Earthquake Physics as a basis of Prediction

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Four Types of Earthquake Prediction

- Time-independent Hazards

  (=> Seismic Risk Estimates)

- Time-dependent Hazards

  (=> Seismic Risk Estimates)

- Earthquake Forecasting

  (=> Seismic Potential Evaluation)

- **Deterministic Prediction**

  (=> Earthquake Prediction)

A direct way to prevent or reduce seismic risk is, of course, the reliable deterministic prediction of an impending earthquake (including the epicenter, occurrence time, and magnitude). For a long time, this has been a dream of earthquake scientists. Up to date, except for very few earthquakes, for example the 1972 Haicheng, China, earthquake, we can say that deterministic earthquake predictions totally failed.

In the seismically active areas, the government and public strongly requests seismologists to provide reliable predictions. But, public education is not enough to help the laypersons to make correct response to un-reliable but exciting predictions.

It is noted that the government and public would pay more from false predictions than correct ones.

Two Different Viewpoints:

Omori's Viewpoint: Un-predictable and random

Immamura's Viewpoint: Predictable

They were professors of seismology of Tokyo Imperial University. Before 1923, they seriously debated about the possibility of occurrence of an big earthquake in the Kanto area.

=> the M7.9 Kanto Earthquake of September 1, 1923

Criteria for Predicting an Earthquake:

1. Time: t±3 days (difficult)

2. Location: r±30 km (less difficult)

3. Magnitude: M±0.5 (least difficult)

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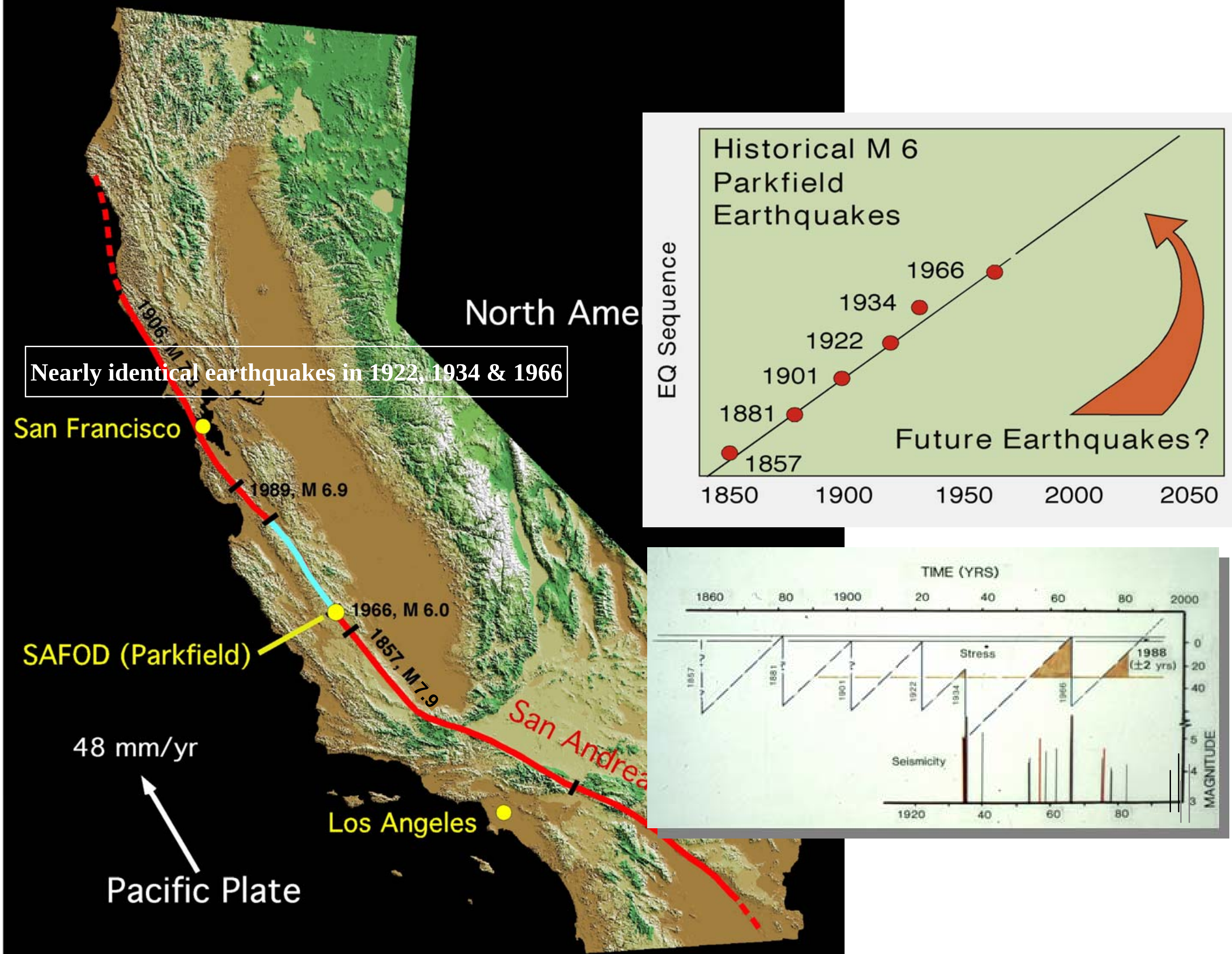
Waiting for Parkfield to Quake

After dark on November 16, a media van collided with a cow while driving through earthquake county near Parkfield, Calif. That may have been the most damaging incident to occur during the 72-hour earthquake alert issued, on November 14, [1992] by the state's office of Emergence Service (OES).

Officials issued the Level A alert [on 20 October 1992] – meaning there was a one in three chance of a magnitude-6 quake within 3 days – following a 4.8-magnitude quake in the town of Parkfield, on the San Andreas fault.

A-level alert: The estimated probability of an M=6 earthquake within the next 72 hours, based on potential foreshocks, aseismic creep or a combination of the two, exceeds 37%.

Nearly identical earthquakes in 1922, 1934 & 1966



Two threads of earthquake prediction are:
(1) The earthquake prediction was approached through a compilation of a succession of isolated case histories of presumed precursors to subsequent earthquakes. The assumption is that these precursory phenomena would appear before many, if not all, subsequent events. But, the assumption for some precursors have either failed or proved extremely difficult to document.
(2) The presumption that small earthquakes are scaled-down versions of large ones. In other words, the supposition is made that the study of small events would reveal important truths about large earthquakes. This is problematic, because large earthquakes cannot be evaluated from small and intermediate-sized events through the Gutenberg-Richter's frequency-magnitude law, i.e., $\log(N)=a-bM$.

Challenges of earthquake prediction are:

(1) Unlike weather, to date predictions are made in the absence of or only few directly visible signals;

(2) There is difficult to debunk unfounded and non-testable predictions, especially for short-term ones;

(3) Decisions are usually made under high uncertainties, because it must take years to validate probability models, and, thus, it is difficult to assess cost-benefit; and

(4) There is lack of a comprehensive physical model.

Why?

In past time, the reductive approach was prevailing for earthquake prediction, while the deductive approach was very weak.

In principle, the reductive approach has no ability to predict something, but the deductive approach can.

The observations of all kinds of precursor must be testable.

Methodologies for Testing

1. Statistical Model (e.g. Kagan)
2. Statistical plus Physical Model: (e.g. M8 Algorithm by Keilis-Borok et al.)
3. Physical Model (incomplete)

Since the Imperial Earthquake Investigation Committee was funded after the Nobi, Japan, earthquake of 1891, earthquake prediction has Been become the major goal of Japanese seismologists.
The "Blueprint" finished by Tsuboi, Wadati and Hagiwara (1962) Was the basis for Japan's prediction program.

SCIENCE, Vol. 264, 17 June 1994

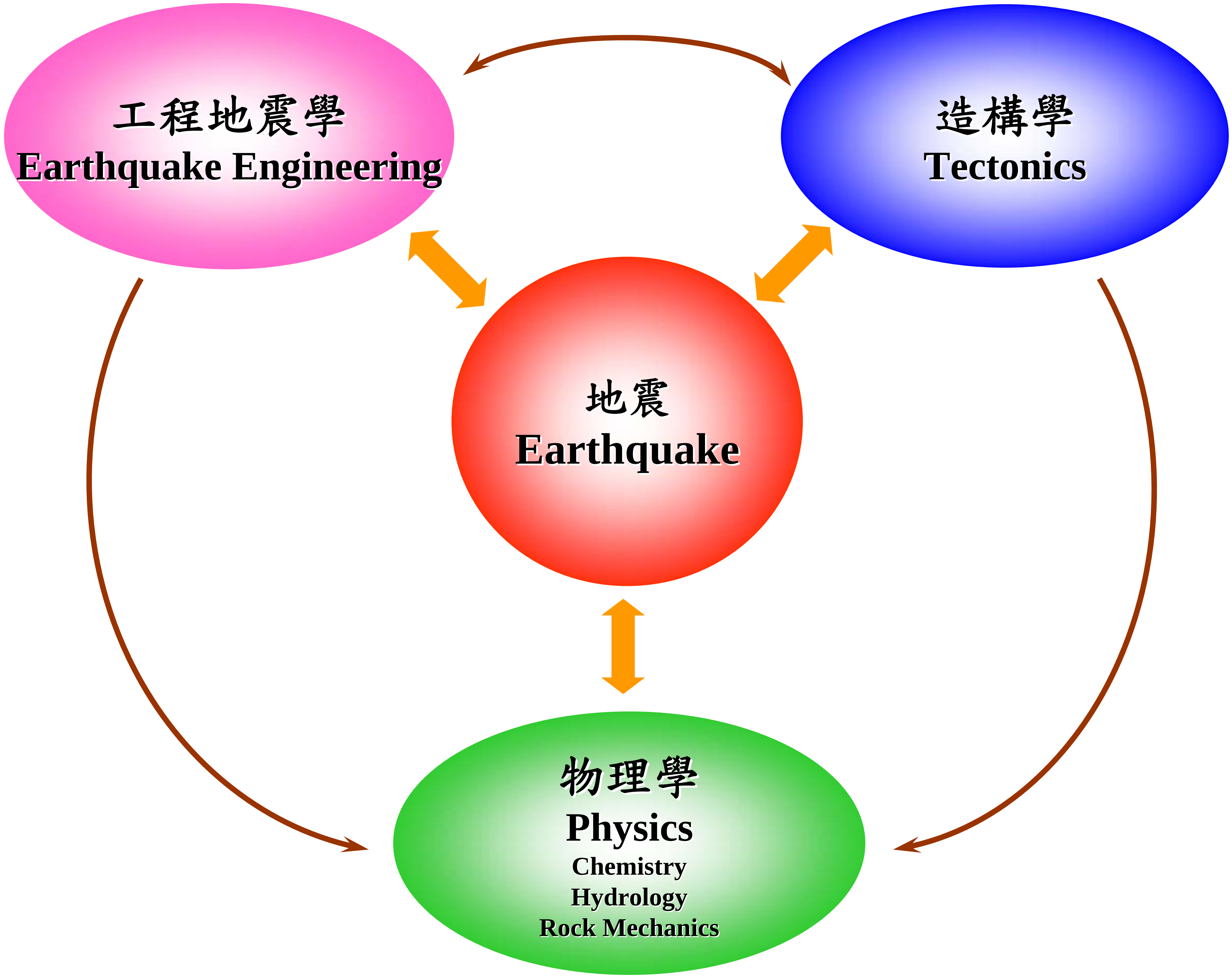
Japan Holds Firm to Study Shaky Science
Most countries have reduced funding for earthquake prediction following a string of disappointing research results, but in Japan it remains a national priority. Scientific criticism is growing, however. (Budget: USD100 million a year)

Nature Vol. 397, 248, 1999

1. Japan to try to understand quakes, not predict them

(<= 15 Jan. 1993 M7.1 Hokkaido Earthquake and 17 Jan. 1995 M7 Kobe earthquake)

2. China clamps down on inaccurate warnings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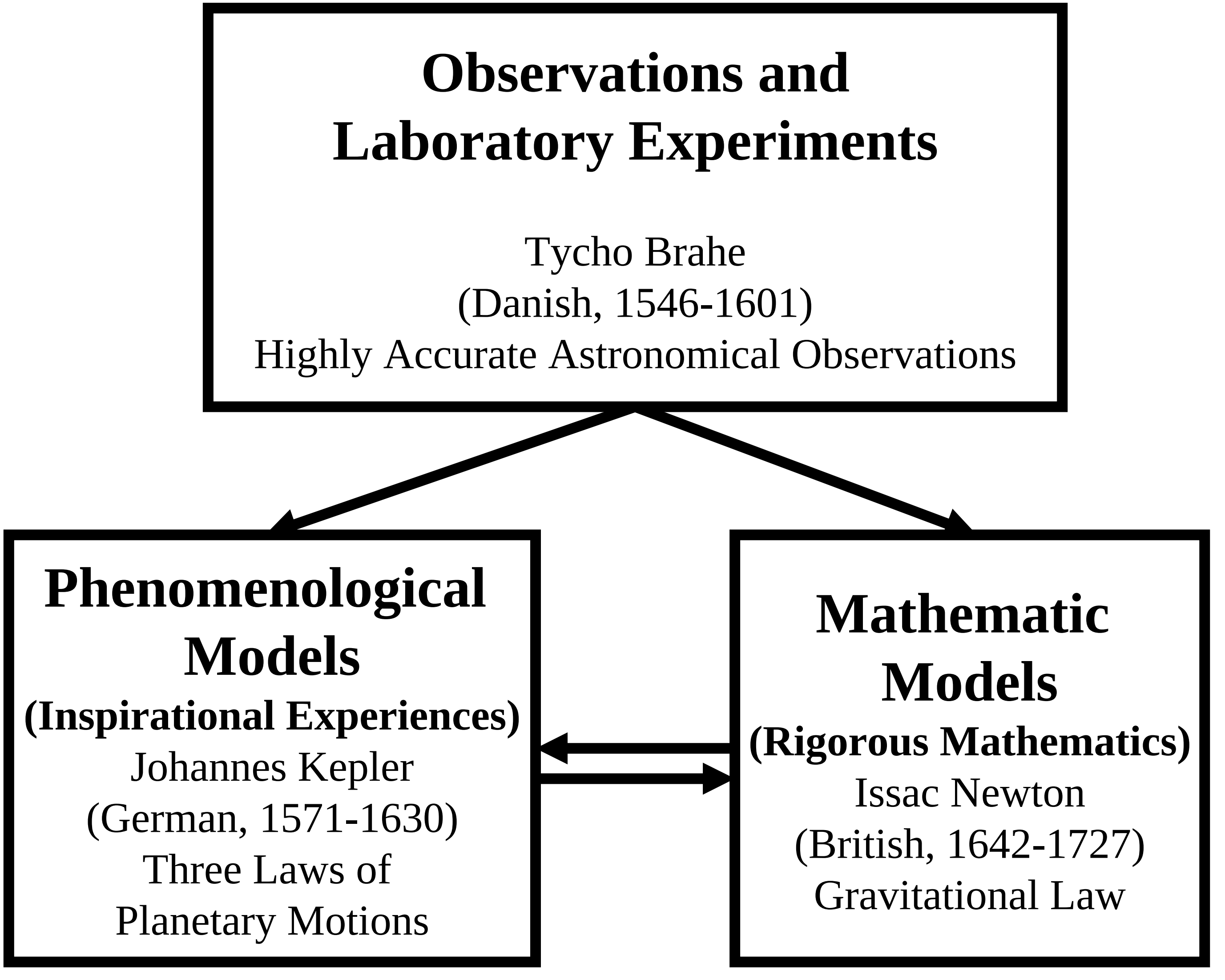

Observations and
Laboratory Experiments
Tycho Brahe
(Danish, 1546-1601)
Highly Accurate Astronomical Observations
Phenomenological
Models
(Inspirational Experiences)
Johannes Kepler
(German, 1571-1630)
Three Laws of
Planetary Motions
Mathematic
Models
(Rigorous Mathematics)
Issac Newton
(British, 1642-1727)
Gravitational Law

A Minimal Set of Ingredients:

1. plate tectonics: to restore energy dissipated in faulting and creeping
2. Ductile-brittle fracture rheology
3. Stress re-distribution after fractures
4. Non-uniform geometry of the fault plane
5. Heating and cooling on the fault
6. The fluid effect in and around the source area
7. The healing process of the fault zone

Current Capability:

1. Model: modest
2. Constitution law of friction: incomplete
3. Initial condition: totally unknown

Models for Earthquake Prediction

1. Stochastic Model (Knopoff)
2. Stochastic+Physical Model:
   - (a) M8 Algorithm (Keilis-Borok et al.)
   - (b) Pattern Dynamics (Rundle et al.)
3. Physical Model:
   - A. Long- and Intermediate-term precursor:
     - (a) Dynamic Model (Burridge & Knopoff)
     - (b) Block Model (Keilis-Borok et al.)
     - (c) Quasi-dynamic Model (Rice)
     - (d) Quasi-static Model (Ward)
     - (e) Traveling Density Wave Model (Rundle et al.)
     - (f) Stress Transfer Model (Stein)
   - B. Short-term precursor:
     - (a) Dilatancy Model (Nur)
     - (b) Nucleation Model (Dieterich)
     - (c) Lithospheric Loading Model (Stuart)
     - (d) Loading/Unloading Model (Yin)
     - (e) Electro-kinetic Model (Fujinawa)

Keilis-Borok, V.I. (1990): The Lithosphere of the Earth As A Nonlinear System With Implications for earthquake Prediction, Rev. Geophys., 28(1), 19-34.

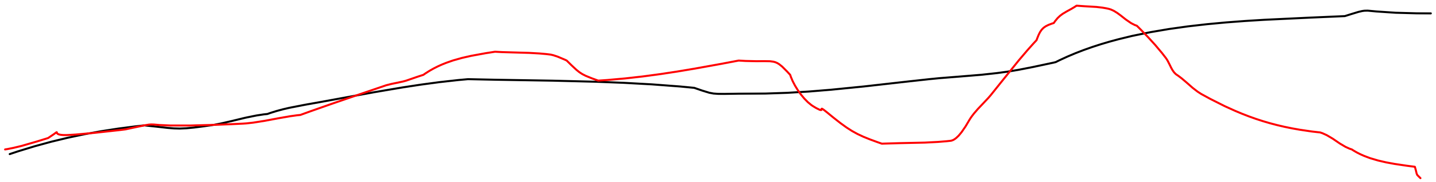
The lithosphere of the Earth can be viewed as a hierarchy of volumes, from tectonic plates to grains of rock. Their relative movement against the forces of friction and cohesion is realized to a large extent through earthquakes. The movement is controlled by a wide variety of independent processes, concentrated in the thin boundary zones between the volumes. A boundary zone has a similar hierarchical structure, consisting of volumes, separated by boundary zones, etc. Altogether, these processes transform the lithosphere into a large nonlinear system, featuring instability and deterministic chaos. From this background some integral grossly averaged empirical regularities emerge, indicating a wide range of similarity, collective behavior, and the possibility of intermediate-term earthquake prediction.

Characteristics of Nonlinearity:

1. Sensitive to Initial Condition (SIC)

2. Capable of Generating Chaos (Unpredictable)

3. Fractal behavior

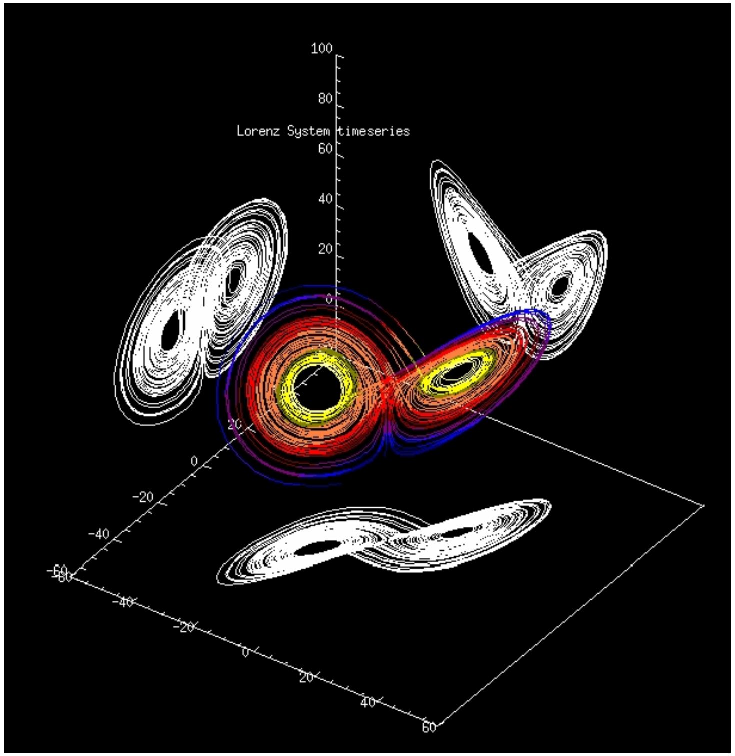


Lorenz Equations (1963)

$$dx/dt=-sx+sy$$

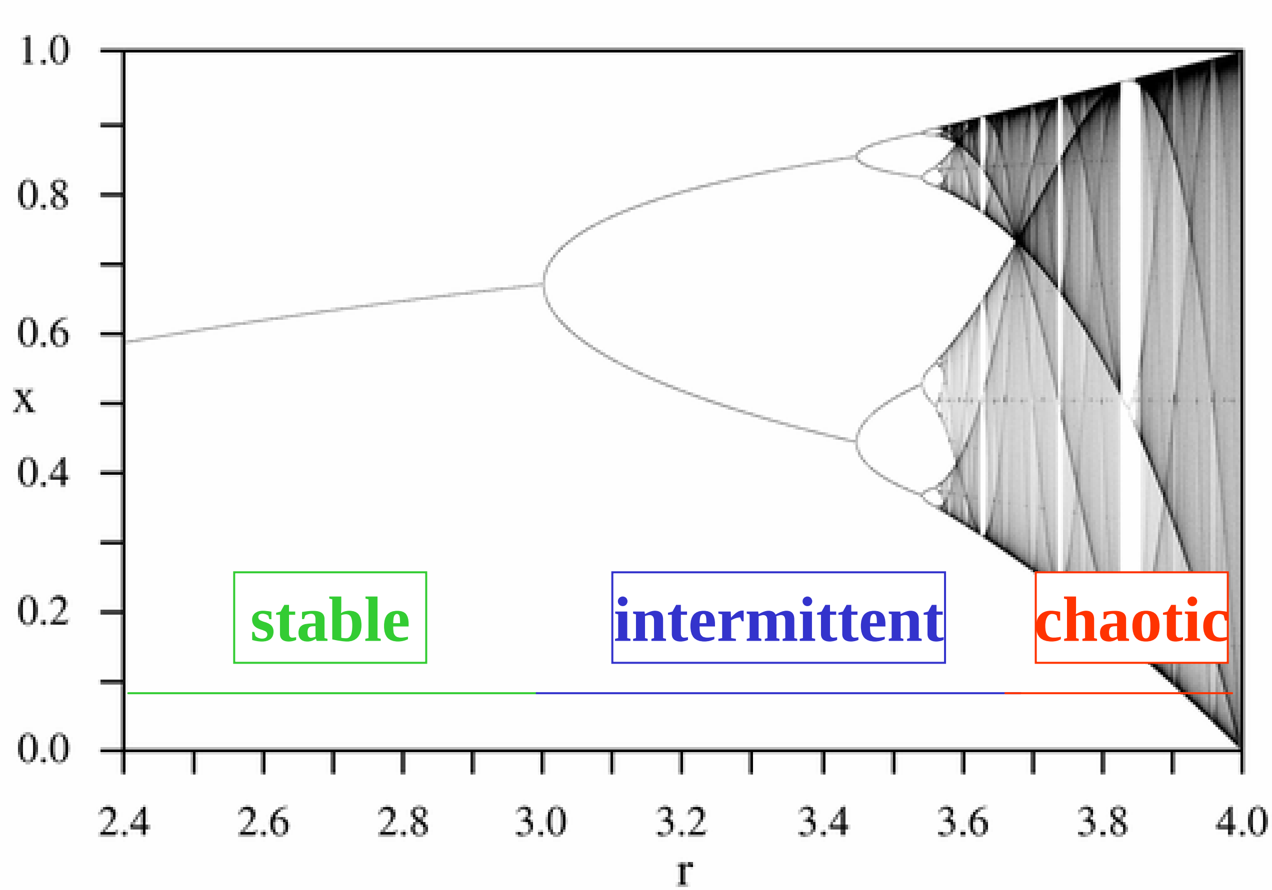
$$dy/dt=Rx-y-xz$$

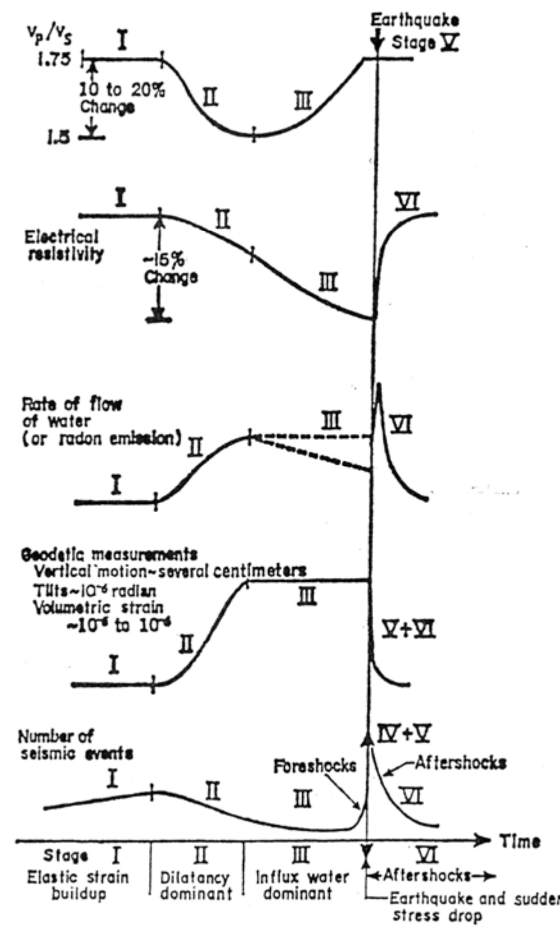
$$dz/dt=-bz+xy$$



Logistic map: $x_{n+1}=f(x_n)=rx_n(1-x_n)$

(x_n: probability of success; $1-x_n$=probability of failure)

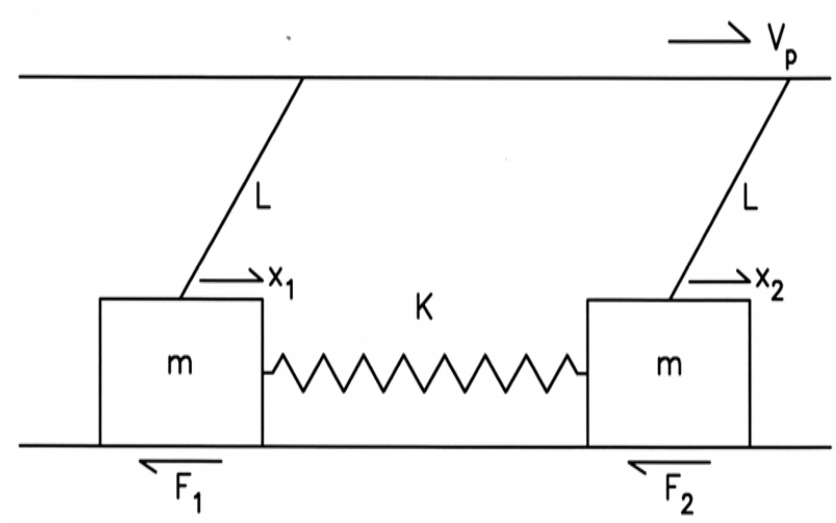




Stable deformation	Preparation stage (pre-event behavior)	Earthquake rupture

The controlling factor r can be a function of time.

Two-body Dynamical Model



where

x_i=the position of the i-th slider, measured from its initial equilibrium position

$v_i=dx_i/dt$

m=the mass of a slider

K=the strength of the coil spring

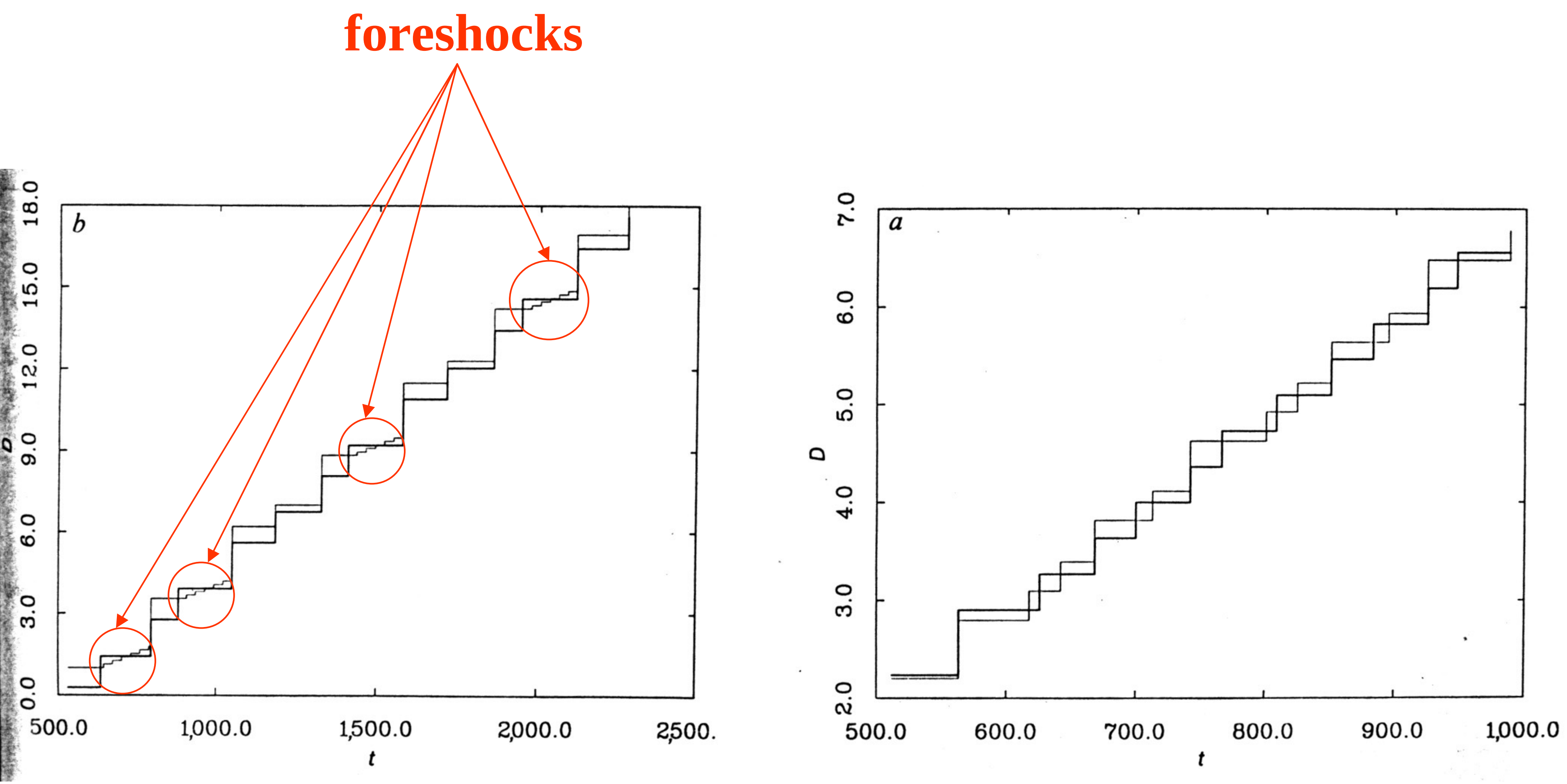
L=the strength of a leaf spring

F_i=a frictional force at the i-th slider

The equations of motion:

$$m(d^2x_1/dt^2)=K(x_2-x_1)-L(x_1-V_pt)-F_1$$

$$m(d^2x_2/dt^2)=K(x_1-x_2)-L(x_2-V_pt)-F_2$$



$Y_i = x_i K / F_{is}$, where F_{is} is the breaking strength.

Turcotte (1992)

[Question] Can we predicate an earthquake, if the fault system is nonlinear?

[Answer]   I do not know.
To possibly predict an earthquake, it is necessary to monitor all related phenomena continuously and completely in the space-time domain of the fault system. On the basis of a comprehensive physical model, Earthquake scientists can examine the physical state of the system step by step, and then adjust evaluation. This might make earthquake prediction possible.