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The Lithosphere of the Earth as a Nonlinear System with Implications for Earthquake Prediction

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WITH IMPLICATIONS FOR EARTHQUAKE PREDICTION

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

The history of science will probably label our time by the sweeping intrusion of the concept of deterministic chaos, with all the 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 Weltanschauung, the perception that well-ordered, predictable phenomena present just an archipelago in the ocean of Nature, which is intrinsically nonlinear and chaotic. Luckily, the chaos can be, to some extent, understood. A limited set of universal patterns can be recognized in the chaotic behavior of exceedingly diverse systems: nonlinear pendulums, living matter, economy, burning fuel, brain, ocean, atmosphere; and here we discuss the implications for the lithosphere.

THE LITHOSPHERE

The lithosphere's 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 in relation to each other. The largest blocks are the major tectonic plates themselves. They are divided into smaller blocks, like shields or mountain chains. After 15–20 divisions we come to the grains of rock of millimeter scale, if not less.

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

Boundary Zone	*Size of Blocks, 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 similar 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; it suffers deformation up to fracturing due to the motion of the blocks; and it somehow heals, since it does not 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 rediscovered during the last 5–6

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years, can rapidly and unobtrusively change the friction and cohesion by a factor of 10^5, if not more, and accordingly change the effective strength within the lithosphere. So, while the energy of the motion is stored within and well beneath the lithosphere, the release of the energy and the motion is controlled mainly by the boundary zones.

We shall now briefly review 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, nonlinear chaotic system.

Rhebinder Effect, or Stress Corrosion

Many solids lose their strength by contact with certain surface-active liquids. A 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 Griffith's criterion is proportional to $\sqrt{\mu}$. Then cracks may appear under very small stress, liquid penetrates the cracks, and the cracks grow with the drops of liquid propelling forward like tiny knives. This mechanism requires very little energy—like unlocking a door, instead of breaking it. It was first discovered for metals, 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. An example is basalt in a sulphur solution [*Pertsov and Kogan*, 1981]. When they meet, the basalt will be permeated by a grid of cracks, and its effective strength may drop instantly by an order of magnitude and eventually decrease by 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. The geometry of a system of cracks can be equally diverse. The geometry of the weakened areas, where the cracks are concentrated, is strictly limited however. Such areas may be of only a few types [*Gabrielov and Keilis-Borok*, 1983], determined by the theory of singularities. Some examples are shown in Figure 1. The light lines are possible trajectories of cracks. Each heavy line is a separatrix, which separates the areas with different patterns of trajectories.

What does this mean for an observer of the lithosphere? Suppose the source of a fluid appears in the place shown by arrows. The fluid 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 the 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.

A new dimension is brought into this picture by the evolution of this stress field. It evolves incessantly, for many reasons, including feedback from the fatigue itself. Such evolution may change the type of singularity, as

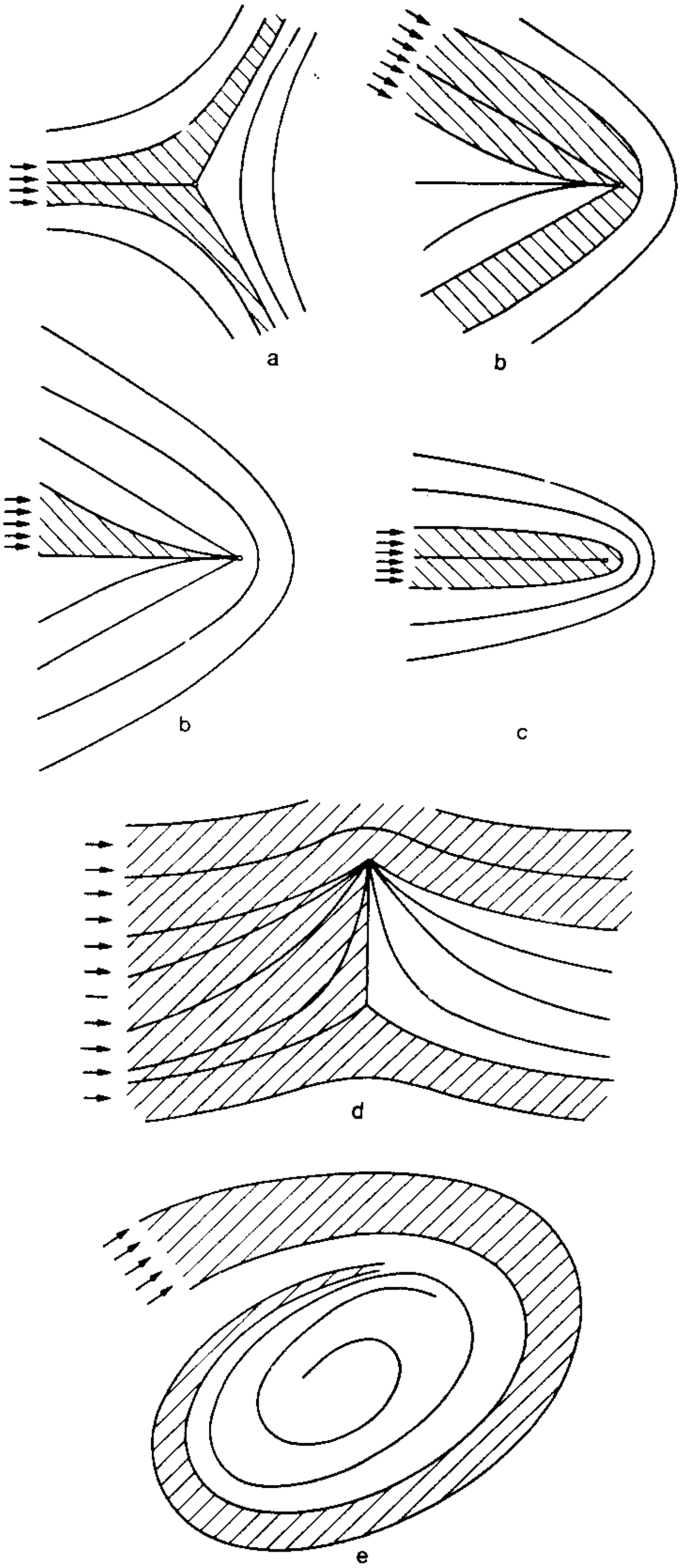

Figure 1. The geometry of fatigue induced by stress corrosion. The sources of surface-active fluids are shown by arrows. The weakened zones are hatched. Figures 1*a*–1*c* correspond to different types of singularities of the principal stress field; Figure 1*d* corresponds to two singularities of the type shown in Figure 1*a*; and Figure 1*e* corresponds to a loop or "limit cycle." After *Gabrielov and Keilis-Borok* [1983].

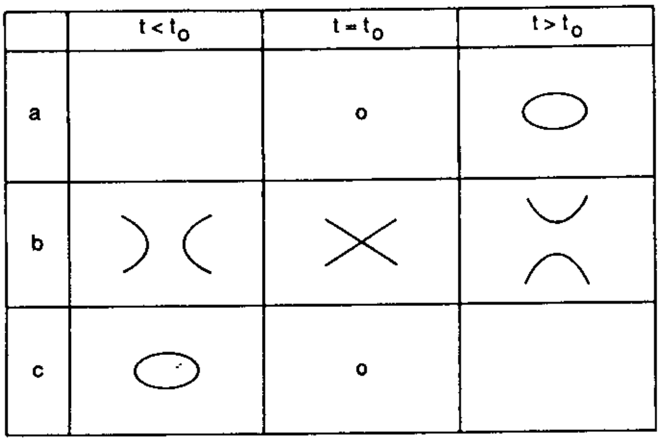

Figure 2. The evolution of singularities in the three-dimensional case: (*a*) birth of a loop; (*b*) bifurcation; and (*c*) annihilation of a loop. After *Gabrielov and Keilis-Borok* [1983].

shown in Figure 2, and the geometry of fatigue will follow suit.

So, the Rhebinder effect brings into the dynamics of the lithosphere a strong and specific instability, controlled by the stress field and by the 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 the 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 this way it is easy to explain also the 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 the stress field may prevent their extension to the scale of premonitory patterns, which is tens to hundreds of kilometers. More probably, these singularities are elements which compose a more complicated infrastructure of fatigue. Second, the Rhebinder effect may decay along the trajectories due to diffusion of the fluids. Finally, this effect is not the single major mechanism by which the boundary zones control the dynamics of the lithosphere, generating deterministic chaos for good measure. Even the fluids alone generate other coexisting 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 [*Barenblatt et al.*, 1985]. A boundary zone between two blocks is modeled as a porous layer. When shear stress exceeds friction, slip begins.

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

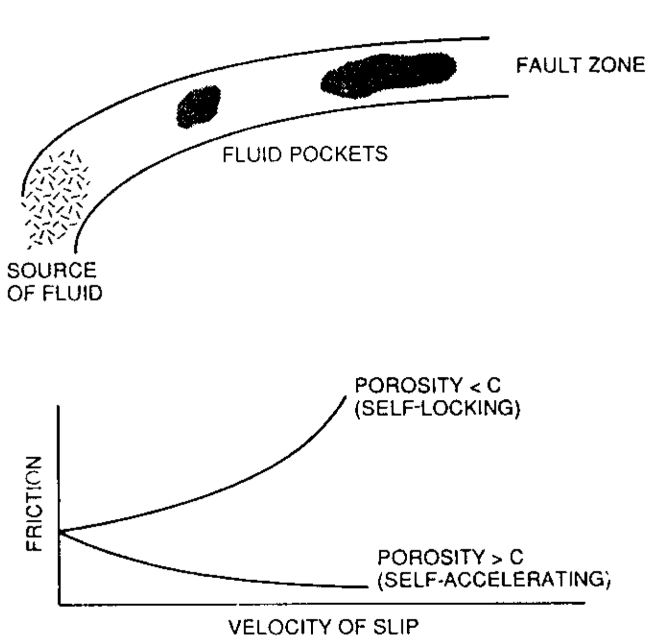

Figure 3. Instability of a fault zone due to filtration of fluids. After *Barenblatt et al.* [1985]. (Top) Fault zone, modeled as a porous layer with residual pockets of fluids between impermeable rigid blocks. (Bottom) The mechanism of instability.

This instability is aggravated by the erratic velocity of filtration. It is described by the nonlinear parabolic equation [*Barenblatt et al.*, 1985]

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

Here P is the perturbation of pressure on the background of steady filtration flow; P_0 is the background pressure; $K = k/(m\rho\nu)$, where k and m represent permeability and porosity of the layer and ρ and ν represent the density and viscosity of the fluid. Though this equation is parabolic, P propagates with a final velocity proportional to $\sqrt{P_0}$. The calculated velocity lies in the range of tens to hundreds of kilometers per year [*Barenblatt et al.*, 1985], the same as the observed rate of migration of seismicity along fault zones.

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

This mechanism may explain even more features of real seismicity that can be explained by the Rhebinder effect. The same premonitory seismicity patterns, the foreshocks and aftershocks, and quasi-periodicity in the recurrence of strong earthquakes are explained by this mechanism. The difficulties with spatial scale do not arise here.

But again, there is no reason whatsoever to single out this particular mechanism. First, such instabilities may develop in parallel within boundary zones of different rank and interact along the hierarchy. This model may be only one element of an infrastructure of filtration-generated instabilities.

The Need for a Generalized Model

The boundary zones feature several other mechanisms of instability, potentially as important and certainly as complicated as those discussed above. One is the usual type of lubrication. Another is petrochemical and phase transitions which may generate lubricators, for example, both in formation and decomposition of serpentines. Boundary mechanisms may also create an instant loss of volume, such as in the transformation of calcite into aragonite. This will create a vacuum and unlock a fault, which will at once be closed by hydrostatic pressure, but an instability may be triggered. Most mechanisms of this type depend strongly on the temperature. Finally, traditional mechanisms, such as buckling, clustering of cracks, and viscous flow, remain important, but I will not dwell on them, hoping that the point is made.

The dynamics of the lithosphere can be viewed as the interaction of its blocks across and along the entire hierarchy of sizes. This interaction is realized through a wide variety of mutually dependent mechanisms. Each of them creates instability. However, none can be singled out as a major factor that allows the others to be neglected.

So what we need is the "whole enchilada"—a generalized theory that 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 the Gestalt concept: the whole is more than just a sum of its components. For example, the laws of biology cannot be derived from the evolution of protoplanetary dust, though life is the result of this evolution. Instead, we hope for a model that directly represents the grossly averaged traits of the lithosphere, in particular, the laws of its dynamics.

The problem of averaging 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 to draw from, except those too general for our purposes. Even a grain of rock cannot be considered as a purely mechanical element of the lithosphere in simple local interaction with its peers. As we have seen, it undergoes a multitude of processes. It can act simultaneously as a material point, a source or absorber of energy, etc. It cannot even be treated exactly as a single element because it may also act as an aggregate of interacting crystals while its surface is engaged in quite different processes.

Therefore, to model the integrated, averaged behavior of the lithosphere, we have to do the averaging for an ensemble—not of mechanical elements—but of processes. The experience of quantum statistical physics shows that this is not easy.

Traditional models are based on the 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, microfracturing is often represented as a drop in elastic modulus, to which a 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 homogeneous; when purely mechanical processes dominate; and only for certain time and space scales. Almost none of the phenomena discussed above can be reproduced by such models, even if we present the parameters as some Pickwickian construction (not to be understood literally) Our search for a generalized theory brings us to the concept of deterministic chaos. The qualitative description of chaos is recalled in the following section.

CHAOS

Chaos arises in deterministic systems because of their specific instability. For example, imagine a billiard game (Figure 4). The player sends the ball into the usual array of other balls. The slightest variation in the direction of the original push will send the ball down quite a different path and the difference will not attenuate but will 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. Newton's laws do determine the trajectory of each ball and the sequence of collisions. But the prediction will be completely wrong after a certain number of collisions even if the initial push is defined with an error as small as the gravitational effect of a single electron on the margin of the galaxy. It is beyond the 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 at any level of precision of the initial conditions. If the boards are convex ("Sinay billiard") even a single ball reduced to a material point will display the same instability. With a multitude of such turning points, a dynamic system may display erratic, complicated behavior, which looks and is called chaotic. 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, like the nonlinear pendulum, for example.

However, this kind of chaos does contain inherent regularities. These regularities can be understood, and some integral traits of chaotic behavior can even be predicted. Quoting Shakespeare, "though this be madness, there is method in't."

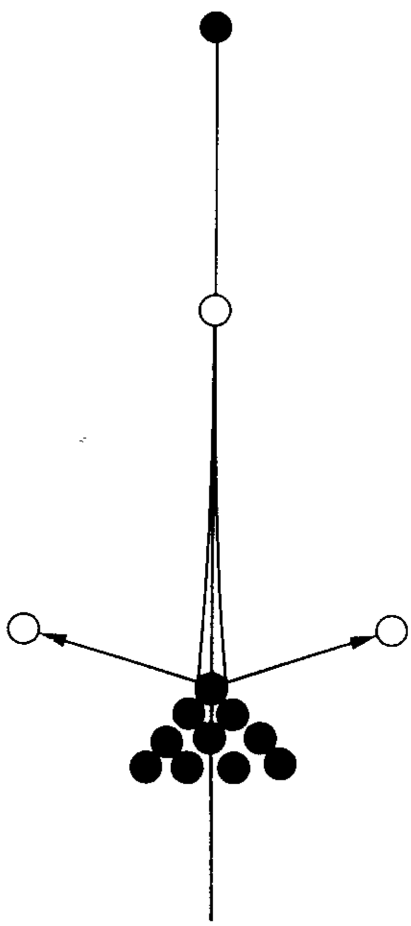

Figure 4. An illustration of the origin of deterministic chaos.

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

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

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

Figure 5 shows a phase space for this system [*Crutchfield et al.*, 1986]. Its coordinates are these three functions, so that a point completely defines the state of the system at some moment of time; the evolution in time is defined by a trajectory. There is a strong divergence. The dots in Figure 5 show 10,000 different states at some moment of time. They evolved from 10,000 initial states, which were so close that they are all merged into one dot in Figure 5 (somewhere in the top right corner). In other words, microscopic initial perturbation leads to macroscopic divergence, and prediction is impossible. However, we see an inherent regularity: all states eventually congregate around the configuration represented by the lines. These lines are the asymptotic trajectories. The evolution of the system will gradually be attracted to them. They occupy the subspace called the chaotic or strange attractor. The subspace has smaller dimensionality than the whole phase space.

A nonchaotic system may have two rather prosaic stable attractors: a fixed state and a harmonic oscillation; in phase space it will be a point and a loop, called a limit cycle, respectively. (One may add quasi-periodic oscillation, formed by two incommensurate 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 Figure 5 has the geometry of the Cantor set. Any small part of this attractor, when examined through a magnifying glass, will show a similar uneven density of lines. If we cut off a small part of this enlarged sample and enlarge it again, we will still see a similar pattern, and so on indefinitely.

The probability that the system will cross any point specified in advance is zero. But the system will certainly pass within an arbitrarily small distance of an attractor. So, we now know of a very restrictive global regularity: the system will eventually move along this attractor. However, we cannot go into much more detail, we cannot predict specific trajectories, and 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.

The global traits of a chaotic system cannot be derived from the interaction of its components: it is a Gestalt phenomenon. The natural tendency to understand such a system by breaking it down into small elements is futile. A large zoo of diverse strange attractors has been encountered, but their general theory has not been discovered so far.

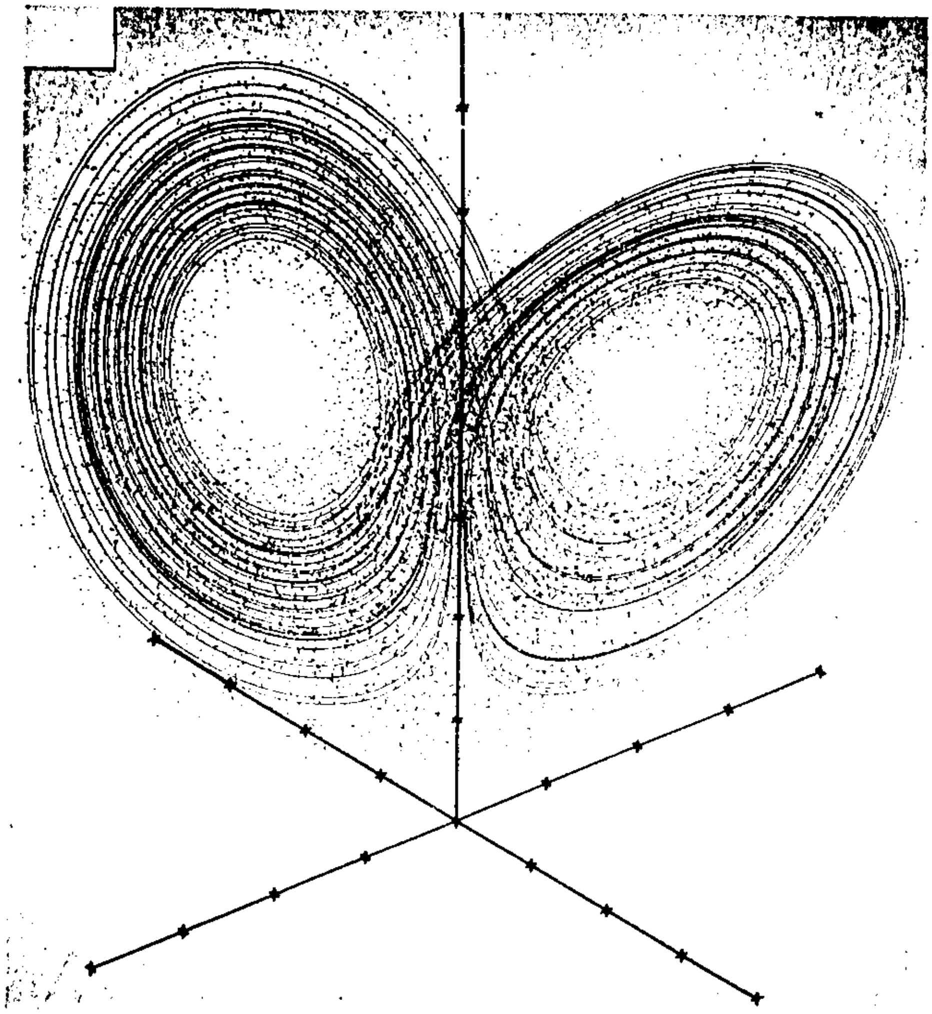

Figure 5. The Lorenz strange attractor. After *Crutchfield et al.* [1986].

Nonlinear systems show many other behavior patterns that are incomprehensible for linearly oriented intuition: intermittency, i.e., alternation of different types of motion; transitions between chaotic and orderly behavior with the change of a "control parameter" (Figure 6); etc. There are also other kinds of self-organization in the lithosphere, of a statistical physics type; they are not considered here.

Chaotic patterns generate a hypnotic fascination, like a waterfall or burning wood. Accordingly, nonlinear science has a dramatic vernacular; for example, the turn of a curve to a vertical asymptote is called blue-sky catastrophe. The temptation is not unknown to stampede into new applications of these patterns like the avant-garde of a 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

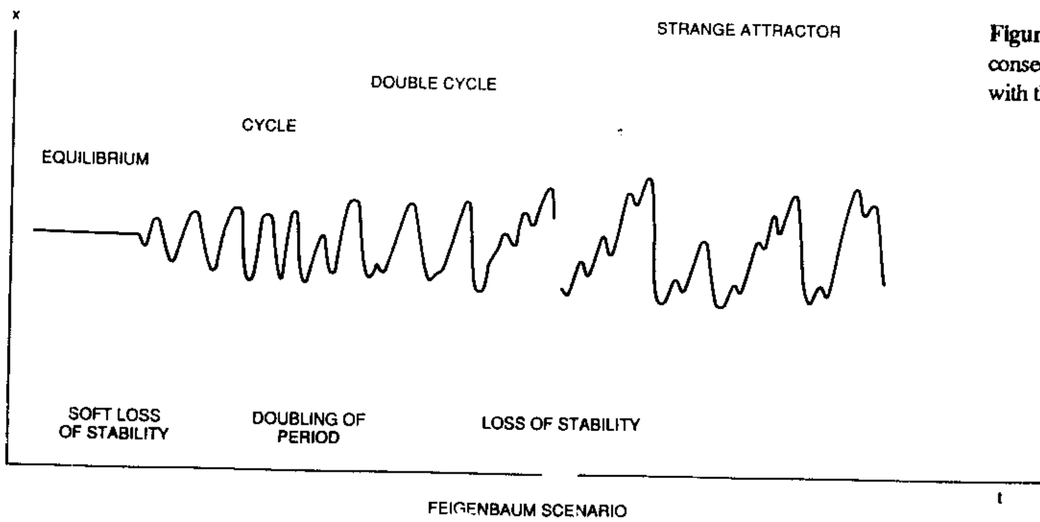

Figure 6. Feigenbaum scenario: consecutive doubling of the period with the change of control parameter.

useful model for the lithosphere. The difficulty of this kind for the modeling of climate is brilliantly described by *Puppi and Speranza* [1988, pp. 23, 25].

> . . . 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.

For the lithosphere, the problem seems even more difficult since the lithosphere, with its fractures and fixed inhomogeneities, does not mix as easily as the atmosphere. For some time and space scales, even the purely mechanical description of the lithosphere would probably require mechanics not of continuous but of fractal media.

Predictability

It may seem unexpected from the previous description, but some features of deterministic chaos can be predicted, though with limited accuracy and lead time. For example, transition to another branch in a Lorenz system (Figure 5) can be predicted with sufficiently small lead time, because it is always preceded by a sharp bend of 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 a 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 of predicting a feature of a hierarchical system with deterministic chaos lies in averaging (smoothing); the more averaged a feature is, the larger are the time and space scales in which prediction may be possible. Accordingly, in the dynamics of the lithosphere, and particularly in the problem of earthquake prediction, we first have to find, for a given time and space scale, an adequate smoothed description, without losing the phenomena we are interested in. A "smoothed description" is the reduction of the system to a small number of integral characteristics along with the relations between them (a low-dimensional phase space). The first steps have to be empirical—this field is in the same prehistoric stage as the theory of gravitation was before discovery of Kepler's laws. The 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 on many scales: the interaction between core, mantle, and crust; unexplained correlations of geochemical, tectonic, and geophysical fields over the Earth's surface; the evolution of the Earth—its whole tectonic history possibly may be rewritten as a sequence of instability episodes, like an intermittency.

We discuss here only the results relevant to the time scale of 1–10 years, which is intrinsic for earthquake prediction. This is particularly challenging, since the bulk of the lithosphere is inaccessible for the direct measurement of earthquake-related stress and strength fields. The lithosphere 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 the time-space domain where strong earthquakes are expected; this process is in accordance with the hierarchical nature of the lithosphere.

Here, however, the formulation of the problem is truncated: we consider only one step, which is the prediction of the strongest earthquakes in a fixed territory with an accuracy of a few years and a few hundred kilometers. This is classified sometimes as intermediate-term and sometimes as long-term forecasting. The second classification is used in the papers referred to, but I will use the first one, which is apparently more common.

General Scheme

The symptoms of an incipient strong earthquake may be different from case to case in the same area and may vary even more from region to region. Nevertheless, we have to look for a uniform diagnosis, applicable at all times in different regions and magnitude ranges, otherwise the test of prediction algorithms would require hundreds of years. We try to overcome this contradiction by considering an integral representation of earthquake activity where the diversity of circumstances is smoothed while the premonitory phenomena are hopefully not smoothed away. The uniformity of diagnosis is made possible by normalization of earthquake flow as described by *Allen et al.* [1986] and *Gabrielov et al.* [1986*b*].

The scheme of diagnosis is outlined in Figure 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 (TIP) of a strong earthquake.

The scheme is open for inclusion of any other hypothetically predictive phenomena, but so far only the traits of the five types listed in Figure 7 have been considered. They were selected for the following reasons.

The intensity of earthquake flow ("activity") was selected because abnormal activity and/or quiescence has

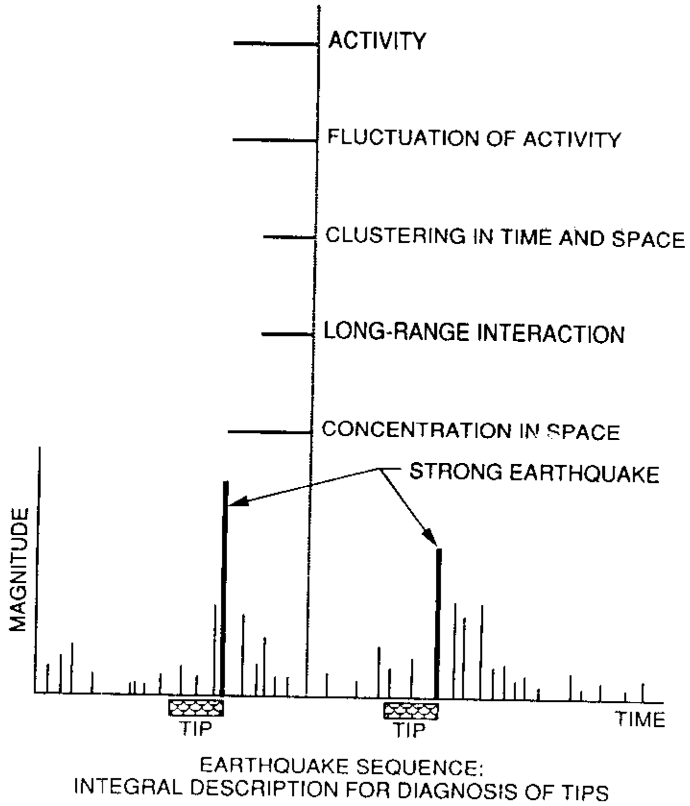

Figure 7. Scheme of description of earthquake sequence for diagnosis of times of increased probability (TIPs). After *Allen et al.* [1986] and *Gabrielov et al.* [1986*b*]. The earthquake sequence is described by several integral traits. Horizontal lines show the sliding time windows, on which different traits are defined. All windows end at the common moment of time, shown by the vertical line. The traits are attributed to this moment.

been reported before many strong earthquakes, separately or in combination. Among different kinds of quiescence, seismic gaps are most popular.

The next three traits represent phenomena common to many nonlinear 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 the distance within which the earthquakes are not independent. Also, clustering is the only promonitory pattern for which statistical significance is strictly established at present [*Molchan et al.*, 1988].

Concentration is suggested by laboratory experiments with rocks; when the density of microfractures exceeds some rather universal threshold, the failure of a whole sample occurs [*Zhurkov et al.*, 1978].

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

1. The traits are defined for large areas and time windows.

2. Each trait is represented by several not independent functionals; for example, the intensity of the earthquake flow is estimated in different overlapping magnitude ranges.

3. We distinguish only large, medium, and small values of each functional, so that their definition is sufficiently robust.

4. Finally, the diagnosis of TIPs is based on the whole set of traits, admitting that each one by itself may be insufficient.

To diagnose the TIPs is a common problem of pattern recognition.

A Soviet-American team considered the seismic history of California and Nevada [*Allen et al.*, 1986; *Keilis-Borok et al.*, 1988]. These traits were compared at moments in the past either preceding or not preceding earthquakes with $M > 6.4$. By this comparison we found the rule for recognizing the TIPs. Roughly quantitatively, this rule is as follows: most of the traits, listed in Figure 7, simultaneously became more prominent during a period of 3–4 years preceding a strong earthquake. Before this period a relative quiescence often occurs. A similar analysis was made for the strongest earthquakes (magnitude 8 or more) over the whole world [*Keilis-Borok and Kossobokov*, 1986]. 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 Figure 8.

Worldwide Tests

If reliable, these algorithms would have significant implications: that the blocks of lithosphere do show a collective behavior even in the erratic process of generating earthquakes; that our traits are promising candidates for basic integral characteristics of this behavior, so far somewhat clumsily formulated; and that we may predict strong earthquakes over the intermediate term. However, these conclusions are merely hypothetical, because in lieu of a theory we had to derive the algorithms by retrospective data fitting, and we improved the success-to-failure score by adaptation of many free parameters such as the length of time windows and the magnitude intervals. To test the prediction on independent data, we had to introduce an additional hypothesis: that the phenomena indicating the approach of a strong earthquake are similar in different regions, independent of the tectonic environment and the level of seismicity. This allows us to test the algorithms on independent data for other regions not involved in the data fitting. Technically, this is possible because the definition of all traits is normalized, so that looking at our representation of earthquake activity we would not distinguish a subduction zone from a mildly active platform, Kamchatka from Belgium.

So far, algorithms CN and M8 have been applied to the regions listed in Tables 1 and 2 [*Gabrielov et al.*, 1986*b*; *Keilis-Borok and Kossobokov*, 1986; V. I. Keilis-Borok and I. M. Rotwain, Diagnosis of time of increased probability of strong earthquakes in different regions of the

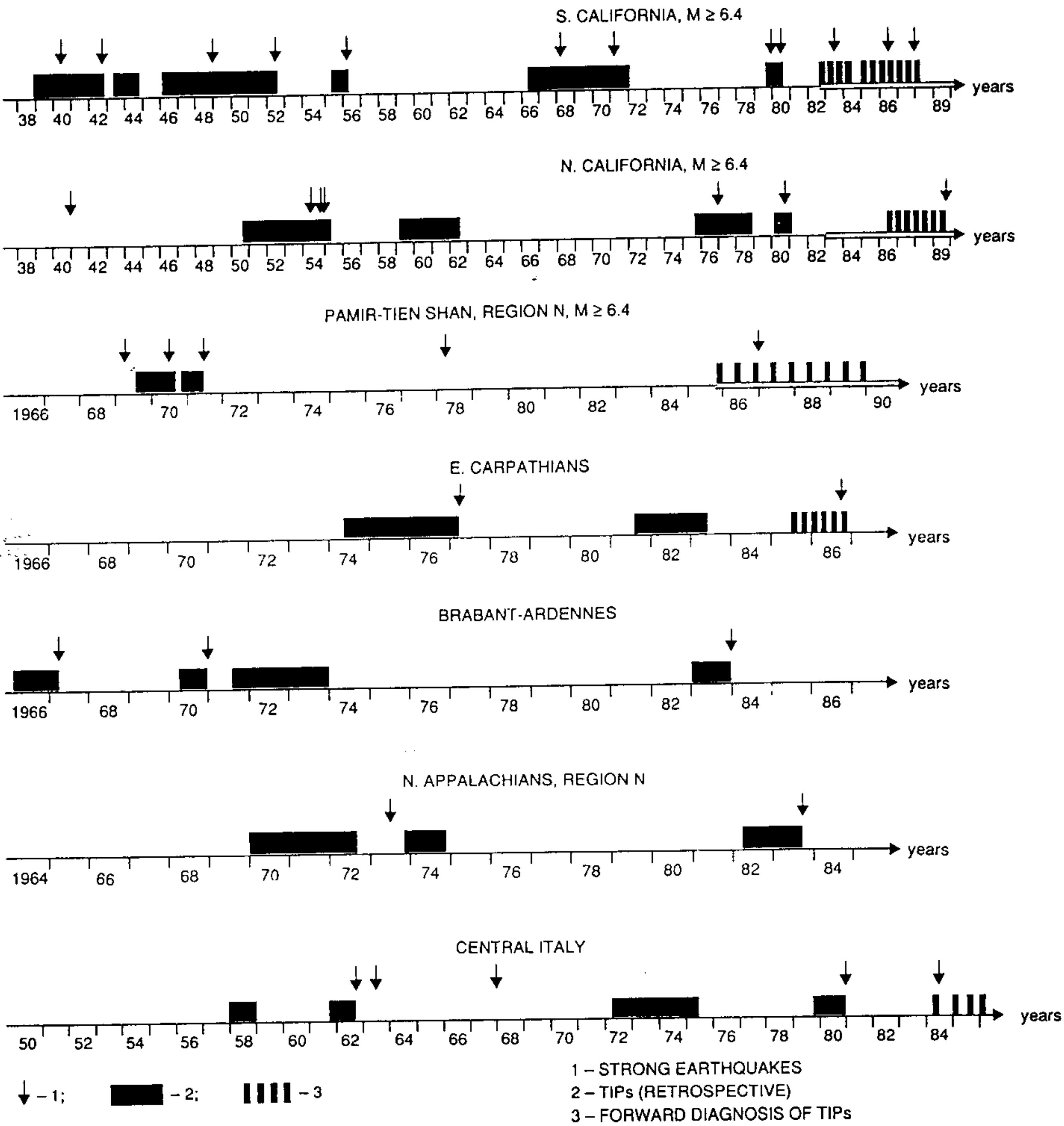

Figure 8. Test of the algorithm CN on independent data. After *Gabrielov et al.* [1986*b*] and V. I. Keilis-Borok and I. M. Rotwain (unpublished manuscript, 1988).

world: Algorithm CN, unpublished manuscript, 1988]. The results are summarized in those tables; for some specific regions they are shown in Figures 8 and 9. So far, TIPs were diagnosed in advance for six strong earthquakes: four in California-Nevada (including that on October 18, 1989), one in Pamir-Tien Shan, and one in Armenia (December 7, 1987).

It is encouraging that the success-to-failure score for these regions is, on the average, not much worse than it was for the regions used for the data fitting (compare, for example, the regions in Figure 8).

The practical value of such predictions is limited, though by no means annulled, by the fact that TIPs extended over areas 5–10 times larger in diameter than the

TABLE 1. Summary of the TIPs Diagnosed by Algorithm CN

Region	Time Considered	M_0	Strong Earthquakes "Predicted"	Strong Earthquakes Missed	Duration of TIPs: Average per Earthquake, years	Duration of TIPs: Total per Region, %
		"LEARNING"				
California-Nevada						
Southern region	1938–1983	6.4	9	0	2.2	42
Northern region	1938–1983	6.4	4	2	2.6	22
		APPLICATION WITHOUT ADAPTATION				
Pamir–Tien Shan						
Northern region	1966–1986	6.4	2	2	1.5	14
Southern region	1966–1986	6.4	5	0	1.9	45
Baikal	1965–1984	6.4	0	0	0	0
E. Carpathians						
(intermediate depth)	1966–1986	6.4	2	0	3.3	30
Gulf of California	1968–1984	6.6	2	1	2.6	31
Cocos plate	1968–1984	6.5	4	0	1.6	38
N. Appalachians						
Northern region	1964–1985	5.0	1	1	3.2	28
Southern region	1964–1985	5.0	0	0	0	0
Central Italy	1954–1986	5.6	3	2	2.0	18
Nepal	1970–1988	6.5	3	0	1.9	30
		APPLICATION WITH ADAPTATION				
Brabant-Ardennes	1966–1987	4.5	3	0	1.9	30
Kangra	1968–1988	6.4	1	0	0.3	2
Gaval-Kumaon	1968–1988	6.4	1	1	3.4	18
Assam	1968–1988	6.4	2	1	2.6	27
Caucasus	1966–1988	6.4	3	2	1.0	13
Total or average			45	12	1.9	23
Total or average, without "learning" and adaptation			22	6	1.8	23

source of the upcoming earthquake. There is some hope indicating, however, that we can pinpoint the place of a coming earthquake within about two lengths of its source (S. Smith et al., Localization of intermediate term earthquake prediction ("Mendocino scenario"), unpublished manuscript, 1988).

A quantitative estimate of the confidence level is still difficult, but the results for these regions, taken together, do support the following conclusions: (1) The dynamics of the lithosphere, having a chaotic component, also shows collective behavior. (2) The traits of the earthquake activity, considered here, provide an integral description of this behavior, which is similar in a 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 within the spirit of ideas about deterministic chaos, this similarity seems very controversial so far. I have heard exclamations (not simply questions): how could it be possible that the same diagnostics are uniformly applicable in such different seismotectonic environments while each single region is eminently inhomogeneous and the stress field changes 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 collapse may be uniformly diagnosed for any of us, e.g., if a single integral parameter, body temperature, exceeds +44°C. Indeed, some universal global phenomena do precede instability in very diverse systems. Since such universality transcends from brain to atmosphere to nonlinear oscillator, it may well transcend the mere differences between 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 earthquake activity and the universality of integral laws. Figure 10 shows a computer simulation of the interaction of lithospheric blocks [*Gabrielov et al.*, 1986*a*]. Energy is provided by the shear movement of boundaries, indicated by the hatched rectangles and arrows. The model generates earthquakes, in stick-slip fashion. In spite of its extremely simple geometry, the earthquake activity is chaotic. Not only is it unstable to the change of structure, but it has bifurcations:

TABLE 2. Summary of the TIPs Diagnosed by Algorithm M8

Region	M_0	Time Considered	Strong Earthquakes "Predicted"	Strong Earthquakes Missed	Space-Time Volume, % of Total: TIPs	Space-Time Volume, % of Total: Tes
		"LEARNING"				
1. The world	8.0	1967–1982	5	2	5	3
		APPLICATION WITHOUT ADAPTATION				
2. Central America	8.0	1977–1986	1	--	16	16
3. The Kurils and Kamchatka	7.5	1975–1987	2	--	17	7
4. Japan and Taiwan	7.5	1975–1987	5	1	20	8
5. Southern America	7.5	1975–1986	3	--	18	13
6. Western United States	7.5	1975–1987	--	--	5	5
7. Southern California	7.5	1947–1987	1	--	12	1
8. Western United States	7.0	1975–1987	2	--	24	10
9. Baikal and Stanovoy Range	6.7	1975–1986	--	--	0	0
10. The Caucasus	6.5	1975–1987	2	1	12	7
11. East central Asia	6.5	1975–1987	4	1	24	11
12. Eastern Tien Shan	6.5	1963–1987	4	--	27	15
13. Western Turkmenia	6.5	1979–1986	--	--	0	0
14. Apennines	6.5	1970–1986	1	--	10	1
15. Koyna reservoir	4.9	1975–1986	1	--	42	38
		APPLICATION WITH ADAPTATION				
16. Greece	7.0	1973–1987	3	--	18	10
17. The Himalayas with surroundings	7.0	1970–1987	2	--	8	2
18. Vrancea	6.5	1975–1986	2	--	58	29
19. Vancouver Island	6.0	1957–1985	4	--	20	14
Total or average			42	5	18	10
Total or average, without "learning" and adaptation			26	3	16	9

the sequence of earthquakes changes drastically when initial conditions are changed just by the lowest few digits in the computer memory. But many integral traits remain the same, e.g., the linear frequency-energy relation, migration, clustering, and 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.

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

Another model, more of a statistical physics type, similar to the well-known "life game," is shown in Figure 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 the stress between two discs exceeds friction, slip occurs, releasing energy; one elementary slip may trigger another. The discs show prominent collective behavior. The most stressed (darkest) discs are self-organized in these linear configurations which eventually become unstable; this triggers the "strong earthquakes" in the model. Again, a slight initial perturbation may drastically change specific patterns; there is no answer as to why this delineation is here and a minimum of stress is there. But, again, the model displays some integral traits of real earthquake activity.

A single disk (if having intellect) would hardly believe that his erratic pressure history from one slip to another, is averaged to some universal regularities. Predictable collective behavior is not uncommon, however, especially in systems with complicated interactions on an elementary level. This can be illustrated by a system of interactive electorate blocks in the American midterm Senatorial elections [*Lichtman and Keilis-Borok*, 1989]. 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 recognition prediction rule are the same for all states and all election years, while both are indeed diverse. Nevertheless, the prediction, published in advance, was correct for 30 out of 34 elections in 1986 (Table 4). The confidence level is above 99.9%. It remains above 97% if we allow only for the outcomes

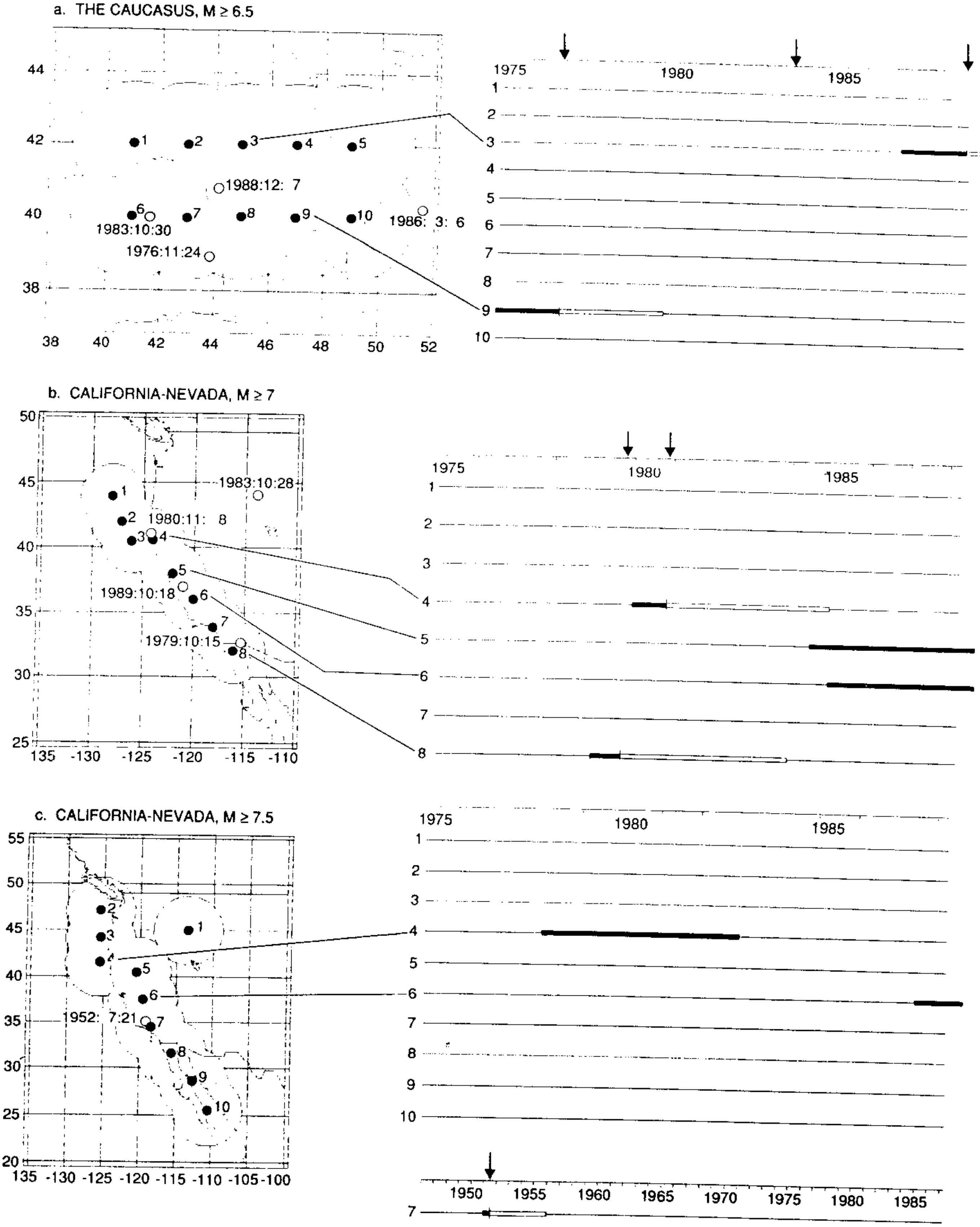

Figure 9. Test of the algorithm M8 on independent data. After *Keilis-Borok and Kossobokov* [1986]. Each line is a time scale for an area, centered around a point indicated on the map. The heavy lines indicate times of increased probability (TIPs). Arrows show the moment of an earthquake; its magnitude is indicated at the upper time scale. (*a*) Caucasus, $M \geq 6.5$. (*b*) California-Nevada, $M \geq 7$. (*c*) California-Nevada, $M \geq 7.5$. The TIPs preceding the Armenian earthquake on December 7, 1988, and the Santa Cruz earthquake on October 18, 1989, were reported in advance.

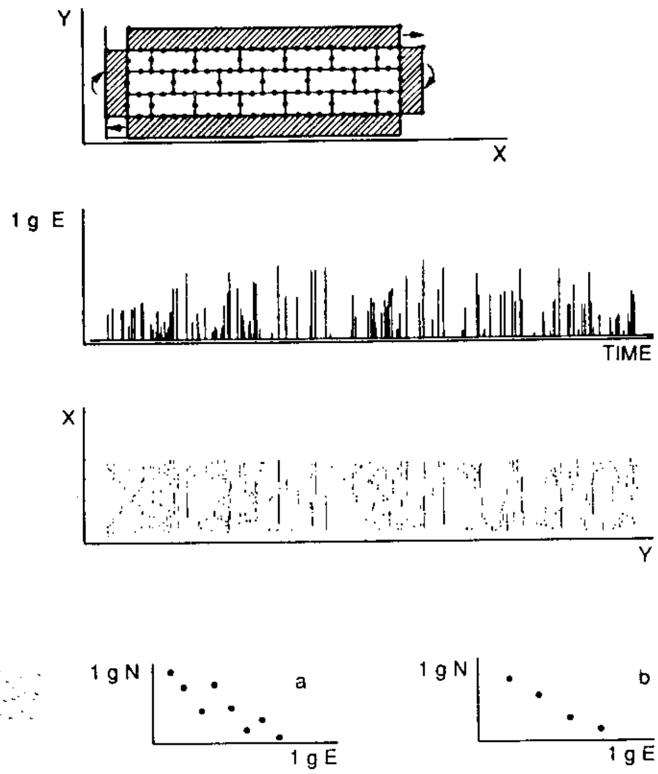

Figure 10. Unstable earthquake activity generated by a simple model of interacting blocks [after *Gabrielov et al.*, 1986*a*]. (Top) Geometry of the model. (Middle) Time sequence of earthquakes, T being the time and E energy; earthquake sources on (T, x) plane. (Bottom) Magnitude-frequency relation of occurrence relation for (a) small and (b) large energy intervals.

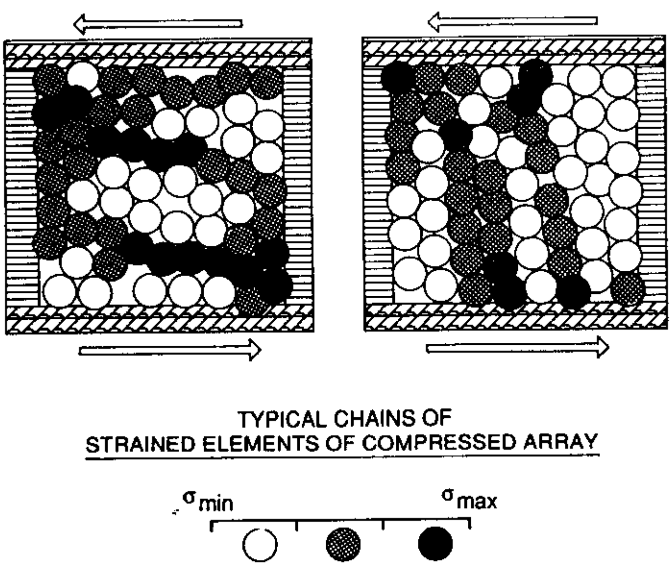

Figure 11. Self-organization of interacting blocks into chains in a simple model (after V. F. Pisarenko et al., unpublished manuscript, 1989).

TABLE 3. The Integral Parameters Depicting a Situation Before the American Midterm Senatorial Elections

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%?

After A. J. Lichtman and V. I. Keilis-Borok (Pattern recognition applied to America mid-term Senatorial elections, unpublished manuscript, 1988).

TABLE 4. Prediction of the Outcome of the 1986 Senatorial Elections From Advance Publication in *Washingtonian* (November 1986, p. 144).

State	*Keys Against*	*Incumbent-Party Candidate*	*Challenger*
		REPUBLICAN SEATS	
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	
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.
☒ Winners ☐ Losers.
* Prediction would change if the spending key changed.
• Incorrect prediction.

which the experts regarded as uncertain. A similar prediction rule was formulated for the Presidential elections [*Lichtman and Keilis-Borok*, 1981]. 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.

The differences of subject matter notwithstanding, these examples illustrate how the behavior of a chaotic system 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 a too detailed perception of the lithosphere.

CONCLUSION

The integral approach to other studies of the lithosphere, besides its dynamics on short time scales, deserves attention. It is a major and, I believe, the major workhorse in the present perestroika of the 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 stages—an empirical search for decisive integral parameters—I will discourse once more from the spirit of a Union Lecture, which should be an ivory tower exaltation. After the circus of elections, the next examples belong to the marketplace: industrial applications of geodesy and geophysics.

One example (Figure 12) is reconnaissance of areas where strong earthquakes, $M \geq 7$, are possible even if still unknown. Such results were obtained in many regions worldwide [*Gelfand et al.*, 1976; I. M. Rotwain et al., unpublished manuscript, 1988], also by a uniform method, and most subsequent earthquakes did appear in the prescribed places. These results illustrate the power of the hierarchical approach, since they are based on rather nondetailed data, provided by the maps of 1:2.5 million and 1:1 million scales, and obtained for large territories all at once. Traditional industrial methods would require 5–10 times more detailed data and, accordingly, a separate survey of each building site. Results such as those shown in Figure 12 drastically reduce the number of areas which require industrial surveys which may cost up to $\$10^7$ for each spot.

Literally the same can be said about the reconnaissance for oil fields (Figure 13). Similarly, analysis of surface waves from earthquakes [*Levshin and Berteussen*, 1979] allows reduction of expensive seismic prospecting by a factor of 5–10 (Figure 14).

Also similarly, game theory analysis of existing data on neotectonics and seismicity, together with demography and economy, allows reduction of the cost of earthquake insurance and optimization of preparedness measures [*Keilis-Borok et al.*, 1984].

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 and hardware. In this way one may save a good part of the cost of industrial surveys. It may even be the only possible way when dealing with chaotic phenomena.

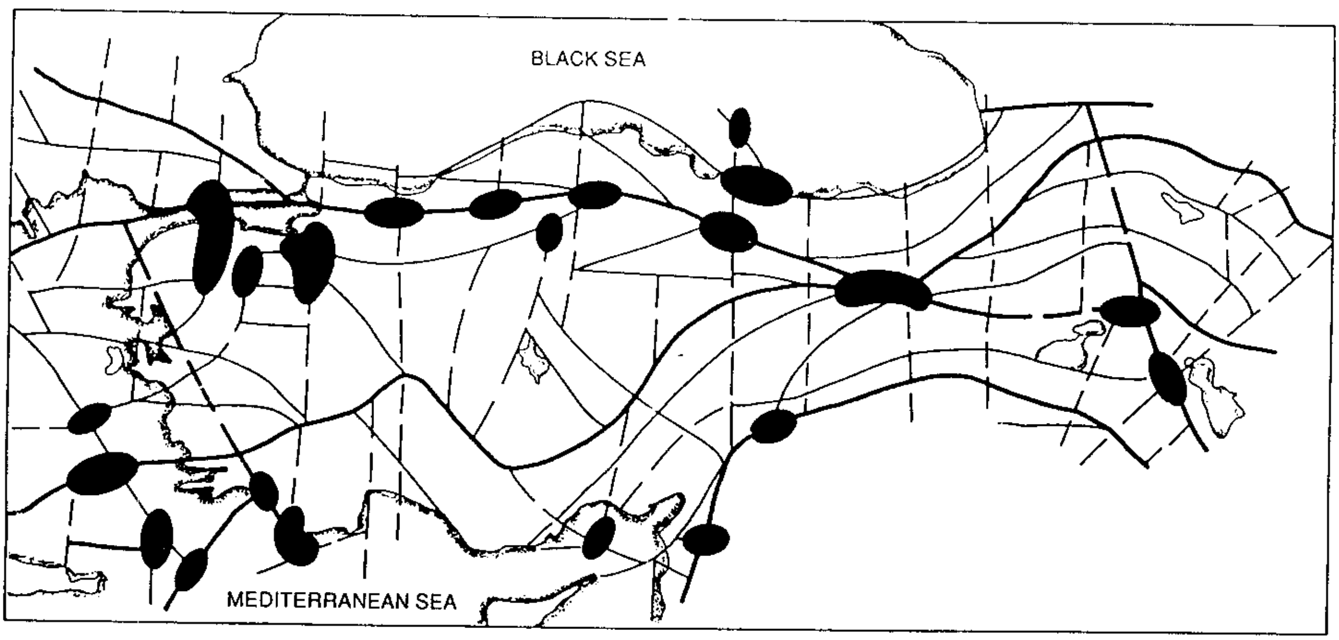

Figure 12. Earthquake-prone areas for $M \geq 7$ (shown as black areas). Areas are recognized by the data from a set of maps (tectonic, neotectonic, gravity anomalies, and satellite photographs). Lines are lineaments of different ranks. Such analysis is made for major regions of the world. Similarity is established. After *Kossobokov and Rotwain* [1976].

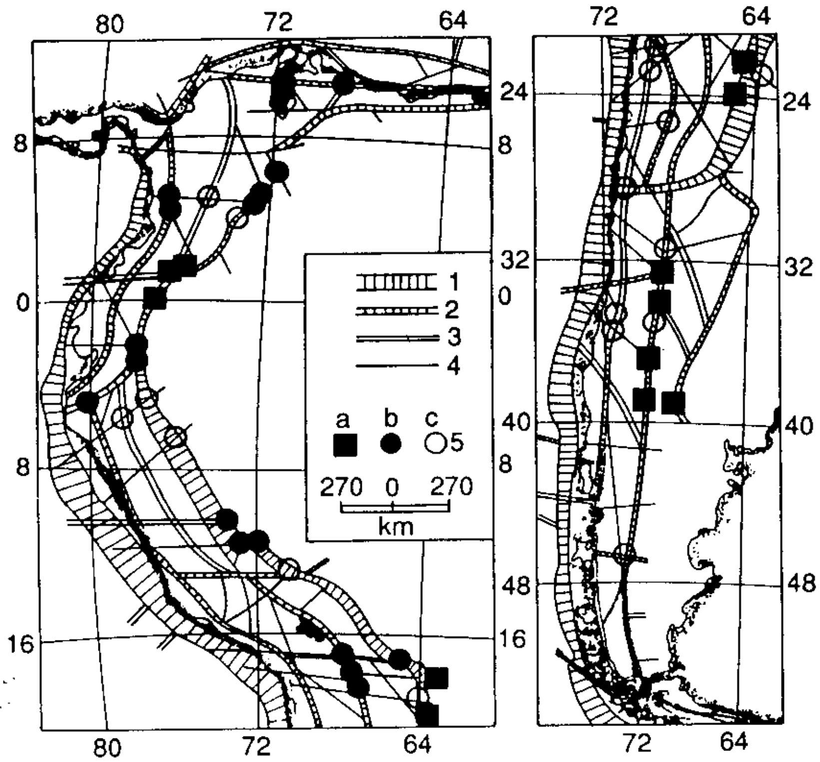

Figure 13. Recognition of areas promising for super large oil deposits. After *Guberman et al.* [1986]. The data used were taken from a set of maps (see caption to Figure 12). The method is tested on independent data.

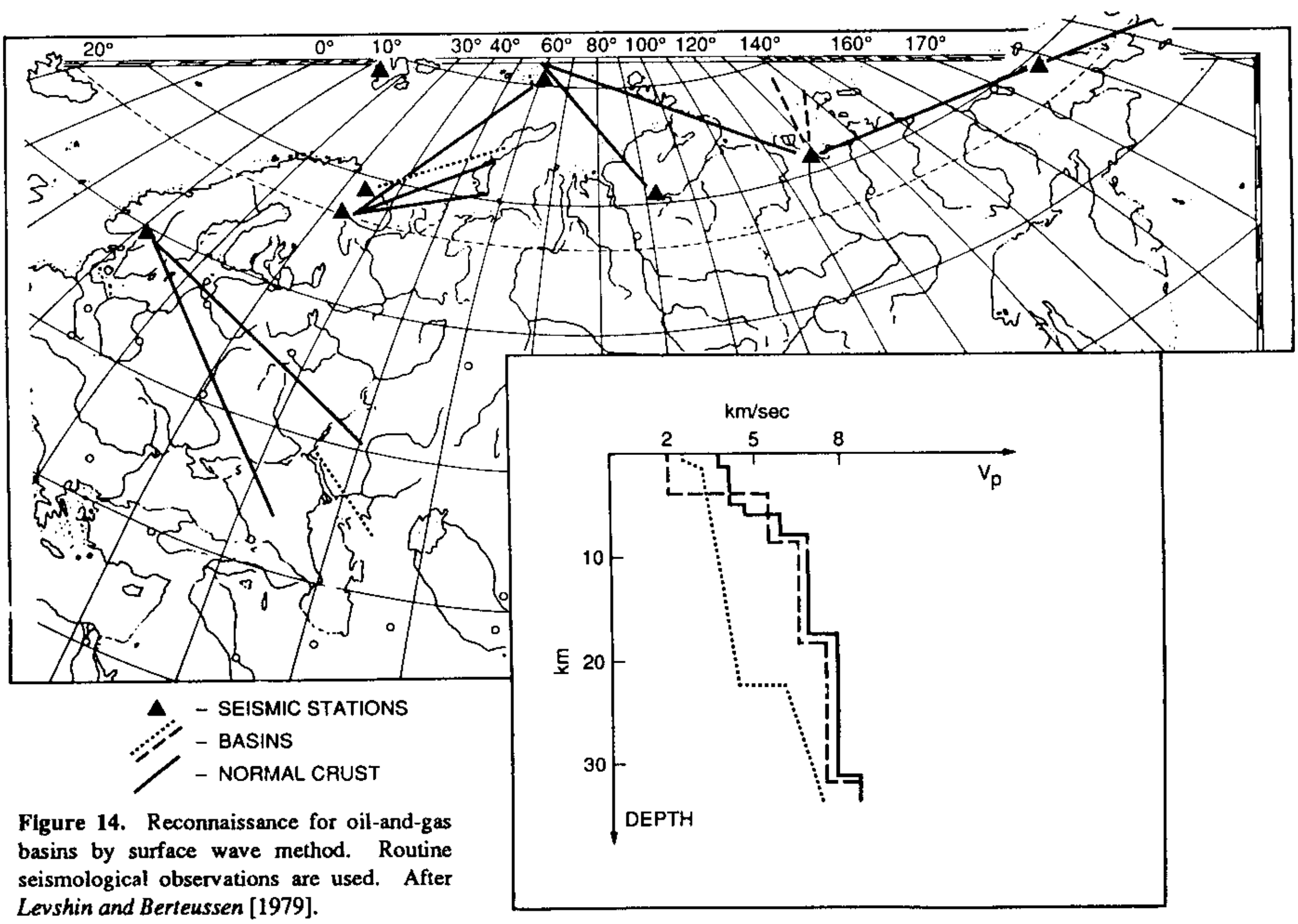

Figure 14. Reconnaissance for oil-and-gas basins by surface wave method. Routine seismological observations are used. After *Levshin and Berteussen* [1979].

In summary, I believe that among the other grand possibilities for better understanding of the Earth, modern nonlinear science in combination with global observational networks does deserve attention. It promises and requires further consolidation of Earth sciences on a new theoretical basis, consolidation and trimming of our observational base and our software, and better perception of the Earth as a whole with sufficient resolution to depict those features important for the economy.

We may even expect that a new kind of chaotic behavior, 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 concepts which revolutionize our perception of Nature.

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