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H4.SMR/1011 - 25

**Fourth Workshop on Non-Linear Dynamics
and Earthquake Prediction**

6 - 24 October 1997

Symptoms of Instability in a System of Earthquake-prone Faults

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Reprinted from

PHYSICA D

Physica D 77 (1994) 193–199

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Subscription data

Physica A (ISSN 0378-4371). For 1994, volumes 201–211 are scheduled for publication. Physica A is published semimonthly.
Physica B (ISSN 0921-4526). For 1994, volumes 192–202 are scheduled for publication. Physica B is published monthly.
Physica C (ISSN 0921-4534). For 1994, volumes 219–236 are scheduled for publication. Physica C is published two to three times per month.
Physica D (ISSN 0167-2789). For 1994, volumes 70–78 are scheduled for publication. Physica D is published semimonthly.
Subscription prices are available upon request from the publisher.
A combined subscription to Physica A, Physica B, Physica C and Physica D is available at a reduced rate.

Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery via SAL is ensured: Argentina, Australia, Brazil, Canada, China, Hong Kong, India, Israel, Japan, Malaysia, Mexico, New Zealand, Pakistan, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request.
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USA Postmasters: Send address changes to Physica D, Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003. Airfreight and mailing in the USA by Publication Expediting.

Printed in the Netherlands

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Physica D 77 (1994) 193–199

PHYSICA D

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 nonlinear dissipative system. It consists of a 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 a 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 response of the system to excitation increases and the background activity (static) of the system becomes more clustered, intense, irregular and synergetic.

1. Introduction

1.1. Background

Earthquakes occur in some parts of the outer shell of the solid Earth, called the lithosphere; its thickness ranges from a few kilometers near mid-ocean ridges to a 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 10^2 km.

Large scale convection currents in the mantle, with characteristic velocities of a few tens of millimeters per year 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.

0167-2789/94/$07.00
SSDI 0167-2789(94)00083-3

1.2. Structure

The largest blocks, of characteristic linear dimension 10^3 km–10^4 km, are called tectonic plates. They are consecutively divided into smaller and smaller blocks, down to the grains of rocks, with characteristic dimensions from plate scales 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].

1.3. 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 10^2 cm/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 a significant part of the relative motion of the blocks is realized through the earthquakes.

1.4. Chaos

The 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 friction on porosity [4] and slip-rate [8, 12]; as well as buckling, fracturing, phase transformation of minerals causing abrupt changes of density, dissolution of rocks and many others. Each of these mechanisms may abruptly – in seconds to days – change the effective 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 nonlinear chaotic dissipative system. Its studies are so far in the pre-equation state: in a search of basic regularities by phenomenological analysis and numerical modeling.

1.5. Earthquake flow

About 10^6 earthquakes per year are recorded 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 long time intervals and regions the following relation ("Gutenberg-Richter law") takes place [13,19,29]:

$$\mathrm{d}N(E) = AE^{-B}\,\mathrm{d}E, \qquad \underline{E} < E < \overline{E}. \qquad (1)$$

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 ("largest 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]:

$$\mathrm{d}N(E) = A\,E^{-B-b\ln E}\,\mathrm{d}E\,. \tag{2}$$

- *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 a few percent 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 on 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],

$$N_i = c t_i^{-\nu}\,, \tag{3}$$

  where N_i is the number of aftershocks in a certain energy range during the ith day after the main shock; according to the most studies ν is close to 1.
- *Migration* [42]. Areas of increased seismic activity in the 10^2 km, 1–10 year scale sometimes migrate along the fault system with characteristic velocity 10^1–10^2 km/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 earthquake flow reflect the approach of a "strong" earthquake. They are considered in the next section.

2. Symptoms of instability

The origin of earthquakes is essentially nonlocal: 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.

2.1. *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.

2.2. *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 a 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 of 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].

3. Conjecture

3.1. *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 is the fact that relation (1) is a power law, rather than an exponential one [41].
- Probably – intermediate number of degrees of freedom.
- Continuance of a 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 the 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 are 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.

3.2. Hypothesis

The dynamics of seismicity was investigated by theoretical and numerical modeling [2,3,5,7,10,15,33,34,39-41]. 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 many 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 nonlinear 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.

Acknowledgements

Constructive criticism of Dr. B. Newman and Dr. A. Molchan is greatly appreciated. The research described was partly supported by the International Science Foundation, Grant MB3000, and the US Man and Biosphere Program, Grant 1753-300205.

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