The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR.1676 - 1

8th Workshop on Non-Linear Dynamics and Earthquake Prediction

3 - 15 October, 2005

Paradigms in Prediction of Critical Phenomena

Vladimir I. Keilis-Borok
Russian Academy of Sciences
International Inst. of Earthquake Prediction Theory and
Matematical Geophysics
Warshavskoye Sh. 79. Kor2
117556 Moscow
Russian Federation

and
Institutute of Geophysics and Planetary Physics &
Department of Earth and Space Sciences
University of California, Los Angeles,
405 Hilgard Ave., ICPP, Los Angles, CA 90095-1567
USA

INTRODUCTION

- Chaos
- Types of premonitory phenomena
- Long-range correlation
- Similarity
- Dual nature

What's next?

In the general scheme of things our course belongs to
predictive understanding of non-linear systems, a.k.a. complex or chaotic systems.

Such systems persistently selforganize into abrupt overall changes, generally called *critical phenomena* or *extreme events*. In applications we call them *crises, catastrophes,* or *disasters*; in non-linear dynamics - *bifurcations*; in statistical physics - *critical transitions.*

***Examples*: the *Earth's lithosphere*, generating catastrophic earthquakes, volcanic eruptions, and landslides; *economy*, generating recessions; *megacities*, generating outbursts of violence; *ecological* systems, generating fast deterioration of environment; etc.**

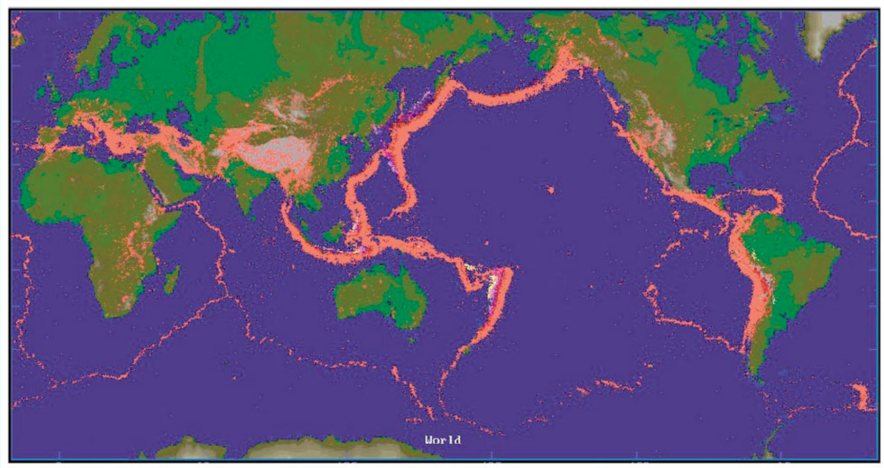
Prediction of extreme events is necessary for:

- ***Development of their fundamental theory.* This is a current frontier of the basic research ("finding order in chaos"),**

and

- ***Protection of population, economy, and environment.* Due to proliferation of high risk objects and rising socio-economic volatility of our world, such disasters became *"a threat to civilization survival, as great as was ever posed by Hitler, Stalin or the atom bomb"* /J. Wisner/. Prediction opens a possibility to reduce the damage by escalation of disaster preparedness.**

GLOBAL SEISMICITY



Red **points show earthquakes with magnitude greater than 4.0 for the last century. They clearly outline the global fault network.**

(From http://www.mitp.ru)

LITHOSPHERE - A HIERARCHICAL COMPLEX SYSTEM GENERATING EARTHQUAKES

STRUCTURE: BLOCKS =>FAULTS =>NODES

- **Earthquakes occur in the lithosphere - the upper shell of the solid Earth, few to few hundred km thick.**
- **It is divided into a *hierarchy of blocks* which move relatively each other. Largest blocks are about 10 tectonic plates; each is consecutively divided into smaller and smaller blocks, down to about 10^{25} grains of rocks.**
- **The blocks are separated by *boundary layers* called fault zones on the top of the hierarchy, then faults, sliding surfaces, cracks, microcracks, sliding surfaces, and, finally, interfaces. Except for the lowest ranks they consist of similar hierarchy of blocks, with more dense fracturing.**
- **Particularly fractured zones called *nodes* are formed around intersection of boundary layers (due to collision of the blocks' corners)**

DYNAMICS

- **The lithosphere is set in motion by external (e.g. mantle convection currents) and internal (e.g. gravity) forces.**
- **In seismically active regions a large part of the motion is realized through the earthquakes, loud and silent.**
- **An earthquake is an episode of rupture and discontinuous displacement on some part of a fault or several faults ("source").**
- **10^6 earthquakes (magnitude 2 or more) are registered each year worldwide, 10^2 of them are destructive, and once or twice in a decade the catastrophic earthquakes occur.**

FAULT NETWORK – STOCKPILE OF INSTABILITY

Seismicity is controlled by {stress – strength} field. The stress and particularly the strength are in turn controlled by a multitude of mechanisms, generating strong instability:

- **"physical", originated at micro level**

and

- **"geometric", depending of geometry of faults network at macro level.**

An example follows.

RHEBINDER EFFECT (STRESS CORROSION)

Gabrielov and Keilis-Borok, Pure Appl.Geophys.,121(3), 477-494,1983

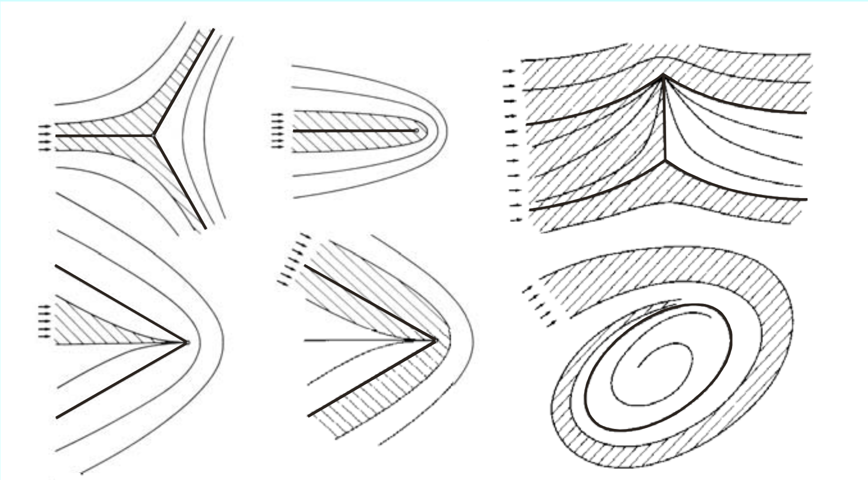
The strength of a solid material may be reduced by the contact with a fluid specific to this material.

The mechanism: fluid reduces the surface tension (*m*) and therefore the strength which is proportional to $\sqrt{m}$.

Under the otherwise harmless stress even gravitational the cracks appear, fluids penetrate deeper, etc.

Cracks, and accordingly, trajectories of fluids are orthogonal to maximal tension or maximal shear stress. Stress field / trajectories might be infinitely diverse, but only few types of singularities/concentration of trajectories are possible.

BASIC CONFIGURATIONS OF THE ZONES OF STRESS CORROSION (FATIGUE)



Examples of geometry of weakened areas.

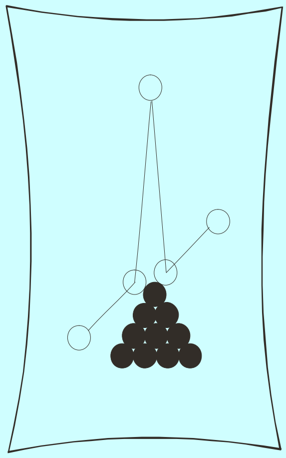
CHAOS

There is a multitude of other mechanisms of instability: petrochemical and phase transitions, fracturing, buckling, viscous flow…

Even a grain of rock may act as: visco-elastic element; aggregate of crystals; source/absorber of fluid, volume, heat; its body and surface are involved in different processes.

Altogether these mechanisms transform the earthquakes - generating lithosphere into a hierarchical dissipative non-linear (chaotic or complex) system.

In such systems excitation does not attenuate but grows in time.



Sinai billiard:
A simple chaotic system

PREDICTABILITY

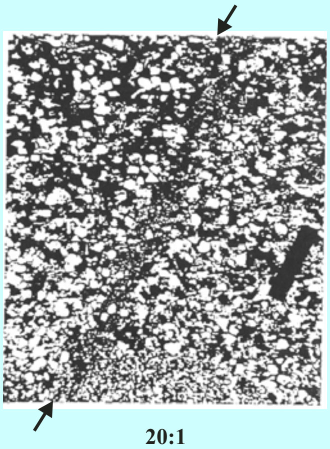
LAPLACE, 1776:
"If we knew exactly the laws of nature and the situation of the universe at the initial moment, we could predict exactly the situation of that same universe at a succeeding moment."

POINCARE, 1903:
"… it is not always so. It may happen that small differences in the initial conditions produce very great ones in the final phenomena. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible.... "

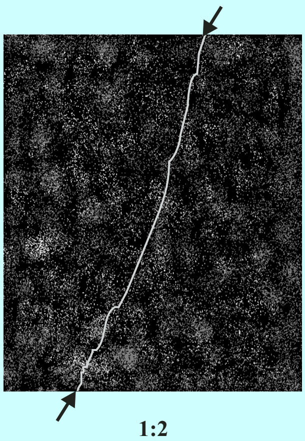
This refers to exact precision. However after coarse-graining (averaging) the regular *behavior patterns* emerge and the system becomes predictable – up to the limit.

That requires holistic approach – from the whole to details.

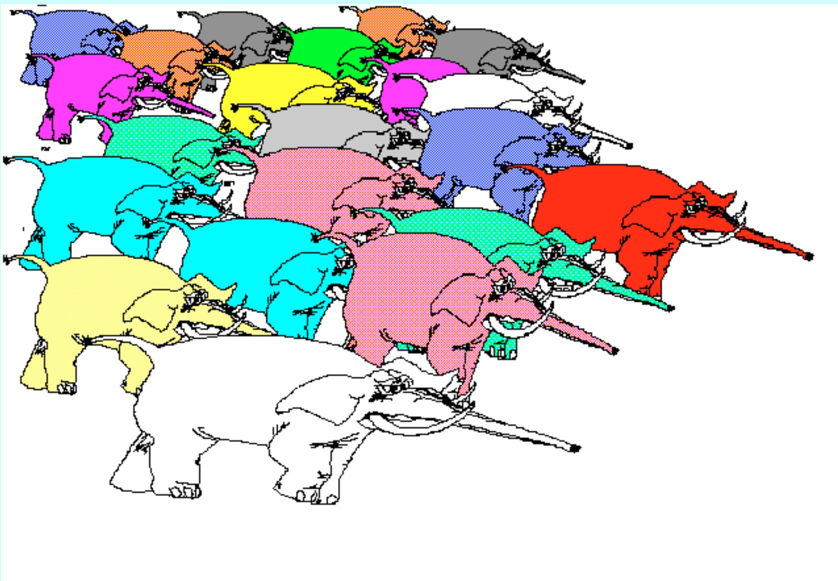
THE NEED FOR HOLISTIC APPROACH



20:1



1:2



"CRUDE LOOK AT THE WHOLE" -
THE KEY TO UNDERSTANDING COMPLEXITY

"…if the parts of a complex system or the various aspects of a complex situation, all defined in advance, are studied carefully by experts on those parts or aspects, and the results of their work are pooled, an adequate description of the whole system or situation does not usually emerge.

The reason, of course, is that these parts or aspects are typically entangled with one another.

We have to supplement the partial studies with a transdisciplinary "crude look at the whole" …"

Murray Gell-Mann, Let's call it plectics

PUPPI, SPERANZA, 1988:

"The reactions and attitudes in respect to such complexity are linked between two extremes: On the one end is he, who identifies as the sole possible solution to the problem a meticulous treatment of every process, operating on a … system, on the other end is he, who considers as the only hope that of "guessing" the right equations."

The problem **of earthquake prediction consists of consecutive, stage-by-stage, narrowing down the time interval, area, and magnitude range where a strong earthquake has to be expected.**

Background: **Maps of seismic hazard: maximal magnitude and return time of strong motions of different intensities.**

Prediction stage	*Characteristic duration of alarms, years*
Long-term	10^{1}
Intermediate-term	1
Short-term	10^{-1} – 10^{-2}
Immediate	10^{-3} or less

Such division is dictated both by:

- **the process of earthquakes' ripening**

and

- **the needs of earthquake preparedness**

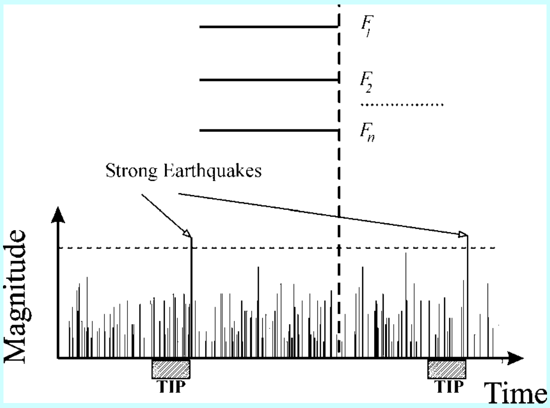
PREDICTION BY ANALYSIS OF EARTHQUAKE SEQUENCES IN LOWER MAGNITUDE RANGE (our time series)

(i) A sequence of earthquakes is robustly described **by the functionals $F_p(t)$, p=1,2, …, each depicting certain premonitory seismicity pattern.**

(ii) Emergence of a pattern P **is defined by condition $F_p(t) \geq C_p$. The threshold C_p is usually defined as a certain percentile of the functional F_p.**

(iii) An alarm is triggered **when a single pattern or certain combination of patterns emerges. That combination is determined by pattern recognition.**

An alarm lasts for a time interval τ.



AN EARLY EXAMPLE: PATTERN Σ

Hypothesis: **strong earthquakes are preceded by increase of seismicity in lower magnitude range. This was first suggested by observations then reproduced by models.**

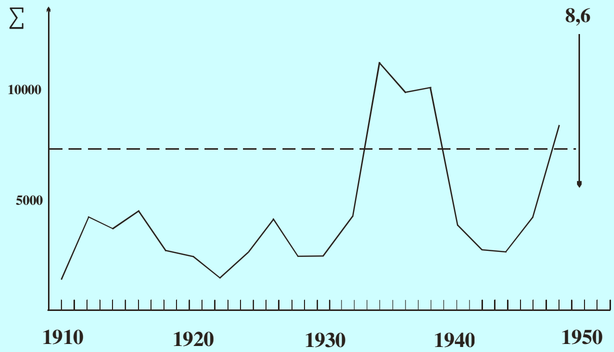
How to measure seismicity? Simple measure is the weighted sum in a sliding time window *(t - s, t)*.

$$\Sigma(t) = \sum_i 10^{Bm_i}, \quad m_i < M$$

m_i is the magnitude of i-th earthquake (a logarithmic measure of energy it released) and M is the magnitude of a strong earthquake targeted for prediction.

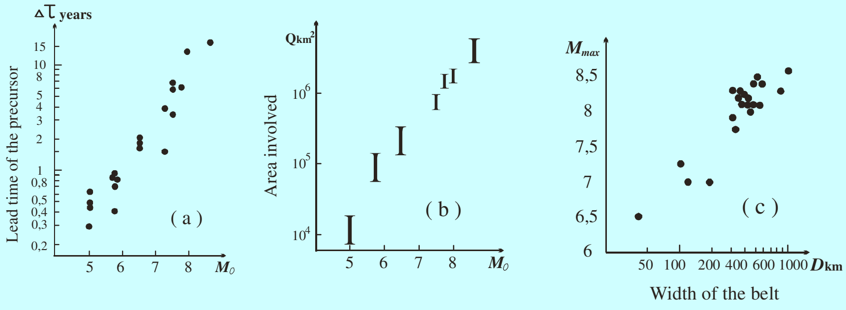
B=1 is used, then the sum is proportional to the total area of fault breaks in the earthquakes within the window;
with B=1.5, it would be proportional to total energy of the earthquakes;
with B=0, it would be the number of earthquakes.

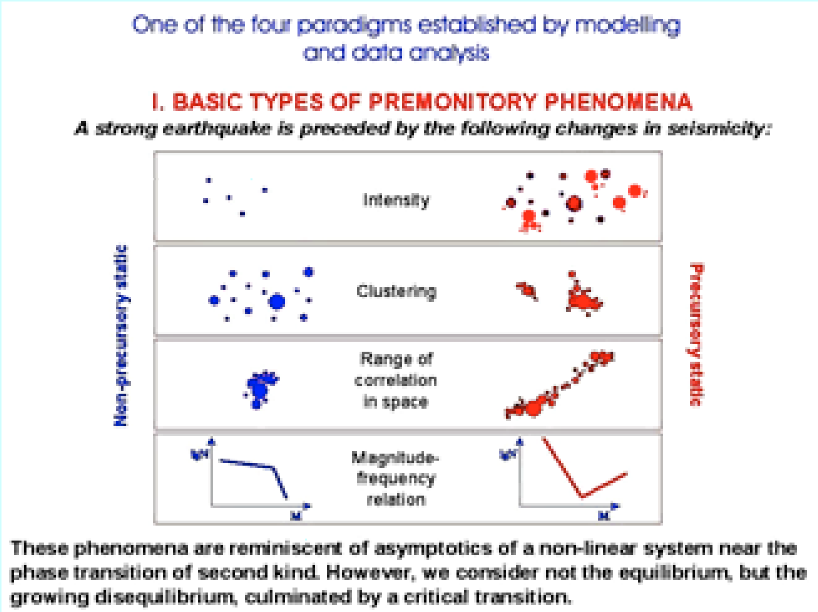
Emergence of this pattern was diagnosed by condition Σ (t) >= C_{Σ}
The threshold C_{Σ} was self adapting to target magnitude M.



Peak of Σ before the Assam earthquake in India, 1950, M=8.6

OBSERVED REGULARITIES





II. LONG-RANGE CORRELATIONS

The generation of an earthquake is not localized around the its future source. A flow of earthquakes is generated by a faults network, rather than each earthquake – by a segment of a fault.

In the time scale up to tens of years, precursors to an earthquake with linear source dimension L(M) are formed with the fault network of the size 10L to 100L.

This is inevitable due to impact of large scale processes
- **Mantle currents**
- **Movement of large blocks**
- **Fluids invasion, etc.**

Redistribution of stress after each earthquake might be more local.

An earthquake may be a critical phenomenon in certain part of fault network, and belong to the background seismicity in a larger volume.

III. SIMILARITY

Premonitory phenomena are similar (identical after normalization) in the extremely diverse conditions and in a broad energy range.

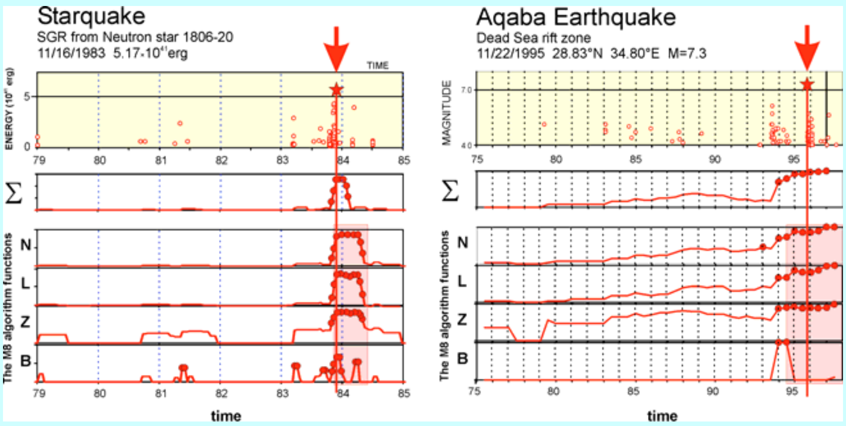
That similarity was observed for

Breakdown of laboratory samples ⇒
⇒ Rockbursts in mines ⇒
⇒ Earthquakes with magnitude from 4.5 to 8+ worldwide ⇒
⇒ Possibly, starquakes

In the energy range from erg to 10^{23} erg, and possibly 10^{41} erg.

The similarity holds only after a robust coarse-graining, and is not unlimited: on its background the regional variations of premonitory phenomena emerge.

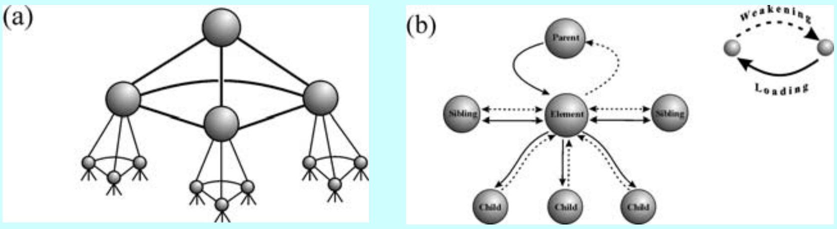
FRONTIERS OF SIMILARITY



IV. DUAL NATURE OF PREMONITORY PHENOMENA

Some are "universal", common for hierarchical complex non-linear systems of different origin.

Some are specific to geometry of the faults' network, or to a certain physical mechanism, controlling the {stress – strength} field in the lithosphere.



Model reproducing known types of PSP

REFERENCES

Reviews:

**1. Keilis-Borok, V., 2002. Earthquake prediction: state-of-the-art and emerging possibilities, Annu. Rev. Earth Planet. Sci., 30, 38 p.
DOI: 10.1146/annurev.earth.30.100301.083856
DOI link: http://dx.doi.org/10.1146/annurev.earth.30.100301.083856**

2. Keilis-Borok, V. I., and Soloviev, A. A. (eds.), 2003. Nonlinear Dynamics of the Lithosphere and Earthquake Prediction, Springer-Verlag, Heidelberg, 337 p.

3. Keilis-Borok, V., Ismail-Zadeh, A., Kossobokov, V., and Shebalin, P., 2001. Non-linear dynamics of the lithosphere and intermediate-term earthquake prediction, Tectonophysics, 338, pp. 247-260.

4. Keilis-Borok, V. I., 1999. What comes next in the dynamics of lithosphere and earthquake prediction?, Physics of the Earth and Planetary Interiors, 111, pp. 179-185.

5. Keilis-Borok V. I. and Shebalin P. N. (eds.), 1999. Dynamics of the lithosphere and earthquake prediction, Physics of the Earth and Planetary Interiors, 111, pp. 179-327.

6. Keilis-Borok, V. I., 2003. Basic science for prediction and reduction of geological disasters. In Beer, T. and Ismail-Zadeh, A. (eds.), Risk Science and Sustainability, Kluwer Academic Publishers, Dordrecht, pp. 29-38.

Data analysis

7. Kossobokov, V. G., Romashkova, L. L, Keilis-Borok, V. I. and Healy, J H., 1999. Testing earthquake prediction algorithms: statistically significant advance prediction of the largest earthquakes in the Circum-Pacific, 1992–1997, PEPI, 111, pp. 187-196.

8. Shebalin, P. N., and Keilis-Borok, V. I., 1999. Phenomenon of local 'seismic reversal' before strong earthquakes, Physics of the Earth and Planetary Interiors, 111, pp. 215-227.

9. Kuznetsov, I.V., and Keilis-Borok, V. I., 1997. Interaction of earthquakes along Circum-Pacific rim, Doklady Akademii Nauk, Vol.355, No.3, pp.389-393

10. Rotwain, I., Keilis-Borok, V., and Botvina, L., 1997. Premonitory transformation of steel fracturing and seismicity, Physics of the Earth and Planetary Interiors, 101, pp.61-71.

11.Knopoff, L., Levshina, T., Keilis-Borok, V. I., and Mattoni, C., 1996. Increased long-range intermediate-magnitude earthquake activity prior to strong earthquakes in California. Journal of Geophysical Research, Vol.101, No B3, pp.5779-5796.

12. Shebalin, P., Keilis-Borok, V., Gabrielov, A., Zaliapin, I., Turcotte, D., 2005. Short-term earthquake prediction by reverse analysis of lithosphere dynamics. Accepted to Tectonophysics.
VKBweblink:http://www.igpp.ucla.edu/prediction/ref/RTP_Tect.pdf
VKB filename: RTP_Tect.pdf

13. Zaliapin, I., Jin, A., Liu, Z., Aki, K., and Keilis-Borok V., 2005. Temporal (un)correlations between coda Q-1 and seismicity – Multiscale Trend Analysis, Pure. Appl. Geophys., 162, 827-841.
DOI:10.1007/s00024-004-2643-x
DOI link: http://dx.doi.org/10.1007/s00024-004-2643-x

14. Jin, A., Aki, K., Liu, Z., and Keilis-Borok, V., 2004. Seismological evidence for the brittle-ductile interaction hypothesis on earthquake loading, Earth Planets Space, 56, 823-830.

15. Keilis-Borok, V., Shebalin, P., Gabrielov, A., Turcotte, D., 2004. Reverse detection of short-term earthquake precursors, Phys. Earth Planet. Inter., 145, pp 75-85.
DOI: 10.1016/j.pepi.2004.02.010
DOI link: http://dx.doi.org/10.1016/j.pepi.2004.02.010
VKB web link: http://www.igpp.ucla.edu/prediction/ref/PEPI_RTP.pdf
VKB filename: PEPI_RTP.pdf

16. Shebalin, P., Keilis-Borok, V., Zaliapin, I., Uyeda, S., Nagao, T., and Tsybin, N., 2004. Advance short-term prediction of the large Tokachi-oki earthquake, September 25, 2003, M=8.1 A case history, Earth Planets Space, 56, 715-724.
Web link: http://www.terrapub.co.jp/journals/EPS/pdf/2004/5608/56080715.pdf
VKB web link: http://www.igpp.ucla.edu/prediction/ref/EPS56080715.pdf
VKB filename: EPS56080715.pdf

17. Novikova, O., Shebalin, P., and Keilis-Borok, V.I., 2002. A second approximation to intermediate-term earthquake prediction: two cases histories for southeastern Mediterranean. Problems of Theoretical Seismology and Seismicity. Comp. Seismol., 33: 186-206.

18. Zaliapin, I., Liu, Z., Zöller, G., Keilis-Borok, V., and Turcotte, D, 2002. On increase of earthquake correlation length prior to large earthquakes in California, Computational Seismology, 33, pp. 141-161.

19. Kossobokov, V.G., Keilis-Borok, V.I., and Baolian Cheng, 2000. Similarities of multiple fracturing on a neutron star and on the Earth. Physical Review E, Vol.61, N4, pp.3529-3533.

20.Shebalin P., Zaliapin I., and Keilis-Borok V., 2000. Premonitory raise of the earthquakes' correlation range: Lesser Antilles, Physics of the Earth and Planetary Interiors, 122, pp. 241-249.

Models

21. Gabrielov, A., Keilis-Borok, V., and Jackson, D., 1996. Geometric incompatibility in a fault system. Proc. Natl. Acad. Sci. USA, Vol.93, pp.3838-3842.
22. Zaliapin, I., Gabrielov, A., Keilis-Borok, V., 2004. Multiscale Trend Analysis, Fractals, 12(3) 275-292.
23. Zaliapin, I., Keilis-Borok, V., and Ghil, M., 2003. A Boolean delay equation model of colliding cascades. Part I: Multiple seismic regimes, Journal of Statistical Physics, 111,pp.815-837.
24. Zaliapin, I., Keilis-Borok, V., and Ghil, M., 2003. A Boolean delay equation model of colliding cascades. Part II: Prediction of critical transitions, Journal of Statistical Physics,111,pp.839-861.
 DOI:10.1023/A:1022802432590
 DOIlink:http://dx.doi.org/10.1023/A:1022802432590
 VKBweblink:http://www.igpp.ucla.edu/prediction/ref/BDE2.pdf
 VKBfilename:BDE2.pdf
25. Gabrielov, A., Keilis-Borok, V., Zaliapin, I., and Newman, W., 2000. Critical transitions in colliding cascades, Physical Review E, 62, pp. 237-249.
 VKB web link: http://www.igpp.ucla.edu/prediction/ref/CC1.pdf
 VKB filename: CC1.pdf
26. Gabrielov, A., Zaliapin I., Newman W., and Keilis-Borok, V., 2000. Colliding cascades model for earthquake prediction, Geophysical Journal International, 143, pp. 427-437.DOI:10.1046/j.1365-246X.2000.01237.x
 DOIlink:http://dx.doi.org/10.1046/j.1365-246X.2000.01237.x
 VKBweblink:http://www.igpp.ucla.edu/prediction/ref/CC2.pdf
 VKB filename: CC2.pdf

27. Gorshkov, A. I., Keilis-Borok, V. I., Rotwain, I. M., Soloviev, A. A., and Vorobieva, I. A., 1997. On dynamics of seismicity simulated by the models of blocks-and-faults systems,

 Annali di Geofisica, vol. XL, N5, pp.1217-1232.
28. Keilis-Borok, V. I., Rotwain, I.M., and Soloviev, A.A., 1997. Numerical modeling of block structure dynamics: dependence of a synthetic earthquake flow on the structure separateness and boundary movements, J. Seismology, 1, pp.151-160.
29. Zaliapin, I., H. Wong, and A. Gabrielov, Hierarchical Aggregation in Percolation Model (June 2005) [PDF, 1.2 M]

http://moho.ess.ucla.edu/~zal/per_tec_B.pdf

30. Zaliapin, I., H. Wong, and A. Gabrielov. Inverse cascade in percolation model: Hierarchical description of time-dependent scaling. *Phys. Rev. E*, 71, 066118, 2005. [PDF, 800K] (doi: 10.1103/PhysRevE.71.066118)

http://moho.ess.ucla.edu/~zal/PRE_percolation.pdf