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PROBLEMS OF NONLINEAR SEISMOLOGY

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Introduction

Until recently the term «Nonlinear seismology» practically was not used either in seismology or in seismic prospecting. The reason was not that nonlinear phenomena were unknown, but because, according to the dominant opinion, elastic nonlinearity is very weak and does not effect distinctly seismic wave fields. The opinion was supported by laboratory experiments with rocks (Nikolaev A. 1988). A broad variety of nonlinear phenomena which are expressed in geodynamic processes - seismicity, seismic and acoustic emission, interaction of processes and geophysical fields - were not analysed from the point of view of nonlinearity, even those which are clear and attractive.

A brief look at the nonlinear elasticity history shows that after Hooke has discovered his linear law that deformation is proportional to the force, Jakob Bernoulli in 1690 found that the relation between force and deformation is hyperbolic. Disputes about nonlinearity of stress-strain diagram which have been for three hundred years, have some times of a dramatic character.

Since the beginning of nuclear epoch active investigations of nonlinear shock waves in hypocenter zone have been carried out in the USSR, USA, and other nuclear countries.

The first attempt to explain some unusual events observed on the Earth surface by strong earthquakes using a nonlinear model of soils was made by author (1967) and then A.Gvozdev and V.Kuznetzov proved the speculations experimentally (1967).

Ten years later a group of scientists from Nijny Novgorod Institute of Radiophysical Measurements and from the Institute of Physics of the Earth, Moscow, launched a study of nonlinear effects due to propagation of seismic waves of weak deformations (Aleshin et al, 1981). The study, which continues up to now is oriented towards developing a method of «nonlinear tomography», uses effects of nonlinear interference of seismic waves.

The other branch of nonlinear seismology is connected with investigations of temporal variations of seismic wave velocities in crust and mantle due to changes of stress field. The first attempt was made in the late 19th century by the Japanese seismologist K.Imamura to find the reducing of shear wave velocity in the Earth crust before the strong earthquakes near Tokyo. He did not find any distinct changes of wave velocity, but the attempt itself is remarkable.

The first obvious result was obtained by K.Aki and colleagues (1970) who investigated temporal changes of wave velocity caused by Earth tide stress variations using a seismic vibrator and borehole seismograph. They found the effect of 10^{-4}.

A.Gamburtzev and colleagues (1992) conducted special investigations with TNT shots in Central Tadjikistan and found that wave velocities in the Earth crust and uppermost mantle change with time due to tectonic stress change, the rate of change being 10^{-3}.

M.Nevskyi studied similar effect in Copet-Dag, Turkmenia, and San Andreas region. Having studied seismic waves, generated by quarry blasts, he revealed that residuals of arrival times are correlated with horizontal component of crustal deformation. The estimated value of nonlinearity factor $\Gamma \sim 10^{3}$ in the upper part of the crystalline crust is greater by one order more than that obtained in laboratory experiments (Nevsky et al., 1987).

Both nonlinear interaction and wave velocity changes are passive effects connected with «tensosensitivity» of elastic modules of rocks, i.e. with «physical nonlinearity».

The other type of nonlinearity is connected with release of elastic energy, a manifestation of geodynamic processes in real media. These effects are displayed in a form of seismic and acoustic emission and so-called «crossing effects». They are more distinct and variable, and appear most clearly in a form of self-organization and chaotization, and combined effect of different processes occuring in energy saturated media. Conspicuous effects are connected with induced seismicity. They are getting more and more strong and evident as a result of rapid increase of technogenic impact on lithosphere (Nikolaev, 1997). The importance of the problem stems from increasing seismic hazard and risk as a result of induced earthquakes. Some of them are devastating, for example, Koina earthquake in India 1978, magnitude M 6,5, and Gazli earthquakes of 1976 and 1984 in Uzbekistan, M 7.1-7.3. Seismicity, seismic and acoustic emission are processes extremely sensitive to stress changes and seismic vibrations, i.e. tensosensitive and vibrosensitive. As a result they respond to different types of natural and artificial impacts: local and distant earthquakes, Earth's tide, changes in the Earth rotation speed, atmospheric pressure variations; filling of reservoirs, exploration for oil, gas, minerals, pumping of poisoned liquids into layers, underground nuclear explosions - all these produce characteristic nonlinear response onto seismic flow, seismic and acoustic emission.

Meanwhile these problems are not investigated comprehensively and regularly as yet. In recent years problems of nonlinearity are getting more and more popular and spreading over other Earth's sciences, geophysics, geology and tectonics (Letnokov, 1992; Pustsharovsky, 1993). In spite of this the subject, areas and methods of nonlinear seismology are still not defined. Studies of nonlinear wave propagation effects, temporal variations of wave velocities and nonlinear active processes are still isolated. No attempts were made to comprehend available results and find out the ways in future investigations.

The article presents a general look at the problems of nonlinear seismology. I will start with nonlinear properties of rocks, then describe briefly some passive nonlinear effects due to wave propagation, next I will present inducing effects which show nonlinear behavior of rocks, Earth crust and uppermost mantle, and I will finish with a look into the near and distant future of seismology.

Nonlinear elastic properties of rocks

Physical properties of rocks vary in a wide range. The fact reflects a broad variety of their structure and texture. Inhomogeneity is the fundamental property, it covers the interval from large parts of the planet to the smallest particles of grains. As a result, the stress field is also of an inhomogeneous structure. Structural defects, cracks, and pores concentrate stresses in very small volumes where they reach threshold of destruction, even if the change of stress is very small. Physical model of destruction, developed by S.Zhurkov (1968), is based on kinetic concept of toughness assuming that macroscopic destruction of rocks occurs even by much lower stresses than toughness limit when the action is very long. In a simple case of single-axis tension the empirical formula is:

$$t = t_o \exp\,(U_o - \gamma\sigma) \,/\, kT, \qquad (1)$$

here t is time of destruction - long-term toughness of rock, U_o- energy of activation, σ - stress, T - temperature, k - Boltzman's constant, γ - parameter characterizing mechanical properties of rock, t_o coincides with a period of temperature oscillations of elementary fraction of rock. The formula describes a process of accumulation of microscopic discontinuties. The process has a statistical character which is due to random distribution of local mechanical properties. Macrofracture occurs when concentration of defects in a given part of medium reaches the critical value.

Formula (1) shows also that even small changes of σ, which are connected with tectonic stress field changes and seismic vibrations, change the speed of microscopic process, and seismic/acoustic emission response could be significant. Especially significant it will be if the macrofracture is about to occur. That means that many cracks are already joined and form clusters, which will join together during the main event. The process could be described by the model of percolation which shows that close to the moment of percolation (macrofructure, earthquake, rockburst) microfracturing is getting very active, intensity of seismic and acoustic emission increases, tenso- and vibrosensitivity of physical parameters of rocks become extremely high.

So, the elastic nonlinearity appears in form of seismic waves interaction, temporal change of in-situ wave velocities, active nonlinearity which displays in high vibro- and tensosensitivity of seismicity, seismic and acoustic emission. Nonlinear properties and manifestations are connected with structure, texture and properties of the minerals.

Interaction of seismic waves

Linear theory is based on the principle of superposition and prevents seismic waves from interacting. The most evident form of interaction is generation of new waves. The result of nonlinear interference of two harmonic seismic waves, whose frequencies are f1 and f2, is appearance of two new waves with frequencies f1 + f2 and f1 - f2. At the same time every wave interacts with itself, the result of «selfinteraction» is appearance of high harmonics 2f1, 3f1, ..., 2f2, 3f2 ... All these waves interact with one another and as a result a huge number of new waves appear.

Let σ and ε are stress and deformation. $\bar{\varepsilon} = \varepsilon - \varepsilon_o$ - change of deformation. One can use a simple presentation of nonlinear quantity following the nonlinear acoustics:

$\bar{\sigma} = \sigma - \sigma(\varepsilon_o) = \sigma'_{\varepsilon}(\varepsilon_o)\bar{\varepsilon} + 1/2\ \sigma''_{\varepsilon\varepsilon}(\varepsilon_o)\bar{\varepsilon}^2,$

parameter $E = \sigma'_{\varepsilon}(\varepsilon_o)$ is linear elastic modulus, parameter

$\Gamma = \sigma''_{\varepsilon\varepsilon}(\varepsilon_o) / 2\sigma'_{\varepsilon}(\varepsilon_o) = 1/2\ \rho V\ (\partial V / \partial \sigma),$

characterizes nonlinear property of rock. Both E and Γ change with stress, but the parameter of nonlinearity is much more tensosensitive.

Spatial distribution of Γ could be obtained by means of nonlinear seismic tomography. The method being developing now uses two seismic vibrators which generate harmonic signals of different frequencies, array of seismometers detects combined waves originated within the nonlinear medium. Parameter Γ is sensitive to stress field changes and could be used for seismic monitoring - to control the state of medium and to predict strong earthquakes.

Monitoring of seismic wave velocities

Changes of wave velocities produced by stress changes are proportional to the latter and the parameter of nonlinearity Γ. The uncertainty could be overcome if the change of stresses is known;

the theoretically calculated value of tidal stress is close enough to the observed ones, so it could be used in the study.

Control of wave velocities need very high precision which could be reached only by using artificial sources, explosions and seismic vibrators. The latter are more stable and precise. The powerful seismic vibrators have a peak force up to a few hundreds of tons. Use of them makes possible to monitor the whole lithosphere by regular soundings (Yushin, 1993).

Seismic tomography which uses regular study of wave velocity distribution and reconstructs both, 3D image of welocities and its temporal changes gives information about stress field and spatial distribution of nonlinearity. The developing of nonlinear tomography technique is now in progress.

Study of longitudinal wave velocity changes in lithosphere beneath Lake Baikal is conducted by Novosibirsk's geophysecists. They use 200 ton vibrator installed on Eastern Coast of Lake Baikal and seismic network on Western Coast. The precision control of first arrivals of seismic waves is $2 \cdot 10^{-4}$. It is enough to see variations caused by tidal change of stress in the lithosphere, whose range is around 5 10E-4. The main purpose of the study is earthquake prediction. The idea is the same as was hundred years ago: elastic modules change before the strong earthquake, one should detect it. But this time the precision is hundred times higher (Yushin,1993). ~~Alexeev)~~

The second problem of the sounding is to study fine temporal and spatial structure of stress changes in Baikal Rift zone, as a part of comprehensive investigations using multidisciplinary observations, including precise geodesy and GPS technique.

Stress monitoring by means of nonlinear seismic tomography should make a significant progress in the near years.

Induced seismicity

Process of preparation of earthquake depends on a number of natural and man-made factors: Earth's tide, local and distant earthquakes, changes of speed in the Earth rotation, atmospheric pressure variations; filling of reservoirs, extraction of oil, gas and minerals , nuclear explosions, water pumping into layers, powerful electric pulses. The essence of nonlinearity is that response on every factor depends on the presence of other factors. Nevertheless it is possible, as the first step, to determine a characteristic individual response using technique of statistical accumulation. The next step should be a multifactor approach in the study of induced seismicity.

Filling of reservoirs, pumping of fluids into layers, extraction of oil and gas influence seismicity and may cause strong earthquakes. Possibility of such events depend on tectonic conditions and seismic potential in every particular place. These influences produce the response of the medium in form of a strong increase of weak events seismicity, seismic and acoustic emission which could be forecasted in general, at the same time probability of strong earthquake remains uncertain. Among reservoirs created in mountain areas about 10% induced significant earthquakes. Shallow weak earthquakes could also cause damages of buildings, boreholes, and technological equipment.

Seismic and acoustic emission accompanies slow crustal movement and creep. Before the strong earthquake the intensity of emission increases in the seismic source domain and this could be recognized as a precursor of a strong event. Special technique of emission tomography which visualizes emission sources scattered within the medium is developed to monitor the Earth crust and control the process of earthquake preparation (Nikolaev, Troitsky, 1987). A significant symptom of earthquake preparation is also increased tensosensitivity of emission process. It could be recognized as increased emission intensity variations induced by the Earth's tide and by variations of atmospheric pressure. This regularity is true of earthquakes in broad range of magnitudes and also of some other catastrophic events, particularly of volcanic eruptions and landslides.

Tidal stress plays special role in studies of induced seismicity. It is comparatively weak and produces deformation of about 10^{-8}. The influence of the Earth's tide onto seismicity was in focus of many studies, the obtained results are significantly contradictory. Some authors reported that seismicity increases during the phase of tidal compression, others in the phase of tension, still others found out that it does not depend on the tide at all. The answer is that all that is true.

Fig.1. shows the spatial distribution of earthquake sources in California, 1970-1990, $M > 4.5$. Every bin has two numbers: the upper one N_- indicates the number of events that occur in the phase of tidal compression, the lover one N_+ in the phase of tidal tension.

The majority of bins have more or less equal number of both, but in some of them N_- or N_+ prevails. That means that the regularities observed in different areas are significantly different (Nikolaev V., 1995).

Fig.2 shows the diagram of temporal change in the seismicity over California. Every line corresponds to some harmonic component of the Earth's tide. The number of events since 1970 to the every particular point of time are compared in term of dimensionless value

$$t = (N_- - N_+) / (N_- + N_+)^{1/2}$$

which is normalized difference of events during the phase of compression and tension for the given component. As is seen, some tidal components influence fine structure of seismicity significantly, bat some don't, some influence during the period of several years. This is a typical case, here we see the manifestation of organization and chaotization of seismicity. Lines denoted as S1(2) and S1(3) correspond to the double and triple frequencies of the component S1, lines S1+Mm and S1-Mm correspond to the stack and antistack frequencies. It is surprising and remarkable that seismicity responds to high harmonics and to stack and antistack frequency waves. The response is also temporally variable. It means that earthquake triggering is evidently a nonlinear process, it is sensitive to frequency of external processes, the sensitivity changes with time.

The result is very instructive. We should understand that the other kind of responses are of the same nature and must be also spatially and temporally changeable. This appears true of seismicity induced by distant underground nuclear explosions, distant earthquakes and powerful electric pulses.

There were a lot of disputes about influence of underground nuclear explosions (UNE) on seismicity. It seems that political reasons hindered the researches, in any case they supported the opinion that UNEs cause no influence on distant earthquakes..

The simple statistical analysis showed that the effect does exist. It is expressed as decrease a frequency of earthquakes ν (reverse to mean time period between events) in the course of five to ten days after explosions. The influence is seen up to 2000 km, it is spatially irregular: in some seismically active regions the response is strong and distinct, some regions show no response, even kind of «gap», but in general UNEs induce short time increase in seismicity. In particular, UNEs in Semipalatinsk Test Site induced significant seismicity of Northern and Southern Tien Shan, Pamir, and Hindu Kush; Caucasus , Eastern Tien Shan and Central China don't exibit any function of nuclear tests; Kopet Dag region displays rather inverse regularity: slight decrease of seismicity (Nikolaev A., 1995).

The strongest effect is observed in deep-focus Pamir - Hindu Kush zone. Fig.3 presents a diagram which shows dependence of earthquake frequency ν versus time τ elapsing after the nuclear test in Semipalatinsk site. As one can see, the response of small magnitude earthquakes $3.4 < M < 4.0$ is stronger than that of magnitude $4.0 < M < 5.0$, deep seismicity when focus depth H is below 150 km and shallow seismicity when it is above 150 km show similar regularities. There are some other phenomena on τ, ν diagrams, in particular slight increase in seismicity when

$\tau =$ 35-45 days, which exists also in other regions, its nature is vague.

A similar picture, in general, was obtained in California where UNEs in Nevada Test Site induce seismicity: the effect is spatially irregular and appears also most distinctly during 10 days after events (Nikolaev A., 1995).

It is evident that vibrosensitivity displayed as a response of seismicity affected by nuclear explosions should be displayed more or less similarly in its response on strong earthquakes. As is known, strong earthquake induces so-called aftershocks in the epicentral zone. The aftershock activity is very high just after the main shock and reduces with time in the course of months and years. At the same time strong earthquakes - «master events» - also include remote aftershocks, at a distance of up to two thousands kilometers. This effect is much less distinct, it was revealed statistically (Nikolaev, et al., 1995). The effect is also displayed in increased mean frequency of earthquakes in some active zone during five to ten days after master event. The rate of increase is up to 30-50%.

Master events and induced earthquakes are in complex interrelations: seismicity of some region is sensitive to master events in some regions and not sensitive to master events in others. For example, Tien Shan and Sagros earthquakes are sensitive to Pamir - Hindu Kush master events, and Western and Central China earthquakes are not sensitive to them; Western Mediterranean earthquakes are sensitive to master events in Turkey and not sensitive to those in Greece.

The most representative example of the direct triggering is the Landers, California M 7.8 earthquake of 28 June 1992. This earthquake induced seismicity in Californis and Big Basin over distances of 1000 km. The effect is unisotropic and mozaik-like. The seismicity in some small areas in California and Big Basin excited while some active areas remained passive. At the same time some other strong earthquakes in California did not excite such strong response of remote aftershocks, for example, Northridge earthquake M 7.0 of 1989.

Summarising, we should conclude that vibrosensitivity of seismicity is unstable spatially and temporally. Short-period changes of earthquakes, up to 10 days after the master event, is a statistical regularity. Each individual earthquake had been induced by all previous earthquakes and UNEs and, in turn, influenced all subsequent earthquakes.

Earthquake triggering by strong electric pulses has been revealed recently (Tarasov, 1997). In the course of 1977-1987 special electric soundings of the Earth crust were conducted in Central Tadjikistan to find some changes in electric conductivity before strong earthquakes. The electric source was a magneto-dynamic generator installed near the Surkhob Fault which divides South Tien Shan and North Pamir. The generator produced 2.5-second powerful electric pulses whose energy was about 5 10 Joule, distanse between electrodes 3 km, electric resistance 1.5 Om. 34 electric soundings were conducted and 11000 local earthquakes were registered during 1976-1978. Technique of ν, τ diagram was applied in the study, but in this case electric pulses were used as the master events. The analysis showed that after master events seismicity in the upper 5-km layer increases gradually up to 20-30% and remained anomalous high during 20-30 days, its maximum was on the seventh day. More Deeper seismicity was not affected by the electric pulses, which could be explained by skin-effect.

Inducing effect is illustrated in Fig.4 which shows the map of epicenters of shallow earthquakes M>2 eight days before the master event and eight days after it. The number of earthquakes before and after are respectively 15 and 28. The difference is significant: formal estimation of confidence level to accept the hypothesis of inducing is 0.93. Moreover, one should take into account that the geometry of epicenters location is significantly different. Some of them are concentrated along Peter the First Fault and Darvas-Karakul Fault, but five earthquakes appear along the line which connects these two faults. This is an independent indication of the inducing effect.

It is surprising how can such a weak amount of energy affect the seismicity. The estimation shows that at a distance of 20 km apart from the generator the energy flowing across one square kilometer, which is more than the dominant size of the earthquake source, is 100 Joule. This is by four orders of magnitude less than the seismic energy emitted by induced earthquakes. Telluric electricity could reach comparable intensity and make tangible contribution into induced seismicity.

Summary

Passive and active seismic processes are due to a very complex structure and texture of rocks, a highly inhomogeneous stress field and energy saturation.

Two general phenomena are fundamental: the one is high value and broad range of variations of nonlinear parameter in in-situ rocks and the other is high sensitivity of seismicity to exciting impacts, mechanical and electric.

As a result of strong elastic nonlinearity, nonlinear seismic effects appear even when wave deformations are very weak, of the order of 10^{-8}. This makes possible to develop a method of nonlinear tomography to study spatial distribution of nonlinear parameter Γ and monitor its temporal changes. Temporal change of nonlinear properties of rocks is very important information regarding stability of dynamic processes and diagnosis of catastrophic events, earthquakes.

The nonlinear character of seismic flow is connected with its high sensitivity to stress changes, seismic vibrations, and telluric electricity. It is displayed in periodical changes of intervals of organization and chaotization , and in inducing effects. The most general characteristics of induced seismicity are spatial inhomogeneity and temporal variety. The latter is a result of interference of many events which affects seismicity. Some events are known and controllable, the others are unknown and contribute a component to the problem which defies cognition. The other complication is nonlinear interference of different processes which

affect. For example, induced effect of UNE depends on the tidal phase in the detonation moment (Nikolaev V., 1995).

High sensitivity of seismicity to external actions could be used for selection of optimal regimes of industrial impacts, to avoid undesirable seismic response and mitigate risk. On the other hand, it could be used for triggering a strong earthquake at some definite moment by artificial seismic and electric sources. Of course, that is a technology of future, let us hope, not the remote one.

So, there are neither nonlinear earthquakes nor noninduced seismicity. To understand seismicity one should study it as a member of family of many processes, endogeneous and exogeneous, natural and industrial. Seismological processes are essentially nonlinear. Seismology is multidisciplinary science, the epoch of linear seismology seems to be over.

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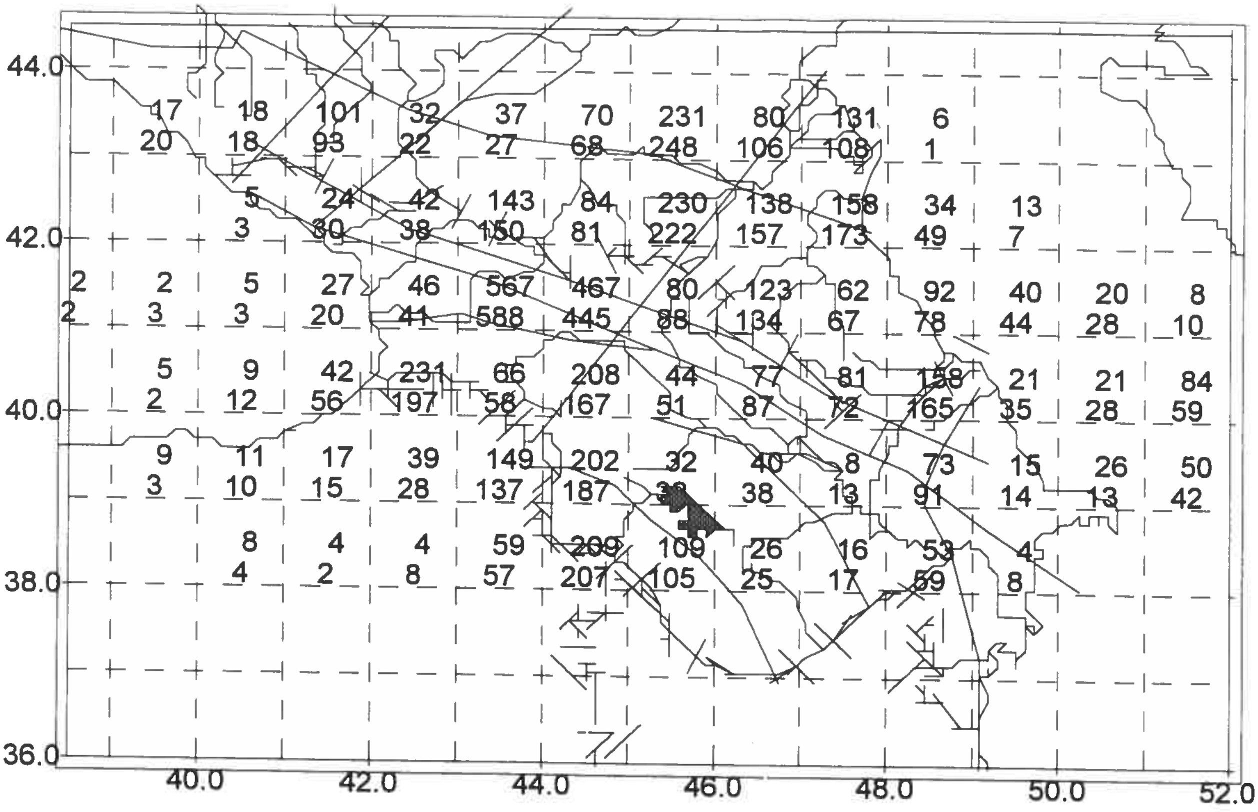

Fig. 1. Number of earthquakes occurred during positive (top) and negative (bottom) phase of vertical component of tidal vector. 1962-1993. M>2.9

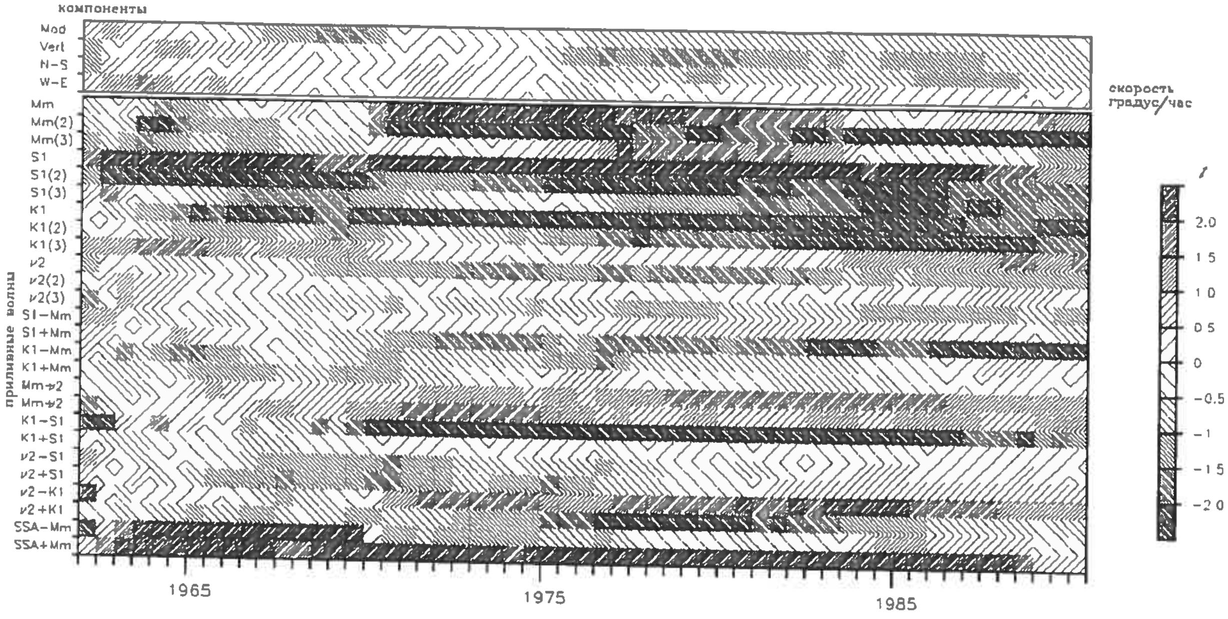

Fig. 2. Spectral-temporal diagramm of standardized differences of earthquakes occurred during positive and negative phases of tidal vaves, tidal waves with multiply, summarized and differenced frequency. Caucasus region, 1962-1993 .

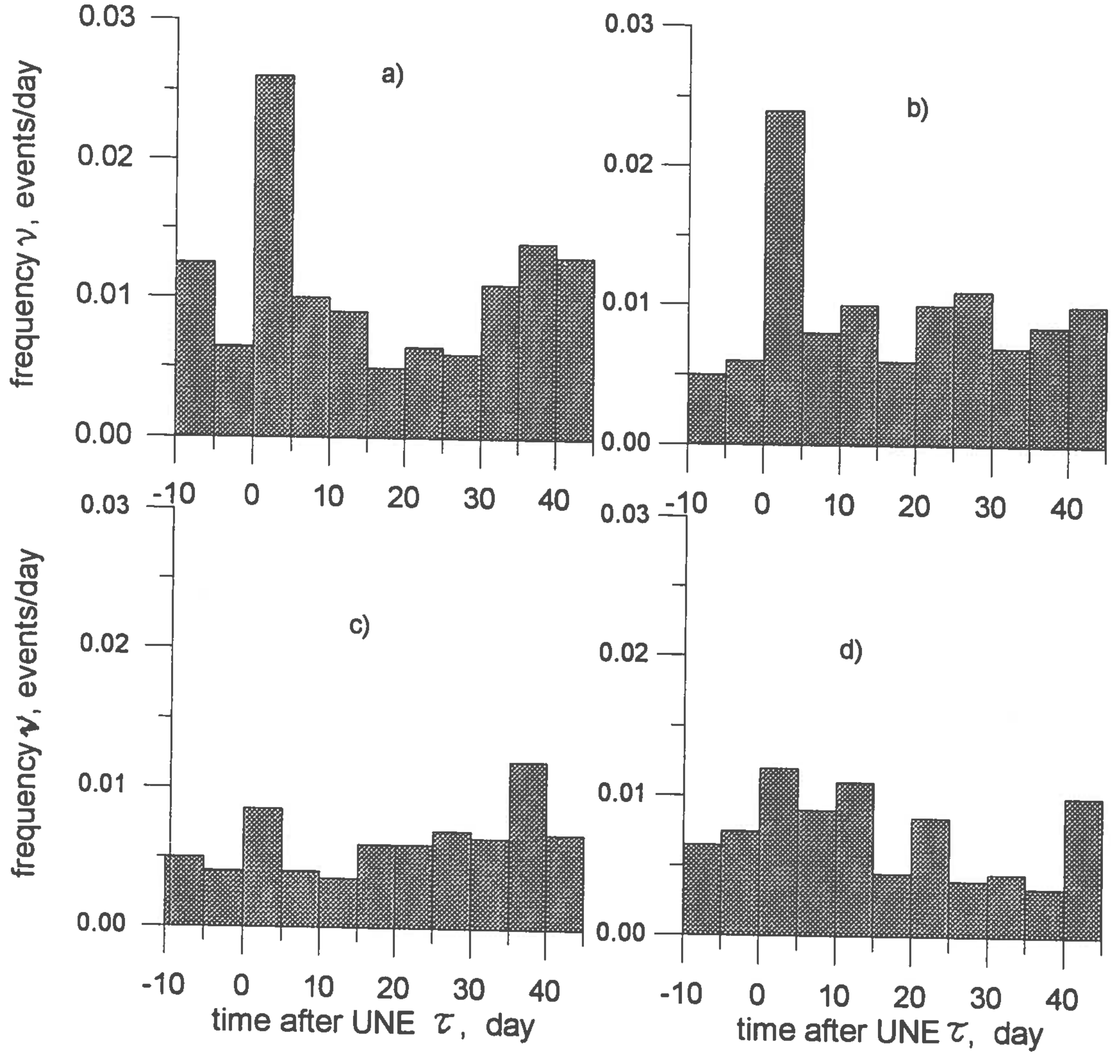

Fig.3. ν,τ diagrams, for the Pamir-Hindukush region.
a - 3.4<M<4.0, H<150 km, b - 3.4<M<4.0, H>150 km
c - 3.9<M<5.0, H<150 km, d - 3.9<M<5.0, H>150 km

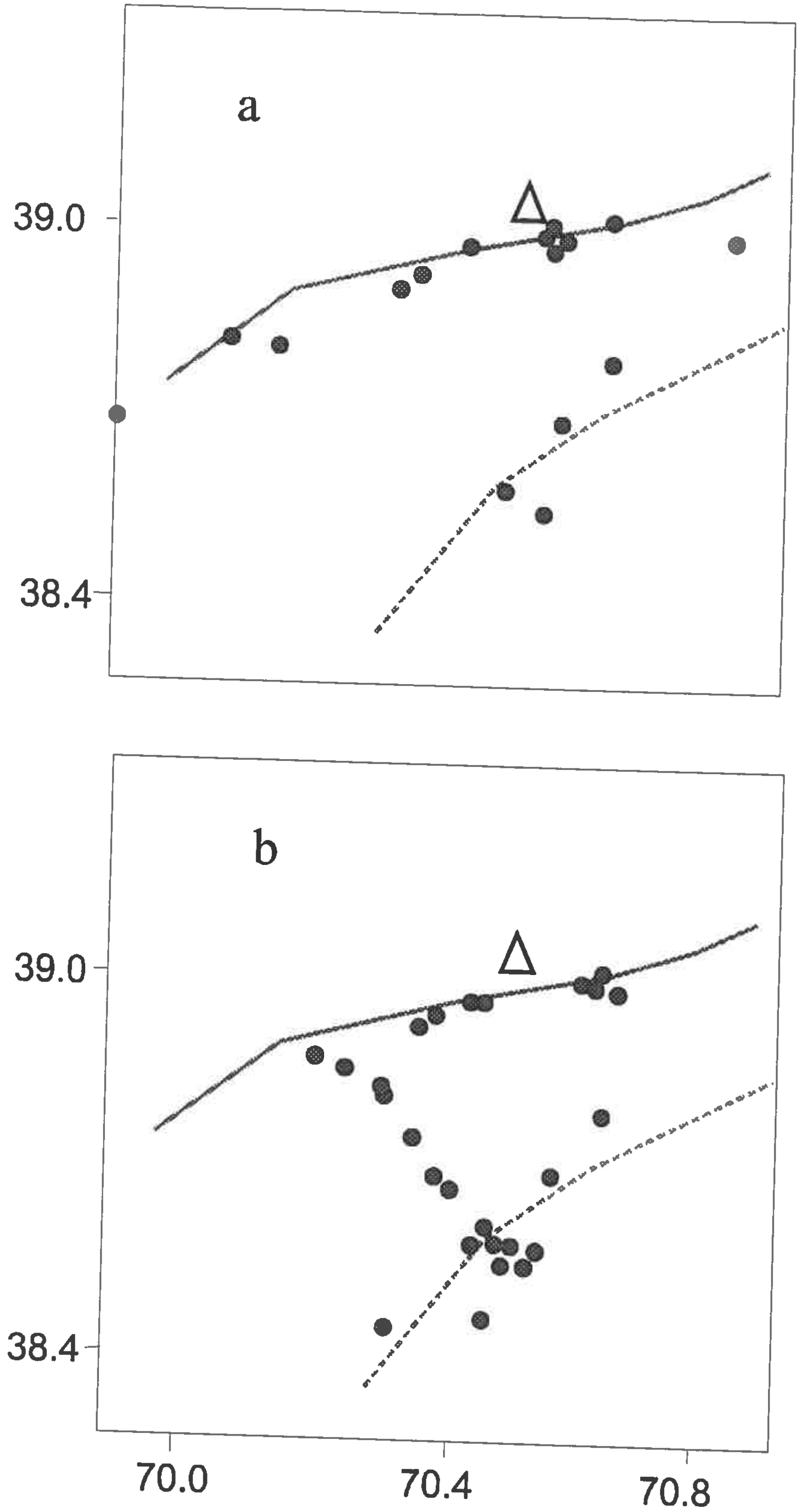

Fig.4. Map of epicenters: a,b - eight days before and eight days after the master event; solid and dashed lines - Peter the First Fault and Darvas-Karakul fault; triangle - electric generator