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LITHOSPHERE OF THE EARTH AS NON-LINEAR SYSTEM WITH IMPLICATIONS FOR EARTHQUAKE PREDICTION

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The lithosphere of the Earth presents a hierarchy of volumes, from tectonic plates to grains of rocks. Their relative movement against the forces of friction and cohesion is realized to a large extent through earthquakes. It 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 non-linear system, featuring instability and deterministic chaos. On this background some integral grossly averaged empirical regularities emerge, indicating a wide range of similarity, collective behaviour and a possibility for intermediate-term earthquake prediction.

The history of science will probably label our time by the sweeping intrusion of the conception of deterministic chaos, with all advantages and side-effects of a bandwagon. Inaugurated by Henri Poincaré near the turn of the century, it keeps infiltrating one science after another, always revolutionizing them. During the last decade the variety of isolated applications started to merge into Weltanschaung, the perception that well ordered predictable phenomena present just an archipelago in the ocean of Nature, which is intrinsically non-linear and chaotic. Luckily, the chaos can be, to some extent, understood. A limited set of universal patterns can be recognized in the chaotic behaviour of exceedingly diverse systems: non-linear pendulum; living matter; economy; burning fuel; brain; ocean; atmosphere..... and today we shall discuss the implications for the lithosphere.

LITHOSPHERE

Its major trait is so fundamental that it is easy to overlook: it is the hierarchical discreteness of its structure and dynamics. The lithosphere presents a hierarchy of volumes, or blocks, which move relative to each other. The largest blocks are the major tectonic plates themselves. They are divided into smaller blocks, like shields or mountain countries. After 15-20 divisions we come to the grains of rocks of mm scale, if not less.

The blocks are separated by less rigid boundary zones, 10 to 100 times thinner than the corresponding blocks. Each zone presents similar hierarchical structure: it consists of blocks divided by zones of smaller rank, etc.; a lowest rank or two may present an exception. The boundary zones bear different names:

a boundary zone called		separates the blocks of linear 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} - ...

The spell of terminology sometimes obscures the fact that all the boundary zones from the San-Andreas fault system to a facet of a grain play not dissimilar roles in the dynamics of the lithosphere.

Until recently, a boundary zone was regarded as a passive interface, which glues the volumes together by friction and cohesion; suffers deformation up to fracturing due to the motion of the blocks; and heals somehow, since it doesn't turn to dust. That is the truth but not the whole truth. Friction and cohesion are controlled in turn by internal processes confined mainly to the boundary zones: by interaction with fluids; phase- and petrochemical transformations; fracturing; buckling, etc. These processes, discovered or recollected during the last 5-6 years, can rapidly and unobtrusively change the friction and cohesion by factor 10^5, if not more, and accordingly change the effective strength within the lithosphere. So, while the energy of the motion is stored within the whole lithosphere and well beneath, the release of the energy, the motion, is controlled mainly from within the boundary zones.

We shall briefly review now the mechanisms of this control. It will lead to the conclusion that for a wide range of time and space scales it is necessary to regard the lithosphere as an unstable, non-linear chaotic system.

Rhebinder Effect, or Stress Corrosion.

Many solids lose their strength if contracted with certain surface-active liquids. The bar of steel may bend under its own weight in this way. The liquid diminishes the surface tension μ, and consequently, the strength, which by Griffits criteria is proportional to $\sqrt{\mu}$. Then the cracks may appear under the very small stress, the liquid penetrates the cracks and they grow with the drops of liquid propelling forward like tiny knives. This mechanism requires very little energy - like unlocking the door, instead of breaking it. It was discovered for metals first, then for ceramics, and during the last decade such combinations of a solid and sympathetic liquid were recognized among the common ingredients of the lithosphere, for example, basalt and sulphur solution [19]. When they meet, the basalt will be permeated by the grid of cracks and the efficient strength may drop instantly by an order of magnitude and eventually by factor 10^{-5} due to this mechanism alone.

The stress-field determines the geometry of such cracks, and this brings us to the realm of deterministic chaos. The stress-fields in the lithosphere are exceedingly diverse, with all the inhomogeneities and fractures. As diverse may be then a geometry of a system of the cracks. Strictly limited however, is the geometry of the weakened areas, where the cracks are concentrated. Such areas may be of only a few types [5], determined by the theory of singularities. Some examples are shown in Fig. 1. The thin lines are possible trajectories of cracks. Each heavy line is a separatrix, which separates the areas with different patterns of trajectories.

What does it mean for an observer of the lithosphere? Suppose, the source of a fluid appears in the place shown by arrows. It will concentrate in the shaded areas and , out of the blue sky, the strength of this area will plummet. A slight displacement of the source across separatrix may lead to gross, global change in the geometry of such fatigue - it may be diverted to quite a different place and take quite a different shape - but not an arbitrary one.

New dimension is brought into this picture by the evolution of the stress field. It goes on incessantly, for many reasons, including the feed-back from this very fatigue. Such evolution may change the type of singularity, as shown in Fig. 2 and the geometry of fatigue will follow suit.

So, the Rhebinder effect brings into the dynamics of lithosphere a strong and specific instability, controlled by stress field and by geochemistry of arriving fluids. Migration of fluids hopefully can be monitored through electroconductivity and by some methods of hydrology. The history of this migration is reflected in mineralogy and isotope geochemistry. In this way, quite a variety of Earth sciences are tied together by Rhebinder effect. It may possibly suggest an explanation of many mysteries: spontaneous tectonic activations; isostatic anomalies in some volcanic regions; stability of hot spots, etc.

In particular, it is easy to explain in this way seismicity patterns, premonitory to strong earthquakes: seismic gaps, clustering, migration, doughnuts - all of them so far suggested; I dare say that any new pattern can also be explained in this way, since the elementary singularities are sufficiently sophisticated. However, such an explanation would be premature.

First, the singularities are local and the natural fluctuations of stress field may prevent their extension to the scale of premonitory patterns, which is tens to hundreds of km. More probably these singularities are the elements, which compose a more complicated infrastructure of fatigue. Second, the Rhebinder effect may decay along the trajectories due to diffusion of fluids. Finally, this effect is not a single major mechanism by which the boundary zones control the dynamics of the lithosphere, generating determinisic chaos for the good measure. Even the fluids alone generate other co-existing mechanisms, as spectacular as this.

Filtration.

One competing mechanism is more conventional filtration of fluids through the pores or cracks along the gradient of pressure [2]. A boundary zone between two blocks is modeled as a porous layer. When the shear stress exceeds friction, the slip begins.

Further development shows a source of strong instability, illustrated by Fig. 3. If porosity is subcritical, the slip, once started, will increase the friction and self-decelerate. At the worst, we will have vacillating creep or a slow earthquake. But if porosity exceeds a critical threshold, the solid frame will be destroyed by the slip, the friction will decrease and the slip will self-accelerate. The porosity can rise above the critical threshold due to infiltration of a fluid itself; it will increase the tension and the pores will expand. So, again, just because some fluid filtered in , the instability instantly arises; the tiny slips, which occur incessantly, will self-accelerate, grow and merge.

This instability is aggravated by erratic velocity of filtration: it is described by the non-linear parabolic equation [2]

$$\partial P / \partial t = K P_0 \Delta P^{\alpha}, \quad \alpha > 2.$$

Here P is the perturbation of pressure on the background of steady filtration flow; P_0 is the background pressure; K depends on physical parameters of the layer: $K = k/(m \rho \nu)$; k and m are permeability and porosity, ρ and ν are density and viscosity of the fluid. Though this equation is parabolic, P propagates with a final velocity, proportional to $\sqrt{P_0}$. Calculated velocity lies in the range of tens to hundreds of km/year [2] - the same as for the observed migration of seismicity along the fault zones.

A new model of an earthquake source naturally arises: a residual pocket of fluid, where background pressure P_0 is large. The front of filtration may quickly cross and destabilize this pocket, turning it into an earthquake source.

This mechanism may explain even more features of real seismicity than the Rhebinder effect: the same premonitory seismicity patterns; also, the foreshocks and aftershocks, quasiperiodicity in the reoccurrence of strong earthquakes, etc. The difficulties with space-scale do not arise here.

But again - there are no reasons whatsoever to single out this particular mechanism. First of all, such instabilities may develop in parallel within boundary zones of different rank and interact along the hierarchy. So this model is again rather an element of some infrastructure of filtration-generated instability.

The Need for a Generalized Model.

The boundary zones feature several other mechanisms of instability, potentially as important and certainly as complicated. One is the usual type of lubrication; another - petrochemical and phase transitions: they may generate lubricators, e.g. both in formation and decomposition of serpentines. They may also create an instant loss of volume, such as in transformation of calcitus into aragonite. This will create a vacuum and unlock the fault; it will be at once closed by hydrostatic pressure, but the instability may be triggered. Most such mechanisms strongly depend on the temperature. Finally, traditional mechanisms, such as buckling, clustering of cracks, viscous flow, etc., remain important but I will not dwell on them, hoping that the point is made:

The dynamics of the lithosphere presents the interaction of its blocks across and along the hierarchy. This interaction is realized through the wide variety of mutually dependent mechanisms. Each of them creates instability. None can be singled out as a major one so that the rest can be neglected in the so called first approximation.

So what we need is the whole enchilada: the generalized theory which embraces all of these phenomena on the background of hierarchical structure. To assemble the whole set of corresponding equations is unrealistic. More than that, it may be misleading because of what at the time of Hegel was called Gestalt conception: the whole is more than just a sum of its components. For example, the laws of biology can not be derived from evolution of protoplanetic dust, though life is the result of this evolution. We may rather hope for a model which directly represents the grossly integrated traits of the lithosphere, in particular - the laws of its dynamics.

The problem of integration is unusual here. Contrary to what would be a typical starting point in such a problem, we have no elementary mechanical bodies to integrate nor local constitutive equations, besides too general ones. Even a grain of rock cannot be considered just as a purely mechanical element of the lithosphere, in simple local interaction with its peers. As we have seen, it is rather a seat of a multitude of the processes, only partly mentioned above. It may act simultaneously as a material point, a source of fluids, a source or absorber of energy, etc., etc. It cannot even be treated exactly as an element, because it may act also as an aggregate of interacting crystals and because its surface is engaged in quite different processes.

Therefore, **to model the integrated, averaged behaviour of the lithosphere, we have to do the averaging for an ensemble not of mechanical elements, but of processes**, probably in a Gilbert space. The experience of Quantum Statistical Physics shows, that it is not easy.

Traditional models are based on mechanics of continuous media, with different rheologies; sometimes porosity and filtration are included. Such models may be applied beyond their formal limits by expansion of the meaning of parameters. For example, the microfracturing is often represented as a drop of elastic modulus, to which so called "effective" value is assigned.

Such an approach has a good track record. But, obviously, it is applicable to a limited range of problems: when the blocks of lithosphere are sufficiently homogenized; when purely mechanical processes dominate; and only for a certain time and space scales. Almost all phenomena discussed above cannot be reproduced by such models, even if we present the parameters as some Pickwickian construction (not to be understood literally). So, our search of generalized theory brings us to the conception of deterministic chaos. Its qualitative description is reminded in the following section.

CHAOS

Chaos arises in deterministic systems because of their specific instability. For illustration, imagine a billiard game (Fig. 4). The player sends the ball into a usual array of other balls. The slightest variation in the direction of the original push will send it down quite a different path and the difference will not attenuate but grow with time. Each collision of the balls with each other will further amplify this divergence.

To prolong the motion, let us assume that the loss of energy is small. The Newton laws do determine the trajectory of each ball and the sequence of collisions. But the prediction will be all wrong after a certain number of collisions, if the initial push is defined with an error compared with the gravitational effect of a single electron on the margin of the galaxy. It is beyond an estimation of necessary precision - it is just a picturesque way of saying that the deviation does not attenuate but grows exponentially in time, so that prediction is impossible with any precision of initial conditions. If the boards are convex ("Sinay billiard") even a single ball reduced to material point will display the same instability. Having a multitude of such turning points a dynamic system may display erratic, complicated behaviour, which looks chaotic and is called so. Though deterministic, it will be unpredictable, because prediction would require paradoxical precision of the initial conditions. This is not an abstract extravaganza. On the contrary, chaotic systems can be surprisingly simple - the non-linear pendulum, for example.

However, this kind of chaos does have inherent regularities. They can be understood and some integral traits of chaotic behaviour can ever be predicted. Quoting Shakespeare, "though this be madness, there is method in't".

One fundamental regularity in chaotic behaviour was discovered by E. Lorenz in 1963; Poincaré apparently suspected its existence. Lorenz studied thermal convection in the atmosphere, which has astonishing ability to self-organize into a honeycomb of convection cells. He introduced for a single cell a grossly simplified model, defined by common derivative equations:

$$\partial x / \partial t = -\sigma x + \sigma y; \quad \partial y / \partial t = Rx - y - xz; \quad \partial z / \partial t = -bz + xy$$

Here functions x, y and z characterize respectively the intensity of the convection stream, horizontal and vertical temperature gradients; σ, b and R are numerical parameters.

Fig. 5 shows a phase space for this system [3]. Its coordinates are these three functions, so that a point defines completely the state of the system at some moment of time; the evolution in time is defined by a trajectory.

In spite of the mild outlook of equations, a strong divergence is rampant. The dots in Fig. 5 show ten thousand different states at some moment of time. They are evolved from ten thousand initial states, which were so close, that they are all merged into one dot, somewhere in the top right corner. In other words, again, microscopic initial perturbation leads to macroscopic divergence, and prediction is impossible. However, we see an inherent regularity: all states eventually congregate around the configuration, outlined by lines. These lines are the asymptotic trajectories. The evolution of the system will be gradually attracted to them. They occupy the subspace, called chaotic or strange attractor. It has smaller dimensionality than the whole phase space.

Non-chaotic system may have two rather prosaic stable attractors: a fixed state and harmonic oscillation; in the phase space it will be respectively a point and a loop, called limit cycle. (One may add quasi-periodic oscillation, formed by two incommeasurate frequencies, that is a torus in phase space, but it is not stable to the change of parameters of the system).

Strange attractors are more exotic. They have fractal structure. Actually, the one in the Fig. 5 has gėometry of the Cantor set. Any small part of this attractor considered through a magnifying glass will show similar uneven density of blue lines. If we cut off a small part of this enlarged small part and enlarge it again, we will still see a similar pattern, an so infinitely.

The probability that the system will cross any point specified in advance is zero. But the system will certainly pass an arbitrary small vicinity of an attractor. So, we know for sure a very restrictive global regularity: the system will eventually move along this attractor. But we cannot go into much more detail: cannot predict specific trajectory, and even the times of transition from one branch to another are completely random. The future cannot be determined from the present, no matter how many observations and supercomputers are engaged.

Global traits of a chaotic system cannot be derived from interaction of its components, that is Gestalt phenomena. Futile will be the natural tendency to understand such a system by breaking it down into small elements.

The large zoo of diverse strange attractors has been encountered, but their general theory has been not discovered so far.

Fig. 6 shows schematically the intermittency in the Lorenz system: unexpected transitions, where frequency depends on control parameters. Other universal regularities are found in the change of the basic properties of a system. Specifically, they often depend on one or just a few "control parameters", that is, coefficients in the equations, for example, the Rayleigh number R in the Lorenz system. The change of control parameters in time may cause transition to chaos from orderly behaviour or the other way around.

There are also other kinds of self-organization in the lithosphere, of Statistical Physics type; they are not considered here.

Chaotic patterns steer hypnotic fascination, like a waterfall or burning wood. Accordingly, non-linear science has dramatic vernacular; the turn of a curve to vertical asymptote is called blue-sky catastrophe, for example.

No wonder, the temptation is not unknown to stampede into new applications like an avant-garde of the looting army, sticking romantic labels on all complicated phenomena in sight. So far, Geodesy and Geophysics have wisely escaped this temptation. Actually, it is difficult to find a useful model for lithosphere. The difficulty of this kind for the modeling of climate is brilliantly described in [21]: "...[considering] the extreme complication generated from the numerous bodies, phases, and processes which interplay, it is not difficult to understand how the modeling of this system of relations is one of the most arduous and attractive scientific challenges...

From the preceding treatment it should be clear, if nothing else, the terrible complexity (in all defined senses) ... The reactions and the attitudes with respect to such complexity are linked between two extremes: on the one hand is he who identifies as the sole possible solution to the problem a meticulous treatment of every process operating on the climatic system, on the other hand is he who considers as the only hope that of "guessing" the right equations" [21,pp.23,25].

For the lithosphere the problem seems even more difficult since it does not mix so easily as atmosphere, having fractures and fixed inhomogeneities; so for some time and space scales it would require probably mechanics not of continuous, but of almost everywhere continuous media, or even of fractal media.

Predictability.

It may seem unexpected from previous description, but some features of a deterministic chaos can be predicted, though with limited accuracy and lead time.

For example, transition to another branch in the Lorenz system (Fig. 5) can be predicted, with a sufficiently small lead time, because it is always preceded by a specific sharp bend at a trajectory. This does not contradict the fact that the time of transition is completely random. Rather the transition itself is not an instant jump, but a continuous though short process, starting with the bend.

One may hope that an earthquake is similarly a part of a more extended scenario. Contrary to the Lorenz system, the lithosphere is hierarchical. The hope to predict a feature of the hierarchical system with deterministic chaos lies in averaging (smoothing); the more averaged the feature is, the larger are the time- and space scales, in which prediction may be not impossible. Accordingly, in the dynamics of lithosphere and particularly in the problem of earthquake prediction we have first of all to find for a given time- and space scales an adequate set of decisive integral features and to establish the relations between them: to find a low-dimensional phase space and constitutive laws. The first steps have to be empirical - this field is in the same prehistoric stage as the theory of gravitation was before discovery of the Keppler laws. Next section considers empirical regularities, relevant to the approach of a strong earthquake.

EARTHQUAKE PREDICTION

The above considerations are not confined to a specific scale. They seem consequential in many directions: interaction between core, mantle and crust; unexplained correlations of geochemical, tectonic and geophysical fields over the Earth's surface; evolution of the Earth - its whole tectonic history possibly may be rewritten, as a sequence of instability episodes, like an intermittency.

We will discuss here only the results, relevant to the time scale of 1 to 10 years, which is intrinsic for earthquake prediction. This is particularly challenging, since the bulk of the lithosphere is inaccessible for the direct measuring of earthquakes - related fields, that is stress and strength. It is virtually a black box. For each strong earthquake it generates a multitude of smaller ones, and we shall try to use this multitude to diagnose the approach of a strong earthquake.

The occurrence of a particular earthquake cannot be entirely isolated from the dynamics of the whole lithosphere. That is why the problem of earthquake prediction consists of consecutive, step-by-step, narrowing of time-space domain, where strong earthquakes have to be expected; this is also in accord with the hierarchical nature of the lithosphere.

Here, however, the formulation of the problem is truncated: we consider only one step, i.e. prediction of the strongest earthquakes of a fixed territory with accuracy of a few years and a few hundred kms. It is qualified sometimes as an intermediate-term and sometimes as a long-term one. The second qualification is used in the papers referred to, but I will switch here to the first one, apparently more common.

General Scheme

Our acquaintance with non-linear systems suggests that the symptoms of an incipient strong earthquake may be different from case to case, in the same area, and even more - from region to region. Nevertheless, we look for a uniform diagnosis, applicable all the time in different regions. We try to overcome this contradiction by considering integral representation of the earthquake flow where the diversity of circumstance is smoothed, while the premonitory phenomena are hopefully not smoothed away. The uniformity of diagnosis is made possible by normalization of the earthquake flow, as described in [1,7].

The scheme of diagnosis is outlined in Fig. 7. It shows a sequence of earthquakes in a region. A vertical dashed line indicates a sliding moment of time. At each moment we look back in time and define several traits of the earthquake sequence within sliding time windows, shown by horizontal lines. We hope, that variation of these traits will indicate the time of increased probability of a strong earthquake, shortly - TIP.

The scheme is open for inclusion of any other hypothetically predictive phenomena, not necessarily representing the earthquake flow, but so far the traits of 5 types listed in Fig. 7 have been considered. They were selected by the following reasons:

The intensity of the earthquake flow - because abnormal activation and/or quiescence were reported before many strong earthquakes, separately or in combination; among different kinds of quiescence seismic gaps are most popular.

The next three traits represent phenomenon common for many non-linear systems: when instability approaches, the fluctuations increase as well as the response to excitation. An earthquake itself is a source of excitation. Therefore, the response to it may be expressed in clustering and in an increase of distance, on which the earthquakes are not dependent. Also, clustering is the only premonitory pattern for which statistical significance is strictly established at present [18].

Concentration is suggested by laboratory experiments with rocks: when density of microfractures exceeds some rather universal threshold, the failure of a whole sample occurs [24].

The smoothing of the earthquake flow is achieved here in several steps:

- The traits are defined for large areas and time-windows.
- Each trait is represented by several not independent functionals; for example, the intensity of the earthquake flow is estimated in different overlapping magnitude ranges.
- We distinguish only large, medium and small values of each functional, so that their definition is sufficiently robust.
- Finally, the diagnosis of TIPs is based on the whole set of traits, admitting that each one per se may be insufficient.

To diagnose the TIPs is the natural problem for pattern recognition.

A Soviet-American team considered seismic history of California and Nevada [1,10,11]. These traits were compared at the moments preceding and not preceding earthquakes with M>6.4 in the past; by this comparison we have found the rule to recognize the TIPs. Roughly quantitatively, this rule is the following: most of the traits, listed in Fig. 7, simultaneously became more prominent during a period of 3-4 years, preceding a strong earthquake. Before this period, a relative quiescence often occurs. Similar analysis was made for the strongest earthquakes of the whole world, magnitude 8 or more [12]. The corresponding algorithms are named CN (for "California and Nevada") and M8 (for "magnitude 8"). The sample of such retrospective diagnosis by algorithm CN is shown at the top of Fig. 8.

World-wide Tests.

If reliable, these algorithms would imply a lot : that the blocks of lithosphere do show a collective behaviour even in the erratic process of generating earthquakes; that our traits are promising candidates for basic integral characteristics of this behaviour, so far somewhat clumsily formulated; and that we may predict strong earthquakes, on intermediate term stage. However, these conclusions were merely hypothetical, because in lieu of the theory we had to data-fit retrospectively the algorithms, including many free parameters - like the length of time-windows, the magnitude intervals, etc. To test the prediction on independent data, we had to introduce an additional hypothesis: that **the earthquake flow is similar in different regions,** independently on tectonic environment and level of seismicity. This allows to test the algorithms on independent data, that is for other regions, not involved in data-fitting. Technically it is possible because the definition of all traits is normalized, so that looking at our representation of the earthquake flow we would not distinguish the subduction zone form the mildly active platform, Kamchatka from Belgium.

The algorithms CN and M8 were applied so far to the regions, listed in Tables 1 and 2. The results are summarized in those Tables; for some concrete regions, they are shown in Figs. 8 and 9.

It is encouraging that the success-to-failure score for these regions is, on average, not much worse than for the regions where diagnostics was data-fitted (compare, for example, different regions in Fig. 8).

The practical value of such predictions is limited, though by no means annulled, by the fact that TIPs are extended to the areas about 10 times larger in diameter than the source of the upcoming earthquake. There is hope, however, to pin-point the place of the coming earthquake within about two lengths of its source [23].

Strict estimate of confidence level is still difficult but the results for these regions, taken together, do support the following conclusions:

The dynamics of the lithosphere, having a chaotic component, features a collective behaviour.

The traits of the earthquake flow, considered here, provide an integral description of this behaviour similar in wide range of regions and are intrinsically relevant to the approach of a strong earthquake.

About 80% of strong earthquakes may be predicted on the basis of these traits, with alarms occupying 10-20% of space-time.

Though being in the spirit of the ideas on deterministic chaos, this similarity seems most controversial so far. I heard the exclamations, not even questions: how could it be possible that the same diagnostics is uniformly applicable in such different seismotectonic environments, while even each single region is eminently inhomogeneous and the stress field is changing from earthquake to earthquake ? The answer is that the choice of integral traits was probably fortunate. For example, the readers of this lecture, if any, may be at least as different as seismic regions. However, the approach of the collapse may be uniformly diagnosed for any of us, if a single integral parameter-body temperature - exceeds +44 $^{\circ}$ C. Indeed, some universal global phenomena do precede instability in very diverse systems. Since such universality transcends from brain to atmosphere to non-linear oscillator, it may well transcend the difference between mere seismic regions. But it is difficult to accept this similarity, if we are traditionally focused on a more detailed scale.

Two simple models of the lithosphere may illustrate both the individuality of an earthquake flow and universality of integral laws. Fig. 10 shows computer simulation of interaction of lithospheric blocks [6]. Energy is provided by the shear movement of boundaries, indicated by the arrows. Model generates earthquake, in stick-slip fashion. In spite of its extremely simple geometry, the earthquake flow is chaotic. Not only is it unstable to the change of structure - it has bifurcations: the sequence of earthquakes changes drastically when initial conditions are changed just by the few lowest digits in the computer memory. But many integral traits remain the same, e.g. linear frequency-energy relation, migration, clustering, average annual energy release. Even the same algorithms for the diagnosis of TIPs are applicable here, though the success-to-failure score is lower, of course.

Another model, more of a statistical physics type, similar to the well known "life game", is shown in Fig. 11. It illustrates how small displacements of elementary blocks can self-organize into a strong earthquake. Elements are elastic discs which can move and rotate, while general compression holds them together. When stress between two discs exceeds friction, the slip occurs, releasing energy; one elementary slip may trigger another. The discs show prominent collective behaviour. The most stressed discs, dark, are self-organized in these linear configurations which eventually become unstable; this triggers the "strong earthquakes" in the model. Again, slight initial perturbations may drastically change specific patterns; there is no answer, why this delineation is here and at minimum of stress there. But, again, the model displays some integral traits of a real earthquake flow.

It seems suggestive that the observed regularities are reproduced by such a simple model, as in Fig. 10. May be they are intrinsic to some general type of deterministic chaos, and not to an exclusive feature of the lithosphere.

The single disk would hardly believe, that its erratic high pressure existence, from one slip to another, is averaged to such universal regularities. Actually, however, predictable collective behaviour is not uncommon indeed among the systems with complicated interactions on elementary level. This can be illustrated a system of interactive electorate blocks in the American mid-term Senatorial elections [17]. The situation before past elections was described by averaged functionals (Table 3) - the "yes" - or - "no" answers to questions referring to the state as a whole. The questions and the pattern-recognized prediction rule are the same for all states and election years, while both are diverse indeed. Nevertheless, prediction, published in advance, was correct for 30 out of 34 elections of 1986 (Table 4). The confidence level is above 99.9% . It remains above 97% if we allow only for the outcomes which the experts regarded as uncertain. A similar prediction rule was formulated first for the Presidential elections [16]. This was based on other but equally simple integral parameters. This rule cannot claim statistical significance, since only two elections, 1984 and 1988 happened after the rule was published. It is encouraging, nevertheless, that correct predictions could be made about a year in advance. All the differences of subject matters notwithstanding, this example illustrates, how the behaviour of chaotic systems may become predictable after proper integration. Accordingly, the existence of uniform diagnostics of TIPs in diverse regions is not so paradoxical as it may seem from too detailed perception of the lithosphere. This approach is consequential for many other studies of the lithosphere, besides its dynamics in short time scales. It is a major and, I believe, the major workhorse in the present perestroika of the whole solid Earth Sciences: their integration and globalization; integration of basic and applied problems; change of theoretical base, etc.

Following are a few more examples. Since most of the studies in this direction are also in similar preliminary stage, - an empirical search of decisive parameters - I will discourse once more from the spirit of Union Lecture, which should be ivory-tower exaltation. After the circus of elections it will be now the market place, - industrial applications of Geodesy and Geophysics.

One example (Fig. 13) is reconnaissance of areas, where strong earthquakes, M< 7 3/4, are possible even if still unknown. Such results were obtained in many regions world-wide [8,13], also by a uniform method, and most of subsequent earthquake did appear in prescribed places. These results illustrate the power of hierarchical approach, since they are based on rather non-detailed data, provided by the maps of 1: 2.5 mln and 1:1 mln scales, and obtained for the large territory at once. Traditional industrial methods would require 5-10 times more detailed data and, accordingly, a separate survey of each building site. Such results, as shown in Fig. 12, drastically reduce the areas, which deserve industrial survey and which may cost up to $ 10^6 just for one such spot.

Literally the same can be said about the reconnaissance for oil-fields (Fig. 14).

Similarly, analysis of surface waves from earthquakes allows to reduce by factor 5 to 10 the areas for expensive seismic prospecting (Fig. 14).

the preparedness measures.

All this calls for reconsideration of the strategy of research, especially, but not only, in developing countries: it may be better to start with intense analysis of existing data, rather than with expansion of local observations, with hardware, as is often the case. In this way one may save a good part of the cost of industrial surveys. It may be even the only possible way when we deal with chaotic phenomena.

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In summary, I believe that among other grand possibilities, which will be discussed at this Assembly, modern Non-Linear Science in combination with global observational networks does deserve attention. It promises and requires further consolidation of Earth sciences on a new theoretical base; consolidation and trimming of our observational base and our software; better perception of the Earth as a whole with sufficient resolution power to depict the features important for economy.

We may even expect that a new kind of chaotic behaviour probably intermediate between deterministic and statistical types will be discovered under our auspices. This would reconfirm the tradition which is older than the present civilization: that the study of the Earth is the major source of basic milestone conceptions which revolutionize our perception of Nature.

Captions to figures.

Fig 1. Geometry of fatigue, induced by stress corrosion.

The source of surface active fluid is shown by arrows. Weakened zone is hatched. a, b and c correspond to different types of singularities of principal stress field; d - to two singularities of the type a; e - to a loop ("limit cycle"). After [5].

Fig 2. Evolution of singularities in the three-dimensional case:

a - birth of a loop; b - bifurcation; c - annihilation of a loop. After [5].

Fig 3. Instability of a fault zone due to filtration of fluids. After [5].

Top: fault zone, modeled as a porous layer with residual pockets of fluids between inpermeable rigid blocks. Bottom: the mechanism of instability.

Fig 4. An illustration of the origin of deterministic chaos.

Fig 5. Lorentz's strange attractor. After [2].

Fig 6. Sheme of intermittency in Lorentz's system.

Fig 7. Scheme of description of earthquake sequence for diagnosis of TIPs. After [7].

Earthquake sequence is described by several integral traits. Horizontal lines show the sliding time windows, on which different traits are defined. All windows end at the common moment of time, shown by vertical line. The traits are attributed to this moment.

Fig 8. Diagnosis of TIPs by the algorithm CN on independent data. After [10, 11].
Upper plot shows original data-fitting. Other plots show the test.

Fig 9. Test of the algorithm M8 on independent data. After [12].

Each line is a time-scale for an area, centered around a point, indicated on the map. Heavy line - a TIP. Arrows show the moment of an earthquake; its magnitude is indicated at the upper time-scale.

References.

1. Allen, C., Keilis-Borok, V. I., Rotwain, I. M., and Hutton., K. A set of long-term seismological precursors; California and some other regions. In: Mathematical methods of seismology and geodynamics. Computational Seismology Iss. 19, Moscow, Nauka(in Russian), 1986. English translation by Allerton Press, N. Y.
2. Barenblatt, G. M., Keilis-Borok, V. I., and Monin, A. S. Filtration model of earthquakes sequence (in Russian). Docladi Academii Nauk SSSR, April, 1965.
3. Crutchfield, J. P., Farmer, J. D., Packard, N. H., and Shaw, R. S. Chaos. Scientific American, Dec 1986, pp. 38-49.
4. Farmer, J. D. and Sidorowitch, J. J. Exploiting chaos to predict the future. Los-Alamos Natl laboratory, LA-UR-88-901, March, 1988.
5. Gabrielov, A. M. and Keilis-Borok, V. I. Patterns of stress corrosion: geometry of the principal stresses, PAGEOPH, vol. 121, No. 3, pp. 477-494, 1983.
6. Gabrielov, A. M., Keilis-Borok, V. I., Levshina, T. A., and Shaposhnikov, V. A. Block model for dynamics of the lithosphere. Computational seismology Iss. 19, pp. 168-178, Moscow, Nauka (in Russian), 1986. English translation by Allerton Press, N. Y.
7. Gabrielov, A. M., Dmitrieva, O. E., Keilis-Borok, V. I., Kosobokov, V. G., Kuznetsov, I. V., Levshina, T. A., Mirzoev, K. M., Molchan, G. M., Negmatullaev, S. Kh., Pisarenko, V. F., Prozoroff, A. G., Rinehart, W., Rotwain, I. M., Shebalin, P. N., Shnirman, M. G., and Schreider, S. Yu. Algorithms of Long-Term Earthquake Prediction. CERESIS, Lima, Peru, September 1986. (Available from Dr A. Giesecke, CERESIS, Lima 14, Peru.)
8. Gelfand, I. M., Guberman, Sh. A., Keilis-Borok, V. I., Knopoff, L., Press, F., Ranzman, I. Ya., Rotwain, I. M., and Sadovsky, I. M. Pattern recognition applied to earthquake epicenters in California. Phys. Earth. Plan. Int. 11, pp. 227-283, 1976.
9. Guberman, Sh. A. et al. On criteria of oil and gas content in morphostructural knots (the Ands of the Southern America). Docladi Academii Nauk SSSR, 1986, vol. 291, No. 6, pp. 14-36.
10. Keilis-Borok, V. I., Knopoff, L., Rotwain, I. M., and Allen, C. R. Intermediate-Term Prediction of Times of Occurence of Strong Earthquakes in California and Nevada. 1988, Nature(in press).

11. Keilis-Borok, V. I. and Rotwain, I. M. Diagnosis of time of increased probability of strong earthquakes in different regions of the world; algorithm CN. Manuscript, 1988.

12. Keilis-Borok, V. I. and Kossobokov, V. G. Premonitory activation of an earthquake flow: Algorithm M8. Manuscript, 1988.

13. Kossobokov V. G. and Rotvain, I. M. Pattern recognition of the earthquake prone areas. VI. Magnitude ≥ 7. Computational Seismology, Iss. 10, Moscow, Nauka (in Russian), 1976, pp. 3-18.

14. Kossobokov V. G. and Mazhkenov, S. A. Characteristics of the spatial similarity of seismicity. Computational Seismology, Iss. 22, Moscow, Nauka, 1989 (in press).

15. Levshin, A. L. and Berteussen, K.-A. Geophys. J. R. Astr. Soc., 1979, vol. 56, pp. 97-118.

16. Lichtman, A. J. and Keilis-Borok, V. I. Pattern recognition, applied to presidential elections in the United States, 1860-1980: Role of integral social, economic, and political traits. Proc. Natl. Acad. Sci. USA, vol. 78, No. 11, pp. 7230-7234, November 1981.

17. Lichtman, A. J and Keilis-Borok, V. I. Pattern recognition, applied to American mid-term senatorial elections. Manuscript, 1988.

18. Molchan, G. M., Dmitrieva, O. E., and Rotwain, I. M. Statistical analysis of the results of long-term prediction, based on bursts of aftershocks. Computational Seismology, Iss. 21, 1988, Moscow, Nauka (in Russian). English translation by Allerton Press, N. Y.

19. Pertsov, N. V. and Kogan, B. S. Physicochemical geomechanicks (in Russian), Docladi Academii Nauk SSSR, 235, pp. 1375-1378, 1981.

20. Pisarenko, V. F., Primakov, I. M., and Shnirman, M. G. The analysis of deformed array of moveable elements using particles, PAGEOPH, 1989 (in press).

21. Puppi, G. and Speranza, A. The physical problem of global climate on Earth. Bologna, Alma Mater Studiorum, n. 1, 1988.

22. Sadovsky, M. A., Bolckovitinov, L. G., and Pisarenko, V. F. Deformation of geophysical media and seismic process. Moscow, Nauka, 1987. (in Russian)

23. Smith S., Keilis-Borok, V. I., and Kossobokov, V. G., Localization of intermediate-term earthquake prediction ("Mendocino scenario"). Manuscript.

24. Zhurkov, S. N., Kuksenko, V. S., Petrov, V. A., Saveljev, V. I., and Sultanov, U. S. Concentration criterion of volume-type fracture in solids. Physical processes in earthquake sources. Moscow, Nauka, 1978, pp. 101-116, (in Russian).

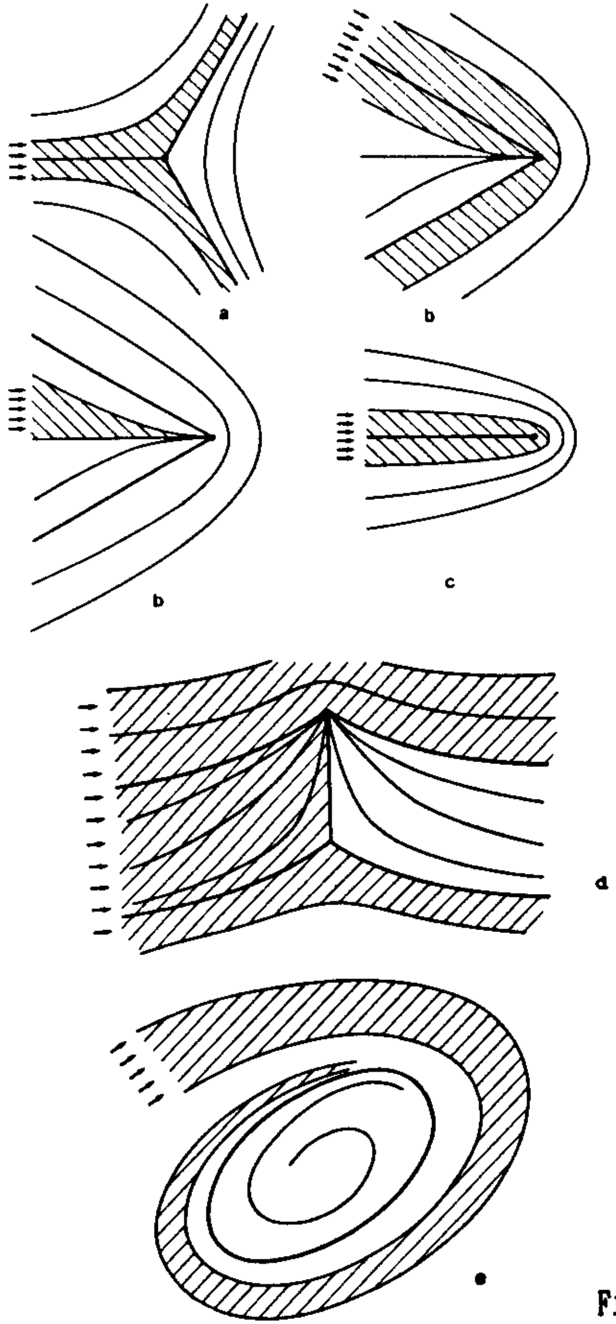


Figure 1

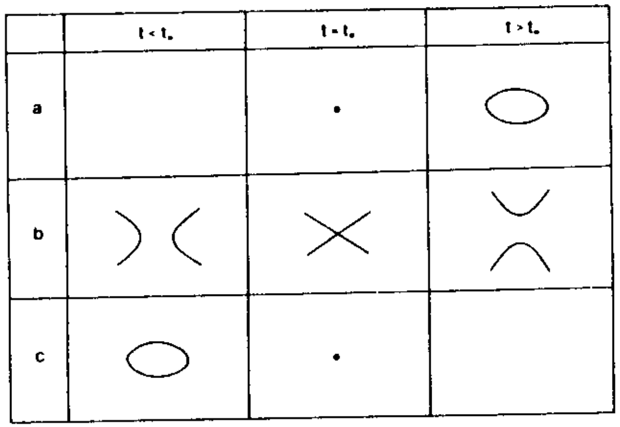
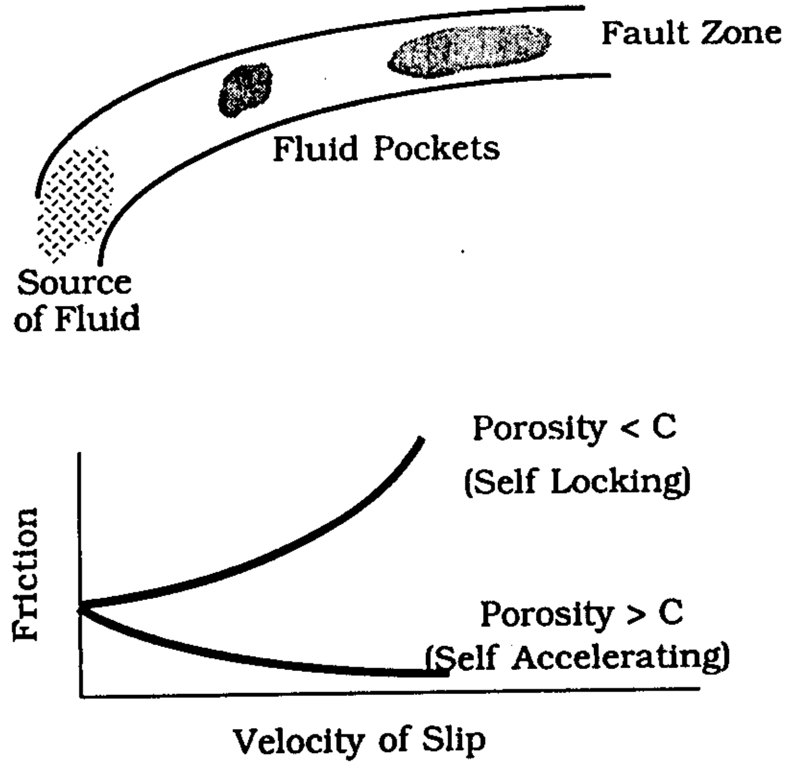


Figure 2



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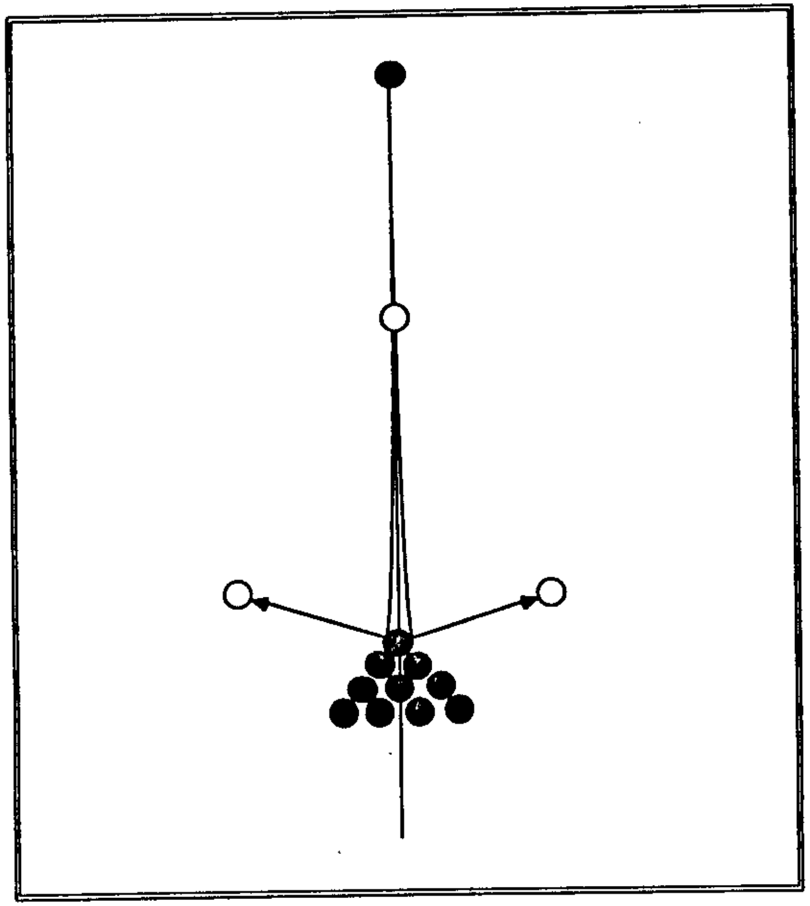

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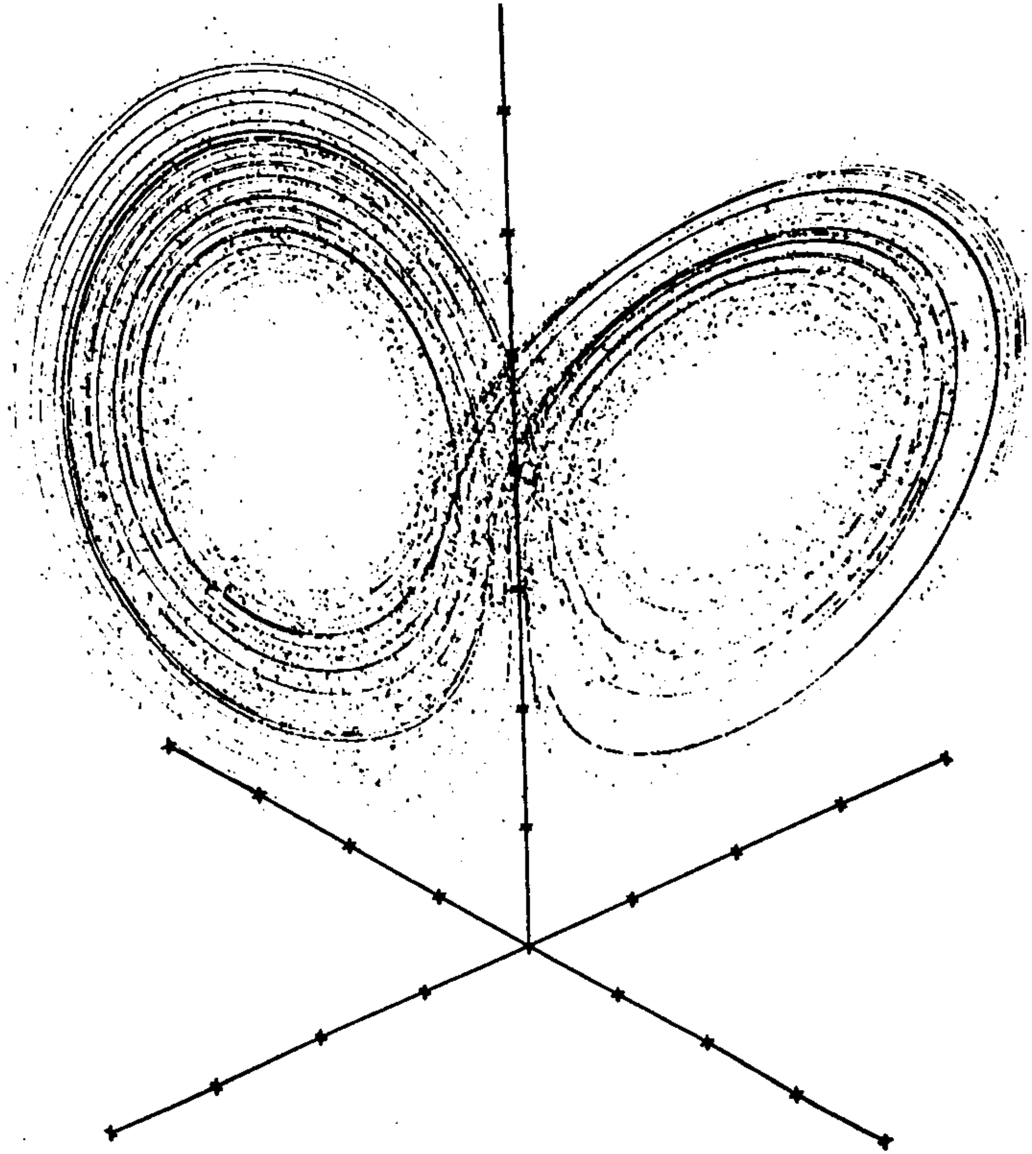

Figure 5

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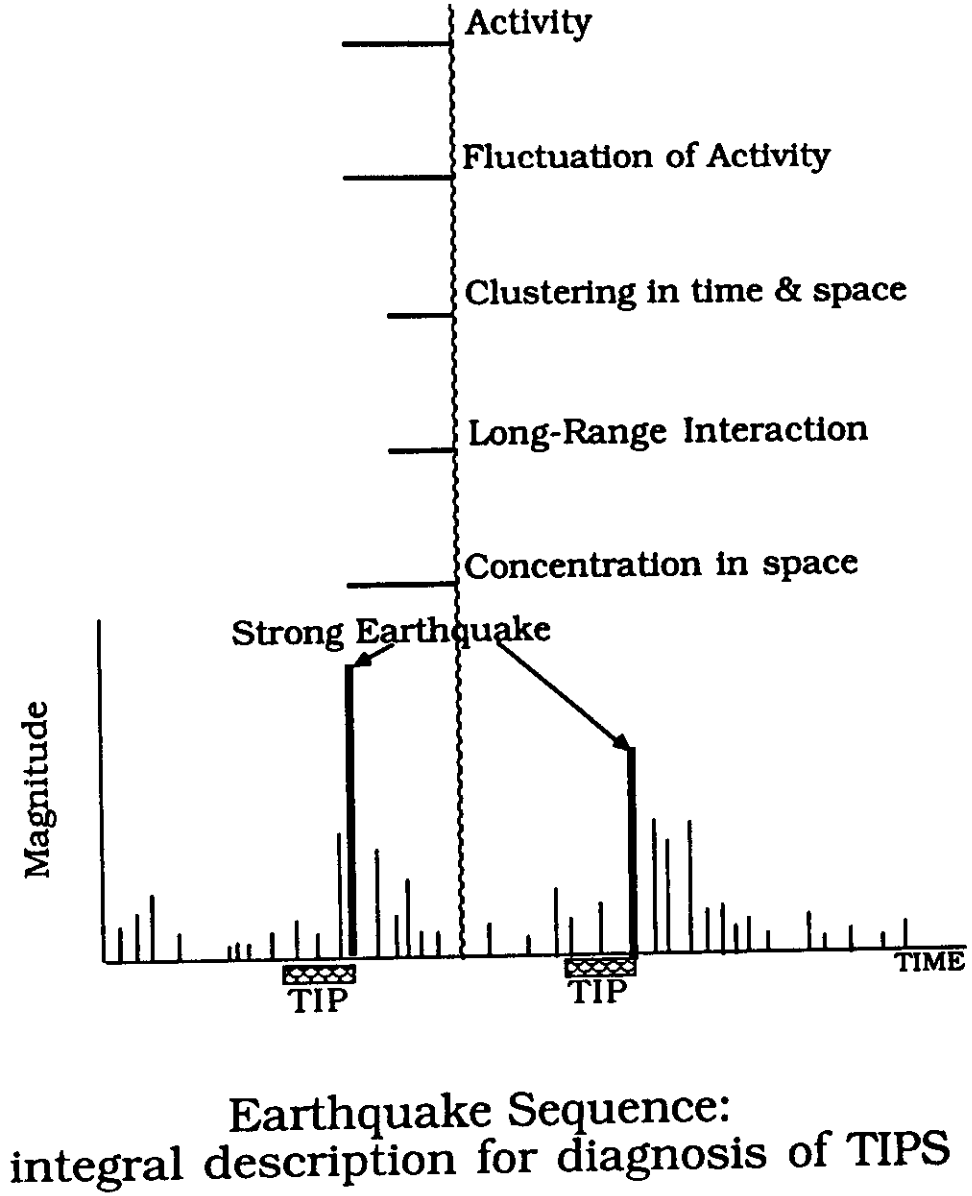
Figure 6



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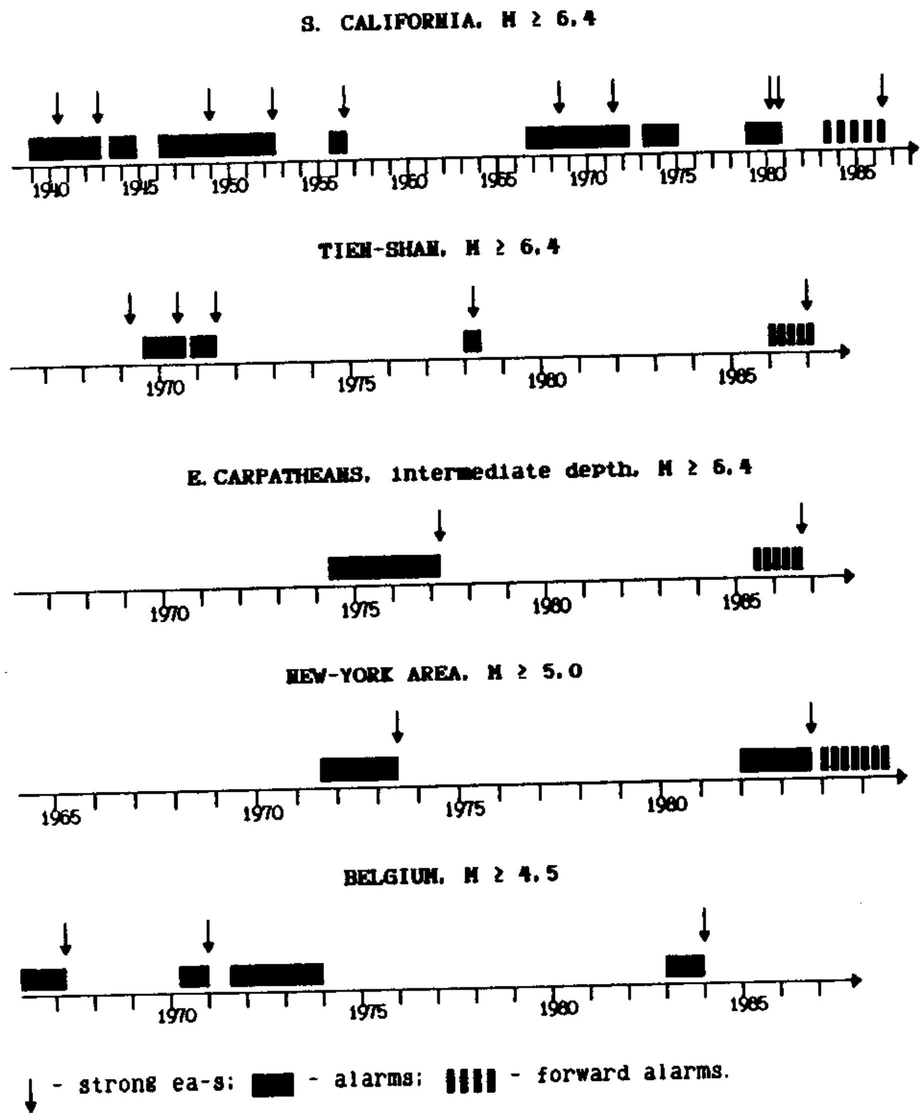


Figure 8

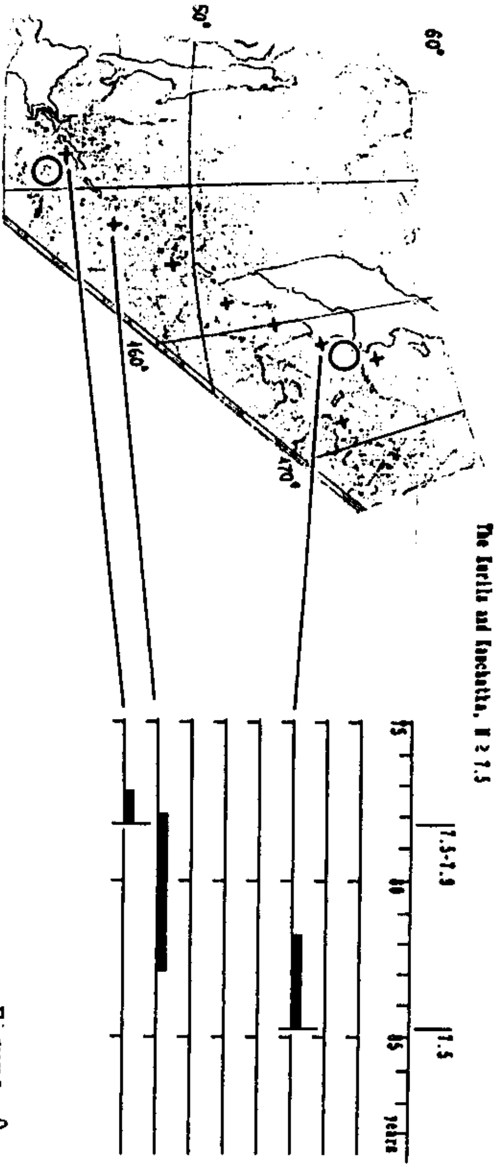


Figure 9

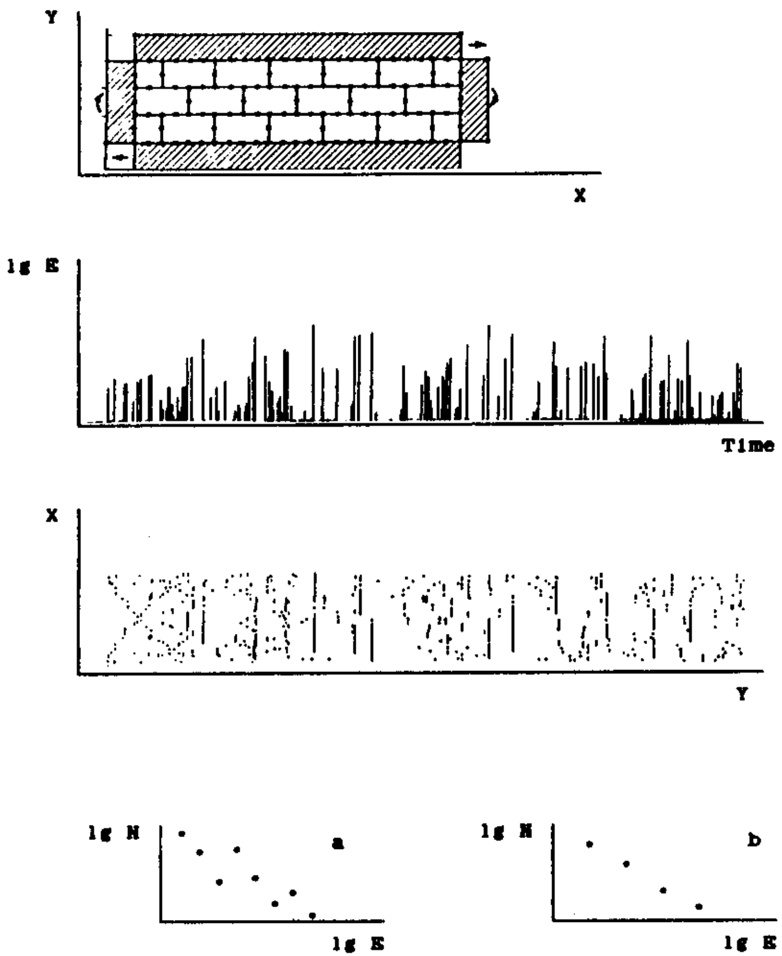
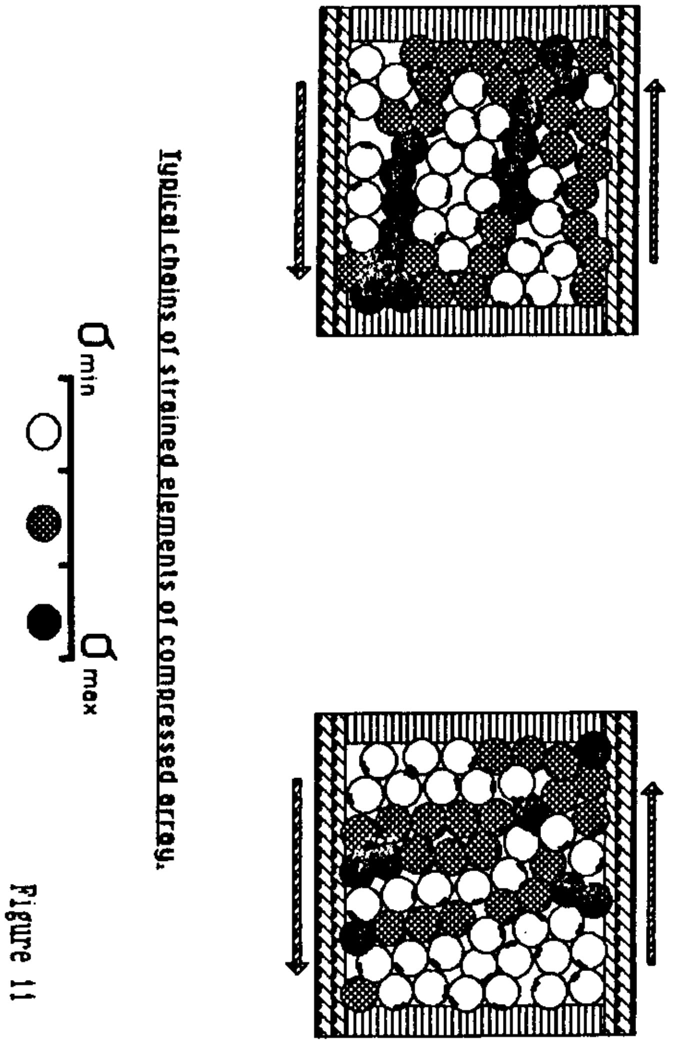


Figure 10



Typical chains of strained elements of compressed array.

Figure 11

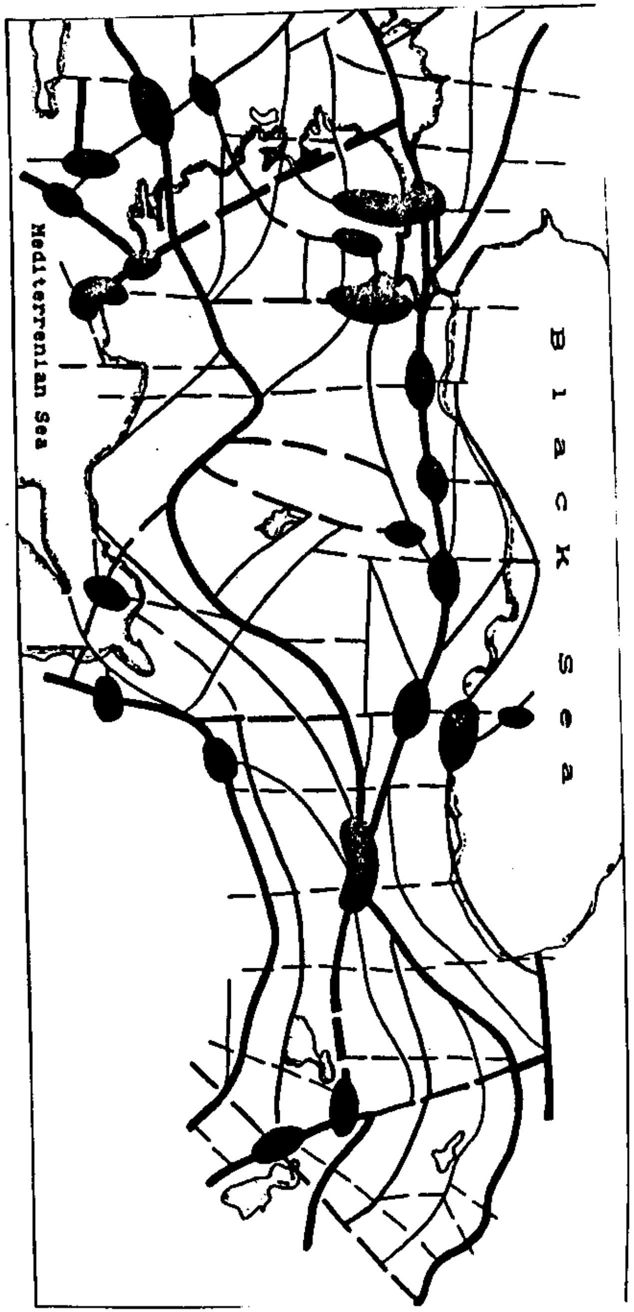
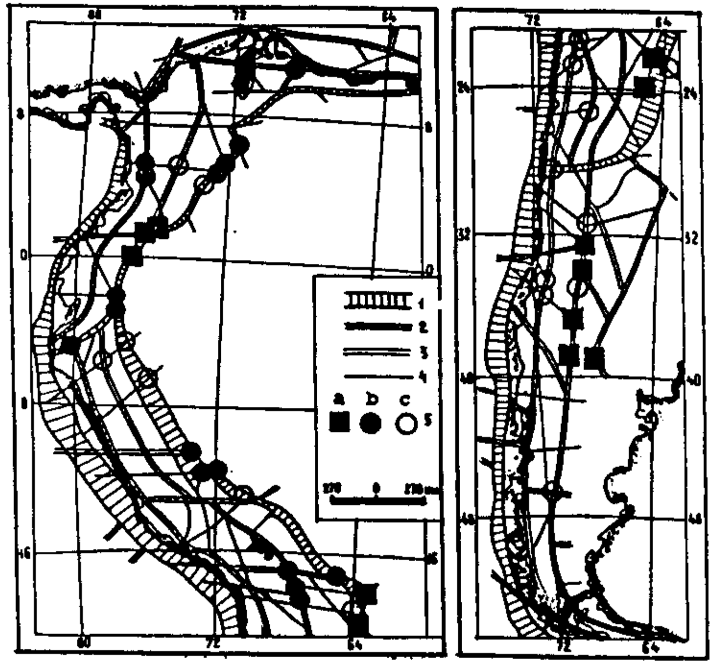


Figure 12



Notations: 1 - oceanic trenches and continental slopes;
2 - major strike-slip faults;
3 and 4 - lineaments of the 2nd and the 3rd rank;
5 - large deposits:
a - known, b - probable, c - possible.

Figure 13

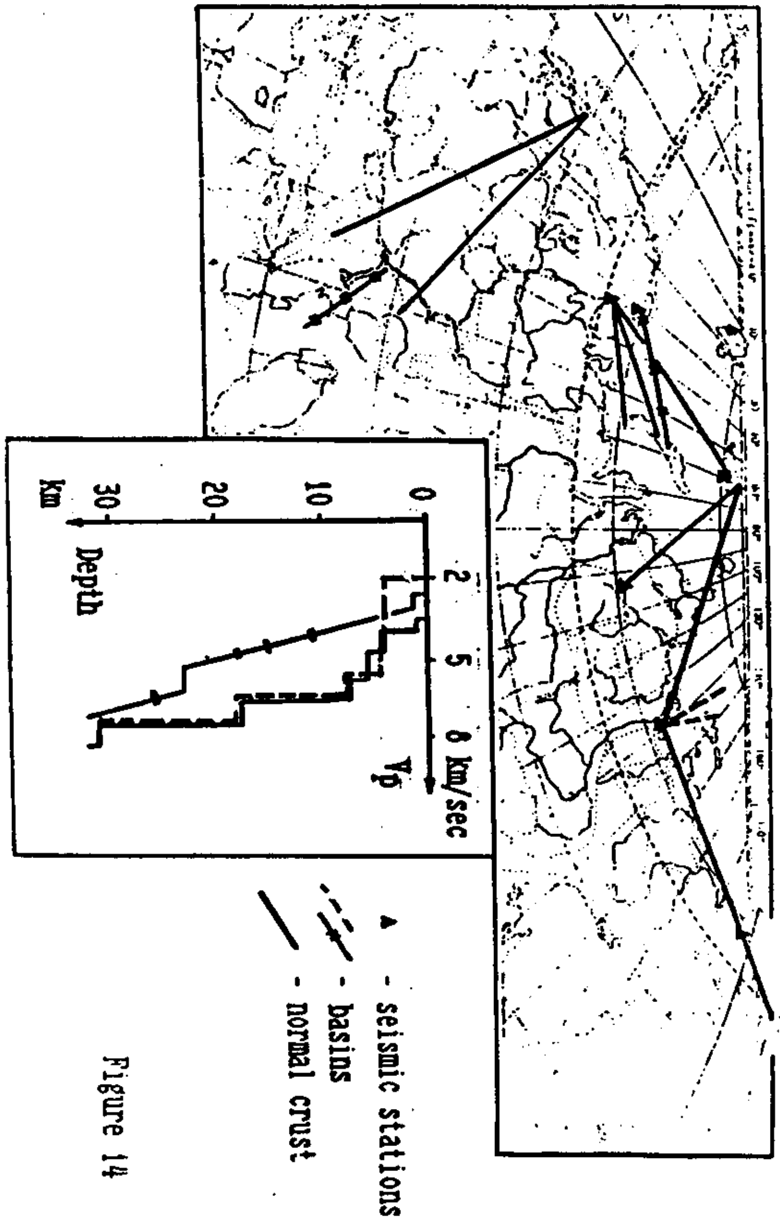


Figure 14

Table 1. Test of the algorithm CN (after [11]).

Territory	Period of diagnosis	Mo	Strong ea-s within TIPs/total	Duration of TIPs per strong ea-ke, years	%
East of Central Asia					
region N	1966-1987.8	6,4	3/ 5	0,5	11
region S	1966-1987.8	6,4	5/ 5	2,0	43
Trans-Baikal	1966-1984.1	6,4	0/ 0	0	0
Vrancea	1966-1986.7	6,4	2/ 2	3,2	30
(E. Carpathean mts.)					
Gulf of California	1968-1984.1	6,6	2/ 3	1,7	31
Cocos plate	1968-1984.1	6,5	4/ 4	1,6	38
N. Appalacheans					
region N	1964-1985.1	5,0	1/ 2	3,2	29
region S	1964-1985.1	5,0	0/ 0	0	0
Central Italy	1954-1986.1	5,6	3/ 5	1,2	18
Belgium	1966-1987.1	4,5	3/ 3	1,9	25

Table 2. Test of the algorithm M8 (after [12]).

Region	Mo	Time considered in diagnostics	Strong earthquakes: all	Strong earthquakes: within TIPs	Space-time volume (in mln.sq.km·year): of TIPs	of TE	total	Number of TIPs: all	S
1. The world	8.0	1967-1982	7	5	124.2 (5%)	76.4 (3%)	2500.0	16	7
2. Central America	8.0	1977-1986	1	1	12.0 (16%)	12.0 (16%)	73.0	2	1
3. The Kurils and Kamchatka	7.5	1975-1987	2	2	4.7 (17%)	1.0 (7%)	26.9	3	2
4. Southern America	7.5	1975-1986	3	3	10.0 (10%)	13.0 (13%)	102.0	8	3
5. Western United States	7.5	1975-1987	-	-	2.2 (5%)	2.2 (5%)	45.5	1	0
6. Southern California	7.5	1947-1987	1	1	3.2 (12%)	0.3 (1%)	27.2	1	1
7. Western United States	7.0	1975-1987	2	2	4.7 (24%)	1.9 (10%)	19.3	2	2
8. Baikal and Stanovoy range	6.7	1975-1986	-	-	0 (0%)	0 (0%)	11.5	-	-
9. The Caucasus	6.5	1975-1986	2	1	1.1 (12%)	0.6 (7%)	9.1	1	1
10. East of Central Asia	6.5	1975-1987	5	4	3.2 (24%)	1.5 (11%)	13.2	6	5
11. North Eastern Tien Shan	6.5	1963-1987	4	4	4.0 (27%)	2.2 (15%)	14.7	5	5
12. Western Turkmenia	6.5	1979-1986	-	-	0 (0%)	0 (0%)	2.9	-	-
13. Apennines	6.5	1970-1986	1	1	0.7 (10%)	0.1 (1%)	7.5	1	1
14. The Koyna reservoir	4.9	1975-1986	1	1	0.1 (42%)	0.1 (30%)	0.3	1	1
15. The Himalayas with surroundings	7.0	1970-1987	2	2	3.1 (8%)	0.7 (2%)	38.0	4	3
16. Vrancea	6.5	1975-1986	2	2	1.0 (50%)	0.5 (29%)	1.8	2	2
17. Vancouver Island	6.0	1957-1985	4	4	2.3 (20%)	1.6 (14%)	11.3	7	5
Regions No.1-17 together			36	32 (89%)	10%	10%		59	39
Regions No.2-14 together			21	19 (91%)	14%	10%		30	22

Table 3. The Integral parameters depicting a situation before the American mid-term senatorial elections (after [17]).

Incumbent party candidate is sitting senator?

Incumbent party candidate is major national figure?

No serious contest for incumbent-party nomination?

Incumbent party got 60%+ in the previous election?

Challenging party candidate is not a national figure or past or present governor or member of Congress?

No serious contest for challenging party nomination?

Incumbent party candidate not of the same party as the President?

Incumbent party candidate outspends challenger by at least 10%?

Table 4. The prediction of the outcome of the 1986 senatorial elections from the advanced publication in "Washingtonian". Four errors are marked with the black dots.

☑ WINNERS AND ☐ LOSERS

REPUBLICAN SEATS

State	Keys Against	Incumbent-Party Candidate	Challenger
Alabama	5	☐ Jeremiah Denton	☑ Richard Shelby
Alaska	3	☑ Frank Murkowski	☐ Glenn Olds
Arizona	4*	☑ John McCain	☐ Richard Kimball
Florida	5*	☐ Paula Hawkins	☑ Bob Graham
Georgia	5	☐ Mack Mattingly	☑ Wyche Fowler
Idaho	4*	☑ Steve Symms	☐ John Evans
Indiana	3	☑ Dan Quayle	☐ Jill Long
Iowa	3	☑ Charles Grassley	☐ John Roehrick
Kansas	2	☑ Robert Dole	☐ Guy MacDonald
Maryland	6	☐ Linda Chavez	☑ Barbara Mikulski
Nevada	6	☐ James Santini	☑ Harry Reid
New Hampshire	3	☑ Warren Rudman	☐ Endicott Peabody
New York	4*	☑ Alphonse D'Amato	☐ Mark Green
● North Carolina	4*	☑ James Broyhill	☐ Terry Sanford
● North Dakota	2	☑ Mark Andrews	☐ Kent Conrad
Oklahoma	4*	☑ Don Nickles	☐ James Jones
Oregon	3	☑ Robert Packwood	☐ Rick Bauman
● Pennsylvania	5	☐ Arlen Specter	☑ Robert Edgar
South Dakota	6	☐ James Abdnor	☑ Thomas Daschle
Utah	1	☑ Jake Garn	☐ Craig Oliver
● Washington	4*	☑ Slade Gorton	☐ Brock Adams
Wisconsin	4*	☑ Robert Kasten	☐ Ed Garvey

DEMOCRATIC SEATS

State	Keys Against	Incumbent-Party Candidate	Challenger
Arkansas	2	☑ Dale Bumpers	☐ Asa Hutchinson
California	3	☑ Alan Cranston	☐ Ed Zschau
Colorado	4*	☑ Timothy Wirth	☐ Ken Kramer
Connecticut	2	☑ Christopher Dodd	☐ Roger Eddy
Hawaii	1	☑ Daniel Inouye	☐ Frank Hutchinson
Illinois	3	☑ Alan Dixon	☐ Judy Koehler
Kentucky	3	☑ Wendell Ford	☐ Jackson Andrews
Louisiana	4	☑ John Breaux	☐ Henson Moore
Missouri	5*	☐ Harriet Woods	☑ Kit Bond
Ohio	1	☑ John Glenn	☐ Thomas Kindness
South Carolina	1	☑ Ernest Hollings	☐ Henry McMaster
Vermont	3	☑ Pat Leahy	☐ Richard Snelling

If four or fewer keys fall, the incumbent-party candidate wins; if five or more fall, the challenger wins.
*Prediction would change if spending key changed.