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The Litosphere as a Complex System

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THE LITOSPHERE AS A COMPLEX SYSTEM

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(October 2007)

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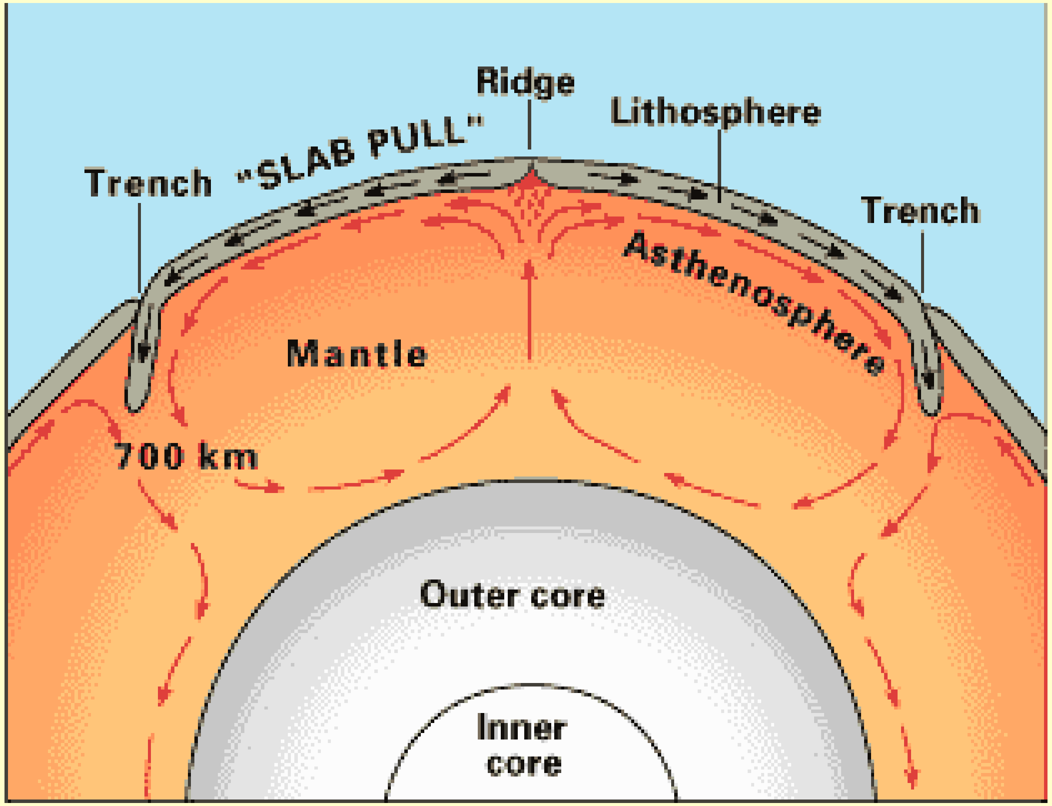
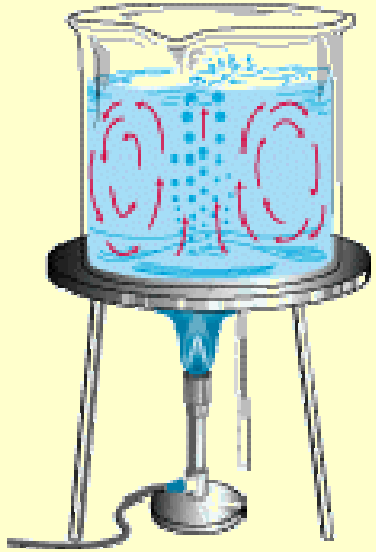
DYNAMICS OF THE MANTLE



Rayleigh-Benard convection



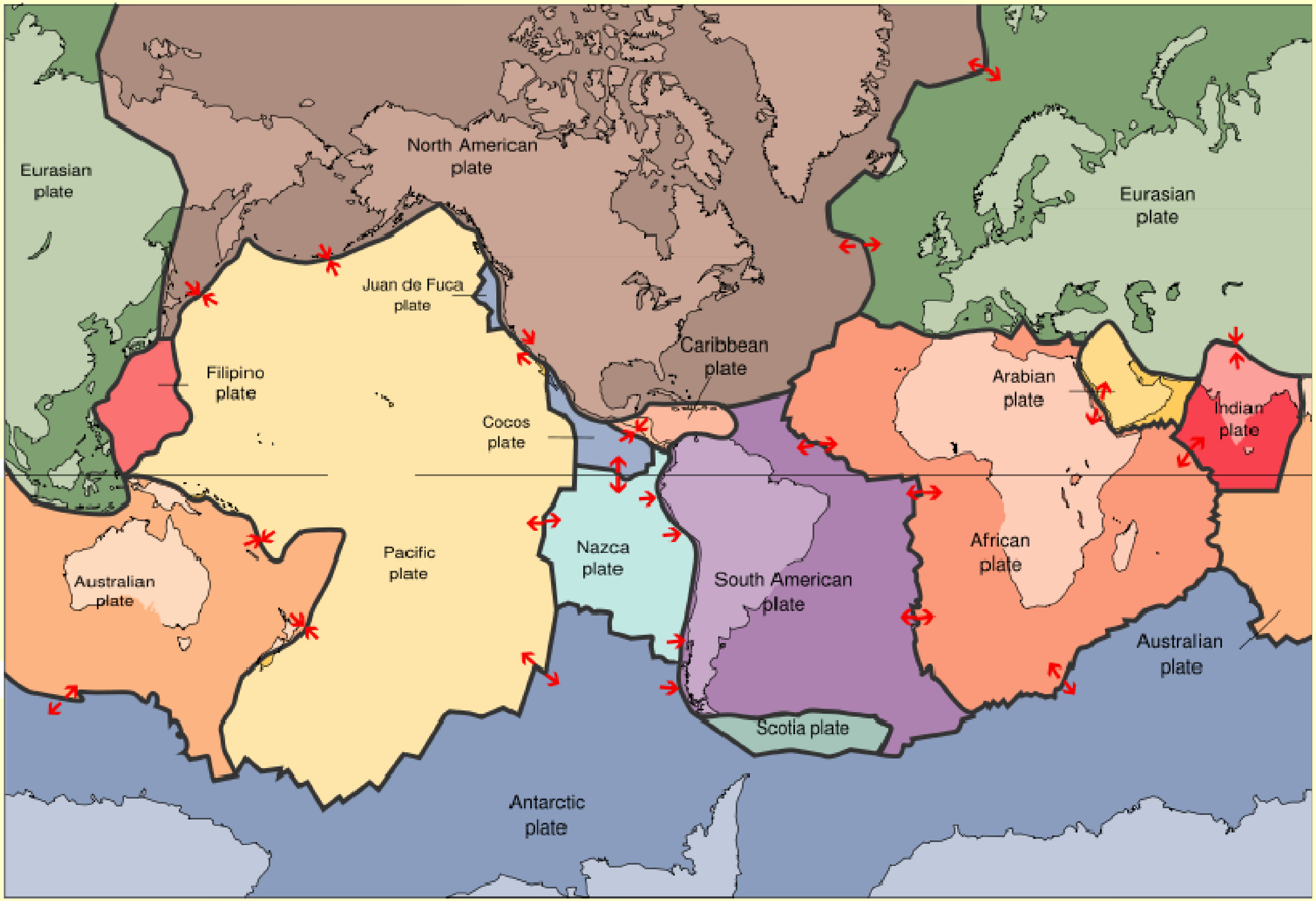
DYNAMICS OF THE LITHOSPHERE

As a consequence of mantle convection, the upper part of the convective cells cools, its rigidity increases and originates the lithosphere.

The lithosphere is not a continuum, but a mosaic consisting in ten or so major plates and some minor ones, all of them in relative motion.

The relative motion between plates originates a variation of the strain field, an thus on the stress field. As the plates motion can be considered as steady, the stress variation can be considered constant until a threshold is reached, in which case the stored energy is suddenly released: an earthquake has occurred. As the plate motion is a nonstop process, the strain field begins again, initiating a new cycle.

This is the contents of the **elastic rebound theory**.

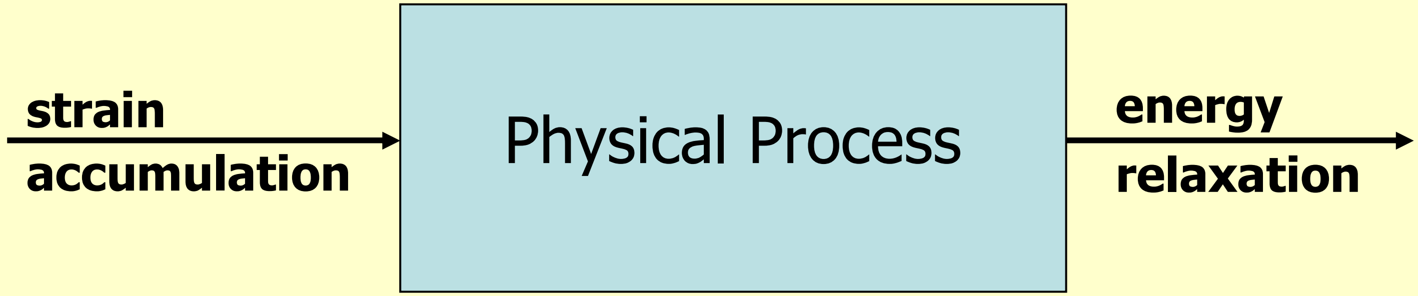


The mosaic of lithospheric plates

PHYSICAL SCENARIO

- Plate Tectonics provides a mechanism to explain earthquake occurrence as a **recurrent phenomenon**, defining cycles.
- The physical scenario of earthquake occurrence is that of a **dissipative (open) system**, with an input of energy that is suddenly released (*failure*). This process repeats again and again, defining earthquake cycles.
- The framework of earthquake processes is that of **far from equilibrium systems**.

THE LITHOSPHERE AS A COMPLEX SYSTEM



Physical process: **medium** response to strain accumulation. The process ends when a failure occurs, i.e., when a threshold in the stress-strain field has been crossed. Strength is controlled by a great multitude of interdependent mechanisms, which brings the system to an **unstable** equilibrium.

On a time scale relevant to earthquake prediction, 10^2 years or less, these factors turn the lithosphere into a **hierarchical dissipative complex system**. A prominent feature of complex systems is the persistent reccurrence of abrupt overall changes called **critical transitions** or **critical phenomena**: the occurrence of **earthquakes**.

MEDIUM. 1

The medium, the lithosphere, is composed by a hierarchy of **blocks** separated by **boundary zones**, with densely fractured **nodes** at junctions and intersections of these zones.

Blocks

The largest blocks are the major tectonic plates of continental size. They include smaller blocks such as shields or mountain belts. After 15 to 20 consecutive divisions, we come to nearly 10^{25} grains of rocks.

Boundary zones

The blocks are separated by less rigid boundary zones, whose widths are 10 – 100 times smaller than the characteristic dimension of the blocks that they separate. They are called fault zones high in the hierarchy and interfaces between gains of rocks low in the hierarchy. Except at the lowest level, a boundary zone presents a similar hierarchical structure with more dense division.

BOUNDARY ZONES

Boundary zone	Block size (km)
Fault zone	10^{4} - 10^{2}
Fault	10^{1} - 10^{-2}
Crack	10^{-3} - 10^{-5}
Microcrack	10^{-6} - 10^{-7}
Interface	10^{-8} - …

These divisions define an interval of more than 12 orders of magnitude!

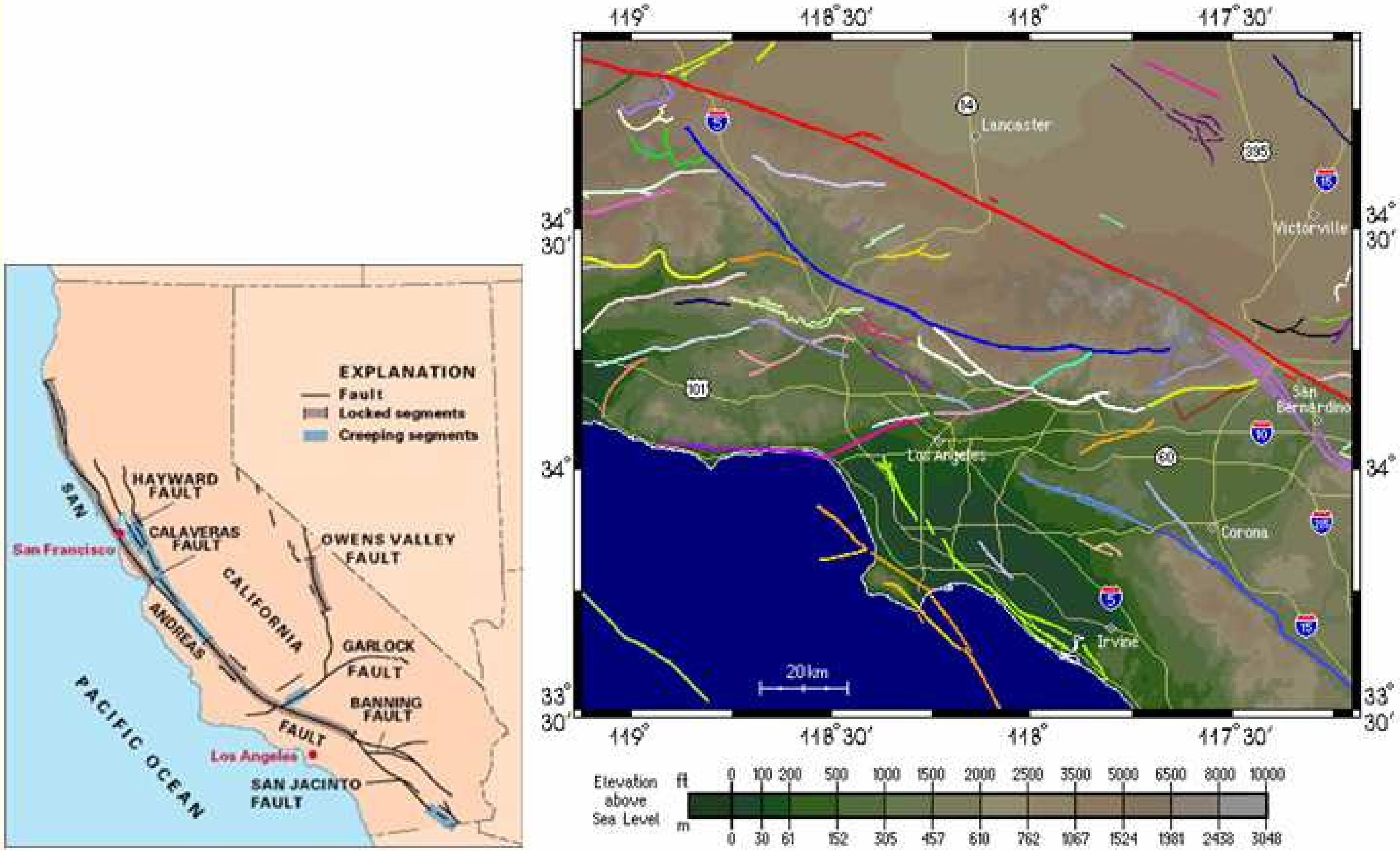
MEDIUM. 2

Nodes

The neighborhood of the intersection and junctions of the faults is characterized by a densely fractured mosaic structure. They origin is due, roughly, to collision of the corners of the blocks

The systems of boundaries and nodes are known as faults networks.

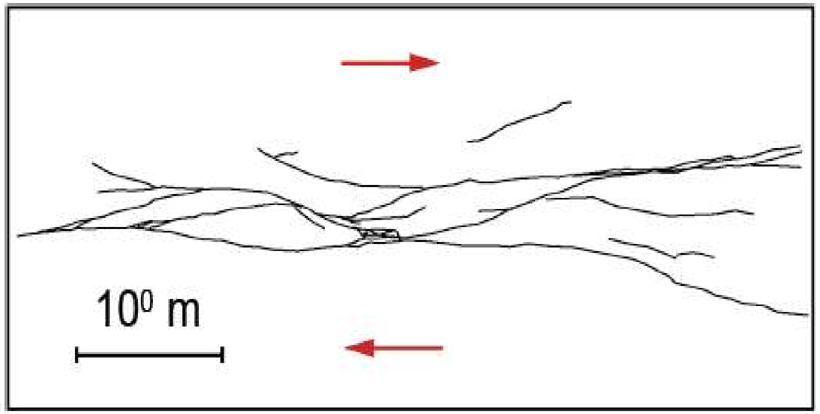
Apart of its hierarchical structure (geometric characteristic), the lithosphere is highly **inhomogeneous** in its rigidity (dynamical aspect), defining patches of different characteristic lengths.



General fault system of California (left) and that around Los Angeles (right).

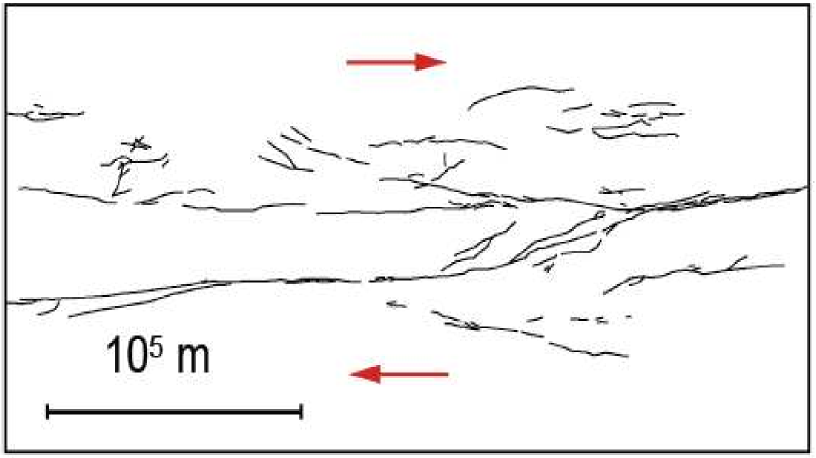
Fault geometry

Individual faults exhibit approximately self-similar roughness



Fault in the Monterrey Formation

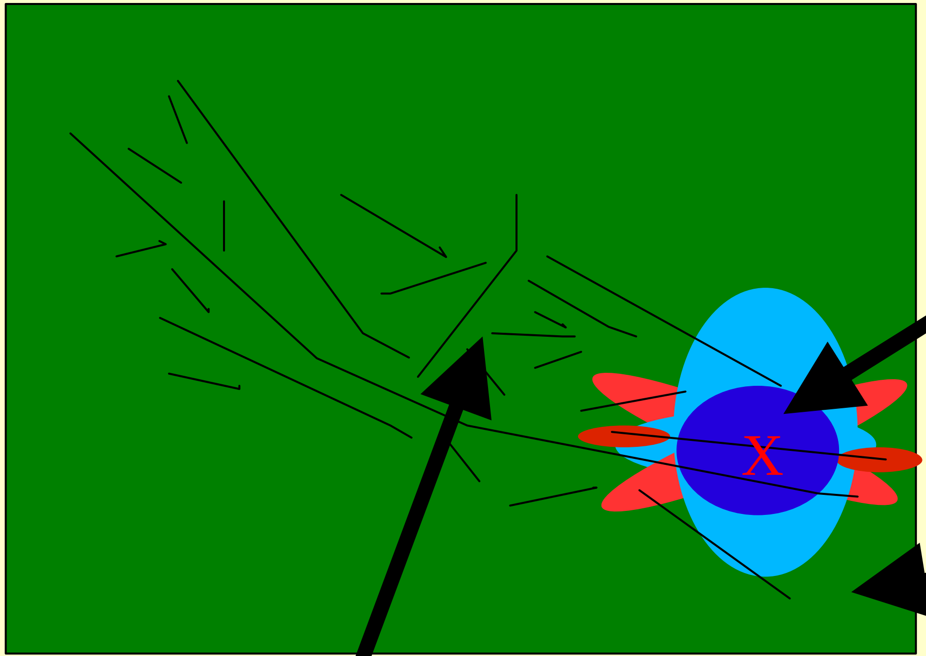
Fault systems also appear to be scale-independent



San Francisco Bay Region

Geometrical characteristics of fault networks

DYNAMICS OF FAULT SYSTEM



Complicated interactions between faults due to stress transfer during Eqs

Nonlinear Rheology

Multi-Fractal fault heirarchy

Earthquake Fault systems are COMPLEX:

- Many degrees of freedom
- Strongly coupled spatial and temporal scales
- Nonlinear dynamical equations & constitutive laws
- Multi-physics: mechanical, chemical, thermal, fluids, (EM?)

D. Weatherley
QUAKES & AccESS
3rd ACES Working Group Meeting
Brisbane, Aust. 5th June, 2003.

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INSTABILITIES. 1

The boundary layers of different rank, from the Circum Pacific seismic belt, with the giant triple junctions for the nodes, to an interface between the grains of rocks, with the corners of the grains for the nodes, play a similar role in lithosphere dynamics.

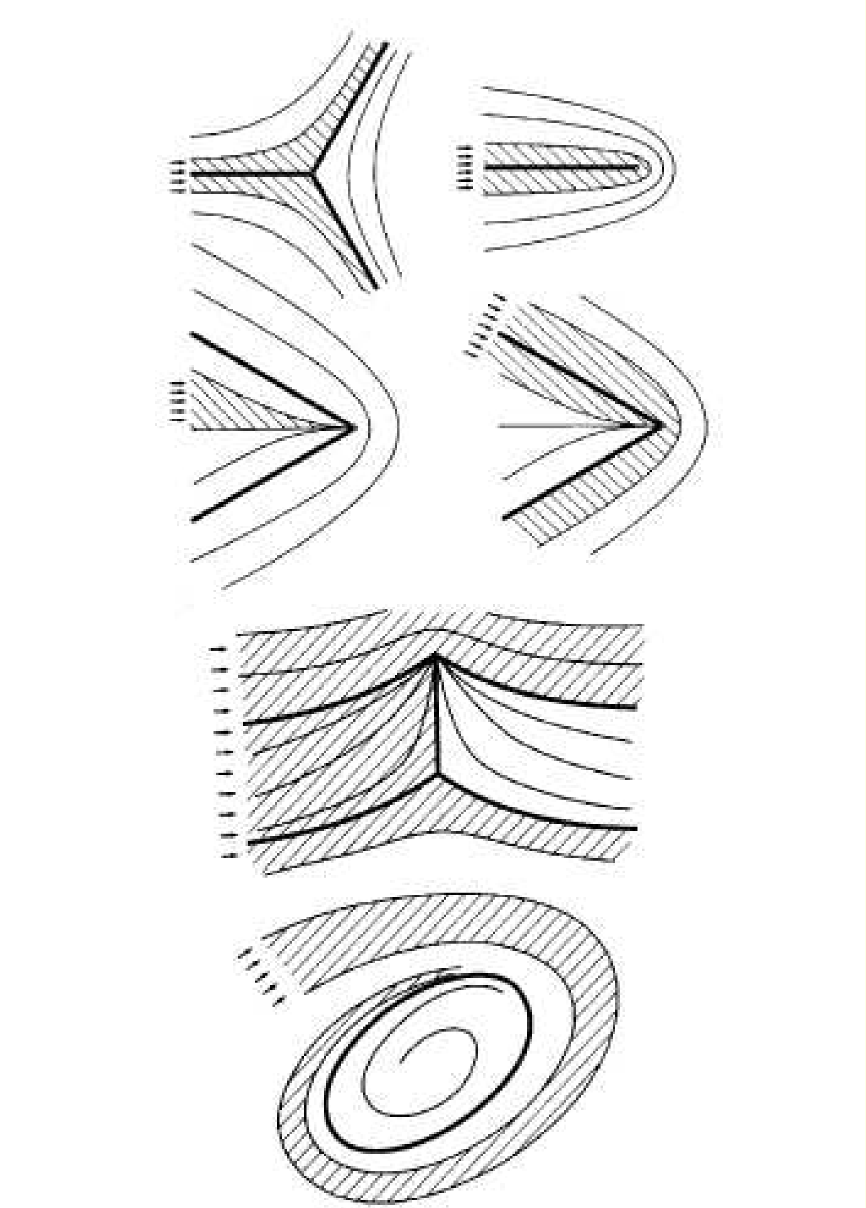
Although tectonic energy is stored in the whole volume of the lithosphere and well beneath, **the tectonic energy release** (through earthquakes and slow deformations) **is to a large extent controlled by the processes in the relatively thin fault networks**. This disparity is due to the following reasons:

1. Deformations and fracturing in the lithosphere are controlled by the {stress-strength} field. At the same time, the strength of the fault network is weakened by denser fragmentation and higher permeability to fluids (compared to the blocks).
2. The strength of the fault networks is not only smaller but also highly unstable, since it is sensitive to many processes there.

INSTABILITIES. 2

Two types of instability coexist in the fault network:

- "physical," originated by a physical or chemical mechanism at the elementary (**micro**) level, and
- "geometric", controlled by the geometry of the fault network on a global (**macro**) level.



PHYSICAL INCOMPATIBILITY. 1

Instability caused by **stress corrosion**. Geometry of the weakened areas depends on the type of stress field's singularity and on direction from which the fluid arrives.

The diagram displays the formation of weak bonds (the upper four diagrams) and asperities (the bottom two diagrams).

However, such effect has at least two limitations: 1) these configurations are of local nature and could be compensated at a global scale, and 2) the fluids may generate other equally strong mechanism.

PHYSICAL INCOMPATIBILITY. 2

Other mechanisms that may generate incompatibilities are

- Nonlinear filtration
- Fingers of fluids
- Dissolution of rocks
- Petrochemical transitions
- Sensitivity of dynamic friction

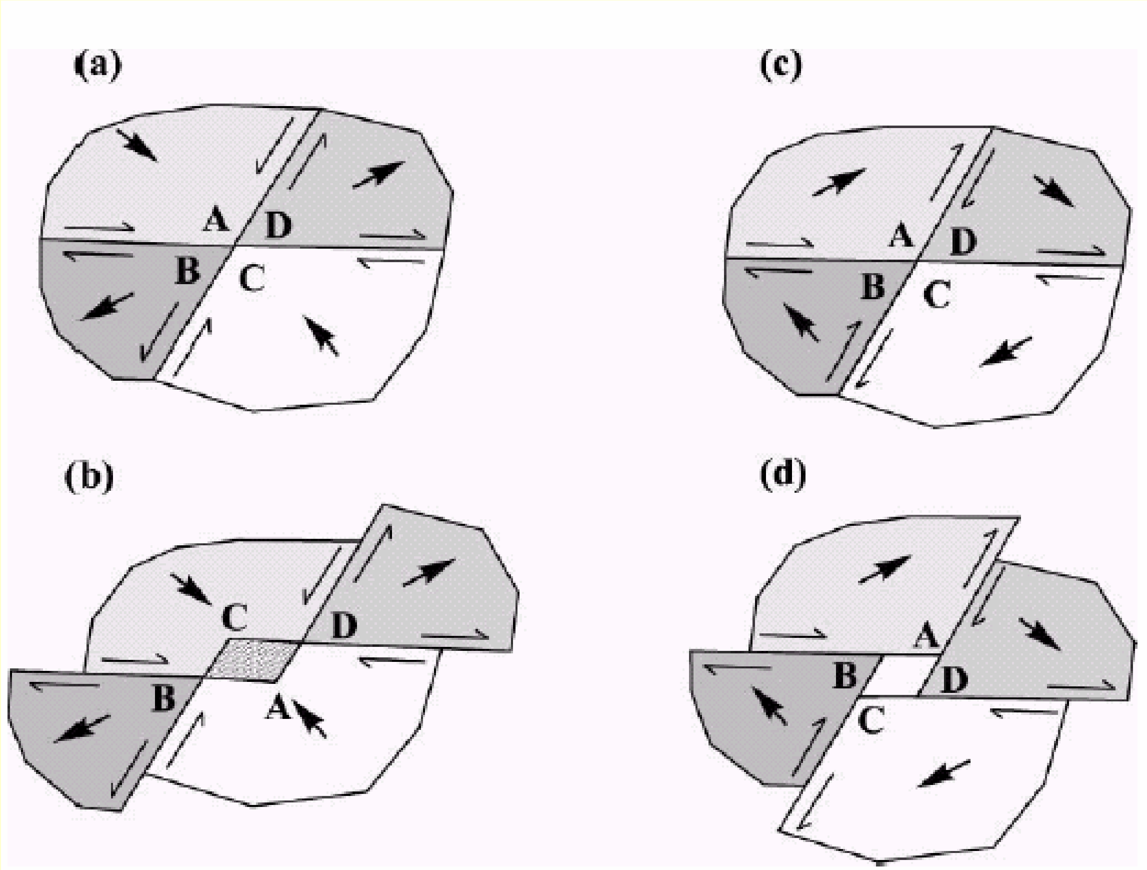
GEOMETRIC INSTABILITY. 1

The geometry of the fault network is often incompatible with tectonic movements. This leads to accumulation of stress, deformation, fracturing, and change of the fault geometry, jointly destabilizing the fault network.

Two integral measures of that instability have been found: (a) geometric incompatibility, concentrated in mosaic nodes, and (b) kinematic incompatibility spread over the whole lithosphere. Each measure estimates an integrated effect of tectonic movements in a wide range of timescales, from seismicity to neotectonics.

The most important types of instabilities are:

- Geometrical incompatibility
- Formation of the nodes
- Kinematic incompatibility



Geometric incompatibility near a single intersection of faults. a, c—initial position of the blocks; b, d—physically unrealizable extrapolation of initial movement. a, b—locked node (penetration of matter); c, d—unlocked node (generation of vacuum).

GEOMETRIC INSTABILITY. 2

Clusters of intersections: In real process we encounter not a single intersection but clusters of intersections in a node, and interacting nodes in a fault network. Geometrical incompatibility is additive, and geometric incompatibility in different nodes is interdependent because the nodes are connected through the movements of blocks and on the faults.

Earthquakes nucleation: There is compelling evidence that strong earthquakes nucleate within certain specific nodes.

Kinematic incompatibility: Assume that the relative movements on the faults can be realized through the absolute movements of the blocks separated by the faults. Kinematic incompatibility is a measure of deviation from that condition; it is also additive

COMPLEXITY. 1

Emergency

The dynamics of the lithosphere is controlled by a wide variety of mutually dependent mechanisms, to a large extent concentrated in the fault network and interacting across and along its hierarchy.

Each mechanism creates strong instability of the {strength-stress} field, particularly of the strength. Except under very special circumstances, no single mechanism prevails so that the others can be neglected.

In the timescale relevant to earthquake prediction problem, 10^2 years and less, the mechanisms destabilizing the strength of the fault network turn the lithosphere into a nonlinear hierarchical dissipative system. As we will see, in that system strong earthquakes are critical phenomena.

COMPLEXITY. 2

Complex systems are not predictable with absolute precision. However, after a coarse-graining (i.e., averaging), in a not-too-detailed scale, premonitory phenomena emerge and a system becomes predictable, up to the limits.

Accordingly, prediction of complex systems requires a holistic approach, “from the whole to details,” in consecutive approximations, starting with the most robust coarse-graining of the processes considered.

DYNAMICS OF THE LITHOSPHERE: OBSERVATIONS. 1

The observed seismic processes are summarized in the **seismic catalog**, that contains tha spatio-temporal location of past earthquakes and its magnitude. A statistical analysis of the events of the seismic catalog exhibits the following characteristics:

1. Earthquakes are rare events.
2. Earthquakes are clustered in both space and time.
3. Earthquakes are rupture events which occur mostly on preexisting faults.
4. Earthquakes have a quasi-constant stress drop which is, on average, much smaller than ambient stress.
5. The external forcing functions , i.e. tectonic strain, is small and constant, inducing extremely low strain rates.

DYNAMICS OF THE LITHOSPHERE: OBSERVATIONS. 2

6. Fault traces are power law distributed in length.
7. Faults are rough surfaces, with power law distributed roughness.
8. The spatial distribution of hypocentral locations of earthquakes and laboratory acoustic emissions are power law distributed in both space and time.
9. Earthquakes are power law distributed in size (Gutenberg-Richter law).
10. Earthquake have aftershock sequences that decay with a power law in time (Omori law).
11. Seismicity can be induced by stress perturbations smaller than the stress drop of individual events. These may be due to previous earthquakes occurring at relatively great distances, or to changes in local pore fluid pressure through man-made activity.

DYNAMICS OF THE LITHOSPHERE: OBSERVATIONS. 3

Observations

The inability of the classical theory to explain the above phenomenology suggests that is should be scrapped and replaced by an entirely new approach: the history of physics contains many instances where apparently reasonable theories had to be discarded because they failed to agree with observations outside the parameter range for which they were originally defined.

(Mulargia and Geller, 2003)

PHASE TRANSITIONS. 1

What is the physical meaning of the ubiquity of power law distributions, which appears to be an important clue to earthquake phenomenology?

Is there a way to use the above phenomenology picture to develop a new class of earthquake models?

Yes! A new class of models exists which appear broadly capable of explaining all the provided evidence, power law behavior in particular.

Acknowledging the complexity of earthquakes, it abandons the deterministic view of the classical approach and turns to the tool that physics uses to deal with systems with a very large number of degfress of freedom : *statistical mechanics*.

By taking such a view, one can only achieve average descriptions of ensembles of similar events, rather than deterministic models of individual earthquakes.

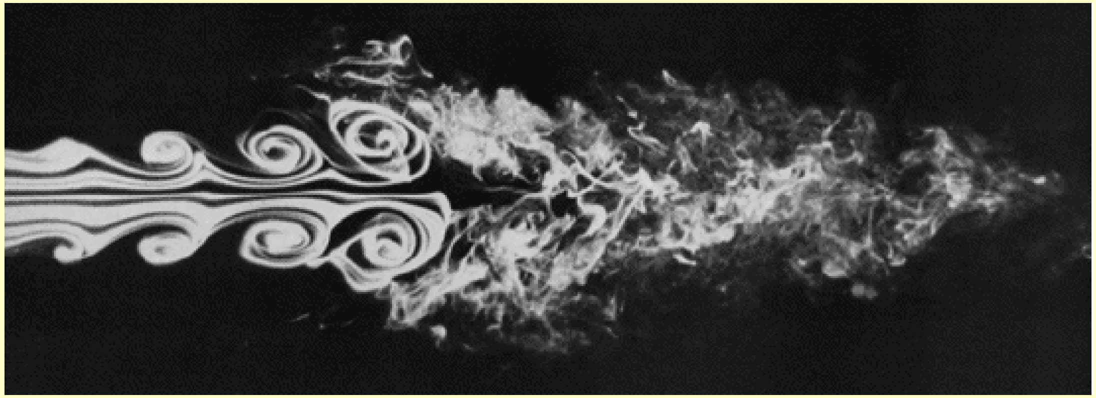
PHASE TRANSITIONS. 2

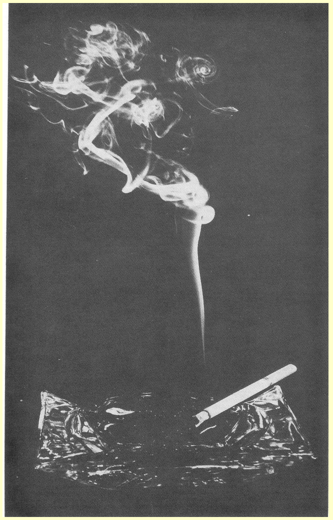
We can recognize that, formally, due to the existence of power laws, and the action at distance, the occurrence of an earthquake can be assimilated to a second order phase transition, order – disorder.

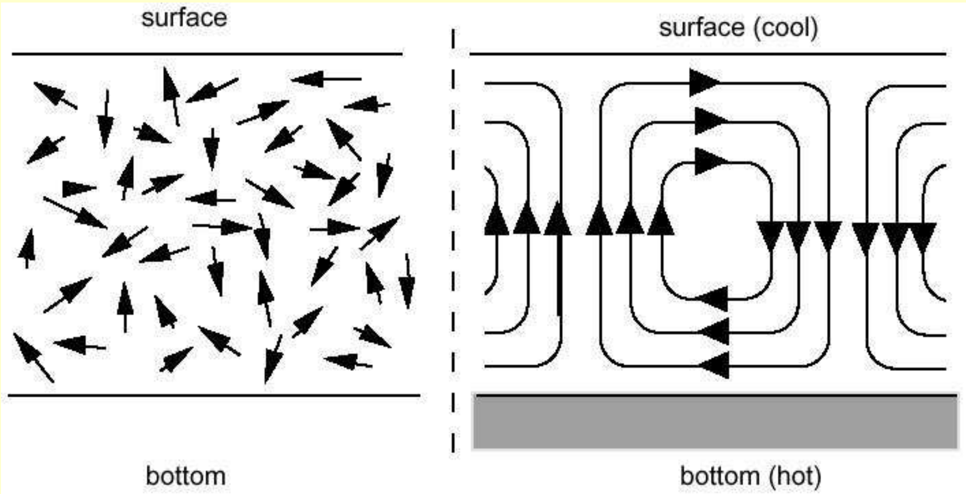
As already stated, the framework of the earthquake occurrence is that of the far from equilibrium systems, for which the paradigmatic example is the convective process that end with the developed turbulence, the equivalent to the occurrence of an earthquake.

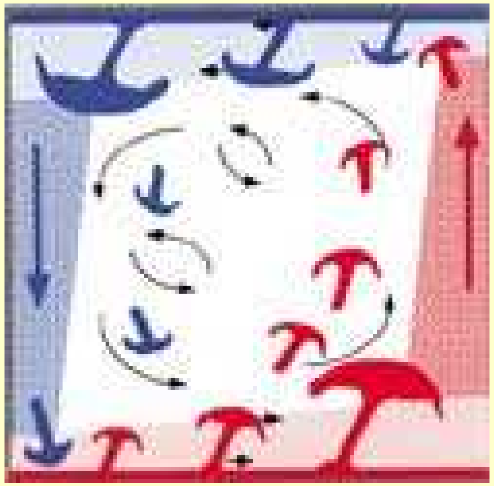
The study of such systems has been very successful in the last two decades, leading to what is called the ***Physics of Complex Systems***.

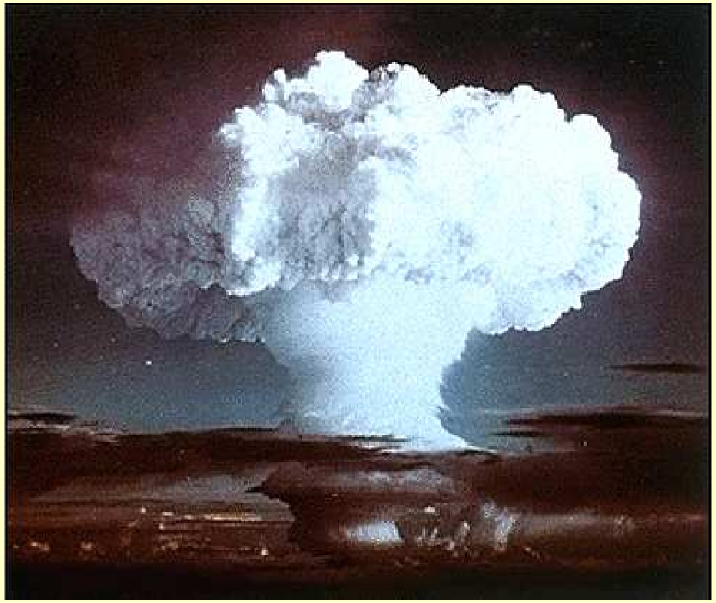
Interpretation











THERMODYNAMIC CRITICALITY & SELF-ORGANISED CRITICALITY. 1

THERMODYNAMIC CRITICALITY

- Occurs when thermodynamic systems are driven through a phase transition by varying properties such as temperature, pressure, etc. These systems require "tuning".
- Characterised by a sudden change is macroscopic properties of the system.
- As a critical point is approached, long-range spatial and temporal correlations emerge → **power-laws**.
- Thanks to mean-field theory etc., thermodynamic criticality is relatively well understood and the values of various measurable quantities (e.g power-law exponents) can be predicted.

THERMODYNAMIC CRITICALITY & SELF-ORGANISED CRITICALITY. 2

SELF-ORGANISED CRITICALITY

- Certain classes of systems do not require "tuning" to go critical.
- Criticality represents an attractor for the dynamics of these systems.
- SOC is elegent because it can explain observations of power-law correlations in natural systems without needing to hypothesize the existence of a "god-like" system-tuner who turns the knobs to cause criticality

WHERE TO GO NEXT?

- Numerical simulations are often based on Cellular Automata models, with the aim of mimic **second order Phase transitions**.
- The Block-Slider and Sandpile automaton, for example, are hardly rigourous models for interacting fault systems, however their simplicity is advantageous. We can study the long-term system behaviour of such models relatively easily.
- The simplicity of the models allows one to experiment with various different approaches for failing sites, redistribution of energy, dissipation, healing of failed sites etc.
- Doing so reveals that SOC is not as “universal” as first thought models in different regimes of parameter space may have significantly different long-term dynamics.

HOWEVER ... 1

Discussion

As shown by the team working in earthquake prediction of the *International Institute of Earthquake Prediction Theory and Mathematical Geophysics*, about an 80% of largest earthquakes have been correctly forecasted in the last decade.

The underlying model in which the predictions are performed is that of critical phenomena, and more precisely, that of second order phase transitions for which precursory phenomena occur. The methodology used is pattern recognition.

What about he remaining 20 %?

Two possibilities arise:

1. Failure of the algorithms (why?)
2. The model of continuous phase transition is not universal.

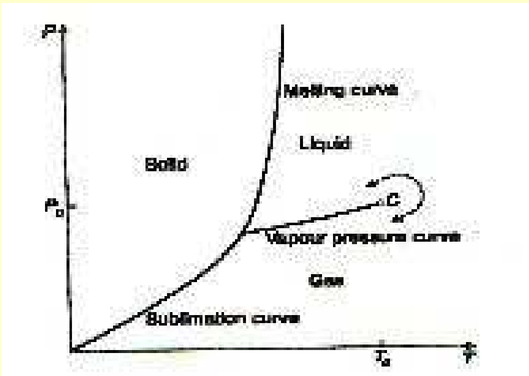
HOWEVER ... 2

Discussion

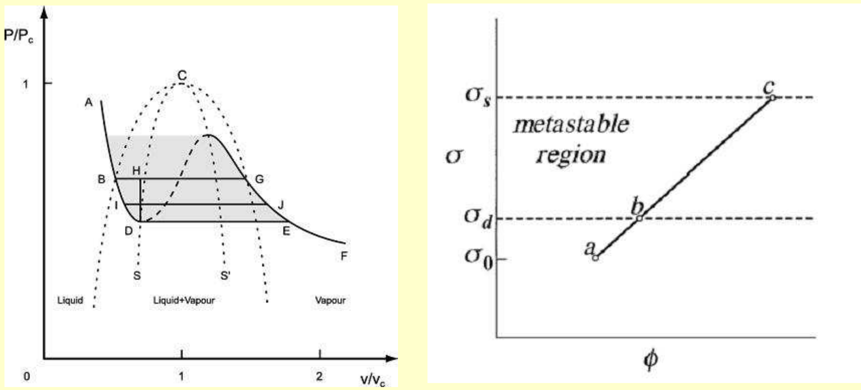
Much evidence has been collected during the last decade that, in some cases, the earthquake is preceded (for a few tens of seconds) by a nucleation phase, the appearance of microcracks in the source region.

From a statistical mechanics point of view, the appearance of a nucleation phase and the subsequent rupture can be assimilated to a first order phase transition, which will take place in a metastable region.

In a first order phase transition there is not any precursory activity, apart of the nucleation.



Continuous ph. t.



1st order ph. t.

CONTINUOUS OR 1st. ORDER PHASE TRANSITION?

A lot of evidences are provided in favor of earthquakes as equivalent to a continuous phase transition (preceded by precursory activity), but there are also some evidences in favor of earthquakes as a 1st order phase transition.

It could very well be that the initial conditions of the dynamics of the lithosphere determine whether continuous of 1st. order.

In statistical mechanics it is well known that the **Potts model** (related to magnetic material) allows for both processes, depending on the number of grown states and the temperature, so from a physical point of view it is possible.

This process has not yet been explored for the case of the dynamics of the lithosphere.

The temperature could be assimilated to the stress concentration, but what about to the grounds states? May be to the order of the hierarchical structure of the lithosphere?

EQUIVALENCE OF TECTONIC MOTIONS

(Lomnitz, 2007)

Tectonic plates are in relative motion. Two tectonic plates are moving against each other while the boundary remains locked. Two different interpretations are possible:

1. The stress $\boldsymbol{\sigma}$(t) at the boundary is an increasing function of time t while the strength $\boldsymbol{\sigma_c}$ at the same boundary remains constant. This is called **elastic rebound**.
2. The stress $\boldsymbol{\sigma}$ at the boundary remains constant while the strength $\boldsymbol{\sigma_c}$(t) at the same boundary is a decreasing function of time. This is called **strength degradation**.

In either case the rupture will occur when $\boldsymbol{\sigma} \geq \boldsymbol{\sigma_c}$.

ELASTIC STRAIN ACCUMULATION?

Geodetic measurements are presented as evidence of systematic relative displacement between adjacent plates, in support of elastic rebound.

However, the available measurements could equivalently be interpreted as resulting from strength degradation, depending on the assumptions used in converting geodetic displacement rate to stress, *i.e.,* on the constitutive relations. The experimental strain rates at the San Andreas fault are below 100 nanostrains per year, and such small strain rates could easily be absorbed by creep deformation at constant tectonic stress if the observed creep rates from GTSM (Glddwin Tensor Strain Monitor) were used.

If plate boundaries have capacity to spare for storing plate tecnonic deformation as creep strain, the argument for elastic strain accumulation at plate boundaries becomes fallacious.

ELASTIC REBOUND MODEL

Is based on five propositions:

1. Fracture is caused by elastic strains exceeding the strength of the rock.
2. These strains accumulate over a long period of time.
3. Coseismic motion represents the elastic rebound or release odm the stored elastic strain.
4. Seismic waves originate at the fracture of the rock.
5. The energy of the earthquake equals the elastic strain energy previously stored in the rock.

These propositions are currently accepted, although nothing is stated about the origin of the strain accumulation.

(Lomnitz, 2007)

DYNAMICS OF TECTONIC PROCESSES

Earth system processes perform work by degrading sources of free energy, thereby producing entropy.

For example, the work required to drive atmospheric circulation is performed by degrading the temperature differences between the equator and the poles. **There is no accumulation of temperature differences anywhere. In elastic rebound, on the other hand, strain energy must accumulate in a bounded region of space**.

How can long-term local and regional accumulation of energy arise in an open steady-state system?

Convection often is invoked, but no energy accumulates anywhere in a convecting system

PRE-EXISTING FAULTS

Earthquakes never occur in the undamaged host rock.

Fault zones are lithospheric features where the rock is damsaged as a result of environment corrosion.

Faults have a much lower strength than the surrounding rock; therefore fracture occurs at a much lower stress, and the amount of heat produced by friction is much smaller than expected.

The phenomenon of environmental stress fracture is caused by decaying shear strength at weaknesses in the material under conditions of constant stress.

Often there is no warming signal of an impending rupture, because there is no stress accumulation.

ELASTIC REBOUND vs STRENGTH DEGREADATION

Prediction experiment at Parkfield. An event of magnitude 6 was predicted to occur around 1998 ± 5 years.

The predicted earthquake did finally occur in 2004, but it was the wrong earthquake: right magnitude and close in location, but different in significant details.

There was no evidence of any long term or short term precursory signals. Borehole strain meters recorded non strain accumulation.

It was concluded that the expected "confirmation" by plate tectonics had ailed. Yet the Parkfield experiment remains the only full scale test of elastic rebound.

Alternate models, such as the model of strength degradation, were not tested. However, the field data of the Parkfield experiment fit strength degradation better than elastic rebound: the striking evidence of precursory signals is against the model of continuous phase transition.

THE PARKFIELD EXPERIMENT

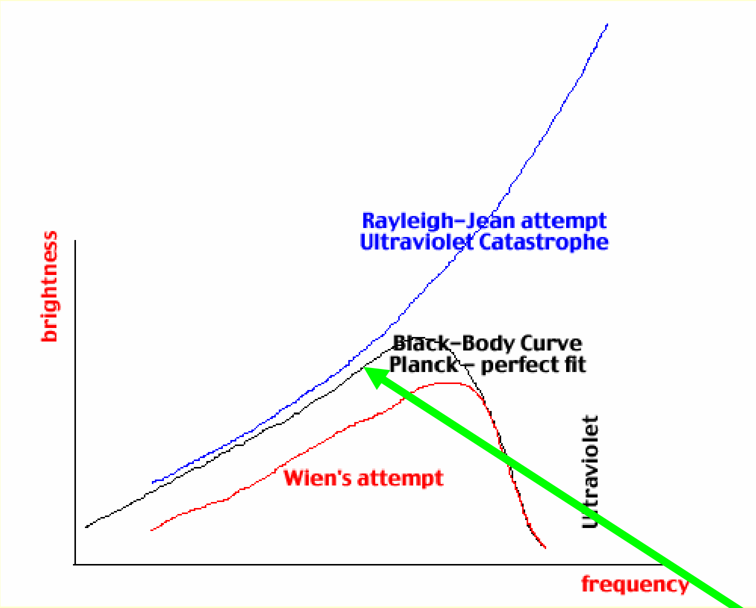
The Parkfield experiment demonstrates unequivocally that, at least in this fault segment, there is no detectable strain buildup at plate boundaries before an earthquake. Thus, tectonic stress are not accumulating at this place.

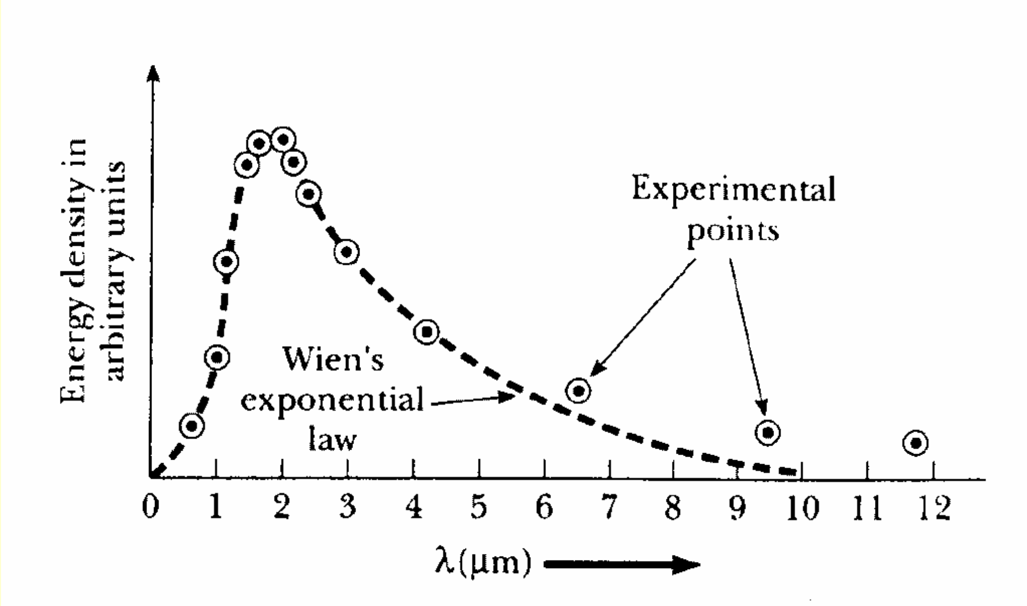
Did the Parkfield experiment achieve what is set out to test? If so, a discussion on alternative models of earthquake causation is mandatory. If not, where and how should the hypothesis of elastic rebound bem tested?

In the mean time, elastic rebound should be put on hold, as being due for a fundamental revision.

BLACKBODY RADIATION

Theoretical framework





Different approaches and Planck's law

THEORETICAL FRAMEWORK. 1

According to observations,

1. About 80% of large earthquakes have been forecasted by pattern recognition, obeying the underlying theory of critical phenomena (continuous phase transition).
2. About 20% of large earthquakes have escaped forecasting due to
    - Algorithmic failure
    - 1st order phase transition / strength degradation
    - Other …

THEORETICAL FRAMEWORK. 2

Does this 20% of “failures” invalidate the model of phase transition?

Not really. Probably, as in the case of instabilities, there is not only one model to reach failure, although the critical process model may be the most frequent, at least for large earthquakes.

As a working hypothesis we advance that there are the initial conditions and/or the boundary conditions which select whether the physical process corresponds to continuous of 1st order phase transitions. Potts model may account for it.

A completely different question refers to whether elastic rebound theory or strength degradation. The underlying physics (for the case of plate tectonics) has not yet dealt with.

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