# Length and time scales of the continental deformation: a lithosphere-scale rock mechanics experiment

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**ABSTRACT**

The new generation of crustal deformation studies aim to build-up physical models of strain accumulation that carry a predictive power for future stress patterns. These studies require models to be consistent with all length and time scales of the deformation field and not just of its single snapshot. The new generation of space geodetic data will very likely revolutionize our understanding of crustal deformation, including fault friction and the rheology of the lithosphere. These parameters were, by necessity, estimated from rock and fault mechanics lab experiments that have to be run on spatial and temporal scales and under conditions far from natural environment. Nowadays, an earthquake initiates a lithosphere-scale rock mechanics experiment. We are able to chase the broad and continuous spectrum of behaviours existing between the seismic and the aseismic slip end-members that characterizes, nowadays, a system of active faults. We establish the geometry, initial and boundary conditions (e.g. kinematic parameters of faulting, geometry of the surrounding fault system and its complexity, structure of the Earth). We take the relevant deformation measurements at a wide range of spatio-temporal scales (e.g. seismology, space geodesy, earthquake geology and paleoseismology).We use models to resolve fault and rock constitutive properties (e.g. rate and state friction laws, visco-elastic modeling). We model the stress evolution and locate regions of stress accumulation. The joint use of the lithosphere-scale rock mechanics experiment together with the earthquake prediction algorithms such as M8, CN and RTP is likely to contribute to the physical understanding of the length and time scales of the preparation of a destructive earthquake. Case studies from the Friuli area and the Apennines will be featured.

**Key words:** deformation, seismology, GPS, tectonics, prediction

## PRESENTER'S BIOGRAPHY

Born in Algeria, I earned an engineering degree in geomechanics and a Ph.D. degree from the University of Trieste (Italy) in solid-Earth geophysics and geodynamics. I have been involved with ICTP since 1994, and has been a long-term visiting fellow until my recent appointment as a UN staff scientist. My major fields of interest are the mechanics of earthquakes and faulting and rheology of the lithosphere. My research is broadly concerned with both steady-state and transient deformation processes in the Earth, as they relate to tectonophysics and, particularly, to the physics of earthquake prediction. Since 2006 I am also serving as the coordinator of the ICTP Earth System Physics Diploma Program, a one year intensive pre-PhD course.

# Seismic Source Parameters in Northern Algeria from Broad Band Algerian Digital Seismic Network (ADSN)

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The Algerian Digital Seismic Network (ADSN) is composed of eight Broad Band and two Very Broad Band seismic stations. More of 50 earthquakes with magnitude M >= 2 are monthly recorded. In this study we present source mechanisms including fault-plane solutions and waveform modeling of six shallow and moderate earthquakes (4 < Mw < 5.5) which occurred in the northern Algerian region (1) Oran and Ech Cheliff (western part), (2) Médéa (South of Algiers, central part) and (3) Kherrata (eastern part). The focal mechanism of Oran earthquake (Mw = 5.2) on 11/01/2008 reveals a compressive regime. The 3 focal mechanism of Médéa earthquakes on 08/05/2007 (M=4.8), on 21/08/2007 (Mw=4.8) and on 22/08/2007 (Mw=5.2) reveal a strike-slip regime with NE-SW trend for the sinistral plane and NW-SE trend for the dextral plane. The Ech Cheliff earthquake on 16/12/2006 strikes near El Asnam fault. The focal mechanism shows a reverse faulting

# The *New Geophys*ics suggests that earthquakes can be stress-forecast by monitoring stress-accumulation at distance in the rock mass surrounding the impending source zone

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**ABSTRACT**

The New Geophysics suggests that, although earthquakes are deterministically unpredictable, earthquakes can be stress-forecast by monitoring changes in microcrack geometry as stress-accumulates in the rock mass remote from the impending source zone. Rock is so weak to shear-waves, that the necessary stress-accumulation before all large earthquakes can be monitored by changes in time-delays in shear-wave splitting (seismic birefringence) at substantial distances from the impending source zone of perhaps several thousand km before the largest earthquakes. Characteristic temporal changes in time-delays been recognised in retrospect before some 15 earthquakes worldwide, where in one case, the time, magnitude, and impending fault break of a *M* 5 earthquake in SW Iceland was successfully predicted in real time.

The range of shear-wave velocity anisotropy in ostensibly-intact rock (~1.5% to ~4.5%) suggests that microcracks are so closely spaced that they are critical systems. Critical systems in are almost universal in complex heterogeneous interactive phenomena, and are what has been called a *New Physics*, hence we have a *New Geophysics*, which imposes a range of new properties on conventional sub-critical behaviour in the Earth's crust.

The temporal changes in time-delays are believed to monitor the stress-accumulation necessary for release of energy by large earthquakes. The logarithm of the duration of the stress increase is proportional (self-similar) to the magnitude of the eventual earthquake. The critical point at which fracturing and earthquakes occur is when crack density reaches fracture-criticality when the microcracks are so closely-spaced that shear-strength is lost and the rock necessarily fractures. Immediately before the earthquake occurs a break of slope is observed, which is thought to be the onset of stress relaxation as the microcracks begin to coalesce onto the eventual fault break. The duration of the coalescence is again self-similar to earthquake magnitude. Although the number of case studies is small, observations of similar changes in shear-wave splitting in both stress-accumulation and crack-coalescence before volcanoes suggest that the approach of stress towards fracture-criticality and rock fracture before earthquakes and volcanoes is similar.

Note that swarms of small earthquakes, providing a source for shear-waves, are far too scarce and irregular for routine reliable earthquake prediction, and a controlled source of shear-waves is required. The optimum configuration is a three borehole Stress-Monitoring Site (SMS), where a controlled shear-wave source transmits shear-waves in specific stress-oriented 3D directions to strings of recorders in at least two adjacent 1km-to-1.5km-deep boreholes. Papers presenting these ideas are available at <www.geos.ed.ac.uk/homes/scrampin/opinion>.

**Key words:** earthquake prediction, fracture criticality, shear-wave splitting, stress-forecasting earthquakes, the New Geophysics.

**PRESENTER'S BIOGRAPHY**

Stuart Crampin: PhD, ScD, FRAS, FRSE; Conrad Schlumberger Award (EAGE); Virgil Kauffman Gold Medal (SEG); highly cited <http://www.isihighlycited.com/>; h-index 36.

Crampin pioneered theory, observation, computation, interpretation of seismic anisotropy in 260$^+$ papers.

Crampin founded biennial International Workshops on Seismic Anisotropy (14IWSA will be in Perth, Australia).

Crampin founded Edinburgh Anisotropy Project (EAP) at BGS for processing multi-component seismograms. EAP still continues with ~20 oil company sponsors.

Crampin developed anisotropic poro-elasticity (APE) model of fluid-saturated crack deformation. APE led to the successful calculation (prediction) of oil production operations, and successful prediction of time, magnitude, and fault-break of $M$=5 earthquake.

Crampin developed prototype Stress-Monitoring Site (SMS) between 500m-deep boreholes which recorded spectacular sensitivity to remote minor seismic activity confirming science/technology/sensitivity.

Crampin is currently promoting the concept of crack-critical crust, where *in situ* cracks are so closely-spaced they are critical-systems. Consequently, low-level deformation can be monitored with shear-wave splitting, modelled/predicted with APE, and in appropriate circumstances, future behaviour controlled by feedback.

# Foreshocks and earthquake prediction: the Greek experience

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**ABSTRACT**

Foreshock activity has been proposed since 60's as one of the most potential tools for the short-term prediction of the mainshock. However, the usually low earthquake detectability of the seismic monitoring systems makes it difficult to identify significant foreshock seismicity patterns in near real-time conditions. The gradual improvement of the monitoring systems in the last years makes it possible to detect more reliably the precursory nature of the foreshock activity. This is exactly the case of Greece which is characterized by the highest seismicity in the western Eurasia. We use data from the routine Greek seismicity catalogue of the time interval 1995-2008 and identify a posteriori foreshock activity occurring before strong earthquakes of $ML \geq 5$. The criteria to identify significant foreshock activity includes the next: time window up to six months before the strong earthquake, space window no more that 50 km from the epicenter of the strong earthquake, increase of the seismicity rate in the particular space-time window at a significance level of at least 95% with respect to the background seismicity rate in the same area. The results indicate that at least of about 50% of the strong earthquakes were preceded by significant foreshock activity. However, further examination of the records in particular seismograph stations of the national Greek seismograph system showed that foreshock activity is not always evident in the routine seismicity catalogue because of reasons related to the detection capabilities of the system. We propose the systematic, automatic monitoring of the daily seismicity with the purpose to identify in near real-time foreshock activity. In another paper we describe the automatic FORMA which is designed to perform such an automatic detection.

**ELENI DASKALAKI'S BIOGRAPHY**

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Professional Preparation:
B.Sc., 2004 in Applied Mathematics and Physics, National Technical University of Athens, Greece
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*2005-today:* 24 hour monitoring of seismicity in Greece and daily analysis of the parameters of the earthquakes occur in the Greek region. *National Observatory of Athens, Greece*
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Study of mechanical coupling of lithospheric plates and the consequences for earthquake forecasting along the Hellenic Arc, East Mediterranean Sea, which is characterized by the highest seismicity and tsunamicity in the European-Mediterranean region, earthquake prediction, time-dependent seismic hazard in near real-time conditions, tsunamis, natural hazards

# Seismic regime anomalies and possible state of crustal medium before the Altay earthquake (M7.3, 27.09.2003)

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The destructive Altay earthquake with M7.3 was happened on September 27, 2003 at the Altay Mountain in Russia near boundaries with China, Mongolia and Kazakhstan. Changes of the seismic activity parameters and the distribution of seismotectonic deformations for preparation area of this earthquake were analyzed. Together with parameters, which are used usually (seismic activation and quiescence, b-value and others), the reaction of seismicity in near-field zone of Altay earthquake preparation on external effects so as regional seismic activations were studied. There was the absence of reaction of seismicity in near-field zone during periods of megaregional seismic activations (1986-1991 and 1994-1995). It points to the isolation of the near-field zone of future earthquake and existence of the rigid crustal structure around this zone. A number of phenomena such as absence of aftershocks with M>2.5 after moderate earthquakes (M~5.0-5.5) in spacious region beginning from 1987 to 2002 and decrease b-value in the same period are evidence of consolidation of crustal medium in this region before the Altay earthquake. We found 2 types of seismic quiescence: the longtime regional quiescence for the M>4.5 earthquakes (1962-2002) and the local horseshoe-shaped quiescence for the M>3 earthquakes (1987-1999). The seismic activation was aroused at 1996 in the region which was located to south from the near-field zone. The space distributions of seismotectonic deformations were calculated from focal mechanisms data for the 30 years period before the Altay earthquake. The Altay earthquake epicenter was located at zone of sign changing for deformation “compression – extension” and near boundary of regional seismic quiescence. So regime of the crustal medium consolidation prevailed at the Altay earthquake preparation area during long time. It is most likely that gradual weakening of the strengthened crustal structure took place at the final stage of earthquake preparation during period of seismic activation (~1996-2003).
This investigation was supported by RFBR, grant 07-05-00986, grant of Presidium RAS 16.3, SB RAS Integration projects 87, 6.18 and grant of Leading scientific schools-2008.

**Key words:** earthquake preparation process, seismic regime, state of medium, seismotectonic deformation

## PRESENTER’S BIOGRAPHY

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Ph.D. in Geophysics (1988).
Scientific fields: earthquake preparation process, seismic regime, geodynamics, numerical modeling and tectonomagnetic monitoring.

# New research project for understanding and estimating the next Nankai mega-thrust earthquakes in southwest Japan and mitigation of damages

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**ABSTRACT**

Along the Nankai trough in southwest Japan, the subduction of the Philippine Sea plate has repeatedly produced mega-thrust earthquakes with an interval of 100-200 years. Incoming 30 years, the recurrence probability of the next earthquakes is estimated as 60% - 70%. The central disaster prevention committee evaluates the huge economical damage amounting to the national fiscal year budget if three mega-thrust earthquakes (Tokai, Tonankai and Nankai) occur simultaneously, as in the case of the 1707 Hoei earthquake. Thus, the evaluation and estimation of the recurrence pattern of the next earthquakes is an urgent problem for Japan.

So far, the structural researches using refraction and reflection surveys have revealed the key structures to understand recurrences of Nankai earthquakes. Furthermore, simulations of mega-thrust earthquake cycle based on a rate- and state-dependent friction law show that the rupture initiates around the Tonankai segment in each cycle, and indicate the different patterns and intervals in each recurrence cycle. These results are, however, not satisfactory for the evaluation and estimation of next mega-thrust earthquakes. Therefore, we have to improve the structure model and the recurrence cycle simulation model with more high reliabilities. Especially, the estimation of recurrence cycle between the Tonankai and Nankai earthquake is very important for disaster preventions. Furthermore, the estimation of coupled mega-thrust earthquake around the Nankai trough such as the 2004 Sumatra earthquake will be analyzed.

To understand and estimate the next mega-thrust earthquakes with detailed structures and improved simulation model, we propose research plans as follows, 1) Construct the detailed crustal medium around the Nankai trough using controlled sources and seismic tomography using dense seismic lines and OBS network arrays. 2) Observations of crustal activities around the Nankai trough and north eastern Japan. 3) Construct the database of long term plate coupling dynamics, and study the diversity of recurrence pattern and scale of next mega thrust earthquakes. 4) Develop the advanced simulation methods. 5) Improve the large scale recurrence cycle simulation model based on theoretical and experimental analyses. 6) Evaluate the precise strong motions and tsunamis for the disaster prevention. 7) Develop the reliable risk management system for next mega thrust earthquake. 8) Develop and contract the real time monitoring system around Kii peninsula. 9) Apply scientific results of Nankai seismogenic zone drilling to recurrence cycle simulation.

New research project consists of mutually interacting three sub-projects; A) structure survey and crustal activity observation research sub-project executing researches of 1) and 2), B) simulation sub-project executing 3) - 5), and C) disaster mitigation research sub-project executing 7) and 8). We started this new project in this year. In this paper, we report the initial results and the perspectives in our project.

**Key words:** Nankai mega-thrust earthquake, Southwest Japan, Structural survey, Earthquake cycle simulation, Evaluation of strong motion and tsunami, Disaster mitigation

## PRESENTER'S BIOGRAPHY

1981: Ph.D. Graduate School of Science, Kyoto University: Title 'Three-dimensional seismic structure beneath the Japan Islands –the subducting Pacific and Philippine Sea plates-'

1983-1989: Researcher at Disaster Prevention Research Institute, Kyoto University: involved in seismic tomography and crustal deformation studies using GPS

1989-1996: Associate Professor at Disaster Prevention Research Institute, Kyoto University: involved in GPS studies including GPS meteorology, array analyses for seismic velocity structure and J-Array project

1996-2005: Professor at Graduate School of Science, Environmental Studies, Nagoya University: involved in receiver function analyses and numerical simulation of earthquake cycles

2005- : Professor at Graduate School of Science, Kyoto University: involved in numerical simulation of earthquake cycles, especially the Nankai trough mega-thrust earthquake cycles, and receiver function tomography study

# Characteristics, scaling, and interpretation of slow earthquakes

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**ABSTRACT**

Along some subduction plate boundaries, slow deformation is observable as unusual seismic events: deep low frequency earthquakes and tremor, very low frequency earthquakes (VLFs), and slow slip events form a family of slow earthquakes that have following characteristics. (1) The seismic moment is proportional to the duration with a constant of $10^{12\text{-}13}$ Nm/s. (2) The seismic energy in 2–8 Hz is in direct proportion to the seismic moment with a constant, scaled energy of about $10^{-10}$. (3) Tremor source regions migrate about 10 km and 100 km within 10 min and 10 days, respectively. (4) The amplitude of tremor observed at surface seismometers is less than 1 mm/s and waveforms are statistically symmetrical in time. (5) VLFs are always observed during tremor, but tremor sometimes occurs without visible VLF. (6) The velocity spectra of tremor and VLFs are almost constant, independent of frequency. (7) Cumulative density function of rms amplitude is described by an exponential law rather than a power law.

First two scaling relations lead to a simple stochastic model of slow earthquakes that can explain all above characteristics. In this model, slow earthquakes are represented as shear slip on circular faults whose radius is a random variable that is governed by a Langevin equation and three parameters, a diffusion coefficient, a damping coefficient, and a slip rate coefficient. This model expands on a previous scaling law for the slow earthquakes by providing a specific image of kinematics. Allowing for spatial variations of the parameters could potentially explain differences in behavior of slow slip events worldwide.

**Key words:** slow earthquakes, scaling relations, Brownian walk.

## PRESENTER'S BIOGRAPHY

Satoshi Ide is an earthquake seismologist in University of Tokyo, Japan. He studies dynamic rupture process of earthquakes, scaling relations of earthquake source parameters, and various recently-found unusual earthquake-like phenomena called slow earthquakes.

# About the Origin and Propagation of Deformational Waves

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**ABSTRACT**

The present paper is devoted to investigations of Earth crust dynamics issues covering mechanical deformational and some other geophysical fields generated by tectonic processes.

Both experimental and theoretical data have been accumulated in geophysics till now evidencing an existence of Earth crust deformation waves, accompanying tectonic processes and tectonic earthquakes preparation in particular. According to these data the deformation waves' propagation velocities amount from one to ten kilometer per day by order of magnitude. These velocities are quite lower than ones of seismic waves and can't be interpreted as propagation of mechanical waves through hard phase crust component, which is good for conducting fast seismic waves, but bad for conducting low frequency deformation waves on hundred and thousand kilometer distances.

The delaying on phases have been observed on different physical fields, such as local geomagnetic field, crust electrical conductivity, electric telluric potentials, geochemical composition and physical properties of underground mineral waters spreading in earthquakes preparation zones with the same velocities as of deformation waves. For the interpretation of the deformation waves' origin one should take into account the underground fluids propagation as a possible mechanism for crust deformations during a tectonic process run. There could be different mechanisms for the interpretation, for instance, traveling fluids under water pressures gradients through porous tectonic faults, crust cracks, wave conductors. In coming or out coming waters disturb the crust balance leading to earth crust deformations in a form of waves.

Experimental results highlighted another problem concerning the directions of deformation waves' propagation during a tectonic earthquake preparation, whether deformation waves are spreading to or from the future epicenter. The crack avalanche, dilatancy or consolidated inclusion models assume the stress accumulation in the beginning, first stage. Accordingly, the fluids are squeezing out of the stressed volume outward. In the cracking phase, like dilatancy, the fluids are to be filtrating inside of opening free porous and cracks. So the directions of deformation waves are varying with time inside the earthquake preparation zones. Besides there are regional and global factors impacting the dynamics of crust stress distribution, stipulating by variations of Earth rotation due to seasonal, solar and lunar tides' impacts, Chandler or large earthquakes' oscillations. The model for a geoblock stability on the Earth's surface, fixed by friction shows that there are three stable zones on the surface, two ones in polar caps and one on equatorial belt. With the raising of acceleration the centripetal force with its normal and tangential components is rising too resulting in the compression of equatorial zone for instance with subduction and decompression the crust in the middle latitudes adjacent to polar caps for instance by abduction. The compression leads to squeezing out of the fluid, decompression leads oppositely to the infiltration.

The physical waves' origin founds satisfactory explanations in frames of underground fluids' spreading, waters in particular, which are well known as an excellent dynamical ground phase component. The seismological experimental data and earthquakes preparation models permit non synonymous interpretation of the deformation waves' propagation direction.

**Key words:** tectonic earthquake preparation, deformation waves.

## PRESENTER'S BIOGRAPHY

Farshed H.Karimov, was born in 1949 in Dushanbe town, Tajikistan. Scientific activity covers General Geophysics, Physics of Earthquakes, Geomechanics, Tectonomagnetism and Physical Bases of Rock Magnetism. Have published more than 150 scientific papers and abstracts. Finished the Physics Department of Moscow State University named after M.V.Lomonosov (MSU) (1972). Have taken the Candidate of Sciences Degree on Physics of Magnetic Phenomena (1979) and Doctor of Sciences Degree on Geophysics (1993) from MSU. Academician of the International Academy of Engineering (2000), professor of the Technological University of Tajikistan (2001). Deputy Director of the Institute of Earthquake Engineering and Seismology, Academy of Sciences of the Republic of Tajikistan (since 2004).

# A new system of broad-band elastic wave measurement in laboratory under triaxial compressive conditions

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**ABSTRACT**

We developed a new system of broad-band elastic wave measurement in laboratory that can be used under triaxial compressive conditions. In conventional triaxial compression tests, only narrow-band transducers having a strong resonance frequency can be used, since the pressure resistance of broad-band transducers are too low to use in a triaxial cell. So, we encapsulated a broad-band transducer in an end-piece cell, and applied Nishizawa-type co-axial feed-through to prevent oil (pressure medium) from intruding into the end-piece (hereafter, we call the assembly as a broad-band transducer assembly). We used a *P*-type broad-band transducer having a band from ~600 kHz to ~1600 kHz at -6db level. Though the broad-band transducer assemblies can be attached only on top and/or bottom of the cylindrical samples, we can use them for AE monitoring and measurements of wave velocity and attenuation even under triaxial conditions.

The effective frequency responses of transducer assembly should be different from that of a broad-band transducer itself, since elastic wave that passes through the end-piece (made of die steel) is attenuated. Then, the frequency response of the assembly was measured in the following way. Two broad-band transducer assemblies are directly attached on each other (without any samples), and axial stress around 80 MPa was applied. 1-cycle sine waves of various frequencies were repeatedly applied to the upper transducer, and waves received at the lower transducer were recorded after 1000-times stacking. We estimated the frequency response of the assembly from the first peak amplitudes. Due to the attenuation in high frequency (> ~800 kHz), the frequency band over -6db response of transducer assembly is further broadened (~200 kHz - ~1800 kHz).

A recording system with high sampling rate and high data transmission rate was also developed. For measurements of wave velocity and attenuation, it can record 2 channels of 160 kS-waveforms at a sampling rate of 80MS/s every 1/40 s. Raw data can be stored, and stacking as is required in conventional systems is not required before recording. So, we can do running stacking and other filtering for noise reduction to improve the temporal resolution of velocity and attenuation changes. For AE monitoring, the recording system can store 2 channels of continuous waveforms at a sampling rate of 40 MS/s. Of course, trigger recording of 2 channels of 160 kS-waveforms at a sampling rate of 80 MS/s is also available.

Using the measurement system and the recording system, we successfully carried out broad-band monitoring of AE and transmitted elastic waves during the faulting process of rock samples. We will show some preliminary results at the meeting.

**Key words:** AE, broad-band system, triaxial compressive condition, faulting process

## PRESENTER'S BIOGRAPHY

I am an associate professor of Ritsumeikan University. My research interest is faulting process of various scales from AEs in rock samples and earthquakes.

# Ring-shaped seismic activity prior to large and great earthquakes: connection with mantle fluids

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**ABSTRACT**

Ring-shaped seismic structures prior to large and great earthquakes have been formed in various regions of the world. In this work we compared characteristics of seismicity and S-wave attenuation field in regions of three great events: Kunlun (14.11.2001, Mw 7.8), Sumatra (26.12.2004, Mw 9.0) and Sichuan (12.05.2008, Mw 7.9) earthquakes. Besides that, we picked out anomalous by these parameters areas in central Tien Shan and northern Kamchatka regions.

Rings of seismicity, being formed by epicenters of shallow events, occurred during several tens of years, were picked out prior to all three great earthquakes; sizes of these structures were of ~700, 700 and 380 km, correspondingly.

When studying heterogeneities of the attenuation field we used a method, based on an analysis of amplitude attenuation speed in early coda of Sn and Lg waves, which allows us to estimate shear wave attenuation in the uppermost mantle of the epicenter area by data of a single station. We were determining an effective Qs value using coda decay within an interval of 70 s on recordings of narrow-band channel with central frequency of 1.25 Hz. We have been analyzing the attenuation field characteristics using seismograms obtained by GSN digital stations at epicentral distances of ~250-1100 km.

The ring-shaped seismicity structures were picked out near source zones prior to all three great earthquakes. We have found, that increased shear wave attenuation in the uppermost mantle corresponds to all rings of seismicity. Attenuation diminishes abruptly within and out of the rings. An absence of modern volcanism in the areas of the rings shows, that this effect is connected with notable content of deep fluids.

Analogous investigations have been carried out for the central Tien Shan region. We have picked out the seismicity ring with the size of ~150 km between 75° and 76° E. Relatively high attenuation in the uppermost mantle corresponds also to this structure. The northern part of the ring is located in the eastern part of Kirgiz range, where no large seismic events with M>~6.5 occurred during several hundred years. Similar data have been obtained for the northern Kamchatka area. Seismisity ring have been picked out between 55° and 56° N, and enough high attenuation is observed in this area. The data obtained may testify to a preparation for large earthquakes in regions of central Tien Shan and northern Kamchatka..

The methods described in this work can be used for solving problems of seismic zoning and middle-term earthquake prediction.

**Key words:** The ring-shaped seismicity, attenuation, shear waves.

## PRESENTER'S BIOGRAPHY

Inna Sokolova graduated Kazakh State University on 1992 and have combined B.Sc. and M.Sc. degree in Applied Mathematics, on 1994 she received Ph.D. in Mathematics, Kazakh State University, Kazakh Academy of Sciences, Almaty (1994).

From 1992 till 1999 she worked on O.Yu. Shmidt Institute of Physics of the Earth, Complex Seismological Expedition, Talgar. From 1999 till now she works in the Kazakh National Data Center Institute of Geophysical Research National Nuclear Center, her position is senior scientist.

Present duties are: Discrimination of nuclear explosions, chemical explosions and earthquakes; study of heterogeneities of shear wave attenuation field in the Tien Shan region; study of geodynamics of Central and South Asia and test site area; study of seismicity in Kazakh platform.

# Geophysical Time Series Synchronization Scenarios

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**ABSTRACT**

Synchronization effects in behavior of geophysical fields, an increase in their collective component, are an important indicator of changes in the state in the crust and, in particular, precursory phenomena related to strong earthquakes. These effects are treated on the basis of very general patterns of the behavior of systems approaching a bifurcation, or a catastrophe. It is very difficult, if at all possible, to give a detailed physical description of the actual synchronization mechanism. This is due to the extreme complexity of the crust and numerous external effects, many of which cannot be measured, and even their presence during the period of observations cannot be established with certainty. Therefore, the use of statistical measures of synchronous behavior for the study of processes preceding strong earthquakes is a means for solving this complicated problem.

The methods for detecting hidden synchronization within multidimensional time series flow are considered which are based on estimating spectral and wavelet-based measures within moving time window. Preliminary nonlinear transform from initial time series to evolution of multi-fractal singularity spectra parameters is regarded as an efficient step for analyzing date which allows construct multi-fractal measures of synchronization within variations of parameters of the noise structure. This is due to the fact that the multi-fractal analysis can effectively explore signals that, in terms of covariance and spectral theory, are no more than white noise or Brownian motion.

The methods are illustrated on the examples of different time series analysis: electrotelluric, underground water level variations, geochemical observation, low-frequency ambient background microseisms within seismically active regions before strong earthquakes.

**Key words:** coherence measures, singularity spectra, synchronization.

## PRESENTER’S BIOGRAPHY

Lyubushin Alexey, was born in town Belogorsk, Russia, 1954. In 1977 he graduated from the Moscow Physical Technical Institute. In 1977-1984 he worked at the Institute of Problems for Mechanics, Ac.Sci., USSR. In 1981 he defended the thesis for Ph.D. in numerical methods of optimal control and its application to flight dynamics problems. From 1984 up to now he is working in the Institute of Physics of the Earth, Russian Ac.Sci. as a senior (1984), leading (1997) and a chief (1998) research scientist. In 1996 he defended a Dr.Sci. in geophysics on using of multidimensional signal processing and mathematical statistics for complex geophysical monitoring systems data analysis. Professor of the Department of High Mathematics and Mathematical modeling of Russian State Geological Prospecting University. Marquis "Who's Who in Science and Engineering", 1999, 2007. Main interests: methods for multidimensional geophysical monitoring time series analysis, earthquake prediction, seismic hazard assessment.

# Physics of time-dependent failure: a theoretical and laboratory-based perspective

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This review describes the theoretical basis for precursors to failure in composite ceramics such as rocks, and examines the extent to which such models are validated in laboratory experiments and in extrapolation to the spatial and temporal scales of natural earthquakes. Fractures nucleate dynamically in brittle materials when the energy release rate $G$ at the crack tip exceeds a critical value that depends on the elastic properties of the medium, the remotely applied stress, and the length of pre-existing flaws in the material. Time-dependent weakening can be modelled by combining the properties of free energy in the crystal lattice with reaction rate theory for the relevant physico-chemical process. This produces an exponential relationship between $G$ and the crack velocity $V$ that has now been elegantly validated experimentally on single crystals of quartz. For more complex materials (rocks) heterogeneities exist on a variety of scales above the atomic spacing, leading to a power-law relation $G(V)$ instead. This can be simply illustrated by a percolation theory based on random disorder, so that the power law is truly emergent. The implied rapid acceleration provides a potential physical basis for a possible time-dependent nucleation signal in variables such as strain prior to earthquakes, and in proxies such as event rate, seismic $b$-value, degree of anisotropy etc. In contrast negative feedback mechanisms (such as stress relaxation) produce a transient decelerating crack growth rate consistent with the observed modified Omori law for aftershocks. By combining only these two processes steady-state creep emerges spontaneously, with a power law relation between strain rate and stress that is consistent both with laboratory experiments and long-term creep in earth materials over geological time periods. If healing is introduced between model earthquakes simple cellular automata of the statistical mechanics of interacting elements can produce model earthquakes with variable properties, from versions that have essentially no predictability (a state known as self-organised criticality), to those with a finite, if limited, degree of predictability (a state known as intermittent criticality). Much remains to be done to test the degree to which laboratory-based constitutive rules (including alternatives such as rate and state friction) scale or do not scale to lower strain rates and larger spatial scales, especially in intermediate-scale problems such as induced seismicity and on a larger scale by passive monitoring in borehole sites, or by direct drilling into active faults. However, much of the current debate on earthquake predictability is not associated with physical models, but on the reliability of the statistical evidence and the lack of universally-agreed procedures or 'rules of the game' to evaluate predictability formally, as done in other examples of geophysics applied to complex (non-linear, multi-scale) systems such as Earth's weather and climate. Critical to this activity is developing an appropriate null hypothesis, quantification of uncertainties and probability gain, minimisation of sample bias (conscious or unconscious) and prospective real-time testing.

**Key words**: rock failure, precursors, laboratory tests, predictability, scaling

## PRESENTER'S BIOGRAPHY

**Ian Main** works on the fundamental physical, mechanical and hydraulic properties of rocks undergoing brittle deformation, including the nature of the earthquake source, the population dynamics of earthquakes as a complex non-linear system, and their practical applications to seismic and volcanic hazard. In rock physics he has worked on the experimental determination of fluid-rock interactions such as sub-critical crack growth and the effect of fracturing on fluid flow and transport through porous media undergoing deformation. He is currently director of the Edinburgh Collaborative of Subsurface Science and Engineering, and has served as Associate Editor with 'Geology', 'Journal of Geophysical Research', and 'Natural Hazards', as a member of the International Seismological Centre governing council, and on IASPEI sub-commissions on 'Modelling the Earthquake Source' and 'Significant Earthquake Precursors'. He gave the Bullerwell lecture in Geophysics in 1997, and moderated the Nature website debate on earthquake prediction in 1999.

# Maximum entropy production as a driver for earthquake dynamics and implications for earthquake predictability

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**ABSTRACT**

We examine the consistency of natural and model seismicity with the maximum entropy production hypothesis for open, slowly-driven, steady-state, dissipative systems. Assuming the commonly-observed power-law feedback between remote boundary stress and strain rate at steady state, several natural observations and scaling relations are explained by the system self-organizing to maximize entropy production in a near but strictly *sub*-critical state. These include the low but finite seismic efficiency and stress drop, an upper magnitude cut-off that is large but finite, and the universally-observed Gutenberg-Richter *b*-value of 1 in frequency-magnitude data. In this far-from-equilibrium state the model stress field self-organizes into coherent domains, providing a physical mechanism for retaining a finite memory of past events and spatially 'characteristic' earthquakes. This implies a finite degree of predictability, strongly limited theoretically by the proximity to criticality and practically by the difficulty of directly observing Earth's stress field at an equivalent resolution.

**Key words:** Entropy, self-organized criticality, earthquake predictability.

## PRESENTER'S BIOGRAPHY

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# Physical Modeling of Seismic Process

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**ABSTRACT**

Laboratory studies at various thermodynamic conditions indicate that, once the long-term strength is achieved, a certain time interval is required for the rock under load to fracture. Two necessary and sufficient conditions should be met for the main shock not to be sudden. First, the applied stress should rise slowly. Second, the medium should include constituents different in strength. Some scientists note the similarity between statistical properties of seismicity and acoustic emission (AE) in the laboratory studies under high pressure. Our experiments under different stress conditions, strain rates, on different scales, with additional mechanical or electromagnetic excitation and water injection are described.

Characteristics of AE in granite sample under confining pressure 160 MPa were studied. The pre-fractured core was deformed by axial load up to stick-slip events. The axial load was modulated by sinusoidal vibrations of a few percent of amplitude peak-to-peak relative to main stress. A time-space spectral analysis for a "point" process was used to investigate peculiarities of AE periodic components. The first result consists of detection of oscillations of acoustic activity correlated with applied oscillating load. These features of acoustic emission are most clearly appeared after stick-slips or during acoustic "aftershock" sequences. It is most probably due to higher strain-sensitivity of failure area when the sample is in transient, unstable mode.

Transient sequences of AE in sandstone cylinder samples were monitored during axial step-like deformation and at a confining pressure of 40 to 70 MPa as well. The step-like load regime was used to investigate the regularities and patterns of AE response structure under different strain rate of step. The data obtained from experiments with big blocks of marble and limestone (0.25 cubic meter) are also analyzed. It was shown that under relatively low stress and small strain rate of step-like deformation the AE intensity increases gradually and time of AE maxima is occurred before the end of increasing stress stage. The moment of activity decay onset begins later as stress increases. It indicates that step-like loading is substantially initiation and AE excitation is self-developing process, controlled by the stress level in the first. With sharp step-like loading of a sample the acoustic decay could be described with Omori law. It is supposed that low-rate step of load generates groups of acoustic pulses similar to swarm earthquakes while the sharp step produces sequences like aftershock series in seismology.

The models composed of silicate sand, crushed granite, and cement were subjected to biaxial compression. During the experiments lasting several months, with quasi static level of stress, small volume of water was repeatedly injected into the model. It has been established that the acoustic emission drastically increased. The shape of seismograms before and after water injection and b-value do not differ significantly, which implies that the effect is of trigger nature.

It was established as a result of laboratory experiments that the rock sample passes some main stages during macrofracture development. Prognostic effects of acoustic quiescence, foreshock activation, swarm and clusterization appearance accompany these stages. The properties of acoustic flow differ in the zone of future macrofracture and in lateral areas. On the basis of the physical modeling regularities, the algorithms were offered to analyze data of natural seismicity. The examples of comparison of laboratory and field patterns are presented.

Integration of different-scale researches and use of all known methods will allow revealing universal characteristics of rock failure process, valid in a broad range of spatial, temporal and energy scales, as well as determination of important factors, influencing and controlling the process of fracture. Analysis of transient processes is an important part of study of initiation and evolution of failure processes in lithosphere. Investigations both in situ and in the laboratory will clarify basic properties of stressed medium and physical mechanisms controlling the dynamics of seismicity.

The work was supported by RF President grant 799.2008.5.

**Key words: seismicity, acoustic emission, triggering, transient processes.**

## PRESENTER'S BIOGRAPHY

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# Complex of Features of Instability Derived from Examination of Generalized Vicinity of Strong Earthquakes

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**ABSTRACT**

The physics underlying the earthquake process is rather vague and even the typical features of seismic regime preceding the earthquake occurrence are debatable. The generalized vicinity of strong earthquake is constructed to examine the typical features of seismic regime inherent to temporal-spatial vicinity of strong earthquakes. This generalized vicinity is a superposition of earthquakes occurring in vicinities of a number of strong earthquakes. The spatial and temporal coordinates of earthquakes are treated here as distances of the current event from the given major earthquake. The spatial distance is norm to the focal size of the given major earthquake. Having in mind the weak dependence of duration of cycle of failure from the earthquake size a simple method of superposition of epochs of strong earthquakes occurrence is used.

For the case of USGS/NEIC catalogue data the change in b-value and in density of a number of earthquakes are examined. For the case of the use of Harvard catalogue the change in apparent stress values, change in mean correlation in orientation of focal mechanisms, in magnitude mb/mw ratio values, and in parameters characterizing the duration and the direction of propagation of the rupture process and the size of the earthquake fault zone are examined also.

In result of the examination a power-law character of evolution of fore- and aftershock cascades was confirmed. In the period of development of fore- and aftershock cascades a few effects indicating a development of some sort of power-law shear instability were revealed. The apparent stress values tend to decrease and a correlation between the orientation of focal mechanisms of the major and the current event tend to increase while approaching to a moment of the major earthquake. Besides this type of instability, a weaker anomaly was revealed in a more wide vicinity of strong earthquake. Thus two different modes of instability were found to exist in the vicinity of strong earthquakes. Possible physical interpretation of a complex of the revealed anomalies is discussed. Note also that these anomalies could be useful in elaboration of prognostic features used in algorithms of forecasting of strong earthquake.

**Key words**: earthquake generation, earthquake prognosis

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# Modeling and monitoring of seismoacoustic emission for earthquake prediction: tidal effects in laboratory and nature

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## ABSTRACT

Object of this work is connection of seismoacoustic emission parameters with medium stress state. In given report the next results are presented:

1. Natural observations of seismic emission in seismoactive regions (Kamchatka, Kurils) and investigation of parametric connection of seismic emission with large local earthquakes and processes of their preparation.
2. Laboratory experiments: slow deformation of rock samples with additional small long-period loading, which simulated Earth tides.

In Kuril-Kamchatka region the investigation of the high-frequency seismic noise (HFSN) are carrying out more then 20 years. During this time three points of long-term observation were established in the areas with low level of anthropogenic activity: «Nachiki» (1987, Kamchatka), «Karymshina» (1999, Kamchatka) and «Shikotan» (2003, Kuriles). A resonance narrow-band vertical seismometer was used as a sensor of the HFSN signals. Similar detectors are used at all three points of HFSN recording (the sensitivity with consideration for the preliminary amplification is not worse than 5×10^9 V/m, central frequency $f$ = 30 Hz, $Q$-factor=100). Possibility of seismic noise using for monitoring of medium stress mode and earthquakes prediction is based on the endogenous components presence. For study of the medium stress mode we use Earth tides as the calibration (etalon) influence. It was shown, that before strong local earthquakes synchronization between HFSN envelope components and the tidal waves of the gravitational potential with the same period appears. For explanation of tensosensitivity increasing before strong earthquakes on the significant distance of real earthquake sources we use the hypothesis on possible development of long near surface zones of dilatancy and fissure activization during seismic source evolution.

In laboratory experiments acoustic emission is analog on seismic emission in nature. Laboratory modeling was carrying out on geophysical complex INOVA (Borok, Russia), which includes (1) programmable electro-hydraulic complex INOVA (hydraulic press); (2) station for registration of slowly varying deformational processes and (3) acoustic measuring system. For study of external periodical influence (tides) we use linearly increasing strain as analog of tectonic process and additional small periodical strain. We use the coherent summation technique for detection of acoustic emission harmonics, which are result of modulation by periodic loading. We performed six monoaxial compression tests on Bentheim sandstone designed to indicate acoustic emission in the samples. For data processing of laboratory experiments we used the same technique as for natural HFSN during real-time monitoring. It was found that synchronization of acoustic emission with the periodical loading is not stable. Synchronization was detected only in the beginning of compression and in dilatancy stage. Phase shifts between periodical loading and response of acoustic emission are different for these two different compression stages. So comparison of laboratory results with natural observation of tidal component in HFSN confirms hypothesis of the tidal tensosensitivity increasing before strong earthquakes due to development of near-surface zones of dilatancy.

This investigation was supported by RFBR, grant 08-05-00692.

**Key words**: microseismicity, seismic emission, acoustic emission, laboratory experiment, Earth tides.

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# Post-seismic release slip observed after two earthquake swarms 2004 in the West Bohemia – Vogtland area (the Bohemian Massif)

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**ABSTRACT**

One earthquake swarm area is located in West Bohemia, Central Europe. The space distribution of individual seismic events is clustered into several seismogenic zones sharply grouped round a few tectonic fault sectors. The Nový Kostel zone dominates by its recent seismicity in the whole region. Its foci tend to cluster in space and the individual swarms took place in relatively narrow volumes. An important feature of the spatial distribution of the hypocenters is a lamella-like character of the earthquake focal belt. Permanent GPS observatories were established close to this seismoactive swarm region. In 2004 the processed GPS data recorded by two of the observatories, MARJ and POUS, detected a linkage between occurrences of individual earthquake swarm events and the Earth surface motions. The relations between origins of earthquake events, their sizes and characters of detected changes of the GPS position differences between both observatories are presented. When the most swarm seismic energy is released, then the position differences display relative monotonous movements: the northern component increases constantly for 7-10 days and the eastern component exhibits decreasing trend. Simultaneously a post-seismic release slip was assessed round 0.75 mm/day for the northern and 0.5 mm/day for the eastern directions. It leads to a deduction that the detected movement trends indicate an existence of post-seismic sinistral release slip of 0.8 mm/day on tectonic NNW-SSE fault system that starts when nearly whole swarm goes out and lasts for 7–12 days. The post-seismic slip trend was compared to the previous seismotectonic model of the area. This research was supported by the Targeted Research Program of the Academy of Sciences CR (Project 1QS300460551), by the Czech Science Foundation (Project 205/05/2287) and by funds of the Ministry of Education, Youth and Sport (Projects LC506 and 1P05ME781).

**Key words:** post-seismic release slip, GPS, earthquake swarm

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# Correlation analysis of seismicity with heliophysical, geomagnetic, and atmospheric processes

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A search for correlations of seismic activity with heliophysical, geomagnetic, and atmospheric processes is performed for Garm Test Site, Tajikistan. The seismic data are represented by three time series of various energy level earthquakes and three series of the number of micro-earthquakes. Time series of atmospheric pressure and local wind speed data are used as the atmospheric process parameters. Wolf numbers (sunspot numbers), solar flux at a frequency of 2800 MHz, neutron monitor cosmic rays data are used as the characteristics of heliophysical processes. Planetary indexes *Dst*, *Ap*, *Kp*, and the Tashkent observatory data of geomagnetic disturbance are used as geomagnetic parameters. The analysis of the cross-correlation functions of seismic activity with all of these time series data did not reveal any statistically significant correlations.

**Key words:** seismicity, correlation, atmosphere, geomagnetism

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Engineer, Institute of Physics of the Earth (IPE), Moscow (1970-74).
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# Initial Rupture of Earthquakes and the Predominant-Period Estimator for Earthquake Early Warning

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**ABSTRACT**

We investigate the characteristics and limitations of the parameter $\tau_p(t)$, which represents the predominant period of the P wave. We analyze the effects of the length of the time window (TW), low-pass filter, and anelastic attenuation as well as the complexity of the source process to elucidate whether values of $\tau_p^{max}$, or the time-dependent maximum value of $\tau_p(t)$ have direct relationships to the physical quantities of earthquakes, using numerical models and real waveform data observed in South African gold mine.

We find that values of $\tau_p^{max}$ have upper and lower limits. For larger earthquakes with source durations longer than the TW, the values of $\tau_p^{max}$ have an upper limit that depends on the TW. On the other hand, the values for smaller earthquakes have a lower limit that is proportional to the sampling interval. For intermediate earthquakes, the values of $\tau_p^{max}$ are close to their typical source durations and can have a large variety due to the complexity of the source process. These two limits and the slope for intermediate earthquakes yield an apparent final size dependence of $\tau_p^{max}$ in a wide magnitude range. As a result, the dependence of $\tau_p^{max}$ on the final size of earthquakes does not suggest that the final size of an earthquake is controlled by processes in the initial part of rupture. It is impossible to conclude whether the earthquake is deterministic or not from the dependence of $\tau_p^{max}$ on the final size of earthquakes. This is because $\tau_p^{max}$ does not always have a direct relation to the physical quantities of earthquakes.

**Key words:** initial rupture, predominant period, earthquake scaling.

## PRESENTER'S BIOGRAPHY

Satoshi Ide is an earthquake seismologist in University of Tokyo, Japan. He studies dynamic rupture process of earthquakes, scaling relations of earthquake source parameters, and various recently-found unusual earthquake-like phenomena called slow earthquakes.

# Map of Expected Earthquakes Before Strong Simushir Earthquakes (2006.11.15, M8.3 and 2007.01.13, M8.2)

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ABSTRACT

The report continues a series of papers devoted to results of MEE algorithm test in various seismoactive regions of the world. In this work the Kuril regional catalog of earthquakes for 1962-2008 compiled by Geophysical Survey of Russian Academy of Sciences was used. Previously it was established, that energy class cutoff $K$=9.5 for all period of observations and largest part of selected territory.

Research results of energy class cutoff for Kuril arch catalogue have been taken into account at carrying out of the subsequent calculations of maps of density seismogenic faults *K*sf, a slope of recurrence curve *b*-value, density of the seismic events flow *N*, realized seismic energy $E^{2/3}$. Using these distributions and Bayesian approach Maps of Expected Earthquakes (MEE) were constructed. The set of conditional probabilities $P(D_1|K)$ for all spatial cells represented in the form of isolines was called the Map of Expected Earthquakes for the time period [$t_0$, $t_0+\Delta T_{MEE}$], where $\Delta T_{MEE}$ is the MEE serviceability time. Occurrence of a strong earthquake in this time interval is assumed to be equiprobable.

A series of Maps of Expected Earthquakes for region of the Kuril island arch has been designed for sizes 50x50 km of space cells with 3 months shift. It covers the period since 1970 till present time. The first 8 years were a data for "tutorial" of the algorithm. Earthquakes with $K\geq 13.5$ were considered as target events.

Pair of Simushir earthquakes which have occurred in November, 2006 and January, 2007, was the strongest seismic events of last decades in this area. Epicenters of both strong earthquakes, their strongest foreshock (2006.09.30, $M_{LH}$=6.9, *K*c=13.7) and the strongest aftershock (2006.12.15, $M_{LH}$=5.7, *K*c=14.1) have taken place in zones with a level of conditional probability about 70%. It is necessary to note, that the zone with a level of conditional probability of 70% has appeared in a source area in 2003, approximately 3-3.5 years prior to earthquakes occurrence.

The resulted example once again confirms opportunities of MEE algorithm for the medium-term forecast of strong earthquakes.

Work is supported by the President of Russian Federation grant for support of leading scientific schools # 799.2008.5 and the grant of the Russian Foundation for Basic Researches # 07-05-12041.

**Key words:** earthquake, prediction, algorithm MEE

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**SCIENTIFIC CONTRIBUTIONS:**
(1) In 1967-1980 he participated in the organization of station network of electrotelluric field registration to reveal earthquakes precursors in Kamchatka and in Central Asia (Garm), in data processing and interpretation.
(2) In 1980, he for the first time introduced the parameter of seismogenic ruptures density based on destruction concentration criterion, which became one of the most efficient earthquake precursors.
(3) He is one of the authors of the method of medium-term prediction by a complex of prognostic features (algorithm MEE) (1985).

**LAST POSITIONS HELD:**

- Head of Laboratory “Continental Seismicity and Seismic Disaster Forecasting”, Institute of Physics of the Earth, Russian Academy of Sciences (2004-Present time).
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