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Symptoms of Instability in a System of Earthquake-Prone Faults

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SYMPTOMS OF INSTABILITY IN A SYSTEM OF EARTHQUAKE-PRONE FAULTS

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ABSTRACT

The major features of the dynamics of seismicity are summarized in order to provide a phenomenological background for its theoretical modeling.

The earthquake-generating part of the solid Earth presents a hierarchical non-linear dissipative system. It consists of hierarchy of blocks, separated by fractured boundary zones where, due to the relative movement of the blocks, earthquakes are generated. This system shows partial self-similarity, fractality, and self-organisation; it remains in subcritical state even after a large discharge of energy; and it probably has an intermediate number of degrees of freedom. The approach of a strong earthquake is reflected in the transient characteristics of earthquake flow; their scaling is indicated.

Phenomenology and numerical modeling of these characteristics suggest that a wide variety of the systems of interacting elements share the following hypothetical symptoms of approaching critical transition: the responce of the system to excitation increases; and the background activity (static) of the system becomes more clustered, intense, irregular and synergetic.

INTRODUCTION

Background. Earthquakes occur within some parts of the outer shell of the solid Earth, called lithosphere; its thickness ranges from a few kilometers near mid-ocean ridges to few hundred kilometers in certain continental regions. Below the lithosphere, down to the depth of about 2900 km, lies the Earth's mantle, partially melted in its top 10^2km.

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Large scale convection currents in the mantle, with characteristic rate up to tens of meters per millennia and internal processes within the lithosphere itself, put it in a state of permanent motion, highly irregular in space and time. Two major distinctive features of the lithosphere are responsible for the generation of earthquakes:

- It is subject to fracturing. Exceptions are the soil at its very top, and the lower depths, where a combination of stress, strength and deformation rate makes fracturing impossible.
- It is hierarchically divided into volumes ("blocks"), which move relative to each other.

Structure. The largest blocks, of characteristic linear dimension 10^3km-10^4km, are called tectonic plates. They are consecutively divided into smaller and smaller blocks, down to the grains of rocks, with characteristic dimension from a centimeter to a fraction of a millimeter. The blocks are separated by boundary layers, called fault zones; at the lower level of the hierarchy they become sliding surfaces and are called faults or (for the grains of rocks) interfaces. Fault zones have a similar hierarchically fractured structure: they consist of blocks, separated by fault zones or faults etc. The fault zones are more densely fractured, than the blocks which they separate. Around their intersections even more densely fractured (mosaic) structures, called "nodes", are formed [1,11].

Dynamics. The integral strength of a boundary layer is smaller than that of the blocks separated by this layer. That is why a large part of the movements and deformations of the lithosphere is realized through relative displacement of the blocks. It takes place in the wide range of displacement rates from 10^{-7}-10^{-8} cm/sec, comparable with convection, to about 10^2cm/sec, associated with the earthquakes. An earthquake starts as an episode of rupture and discontinuous displacement in a certain part of a fault system which is an earthquake source. These episodes alternate with slower deformations ("stick-slip" sequences). In seismically active regions significant part of the relative motion of the blocks is realized through the earthquakes.

Chaos. Relative movement of interacting blocks of the lithosphere is controlled by the forces of friction and cohesion in the fault zones. These forces in turn are controlled by many interdependent mechanisms, generating strong instability [23]. Such mechanisms include: lubrication of faults by migrating fluids [4]; fatigue or stress-corrosion, caused by chemically active fluids [9]; dependence of the friction on porosity [4] and slip-rate [8,12]; also buckling; fracturing; phase transformation of minerals, causing abrupt change of density; dissolution of rocks and many others. Each of these mechanisms may abruptly - in seconds to days - change the efficient strength of a fault zone by a factor up to 10^5, if not more. Except for some special circumstances, none of these mechanisms can be singled out as a dominating one so that the others can be neglected in valid approximation. Even the simplest element of the lithosphere - a grain of rock - may act simultaneously as a material point, a visco-elastic element, an aggregate of crystals, a source or absorber of volume, fluids, energy, with its surface and body engaged in quite different processes.

In the time scale relevant to earthquake occurrence - years or less - these mechanisms altogether turn the lithosphere into a non-linear chaotic dissipative system. Its studies are so far in pre-equation state: in a search of basic regularities by phenomenological analysis and numerical modeling.

Earthquake flow. About 10^6 earthquakes per year are recorded and located worldwide; about 10^2 of them are strong enough to cause damage. The earthquake flow is chaotic, but after averaging, the following regular features emerge:

- *Frequency of earthquake occurrence* in different energy ranges. After averaging over sufficiently large time intervals and regions the following relation ("Gutenberg-Richter law") takes place [13,29]:

$$dN(E) = AE^{-B}dE\ ,\quad \underline{E} < E < \bar{E} \qquad (1)$$

Here N is the average annual number of earthquakes in a certain region. E is the energy of seismic waves generated by an earthquake; it is roughly proportional to the total energy released. Its logarithmic measure is called magnitude. Typically B = 5/3.

The N(E) curve bends downwards on both ends. The bend for smallest E is possibly, but not necessarily, due to incompleteness of observations. The bend for the largest E is associated with the fact that E is limited from above by a site-dependent threshold ("maximal possible earthquake"). A better description for E may be the Kolmogoroff relation, describing the distribution of the size of the rocks in a fractured massive [26,29]:

$$dN(E) = AE^{-B-b\ \ln E} \qquad (2)$$

- *Clustering* [14,16,17,30,32,35]. Earthquakes usually occur in clusters, concentrated in space and time. In most of the clusters the strongest earthquake ("main shock") comes first; the rest are called "aftershocks". In few per cent of clusters, the strongest one is preceded by "foreshocks". Some clusters ("swarms") are formed by main shocks of about the same energy [6,21]. Aftershocks form at least half of the whole earthquake flow; they also fit the power law (1) [29,32].

Clustering takes place in several time and space scales. The clusters are overlapping and branching: an aftershock or a foreshock may have its own aftershocks and/or foreshocks etc. Accordingly, a statistical model of earthquake flow is a self-exciting branching process [14,16,17,35]. The flow of aftershocks is on average decreasing with time: this is roughly described by the Omori law [37],

$$N_i = ct_i^{-v}\ , \qquad (3)$$

where N_i is the number of aftershocks in a certain energy range during the i-th day after the main shock; according to the most studies v is close to 1.

- *Migration* [42]. Areas of increased seismic activity in the 10^2km, 1-10 year scale sometimes migrate along the fault system with characteristic velocity 10^1-10^2km/year. Separate earthquakes may also "migrate" along a fault zone in the following sense: the time interval between consecutive earthquakes is proportional to the distance between their epicenters (measured along the zone). The migration rate is about the same as for clusters, 1-10 km/year; it is larger for stronger earthquakes. Migration takes place just occasionally, but the existence of at least the second type is statistically significant [42].

Other averaged characteristics of earthquakes flow reflect the approach of a "strong" earthquake. They are considered in the next section.

SYMPTOMS OF INSTABILITY

The origin of earthquakes is essentially non-local: a flow of earthquakes is generated by a system of blocks and faults rather than each single earthquake by a single fault. Nevertheless, the symptoms of the approach of a specific earthquake may be singled out - up to a limit. Here we describe the "intermediate-term" symptoms, formed within years prior to an earthquake, since such symptoms are relatively better tested compared with long-term (tens of years) and short-term (weeks or less) ones.

Scaling [20,22,25]. Consider an earthquake with energy E; let L(E) be the characteristic linear dimension of its source. There are different forms of evidence, that the approach of such an earthquake is reflected in the dynamics of the earthquake flow within an energy range of about $\geq 10^{-5}E$ or so, averaged over a sliding time window with a characteristic duration of 1-5 years and over an area S(E) with a characteristic linear size of 5L-10L. In the lower energy range, $\geq 10^{-7}E$ or so, the area of averaging may be possibly reduced to 3L-5L [27].

The time scale here does not depend on E ("the areas of each size tick with the same frequency"), while according to the power law (1) the earthquakes with smaller E are more frequent. This is not a paradox: relation (1) refers to a fixed region, while premonitory patterns are defined in the areas, scaled by E, so that the smaller the value of E the larger is the number n(E) of

such areas in a region. The average time interval between earthquakes in an area is proportional to $n(E)E^B$. The existing observations do not contradict the assumption, that this product is independent of E.

Premonitory patterns [6,18,20-22,24,25,27,28,36,39,43]. With the above scaling, the following averaged characteristics of earthquake flow tend to increase before the relatively strong earthquakes:

- Clustering of the earthquakes in space and time.
- Intensity of earthquake flow. It was measured in the number of main shocks, and/or in the total area of ruptures in their sources, and/or in the relative number of the main shocks with larger energy, say, $\geq 10^{-2}E$; the last symptom may be seen as an upward bend of N(E) curve on its large E side [33].

An increased intensity is sometimes preceded by a decreased one ("quiescence") [22,36,43].

- Deviation of intensity from long-term trend.
- Spatial concentration of sources.

At least the first pattern (increased clustering) can be interpreted as an increased response of a block and fault system to excitation.

Less substantiated so far are the following premonitory patterns:

- Increased radius of spatial correlation within the earthquake flow.
- Increased correlation between its different characteristics.
- Concentration of earthquakes on a subsystem of faults; it may be seen as the decrease of fractal dimensionality of the cloud of epicenters.

All these patterns are not independent; it is yet not clear how they are organized in scenarios.

Some but not necessarily all of these patterns precede a specific earthquake. Accordingly, the prediction algorithms, based on these patterns, in a robust formal definition [22,25,27], diagnose the increased probability of a "strong" earthquake when sufficient number of premonitory patterns emerge within a certain narrow (few years) time interval. The combinations of these patterns were selected by pattern recognition methods [11,38]; this was inevitable in lieu of knowledge of the fundamental equations. The scaling indicated above allowed a uniform worldwide test of these algorithms. The results are encouraging: by and large, the "alarms" occupy about 20-40% of the time-space and precede about 80% of strong earthquakes [24,25]. Practical usefulness of such predictions is rather limited, though not negligible. A comparison of results for different regions implies the similarity of premonitory phenomena in very diverse fault systems, including even artificially induced seismicity, in the energy range of at least 10^6 cgs. However statistical significance is strictly established so far only for one premonitory pattern - increased clustering [31].

CONJECTURE

Summary. The following features of the blocks-and-faults system are implied by the observed properties of the averaged earthquake flow:

- Similarity.
- Partial self-similarity and fractality; among evidences the fact that relation (1) is a power law, rather than an exponential one [41].
- Probably - intermediate-term number of degrees of freedom.
- Continuance of subcritical state even after a large discharge of energy [2,3,7,15,33,34,41]. One form of this phenomenon is self-organized criticality [3,15,41]. In common with many dissipative systems we observe a hierarchical transfer of instability from smaller to larger structures and energy levels. One indication to this is scaling of premonitory patterns: an earthquake with energy E discharges a significant part of energy in an area S(E). A group of such earthquakes (and areas) merge in premonitory patterns for an earthquake of larger energy etc.
- Long-range interactions, within 5L-10L at the intermediate-term stage. This was sometimes regarded as counterintuitive, since stress redistribution by known mechanisms would be confined to areas of the size hardly exceeding 2L. On the other hand the strongest earthquakes are correlated with deformations in the whole Earth [38].

Yet unknown remain not only fundamental equations for block and fault systems, but also many of their essential features: types and scenarios of critical transitions; minimal set of parameters controlling instability; relation between its internal state and "observable" fields etc. The dynamics of this system is reflected in many such fields besides seismicity: creep, deformations, geodetic movements, migration of fluids, their composition, electromagnetic variations, etc. Only the data on seismicity are considered here, since they are so far the most complete ones.

Hypothesis. The dynamics of seismicity was investigated by theoretical and numerical modeling [2,3,7,10,15,33,34,39-41]. It was demonstrated, that many regular features of earthquake flow can be at least qualitatively reproduced by simple numerical models consisting of a lattice of interacting elements (e.g. cellular automata) or of interacting blocks with the simplest geometry (a "brick wall") and with elastic boundary layers. The major exception so far is the composition of clusters: contrary to reality, most models generate much more foreshocks than aftershocks.

Even some prediction algorithms are confirmed on such models [10]. This suggests that premonitory patterns described above may reflect more general symptoms of the approach of instability, which are common for many other non-linear systems of interacting elements. Generalizing the definition of these patterns and the observations on some other systems, one may formulate qualitatively the following hypothesis:

Hypothetical symptoms of the approach of a critical phenomenon:

a. The response of the system to excitation increases.
b. The permanent background activity ("static") in a system shows the increase of at least some of the following features:
    b1. Clustering in space and time.
    b2. Transient intensity.
    b3. Irregularity in space and time.

b4. Radius of spatial correlations.

b5. Correlation between components (synergetics).

A qualitative formulation of this hypothesis is still not clear.

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"Love is not the passion, but understanding"*

B.Spinoza

"Far better an approximate answer to the right question, which is often vague, than an exact answer to the wrong question, which can always be made precise"

J.W.Tukey

---

* Similarly, prediction is yet not so much declaration of alarms, but understanding of the lithosphere dynamics.

Explanations to figures

Page 25.

Reduction of area of alarm by Mendocino scenario.
Squares - areas of TIPs determined by M8 algorithm.
Reduced areas are shaded.
Dots - actual epicenters.
Reduction is by factor 4-14.
After [27].

Page 28.

Seismic flux in a point as a function of time.
Horizontal lines are percentiles of different level.

Pages 26-30 - after A.Khokhlov.

Pages 29-30.

Arrows indicate epicenters of strong earthquakes, which occurred near maxima (page 29) or minima of seismic flux, on 85% and 15% levels respectively.

Vhat do we know about
arthquakes?

Power law (Gutenberg-Richter)

$$dN = E^{-2/3} dlgE$$

'his is also a source of
nstability:

Area unlocked $E^{2/3}dN \sim dlgE$,
Energy released $EdN \sim E^{1/3}dlgE$,

o, energy release falls behind
he areas' unlocking, though the
ealing partly compensates this.

- Clustering, mainly through aftershocks. "Omori law", $N_i \sim (t_i + \sigma)^{-1}$
- Migration of activity, 10 - 10^2 km/yr
- An earthquake (at least sufficiently strong one) can be triggered only near the corners of the blocks (intersections of faults).
- Premonitory seismicity patterns

FOUR PARADIGMS

Worldwide studies
and numerical simulation of
seismicity have led to the
following conclusions:

1. Worldwide similarity of
   dynamics of seismicity
2. Long-range interactions
3. Common set of premonitory patterns
4. Relevance of non-linear dynamics

SIMILARITY

Premonitory phenomena
(in robust definition)
are similar for a wide range of
neotectonic environments,
from subduction zones
to intraplate faults
to induced seismicity
to cellular automata models

LONG-RANGE INTERACTIONS

An earthquake is generated not by an isolated single "homogeneous" fault, but by a system of interacting faults, strictly speaking - worldwide one, with different dominant types of motion, strike-slip, dip-slip etc.

In time scale of years, the range estabilished - 10L - is covering: Coast Ranges - Sierra Nevada, via Great Valley; Appennines-Sicily; Pamir-Tien Shan border; Brabant-Ardennes-Rhein graben etc.

The strongest earthquakes, M › 8, interact even with the whole Globe (Chandlers wobble, Earths rotation, inner core) - F.Press.

MECHANISM?

Before a strong earthquake the following traits of seismicity in lower magnitude range are increasing:

intensity of earthquakes' flow;

its irregularity in space and time;

clustering of earthquakes;

range of their interdependence (radius of spacial correlation);

HINTS OF SELFSIMILARITY:

phenomena of the same kind

- **if defined for smaller magnitudes,** *precede a not-so-strong earthquake in a smaller locality*

- **if defined on the aftershocks' flow,** *precede strong aftershocks.*

Scaling of
intermediate-term premonitory
seismicity patterns

The approach of a main shock
with magnitude M
and linear size of the source L(M)

is reflected in dynamics
of earthquakes flow

in the magnitude range (M-4) to M,
within an area 5L to 10L and
in time interval 1 to 5 years

Second approximation:
(M-6) to (M-3); 2L to 4L

Traits of earthquakes flow
are averaged accordingly

Intermediate-term prediction algorithms based on the traits of transient seismicity:

	based on	magnitude range	
"Sigma	area of faultbreaks	M-2	
"B"	number of aftershocks	M-3.5	statistical significance established
"BG"	"	"	insensitive to errors in M
"S"	clustering of main shocks and high activity	M-3	
"CN"	triplets of different traits	average 3 main shocks per year and a-shocks	a priori area
"M8"	different traits	average 20 main shocks per year and a-shocks	scanning by circles or squares

"Mendocino"	high irregular activity	M-4
"SRE"	different traits of aftershocks	M-3

Success to failure score:

80-90% of strong earthquakes are preceded by TIPs ("times of increased probability"), which occupy 10-50% of time-space.

Probability gain 3-6.

References:
Physics of the Earth and Planetary Interior, May 1990, N 1,2
Lectures and exercises on previous Workshops.

"Mendocino scenario"

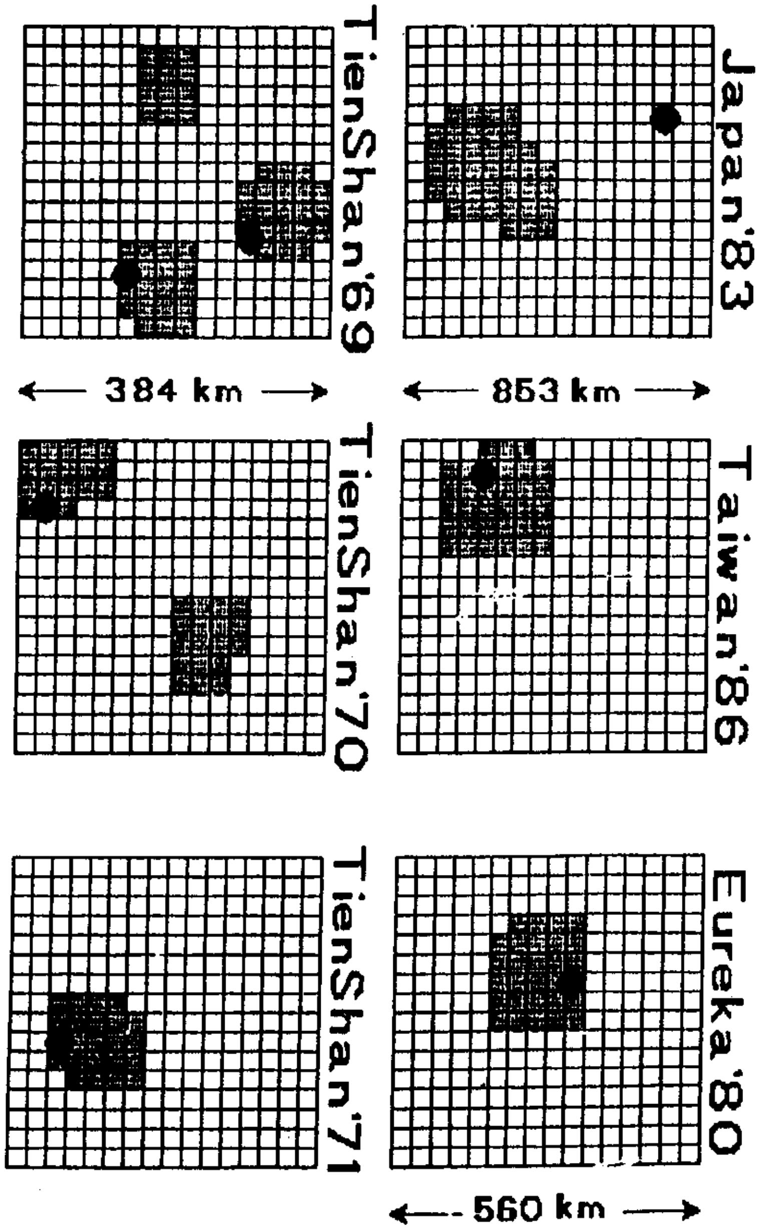
The problem:
TIP is announced for magnitude M in an area, using magnitudes m > (M-3).
To reduce this area, using m > (M-4).

Algorithm:

Divide the area into 16x16 squares.

Find squares with high activity interrupted by short-term (2months) quiescence, i.e. activity below 10% percentile for this square.

Find connected time-space volume of such squares. If it is large enough - expect an earthquake in these squares (ref.[27]).

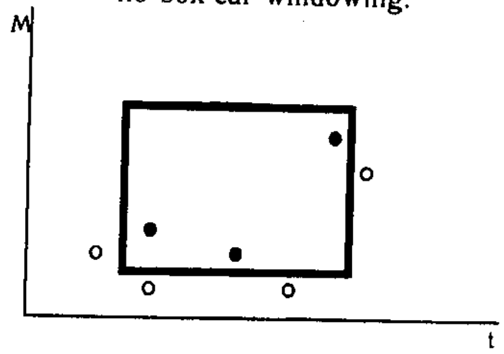


Seismic Flux ("SF")

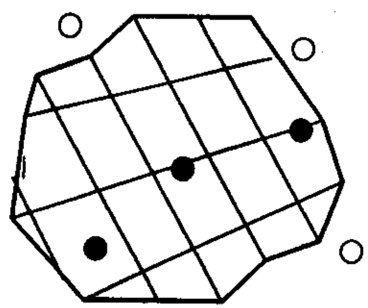
is a representation of transient seismic activity smoothed over time, space and magnitude

SF is free from instability, created by "yes or no" selection of earthquakes in other representation of earthquakes sequences (e.g. CN and M8)

no box-car windowing:



no regionalization on the map:



(● -- earthquakes counted ; ○ --- earthquakes not counted)

DEFINITION of the Seismic Flux. Seismic Flux $P_{[a,b]}(t,\vec{r})$ is the function of the space $\vec{r}$ and time t arguments

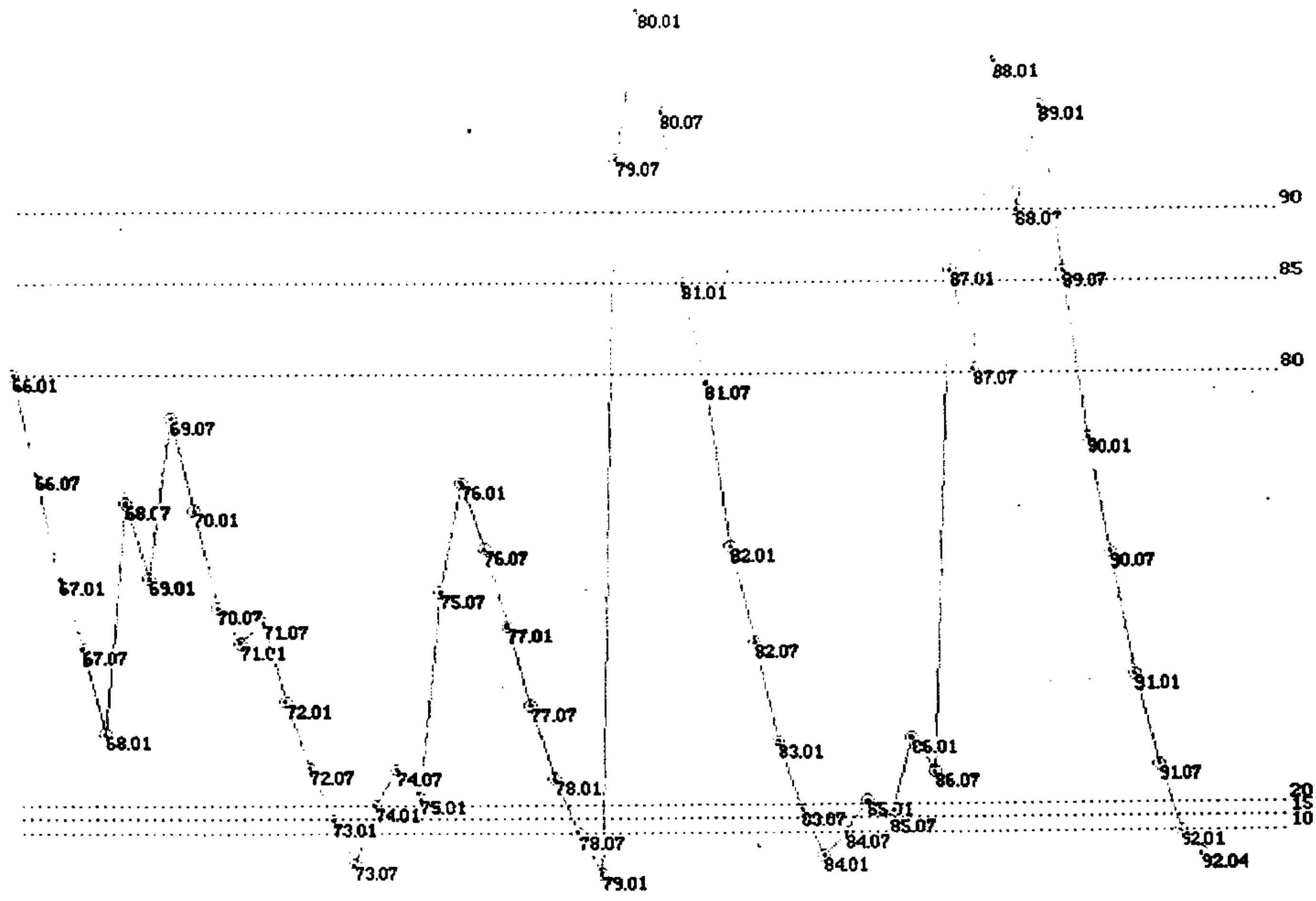
$$P_{[a,b]}(t,\vec{r}) = \sum_j p_j(t,\vec{r}),$$

where summands are taken over all the earthquakes q_j with magnitude $a \le M_j \le b$, and

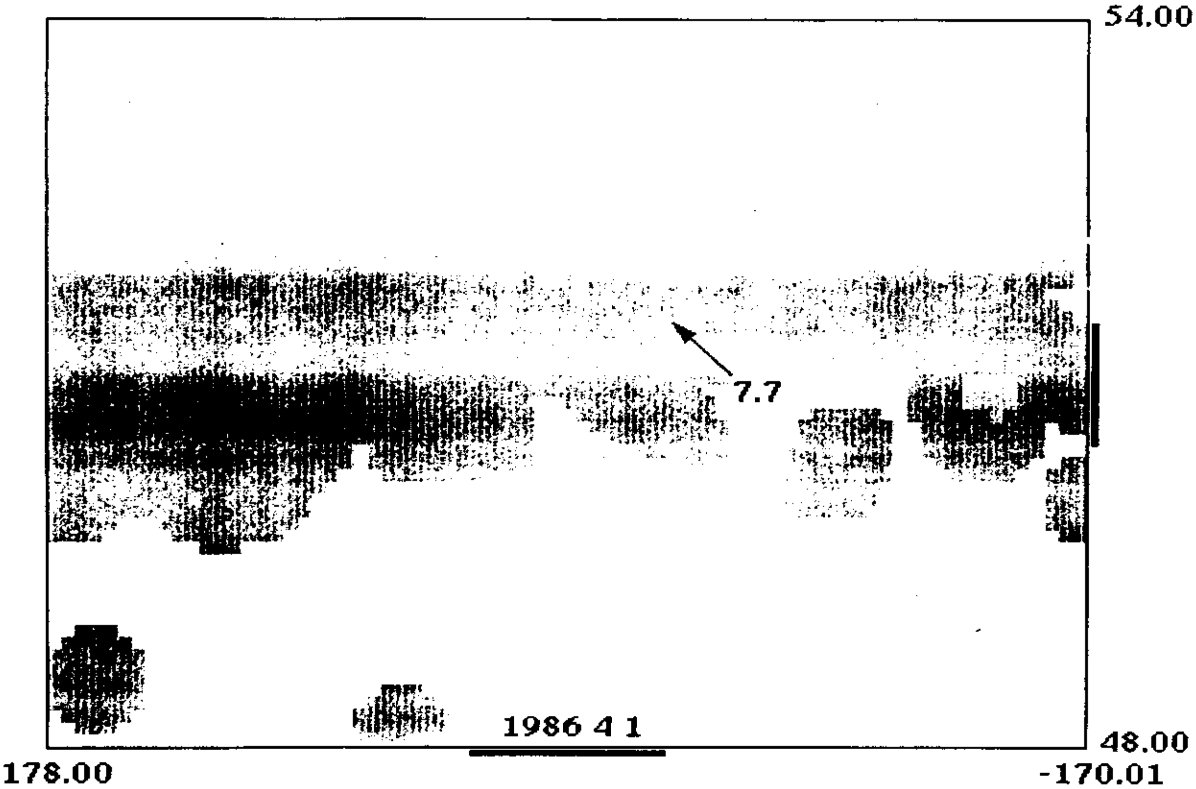
$$p_j(t,\vec{r}) - 10^{0.25M} \exp\left(-\frac{1}{2}\left(\frac{\|\vec{r}-\vec{r}_j\|}{\beta 10^{0.25M}}\right)^2\right) \cdot \exp\left(-\frac{1}{2}\left(\frac{t-t_j}{\gamma}\right)^2\right),$$

$$\beta = \frac{66\text{km}}{10^{1.5}} \qquad \gamma = 20\text{months}$$

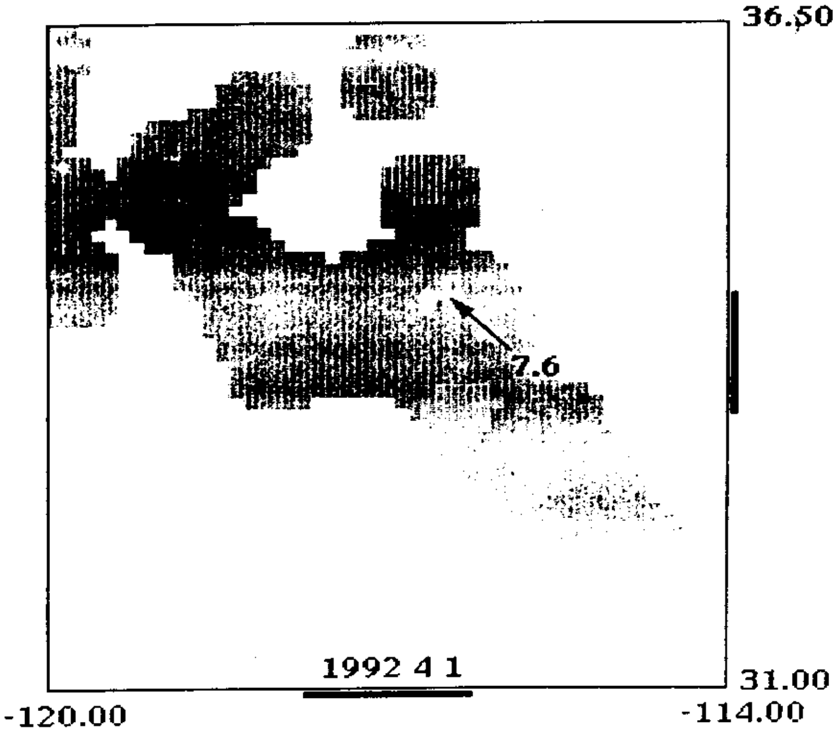
HYPOTHESIS. *Earthquakes with magnitude M are predicted by either abnormally large or abnormally low values of seismic flux $P_{[M-a,M-b]}(t,\vec{r})$*



M[4.5;7.0] {SLPb} D33 60 MONTHS



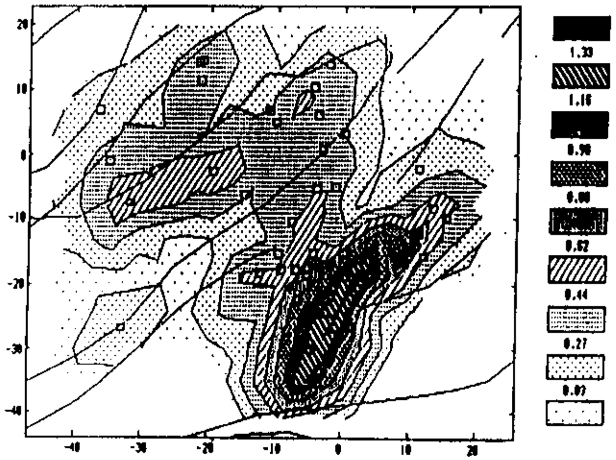
M[4.5;7.0] {SLPb} D33 60 MONTHS



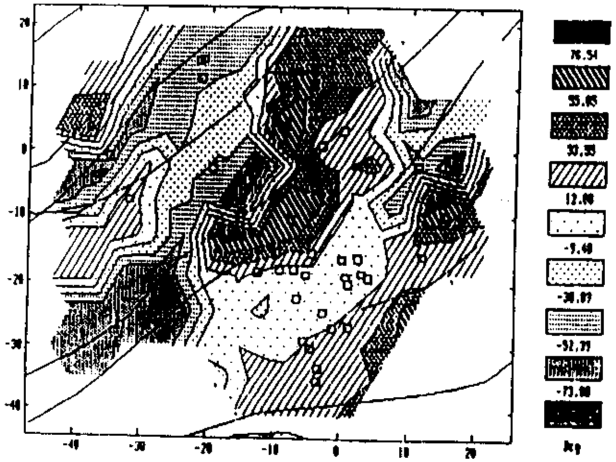
New method of Strain-Stress field reconstruction.
Input data may include single first motion polarities from weak shocks without fault-plane solutions.
Thus the data used are increased by factor 3-5.
(A. Lander, A. Kiriushin, IIEPT, Moscow, Russia)

Epicentral zone of Koryak earthquake 8 march 1991:

Strain scalar Amplitude



Compression Axis - Azimuth



CONCEPT OF CHAOS REVOLUTIONIZED UNDERSTANDING OF CRITICAL PHENOMENA IN LITHOSPHERE EVEN IN THE PRESENT - "PRE-EQUATIONS" STAGE

"In the critical moments of history the words are the deeds"

(C. R. Attlee)

SPECIFICALLY IT BROUGHT

AVERAGING - TO ACHIEVE PREDICTABILITY

SIMILARITY - TO CONSOLIDATE AND TRIM THE DATA BASE

SCENARIA OF PHASE TRANSITIONS - TO RECOGNIZE THEIR APPROACH

MERGER with theoretical physics and the use of its powerful tolls

AN EXCEEDINGLY **COSTLY ILLUSION** ($ 10^8, tens of years) - THAT ONE MAY UNDERSTAND NON-LINEAR SYSTEM BY BREAKING IT APART - IS PARTLY DISSPELLED

EARTHQUAKE PREDICTION STARTED - VERY LIMITED BUT REPRODUCIBLE

* * *

TRIVIALIZATION IS MILD SO FAR

New possibilities:

Existing algorithms allowed to establish:
scaling; similarity and selfsimilarity;
range of interactions;
set of premonitory seismicity patterns.

The major drawback:
low probability gain and
large number of false alarms;
accordingly, predictions allow to
prevent only part of the damage.

Further possibilities which will be discussed:

- To use new traits of the earthquakes flow, e.g. fractal dimensionality of the cloud of hypocenters; it may decrease prior to a strong earthquake, as earthquakes concentrate on some faults.
- To use geometry of fault system.
- To smooth representation of earthquakes sequence as in *seismic flow.*
- To use other relevant data: fault-plane solutions; spectra of seismic waves; slow earthquakes; stress; slow deformations; precise geodesy (Global Positioning System) migration, fluid regime etc.

The common plaiform to integrate these data is provided by the above scaling and by actual areas of premonitory activation.

Implementation of these possibilities by

MODELING

is the focus of this Workshop.

Among major goals

- to organize symptoms of approaching earthquake into a scenario;

- to integrate long-, intermediate- and short-term premonitory phenomena;

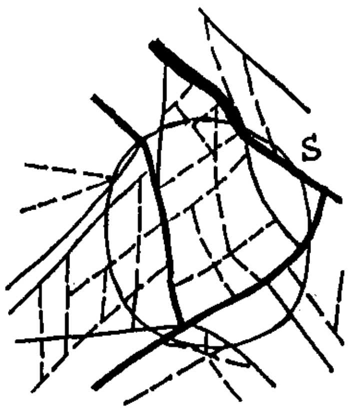
- to separate 3 types of phenomena: universal, fault geometry dependent and site-specific

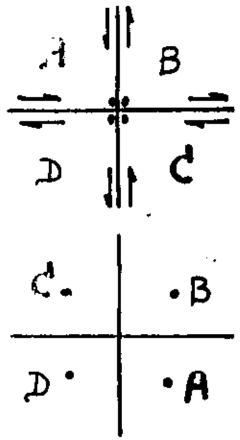
PREMONITORY PHENOMENA:

UNIVERSAL - REPRODUCIBLE AT LATTICE MODELS

GEOMETRY-DEPENDENT

VERY RELEVANT AND STILL UNEXPLORED ARE TWO INTEGRAL CHARACTERISTICS OF A FAULT SYSTEM: KINEMATIC ΣV_i (SAINT VENANT'S) AND GEOMETRIC $G = \ddot{S}$ INCOMPATIBILITIES OF THE MOTIONS.





REGION/MECHANISM - DEPENDENT???

$$\frac{\partial u}{\partial t} + u\,\frac{\partial u}{\partial x} = \varepsilon\,\frac{\partial^2 u}{\partial x^2}\,, \quad \varepsilon \to 0$$

Initial condition:

Brownian trajectories,
standard and fractional (non Markovian).

Solution tends to selforganize into

"Devils staircase"

(smoothed)

PROBLEMS:

- CONTROL PARAMETERS

  $\sin 1/t$, $e^{\sin t}$, $\ln\ln t$, ...

- RELATION BETWEEN "OBSERVABLE" AND "NOT OBSERVABLE" PARAMETERS

- DIMENSIONALITY OF ATTRACTOR

- RELATION BETWEEN TIME- AND SPACE SCALES

- LIMITS OF SIMILARITY/SELFSIMILARITY

- LIMITS OF PREDICTABILITY

- FUNDAMENTAL EQUATIONS (NON-LINEAR SYSTEM OF "MEDIUM" DIMENSIONALITY)

THE PROBLEM:

WE POSSIBLY ENCOUNTERED NEW TYPE OF PHASE TRANSITION:

NOT THROUGH CONCENTRATION BUT THROUGH DYNAMICS, WITH ITS OWN SCENARIA OF TRANSITION TO CHAOS

Basic Study of Solid Earth: New Responsibility

urgency:

- destabilization of ground in megacities

- increase of vulnerability to geological disasters:
earthquakes; volcanic eruptions and effusions; landslides . . .

- marginal accessibility of new mineral deposits:
deep; underwater; ecologically forbidding

The situation is deteriorating in spite of huge investments ($\$10^{11}$ per yr)

"Surely these problems (ecology and natural disasters) are the moral equivalent of the war; they are a threat to civilization's survival as great as any posed by Hitler, Stalin and the atom bomb... Only an international effort will be able to cope (with them)."

J. Wiesener