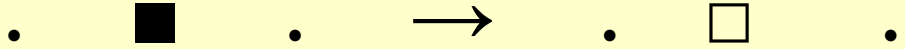
MASS TRANSFER MODEL

Is a toy model designed to describe an extended system with active propagation particles interacting with other active or passive static particles. Starting from a homogeneous mass distribution of *active* and *passive* cells, the system evolves to a *self-organized critical state*.

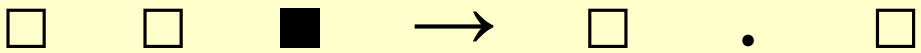
Define a regular 2-D lattice. The cells of this lattice might be found in three possible states: *active*, *passive* or *empty*.

UPDATING RULES

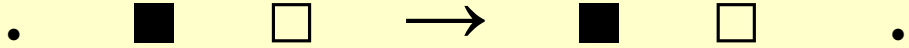
1. Active cells at *t burn out* and become passive at time *t+1*.



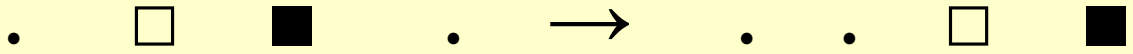
2. Passive cells are annihilated when they have one, and only one, active neighbor.



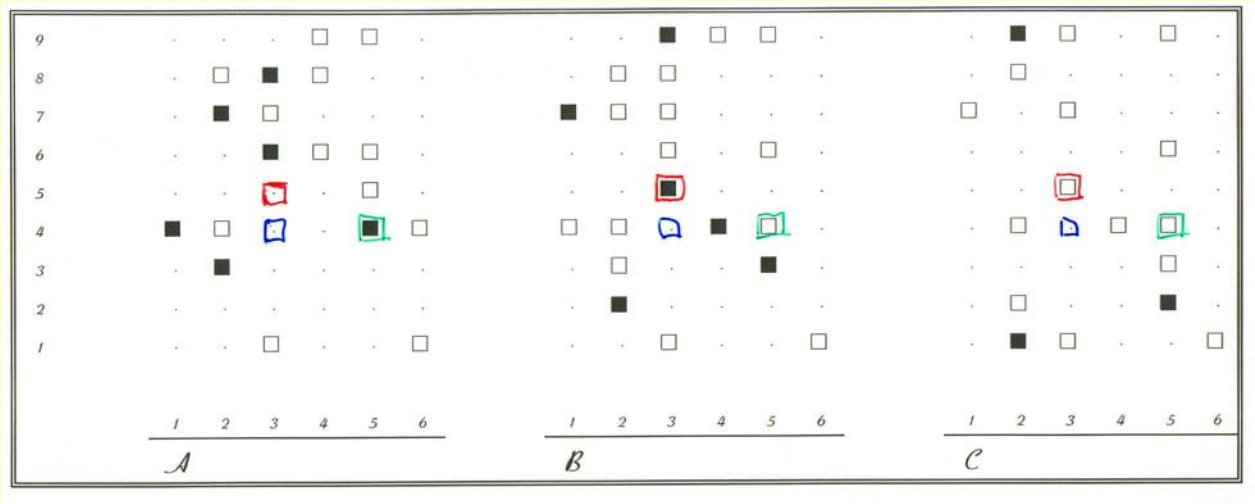
3. Active cells are3 created from empty cells when they have one, and only one, active neighbor, which must have a passive cell at the opposite direction.



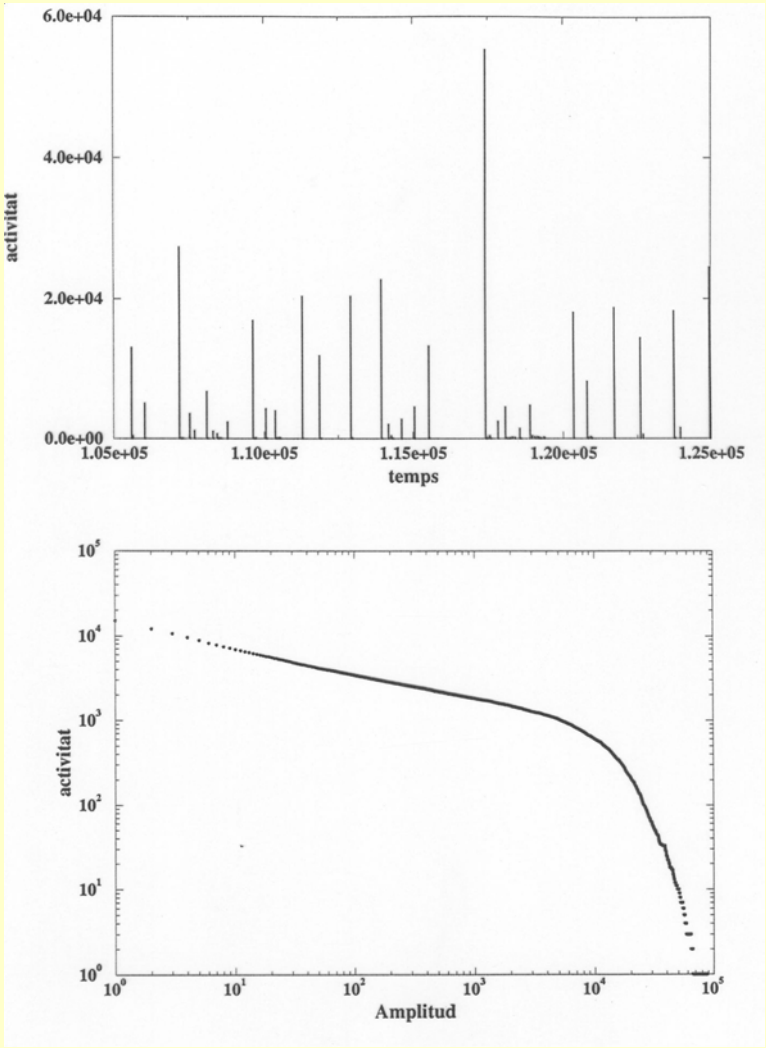
PROPAGATION



EVOLUTION



MODEL CATALOG



EQUIVALENCE TO SEISMICITY FLOW. 1

- The equivalence between the mass transfer model and the flow of seismicity can be clearly stated in terms of a model of nucleation and origin of seismicity developed by Cochard and Madariaga (1994, 1996).
- These authors modeled the dynamics of the faulting through a rate-dependent friction law, and starting from an homogeneous initial stress distribution, found that when friction is strongly rate dependent, the healing process destabilizes producing premature healing of slip and partial stress drop, that in turn results in large variations of the state of the stress.
- As noted by Cochard and Madariaga (1996), the rupture propagation "adjusts" itself to satisfy a scaling law, suggesting that a state resembling that of self-organized criticality has been reached.

EQUIVALENCE TO SEISMICITY FLOW. 2

In short, the equivalence between the mass transfer model and tectonic seismicity can be stated as follows:

Passive cell $\leftrightarrow$ broken asperity

Active cell $\leftrightarrow$ asperity ready to break

Annihilated cell $\leftrightarrow$ healed slip

TUNING PARAMETER