РОССИЙСКАЯ АКАДЕМИЯ НАУК

НАЦИОНАЛЬНЫЙ ГЕОФИЗИЧЕСКИЙ КОМИТЕТ

RUSSIAN ACADEMY OF SCIENCES

NATIONAL GEOPHYSICAL COMMITTEE

НАЦИОНАЛЬНЫЙ ОТЧЕТ

Международной ассоциации сейсмологии
и физики недр Земли Международного
геодезического и геофизического Союза
2003 – 2006

NATIONAL REPORT

to the International Association of Seismology
and Physics of the Earth's Interior
of the International Union of Geodesy and Geophysics
2003 – 2006

Москва 2007 Moscow

К XXIV Генеральной ассамблее
Международного геодезического и геофизического союза

Presented to the XXIV General Assembly
of the International Union of Geodesy and Geophysics

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In the national report, major results are given of research conducted by Russian scientists in 2003-2006 on the topics of the International Association of Seismology and the Physics of the Earth's Interior of the International Union of Geodesy and Geophysics. The structure of seismic observation stations network of the Russian Federation is given and its prospects are outlined in the report. The results of research in strong and perceptible earthquakes in Russia in 2003-2006 are presented as well as the results obtained in seismic danger assessment, the physics of seismic process, and earthquake prediction. Major achievements in the physics of the Earth, geothermy, geodynamics, and physical properties of geomaterial are featured. Information on constructing geoinformation systems in geophysics, and on pit seismicity monitoring is given. The results of research in comparative planetology and artificial intelligence application in geophysics are covered for the first time as well as seismic risk assessment and monitoring. All the required references are given.

Contents

Introduction

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This report submitted to the International Association of Seismology and the Physics of the Earth's Interior (IASPEI) of the Intyernational Union of Geodesy and Geophysics (IUGG) contains results obtained by Russian geophysicists in 2003-2006. In the report prepared for the XXIV General Assembly of IUGG (Italy, Perugia, July 2-13, 2007), the results are briefly outlined of basic research in seismology, geodynamics, geothermy, in the studies of physical properties of rocks under high pressures and temperatures as well as in some other directions.

The periof from 2003 to 2006 was still difficult for Russian geophysics. Owing to economic reasons scientific career is Russia is still believed to be lacking in prestige. Thus recruiting younger scientists for fundamental research in geophysics actually failed. Economic difficulties were redoubled by difficulties arising from reorganizing the Russian Academy of Sciences, Russian science and the educational system of Russia initiated by the leaders of the country. The number of Russian scientists in governing bodies of IUGG, IASPEI, ESC and their commissions is decreasing. In spite of the difficulties, Russian scientists participated in practically all conferences of the International Association of Seismology and the Physics of the Earth's Interior (IASPEI), in the General Asssemblies, international projects and international centers.

Even in such difficult conditions high scientific potential, great experience in research and the traditions of Russian geophysics allowed obtaining a number of fundamentally important new results in the period under review. Many of them are presented in the following sections of this report. Each of the sections has a list of the most interesting scientific papers published in 2003–2006 including publications prepared in cooperation of Russian scientists and their colleagues from other countries.

For a number of reasons not all results obtained by Russian scientists on the problems of seismology and physics of the Earth's interior in 2003-2006 are included in the report. At the same time it is hoped that authors may present these results at symposia of IUGG XXIV General Assembly.

1. The system of seismic observations in Russia

1.1. Seismic observation network in Russia in 2003-2006

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The seismic observation network in Russia carries out continuous seismic monitoring of the territory of the country. It has a hierarchic three-level structure. It comprises a teleseismic network and 10 regional seismic networks, which in their turn comprise local nbetworks.

More than 250 seismic stations and 10 information-processing centers (IPC) operate in the network, collecting on regular basis and processing primary (raw) data and distribute IPC products.

The Geophysical Survey of the Russian Academy of Science (GS RAS) unites the seismic observation network, controls its work and provides guidance in science and methods. The Geophysical Survey interacts with international and national seismological centers and institutes with the aim of intergrating the Russian seismic network into the world system of seismic observations. It exchanges data and products of seismic networks operation, develops and puts into observation practice new devices and methods to produce and process seismic data. The Geophysical Survey annually publishes collected papers "Earthquakes of Northern Eurasia" and began to publish col-

lected papers "Earthquakes of Russia" from 2003, in which catalogs of teleseismic and regional observations are given in both hard copy and CD and strong earthquakes in the territory of Russia and CIS countries are described in detail.

Teleseismic network

The teleseismic network is a basic network for seismicity monitoring of Russia in operative and current regimes. It comprises about 40 stations. All the stations have wide-band channels of registration. Digital registration at 12 stations is made with the use of equipment provided by IRIS (Incorporated Research Institutions for Seismology) of USA. Theses stations are basic in the Russian teleseismic network. At the same time they are stations of the Global Digital Seismic Network. The characteristics of the stations are similar to characteristics of global seismic network GSN (Global Seismographic Network).

In GSN, channels also in close to real time regime transmit data. The Center of Teleseismic Network in Obninsk on a regular basis receives data in such regime from more than 40 Russian and foreign stations located in different continents. Besides the Center has access to a number of foreign databases in both operational and current regime.

A computer network has been constructed in the Center, in which more than 20 computers of SUN family and several tens of personal computers PC are operated. The Center has software that allows using modern methods of data processing including data collection in different modes, automated detection and association of phases, determination of event parameters in interactive mode, formation of seismic events bulletins and communications that are regularly put in the Geophysical Survey sites.

A part of teleseismic network is day-and-night service of urgent reports on strong and appreciable earthquakes with the goal of providing governmental and other relevant bodies with timely information on major parameters of earthquakes that occurred (time of occurrence, epicenter coordinates, source depth, perceptibility, and destruction). This information is required if urgent steps should be taken to render help to areas that suffered earthquake, to save lives, and to eliminate consequences of natural disasters. Prompt collection and processing of observation data is of primary importance. The first report is formed within 20-30 minutes after the earthquake and the report is sent to governmental bodies. On the basis of information collected and processed during 1-2 hours after the earthquake the service of urgent reports forms an urgent report in which more accurate data on the source parameters and additional information on macroseismic consequences are given. The service of urgent reports shows the results in the information service site (http://www.ceme.gsras.ru) continuously updating them.

The teleseismic network operating in urgent reports mode allows us to monitor seismicity beginning with magnitude 4.5 on the whole territory of Russia and beginning with magnitude M=4.0 in individual regions, for example in North Caucasus, Baikal and Kamchatka.

In the last few years, the service of urgent reports of Russia detected more than 3000 earthquakes per year that occurred in Russia and the world and informed about them.

The second level of teleseismic network operation, which provides impovement of epicenters locations in the mode of Rapid Seismological Bulletin (with a delay of 1-2 months), encompasses all the stations that are equipped with wide-band receivers irrespective of the type of connection with the center. The Geophysical Survey RAS teleseismic network of the second order contains about 70 stations located at the territory of Russia. The teleseismic network sensitivity provides registration of earthquakes with M=3.5 approximately for 40 per cent of the Russian territory and of earthquakes with M=4.0 and M=4.5 for the total territory of Russia.

Regional seismic networks

The seismic network of Altai-Sayan region (the network international code is ASRS) comprises 41 seismic stations.

All the stations have equipment for dighital registration. The frequency range of the major part of the stations is 0.5–20 Hz. Five wide-band stations have frequency range of 0.05–20 Hz. The dynamic range of registration is determined by 20-bit analog-to-digit convertion. All the stations use seismometers of the type SM3-KV, SKM-3, SKD, SK developed for analog registration.

The network is controlled from Novosibirsk. The information-processing center, which processes data and issues the operative earthquake catalog, is located there. You can find earthquake catalog with magnitude greater than 3.0 there and in site http://www.gs.nsc.ru.

The seismic network of Baikal region (the network international code is BYKL) comprises 23 digital seismic stations. All the stations are digital with frequency range of 0.5-20 Hz with 20-bit analog-to-digit transformation. The network has one wide-band station with frequency range of 0.0028–25 Hz. The network registers more than 3-4 thousand strong and weak earthquakes annually. The Network Data Center is situated in Irkutsk. From observations of the regional station network cumulative processing of seismic events is carried out and "The Bulletin of Baikal Region Earthquakes" is published.

In urgent and operational modes all the stations transfer the results of processing to the Information-Processing Center. At present 22 seismic stations have short-wave band radio stations and 14 stations have Internet access via satellite and telephone modems. Continuous records in compact disks arrive to the collection center in Irkutsk by mail.

Kamchatka regional network (international code is KRSC), which consists of stationary and radiotelemetric (local) networks (PTCC), carries out seimic monitoring in Kamchatka Peninmsula and Komandor Islands.

The network of stationary seismic stations comprises 11 stations equipped with wide-band devices with digital registration.

In Kamchatka three local networks were created that have radio telemetric system of data collection (Petropavlovskaya, Kozyrevskaya and Kliuchevskaya). They make the base for the automated regional network of Kamchatka.

Petropavlovskaya network comprises 15 stations, Kozyrevskaya network has 7 stations and Kliuchevskaya network consists of 9 stations. Three-component short-period seismometers SM3 were established in all the stations. Prompt access to current data is via the local net or the Internet. All the three local centers are connected through intercomputer channels with Information Processing Center in Petropavlovsk Kamchatskiy.

Hypocenters are continuously defined in Information Processing Center of earthquakes with M>4 from Avachinskiy Bay and of earthquakes with M>5 for the total area of Kamchatka. Hypocenter location is estimated within 15 - 0 minutes. Since 2004, earthquake parameter estimates obtained in the regional service of urgent reports have been sent by E-mail and have been available in the Internet page and as SMS communications as well. Besides, rapid seismological bulletin on Kamchatka and Comandor Islands area is issued on regular basis.

Information Processing Center provides three levels of access to observation data and data processing:

- earthquake digital records and results of cumulative processing (bulletins and catalogs) are put into a database that has a free user's access via the local computation network;
- bulletins and catalogs arrive rapidly at Web-server of the Internet global network, which makes the data available for wide seismological community;
- urgent reports on strong earthquakes in Kamchatka in close-to-real-time mode are transferred to the local administration bodies to render help to areas that suffered earthquakes.

Station "Petropavlovsk" is included in tsunami warning system (TWS) in the Far East and when a strong earthquake occurs near Kamchatka shore the station gives a warning of a possible tsunami danger.

Sakhalin regional network (international code is SKHL) conducts seismic monitoring in Sakhalin Island, Kuril Islands, Primorskiy Krai region and the Amur River region.

In the zone covered by Sakhalin regional network, 27 seismic stations operate. Eight of them are high-band with 24 bit analog-digital converters and 10 are digital short-period with 16 bit analog-digital converters (9 are of DAT type and 1 is Datamark) established according to an agreement with Japan. Nine stations have out-of-date equipment with analog registration. The network center is located in Yuzhno-Sakhalinsk.

Digital short-period stations established in the southern area of Sakhalin Island provide monitoring with M>2.0. At the rest of the island, presentation magnitude is M>3.5. In Kuril Islands, three analog stations operate, providing presentation of earthquakes with M>4.0-4.5 in this region. Stations "Yuzhno-Sakhalinsk" and "Severo-Kurilsk" participate in the work of tsunami warning service. From the results of processing data, the network issues earthquake catalog every decade (ten days) and "The Seismological Bulletin of the Far East".

North Eastern network (the international code is NERS) carries out seismic monitoring in Magadan region, Chukotka and the shelfs of the Sea of Okhotsk and the Bering Sea.

The seismic network comprises 15 digital seismic stations. The major part of the stationonly has short-wave channels with seismic meters SM-3 with frequency band of 0.5-10 Hz and 24-bit ADT. At three stations of 4 wide-band stations, seismometers STS-1 are used and at one station, seismometer KS-2000 is used. The stations of the network conduct monitoring of earthquakes starting with M=3 only on Magadan territory. For the major part of the area covered by the network, the representation magnitude makes 4.5.

The network center is in Magadan where cumulative processing of the network data is carried out and monthly catalog of earthquakes is issued.

Collection and processing of information is carried out in urgent and operational regimes. At the stations, data are recorded in hard discs and sent to Magadan. The Center communicates with stations by electronic mail and telephone channels. Earthquake data are processed with the use of DIMAS program developed in Albukerk seismological laboratory (USA).

If perceptible earthquake is recorded as well as if a local earthquake of M>4.0 occurs in the region, collection and processing of information is carried out in urgent regime. In the service of urgent reports on local events, seven stations of the network participate. Data are collected, processed and transferred to the Ministry for Emergencies headquarters and to the Information Processing Center no later than 1.5 hours after the event.

Yakut regional network (International code is YARS) carries out seismic monitoring of the Sakha Republic territory. The center of the netwirk is in Yakutsk.

The network comprises 16 continuously operating stations. All the stations have equipment with digital registration. All the stations are equipped with digital registration devices. In two stations "Yakutsk" and "Tiksi" wide-band seismometers are established by proghram IRIS; at the rest of the starions, the frequency band of registration is 0.02 – 7-10 Hz. Connection is by e-mail and through telephone channels. Stations "Yakutsk" and "Tiksi" have Internet.

Cumulative processing of data on the region earthquakes is conducted in Yakutsk by the program WSG developed in the Geophysical Survey. The results of data processing are presented in the form of annual catalog of earthquakes in Yakutia. The regional network sensitivity varies from M=2.0-2.5 in the south of the region to M=4.0-4.5 in the north.

The regional service of urgent reports on strong earthquakes is based on data of 8 stations, which send their reports to station "Yakutsk", where urgent report are formed and sent to the regional service of the Ministry for Emergencies.

Kola regional network (international code is KORS) carries out work on continuous seismic observations in the territory of Kola Peninsula, Karelia, and Spitsbergen Island.

The following seismic stations are operated in the network: seismic group APA0 (Apatity ARRAY) at 17 km from Apatity; digital three-component wide-band seismic station APA in Apatity; two digital short-period stations at Kirov mine and Rasvumchorr mine in Khibiny massif, two digital three-component seismic stations BRBA and BRBB in Spitsbergen archipelago in the area of Barentsburg town. Continuous seismic monitoring is carried out by station APA and seismic array APAO. Stations in Hibiny massif and in Spitsbergen are used to improve velocity model and to

locate most significant events within the mines. The center of the network is in Apatity. From the results of seismic data processing the network issues a monthly earthquake catalog.

Work on continuous seismic monitoring of the Caucasus region is carried out by two regional networks: the regional network of North Osetiya Republic (the international code is NORS) and Dagestan regional network (the international code is DRS).

The regional seismic network of the North Osetiya Republic started to be created in May 2003. In 2003-2005, the network of 12 digital stations was developed that is operating now. It is one of the densest seismic networks of the Geophysical Survey, which provides seismic monitoring of North Osetiya Republic beginning with M=1.0 and the accuracy of earthquake hypocenters location is approximately 3-5 km. This network data are used to study seismicity in the time-space distribution of earthquakes in relation to the search for precursors of strong earthquakes.

Data from four stations are transferred by communication channels to the information processing center in Vladikavkaz, which is connected with information processing center in Obninsk by satellite communication channel.

Dagestan regional network carries out seismic monitoring of the territory of Dagestan Republic in the eastern area of North Caucasus. The network center is in Makhachkala. The network comprises 16 seismic stations equipped with short-period channels with analog registration. Digital devices with frequency band of 0.02-20 Hz and dynamic range of registration up to 120 dB are set up at two stations. To register earthquake precursors three stations are equipped with geochemical and electrometric devices.

The seismic observation network in Dagestan Republic registers earthquakes and determines their parameters beginning with M 2.5-3.0 and more and beginning with M >1.5 for the area of water reservoirs of Sukakskiy cascade of hydroelectric power stations. Earthquakes are located with an error of the order of 20-30 km. If strong or perceptible earthquakes occur at the territory of Dagestan Republic their parameters including available macroseismic information are reported to the Ministry for Emergencies of the Republic and to the local government bodies.

In the last few years the task of studying weak seismicity of the East European platform (EEP) became pressing in the Russian observation seismology.

It is related to the growing interest in real assessments of seismic danger of the territory that has been considered aseismic for a long tome though from historical data considerably strong earthquakes occurred there with shock intensity up to 6-8. Recently significant earthquakes have occurred in Kalaningrad region, Arkhangelsk region and the land along the Volga. Largest cities of Russia (Moscow, Saint Petersburg, Nizhniy Novgorod, Volgograd and others) are situated in East European platform; several tens of million people live there; industry is developed and intense construction is going on.

In 2003-2006 the Geophysical Survey opened four stations at the territory of Arkhangelsk region, a local seismic network was set up in the area of Voronezh crystalline massif, a seismic station was established in Kaliningrad, a local seismic network in Perm Krai goes on operating and developing, a stationary seismic station was set up in the area of Orenburg in Ural.

Digital seismic stations SDAA were established everywhere. The station was developed in the Geophysical Survey RAS and scientific and industrial enterprise “GEOTEKH”. The station comprises two sets of seismic receivers (3 wide-band and three short-period); no-break power with external battery and output volage of 12 V, GPS antenna with interface cable and software to control, collect, process and archive data.

The station is operated independently, remote access is provided to data, the station may be controlled by different telecommunication channels. The dynamic range is up to 140 dB and the registration band is 0.02-30 Hz.

The package of original programs to process seismic data WSG included in the software of the station allows us to define major parameters of registered earthquakes from both data of one station and data of several ststions.

1.2. Development of seismic observation methods

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Systems of stationary seismological observations are extremely important for modern geology and geophysics. The data obtained by these systems, or by seismic networks in the XX century included the fundamental data not only on seismicity and seismic processes, but on the Earth interior structure and characteristics of its physical processes. The ideology of creation of seismic networks in the last century has been undergoing a long evolution, starting from traditional approaches, related to seismic networks consolidation, up to creation of seismic large (LASA, NORSAR) and small (NORESS, ARCESS, GERESS and others) aperture groups.

Seismic groups of small aperture, or small aperture seismic aerials (SSA), over the past 15-20 years were set up in many regions of the world. Their practical application in experimental seismology turned out to be very successful after digitizing of registration methods and seismic data collection. SSA are very effective in detection of relatively weak seismic events (earthquakes and explosions) on regional distances. The use of SSA provide an opportunity of remote control of seismic situation on spacious territories, especially in those areas, where installation of individual seismic stations on the surface or near it turn out to be inefficient due to high level of seismic noise of industrial nature. At the same time in many regions the necessity of holding systematic seismic monitoring of megapolital territories, large industrial centers, zones of location of energy sites, oil and gas pipelines and other specially important sites of industrial and energy structure of the world community is becoming essentially important.

Territory of the Russian platform within the borders of the Russian Federation remains badly investigated in seismological respect up to present time. The reason is due to low density of seismic stations location in this region. But it is the place of location of the Russia's biggest megacities, important industrial, energy objects, oil- and gas pipelines etc. The population density is this region is also very high. All abovementioned reasons induce us to describe in this report for 2003-2006 the main results of study of development of methodology of two and three-dimensional aerials.

Three-dimensional small aperture seismic aerials (TSSA). The concept of TSSA design was based on the results of research of parameters of short-period microseisms in deep (about 1 km) boreholes. These results were obtained by the scientists of the Schmidt Institute of Physics of the Earth RAS (IPE RAS) in a number of big industrial centers [1, 2]. For evaluating the possibility of developing the system of seismic monitoring of the territory of Moscow, the Schmidt Institute of Physics of the Earth RAS has studied the level, spectral distribution, coherence of short-period seismic noises on different levels in one of boreholes in Moscow at a depth of 850 m. Special borehole equipment with frequency range of 0.5 – 30.0 Hz was designed in the IPE RAS. As a result of analysis of three series of observations it was established that the mean-square amplitudes of noises by shift velocities decrease with depth by the exponential law and at a depth of 850 м are 40-50 times lower, than on the surface. Such a considerable decrease of the level of noise occurs mainly due to the relatively high spectrum components, at frequencies higher than 3–4 Hz. Exactly in this frequency range the influence of industrial noises finds its maximum. Analysis of daily variation of the level of noise on the surface and at a depth of 850 m shows, that on the surface the energy contribution of industrial noise is not less than 56%, and at the same time at a depth of 850 м this estimation reaches only 9%. Thus in the depth interval of 0 – 850 m the mean-square amplitudes of industrial noises by displacement velocities decrease more than 75 times. Based on the data comparison on spectra parameters of noises at a depth of 850 m [2] and the world data on spectra ampli-

tudes of seismic waves from micro earthquakes, summarized by K. Aki and P. Richards (1980), the possibility of registration in deep boreholes in the megacity of Moscow of micro earthquakes with magnitude M>=3.0 at epicentral distances up to 30 км. These results give ground for the possibility of setting a seismic monitoring system of the territory of Moscow and other megacities and big industrial objects on the Russian platform in deep (~1 км) boreholes, based on the observations obtained. Altogether with the abovementioned results in [1] the physical foundations of a three-dimensional grouping in seismology and the basis of technology for design of TSSA for solving a number of tasks of modern experimental seismology were developed. Noteworthy, that the results obtained can be used not only in seismological environment of the Russian platform, but for other ancient platforms with a thick sedimentary mantle.

Two-dimensional small aperture seismic aerials. The most substantial result in the domain of seismological observations methodology with application of TSSA for the period of 2003-2006, apparently, is the design and experimental study of TSSA «Mikhnevo» of the Institute of Dynamics of Geospheres RAS (IDG RAS) [3-5]. Aerial «Mikhnevo» was set in 2004 on the geodynamic training ground of IDG RAS located about 70 km to the south of Moscow. At its creation experience of long-term researches with application of small aperture groups in the Western Europe (NORESS, ARCESS, GERESS), and also experience of researches of IPE RAS and IDG RAS on the Russian platform with application of mobile seismic small aperture antennas [6, 7, etc.] was taken into consideration. At installation of aerial "Mikhnevo" the symmetric ring configuration with three concentric circles in radius of 130, 320 and 600 m was chosen. The aerial includes 12 items of registration with 10 vertical seismometers and 2 three-component installations. The central vertical seismometer is set at a depth of 20 m, all other gauges - in sealed containers at a depth of 0.5 m.

As gauges of fluctuations short-period seismometers SM-3KV, widely put into practice by the Russian experimental seismology, are used. The amplitude-frequency characteristic of the seismic channel of the aerial is uniform for displacement velocities on frequency band of 0.5 – 40.0 Hz. Frequency of interrogation of records on each channel makes 200 Hz. Registration of events is conducted in system GMT, time reference is carried out by the receiver in system GPS. The dynamic range of digital registration for seismic aerial "Mikhnevo" makes 96 dB.

For the area of antenna installation, as for many other areas of the Russian platform the presence of a thick sedimentary mantle (1.5–2.0 km) is typical. It often leads to a relatively high level of microseismic noise on the background. However, systematic spectra parameters measurements of short period microseisms during the yearly period testify to the contrary. Thus, the mean value of the level of spectra capacity of microseisms on displacements at frequency 1 Hz for aerial “Mikhnevo” reaches 2 nm^2 / Hz, concurring with the estimation for aerial GERESS and is approximately 5 times lower than for aerial NORESS. At frequency of 10 Hz the corresponding spectra density value for TSSA “Mikhnevo” reaches the value of $5x10^{-5}$ nm^2, that is comparable to evaluations of spectra capacity of noises for antennas NORESS, GERESS. Noise correlation in the aperture limits decreases to insignificant values (< 0.2) at a distance of 300 м.

All this creates relatively good opportunities for detecting on aerial “Mikhnevo” relatively weak regional seismic events. During 2.5 years of experimental works the aerial has registered a big number of regional seismic events, mostly explosions in industrial open-cast mines, and also strong earthquakes in many regions of the world.

In conclusion of this section of the report it is worth mentioning one more important achievement of the Russian seismology. The monograth by O. K. Kedrov [8] comprises an important summary on the seismic method of control of nuclear tests. During many years these methods were elaborated in Russia and abroad. Considerable attention was focused in this work on application of small aperture seismic aerials.

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1.3. Equipment for seismic observations

1.3.1. Apparatus developments of the Geophysical Survey RAS

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The Geophysical Survey RAS uses seismic station "Baikal" and wide-band digital station "Ugra" as seismic registration devices. Their brief description and technical specifications are given below.

Seismic station "Baikal" is intended for creating local observation networks, seismic monitoring with the use of explosions and vibration sources, reseach into geodynamic characteristics of engineering constructions. The station is in small-sized sealed module, which contains card of 3-channel 24-digit analog-to-digit converter with preliminary small-noise amplifiers and controller, supply source card with the line driver and optical isolation.

High-band digital seismic station "UGRA" is designed for conducting regional and teleseismic observations in stationary and mobile modes. The station was developed to replace out-of-date equipment of the observation networks of the Geophysical Survey, Russian Academy of Science. Major parameters and characteristics of the station meet all the requirements set by the Geophysical Survey RAS to registering devices to monitor seismic phenomena of the Earth.

The station provides autonomous operation as well as remote access to data and control of the station by different telecommunication channels.

Specifications of "BAIKAL" station

Characteristics	Unit	BAIKAL-10	BAIKAL +11	BAIKAL+15
Number of measured channels		8	6	3
Word length	Bit	16	20	24
Digitizing frequency	Hz	1100	400	800
Input type		Differential	Differential	Differential
Input resistance	KOhm	100	100	10
Non-linear distortion coefficient (20 Hz)	%	< 0.1	< 0.1	< 0.01
Operating band (-3 dB)	Hz	0.2 - 20	0.15 - 30	0.15 - 30
Common-mode rejection ratio	dB	>100	>100	>110
Noise referred to input (0.15 + 20 Hz)	μV(eff)	< 0.2	<0.15	< 0.08
Number of effective digits	Bit	3	3	3
Supply voltage (constant)	V	9 - 15	9 -15	9 - 15
Power consumption	Wt	< 1.5	< 0.8	< 3
Electric strength of electroplate isolation	V	1000	1000	1000

Specifications of "UGRA" seismic station

No.	Name	Characteristics
1.	Word length of A/D converter	24 bit
2.	Number of registered channels	3
3.	Input signal sampling frequency	50, 100, 200 sample/sec
8.	Operation mode	Autonomous mode and connection with external computer
10.	Removable media	Flash-card MMC of capacity up to 2 Gb, Type MMC
11.	Data transfer to remote computer	In real time
12.	Detector channel type for connection with computer	Ethernet 10 Mbit/s
14.	Mde of information recording	Continuous
15.	Type of the system for accurate timing	GPS
17.	Accuracy of timing	No worse than 10 μs
18.	Calibration	Impulse, pseudorandom binary signal
19.	Control of station settings	From registarion block and via Internet
20.	Indication in registration block	Light-emitting diode and LCD panel
21.	Operating temparature range of A/D converter block	-20^0C /$+40^0$C
22.	Type of enclosure (dust- water-tight)	IP65
23.	Power consumption	No more than 7 Wt
24.	Supply voltage	Direct current ranging from 9 to 18 V
25.	Dimensions	No more than 300x300x300 mm

Program package to process seismic data WSG included in the station software is used in seismic stations and in the information processing centers of the Geophysical Survey RAS. The package allows us to determine major parameters of earthquakes of recorded earthquakes from both data of only this station and data of other stations as well. The package has Russian interface and can be operated with OS Windows that are widely used.

1.3.2. Equipment developed by the Institute of Physics of the Earth RAS

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In 2003–2006 we did intense work on equipment to record local earthquakes, and microseism background of anthropogenic and natural origin. To carry out fieldwork a compact velocimeter and accelerometer were developed that were intended for continuous and prolonged operation in economical digital seismic stations.

Three-component small-sized velocimeter S2123A

The appearance of the velocimeter is shown in Fig. 1.1.

Fig. 1.1.

The sizes are given in the chart with specifications in the section “Exterior data”. There is one vertical seismometer and two horizontal seismometers in the case. The converter and amplifier electronics is in the same case. The case is sealed and allows operation with humidity of 100 per cent. The device is easy to set up and maintanance is simple: zero points of seismometer outputs do not need adjusting when they are set up at observation points and during observations. In this sense, the velocimeter is fully automated and it is in working order unless the tilt is more than 20 degrees.

The specifications of three-component small-sized velocimeter S2123A

General	
Cinverter type	Capacitive
Components	One vertical, two horizontal
Main output	
Conversion coefficient K_{conv}	1500
Operating frequency range (3dB)	0.5 … 70 Hz
Ratio signal max./noise eff.	102 dB
Transversal sencitivity, no more than	1%
Low-frequency filter discrimination	80 dB/decade
Control	
Zero-point adjustment	not required
Calibration	External
Power	
Voltage Upower, nom.	±12 V ±10%
Consumption current	25 mA (arm)
Exterior data	
Length	140 mm
Width	140 mm
Height	80
Weight	2.5 kg
Operating conditions	
Temparature range	–20 ^{O}C … +45 ^{O}C
Water proofness	DIN IP66

Amplitude-frequency type characteristic is given in Fig. 1.2.

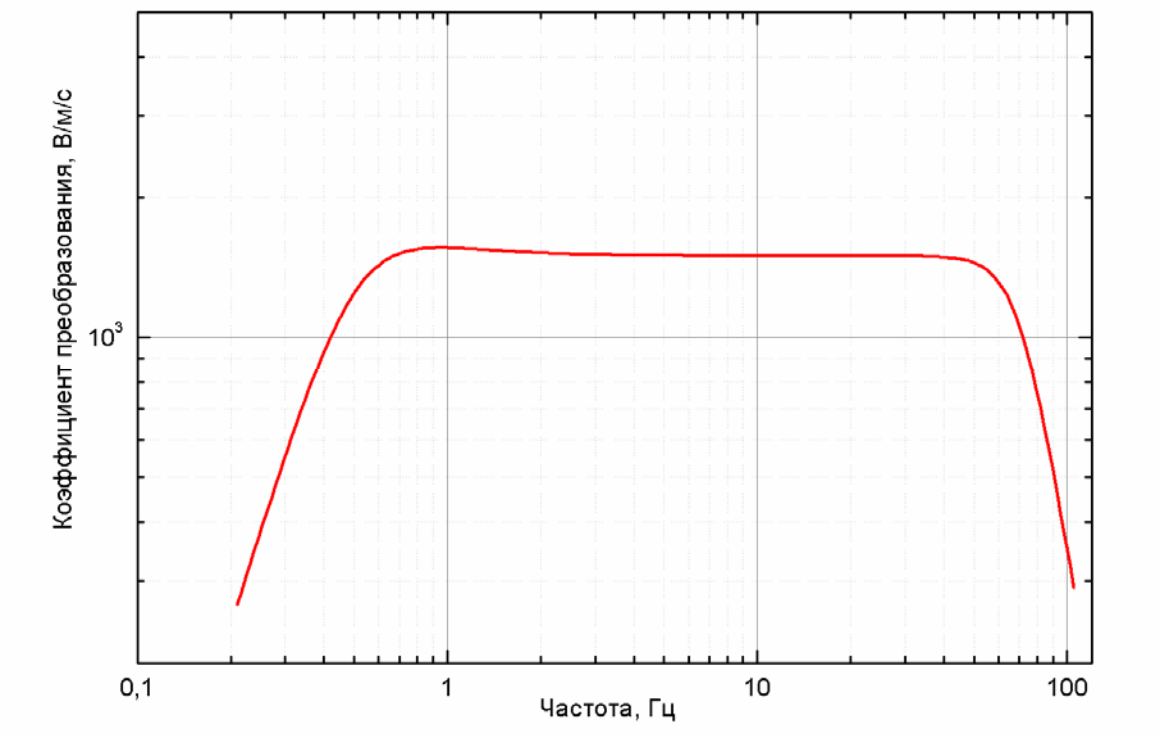

Fig. 1.2. The amplitude-frequency characteristic of velocimeter.

The total amount of velocimeters made in laboratory is more than half a hundred. All these devices are used in field and industrial observations to monitor seismic conditions in various objects.

Three-component accelerometer S1073

The general apearance is given in Fig. 1.3.

Fig. 1.3.

The sizes are given in the Specifications in the section "Exterior data" There are three orthogonal piezoconverters with one common inertial mass in the case. The converter electronics is in the same case. The case is sealed and allows operation with humidity of 100 per cent. The device is easy to set up and maintanance is simple: zero points of accelerometer outputs do not need adjusting when setting up at observation points and during observations. In this sense, the accelerometer is fully automated and it is in working order in any position of the device.

Specifications of three-component accelerometer S1073

General	
Converter type	Piezoelectric
Components	Three symmetric
Main output	
Conversion coefficient K_{conv}	0.4
Operating frequency range (3dB)	0.2 – 1000 Hz
Ratio signal max/ noise eff.	102 dB
Transversal sensitivity no more than	5%
Control	
Adjustment of zero-point	Not required
Calibration	External
Servicability in the range of Upower	±2 ... ±16 V
Consumption current	8 mA
Exterior data	
Diameter	85 mm
Height	150 mm
Weight	2.1 kg
Operational conditions	
Temperature of the environment	-20°C ... +40°C
Water proofness	DIN IP66

Amplitude-frequency type characteristic is given in Fig. 1.4.

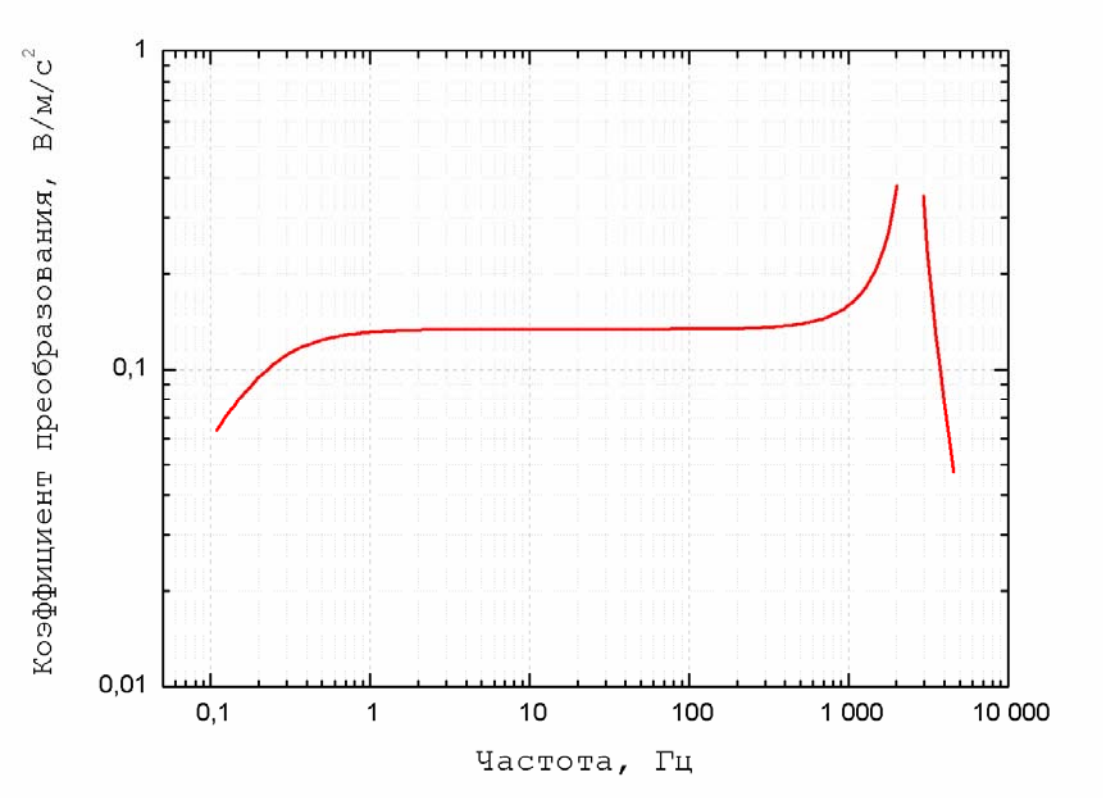

Fig. 1.4. Frequency range is practically linear from 0.5 to 1000 Hz at the level of 3 dB.

2. The strongest earthquakes in the territory of Russia in 2003-2006

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In the period covered by this report several large earthquakes occurred at the territory of Russia. Fortunately earthquakes were located in thinly populated areas and did not lead to human life loss. In Fig. 2.1, a map of earthquakes in Russia and abutting areas is given, in which stars show the most important earthquakes with M≥6.0 that occurred from 2003 to 2006 and are briefly discussed in this section. Note that we define the degree of earthquake significance not only from its magnitude but from the area of occurrence, degree of unexpectedness, social significance and other features as well. Therefore relatively small Kaliningrad earthquake of 2004 is represented there as well.

In the period from 2003 to 2006 earthquakes of the highest magnitude occurred in the Far East of Russia. However Altai (Chuiskoe) earthquake in the central area had a high magnitude, was of considerable interest and was studies to a greater detail.

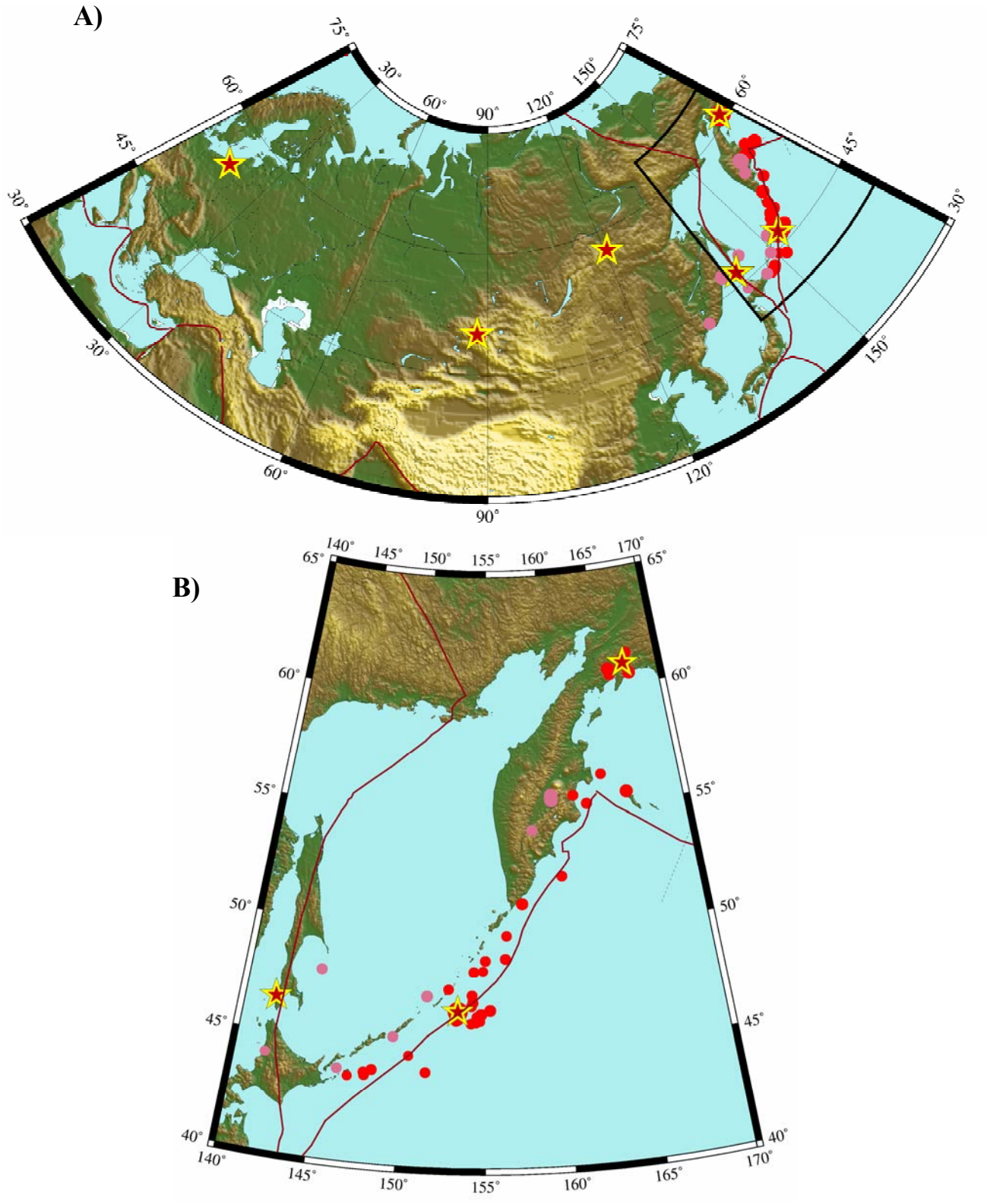
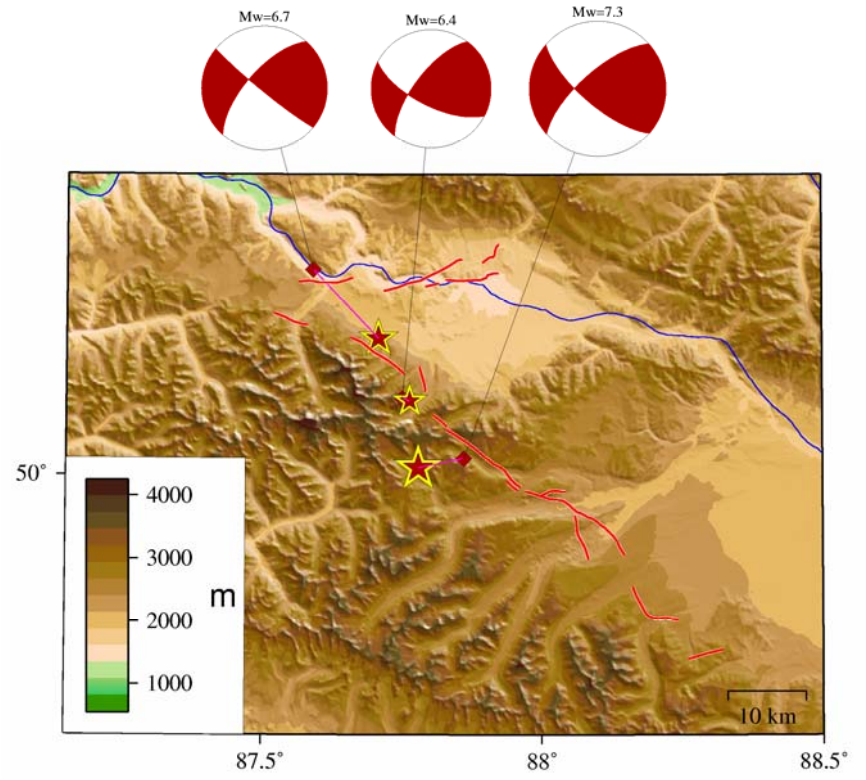


Fig. 2.1. Earthquakes with M≥6.0 (circles) and earthquakes studied to a greater detail (stars). Light violet circles indicate earthquakes of the depth of more than 80 km. A) – the whole territory, B) – inset map for the Far East.

Gornyi Altai (Mountain area of Altai)

A)



B)

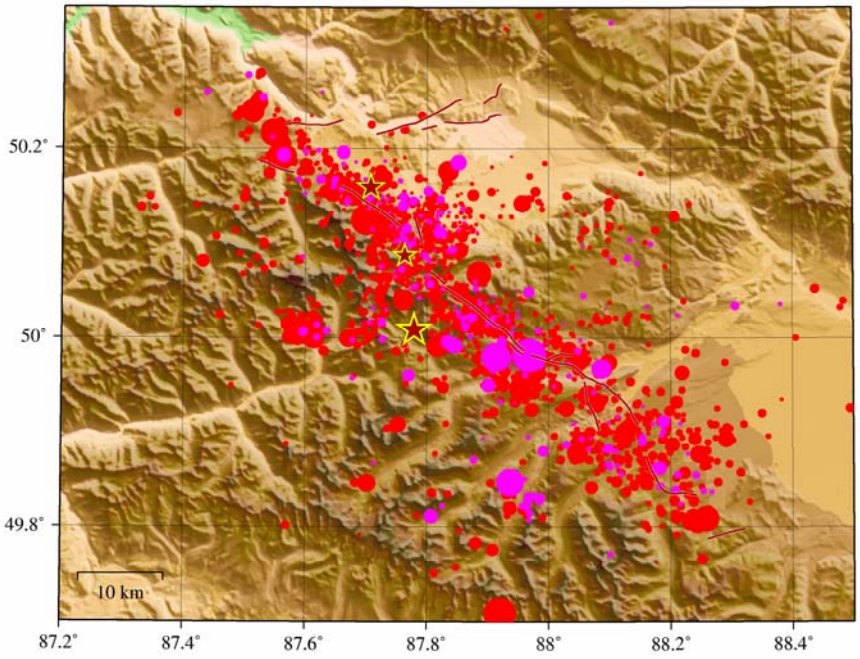


Fig. 2.2. Altai (Chuiskoe) earthquake. A) – the main shock and strongest aftershocks (small rhomb indicates the position of the moment tensor centroid, lines show the rupture exposure on the surface), B) – a map of aftershock epicenters in the field season of 2004 (red circles) and of 2005 (violet circles) from data of the Institute of the Physics of the Earth RAS.

Altai (Chuiskoe) earthquake occurred on 27 September 2003. It was the strongest earthquake recorded with the use of equipment in Gornyi Altai. From the Geophysical Survey RAS data the earthquake had magnitude M_S=7.3, from Harvard data it was M_W=7.3. The area of focal zone is thinly populated. Owing to this fact and by a happy chance the earthquake did not cause the loss of human lives, though there were injured people and many buildings were severely damaged.

The earthquake epicenter zone belongs to the vast Altai-Saiany region. The general zoning map was correct in this case. In spite of lacking instrumental and historical data on paleo seismological results the seismic hazard was adequately assessed. In this connection, the Geophysical Survey of the Siberian Branch, RAS is constantly improving the seismic network and approximately two years before the earthquake seismologists from Novosibirsk organized observations with the use of modern digital equipment in the immediate vicinity of the source of earthquake of 2003. Besides, the network continued observations after the earthquake, monitoring not only the epicenter zone but the abutting area as well.

The focal area of the earthquake is located in the vicinity of the frontiers of Russia, Mongolia, and China, therefore research teams from different organizations and countries carried out field research on the earthquake. In the first place, they are teams from Novosibirsk (The Geophysical Survey of Siberian Branch RAS, Institute of Geology of Siberian Branch RAS), Moscow (Schmidt Institute of the Physics of the Earth, RAS), and Irkutsk (Institute of the Earth's Crust, Siberian Branch, RAS). Mongolian seismologists with support of their French colleagues organized a temporary station network in their territory to study aftershocks of Altai (Chuiskoe) earthquake.

The Institute of Physics of the Earth organized a trip of a team of geologists who investigated surface dislocations immediately related to the processes in the earthquake source. Geologists mapped a 20-kilometer area of a rupture near the village of Beltir, which was badly damaged. Subsequent work of this team in 2004 revealed that the general length of the rupture exposure on the surface in the earthquake source was approximately 65 kilometers. Fieldwork conducted in 2005 allowed us to define more accurately the rupture exposure and to reveal the northeastern area (Fig. 2.2).

The Institute of the Physics of the Earth conducted instrumental observations in the summer of 2004 and 2005. Accurate locating of aftershocks showed that their position in space is in good agreement with the main rupture exposure on the day surface. However northeastern branch practically is not traced with aftershocks. From data on aftershocks the earthquake source had the following dimensions: length 75 km, maximum width 20 km, vertical extent 17 km and the average shift on the rupture in the source was 2.5 km. In the cloud of repeated shocks, clusters are distinguished that have different directions of the dip plane. The clusters are interpreted as different segments of the rupture combined surface in the Altai earthquake source.

Kaliningrad region

Kaliningrad earthquake was a completely unexpected seismic event. Though the magnitude was not high it caused a noticeable macroseismic effect. In this case the general seismic zoning map did not consider this area as seismically dangerous. The earthquake occurred on 21 September 2004 and had two shocks instrumentally registered (Fig. 2.3). Surface effect of the first shock was 5-6 and seismic effect of the second shock was 6 by MSK-64.

In Kaliningrad, all the residents felt shakings especially in old houses and shakings were perceived on the top floors in new houses. Rocking of walls was noted, furniture, things and appliances fell down, in some houses plaster fell down, fissures appeared, and flue system was damaged in some cases. From mayor's data, approximately one thousand of buildings were damaged to some extent.

Immediately after the earthquake, the Institute of Physics of the Earth organized macroseismic survey and in the summer of 2005 it carried out the first seismological observations with the network of three seismic stations. Unfortunately they failed to register the earthquake aftershocks

owing to high microseismic noise and correspondingly to the lack of considerably strong seismic events.

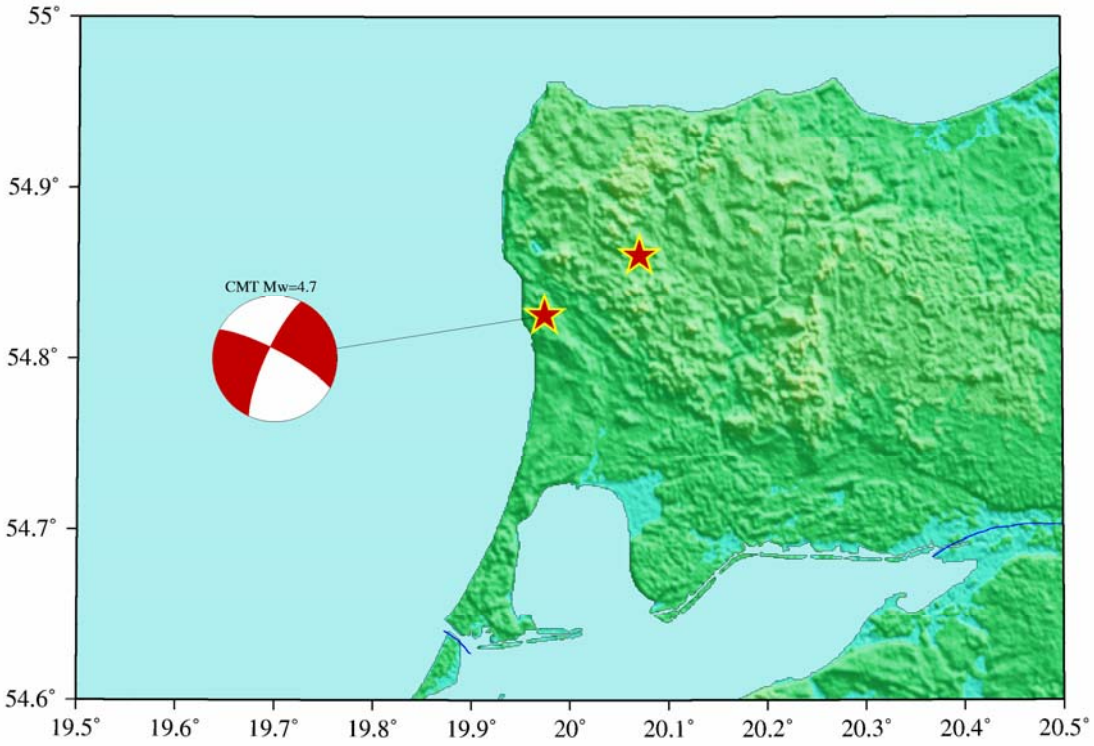


Fig. 2.3. Earthquakes of 2004 in Kaliningrad region

The results of research allow us to conclude that the territory of Kaliningrad Region is not aseismic and thus a system of seismic monitoring, which the region did not set up before, should be established and maintained. The level of microseismic noise in the territory of the peninsular is very high, which hinders effective seismological observations. The possibility of using borehole seismic receivers should be considered. To adequately consider seismic danger we recommend carrying out combined work on detailed seismic zoning of the region.

Olyutorskii area

The earthquake occurred on 20 April 2004 in Olyutorskii area of Koriak autonomous district of Kamchatka region, magnitude M_W =7.6. The area of maximum shakings belongs to zone 8 by the General Seismic Zoning Map-97 A and B.

The epicenter zone of earthquake 2006, which considerably coincides with the epicenter area of Khailinskiy (Koriak) earthquake of 1991, was located between two large ranges of Koriak highland (Fig. 2.4).

The mechanism of the source is almost pure upthrust (Fig. 2.4). The both nodal planes have northeastern strike coinciding with the direction of Kuril-Kamchatka arc and the strike of Koriak highland ranges. From NEIC data, the spatial distribution of aftershocks shows two directions of orientation perpendicular to each other (Fig. 2.4).

Immediately after the earthquake, IPE RAS organized a trip of geologists specialized in seismic tectonics to the epicenter area and the Kamchtka branch of the Geophysical Survey set up several temporary seismic stations. Seismological data are still being processed. From geological results, the seismic source exposure on the surface was revealed and mapped as an echelon-like system of seismic ruptures of the overall length of approximately 140 km and of general northeastern extension. From the kinematics of dislocations the rupture may be divided into two segments. Southwestern segment located to the southeast of Khailino practically is a pure right-lateral fault.

The northeastern segment is an upthrust fault with vertical displacement amplitude up to 3.0 m and horizontal right-lateral shift amplitude of approximately 1 m. The seismic rupture at considerable lengths in the northeastern segment has near-meridian extension.

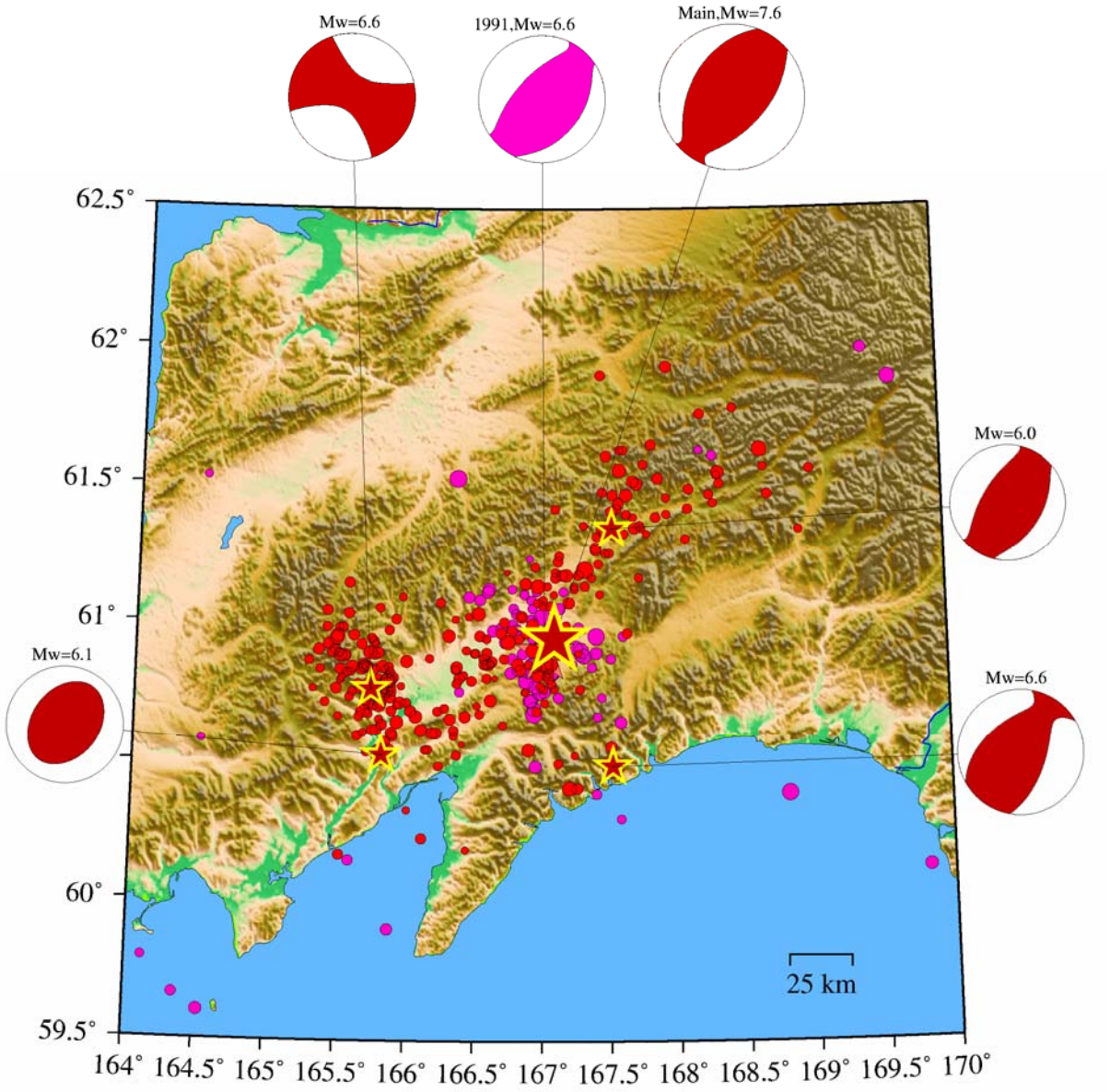


Fig. 2.4. The main shock and the strongest aftershocks of Oliutorskii earthquake (stars). The rest of the aftershocks of 2006 are shown with red circles, shocks of 1991 are shown in violet color.

The system of primary and secondary seismic dislocations generally encompasses an area, which is oval in plan, has a length of 180 km and a width of 60 km with the long axis oriented from southwest to northwest. Macroseismic effect is assessed as 9-10 by INQUA scale in the epicenter area, which exceeds the assessments by General Seismic Zoning 97.

Olekminsk, Transbaikal region

The earthquake occurred on 10 November 2005 and was felt at a large territory. The earthquake magnitude is from Mw=5.8 to MLPL=6.4 by different assessments. The focal area of the earthquake is shown in Fig. 2.5. The mechanism is established from Harvard data, aftershocks are taken from the regional catalog data (Baikal and Yakut branches of the Geophysical Survey RAS).

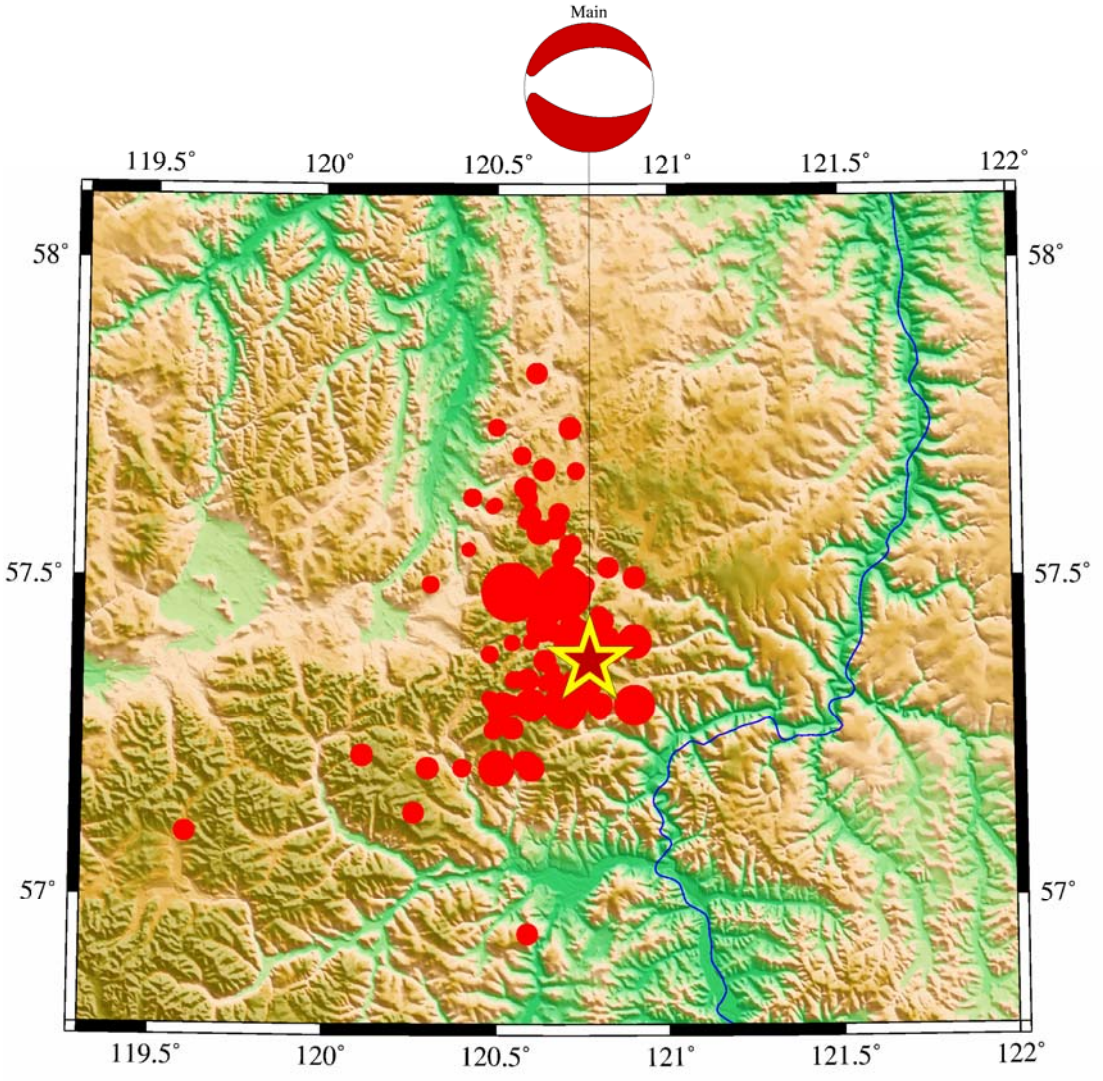


Fig. 2.5. Focal area of Olekminsk earthquake

The maximum macroseismic effect observed is 6. In Khani, the earthquake was accompanied with a boom. Yakutian Branch of the Geophysical Survey RAS carried out nacroseismic survey and set up a new seismic station in Khani.

Simushirskoe earthquake

The earthquake occurred on 15 November 2006. Its magnitude was Mw =8.3, and it was the strongest seismic event in the world in 2006. Specialized research in the focal zone of the earthquake was not conducted owing to its position (See Fig. 2.6). The earthquake is of great significance, because it occurred in the northern Kuril arc, where earthquakes of magnitude greater than 8.0 had not been registered before (See Fig. 2.7) and a strong earthquake has been expected for a long time in the context of the seismic cycle theory.

South of Sakhalin

The earthquake occurred on 17 August 2006. Its magnitude was Mw=5.8, the earthquake was felt in many points of the south of Sakhalin. From Harvard CMT data, the mechanism of the source is upthrust (Fig. 2.8). Local seismologists conducted the survey. Now the data are being processed.

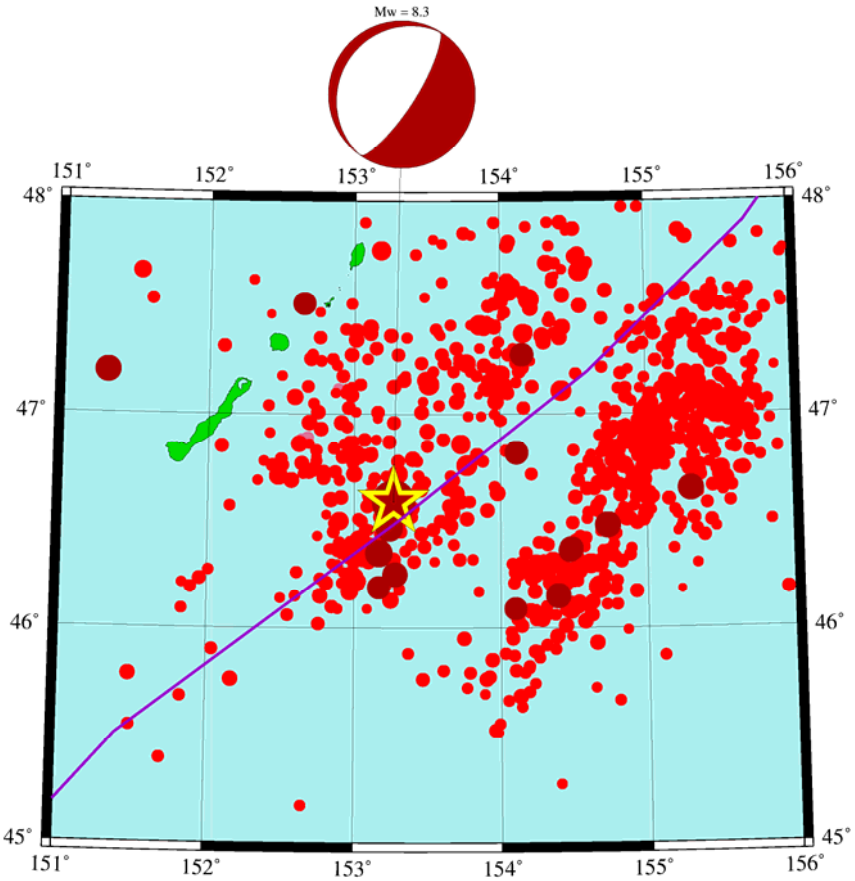


Fig. 2.6. Main shock (star) and aftershocks of Simushirskoe earthquake. Dark circles indicate shocks of M≥6.0.

We used data of the Geophysical Survey RAS and NEIC to prepare this section, moment magnitude was determined from the results of Harvard CMT decisions.

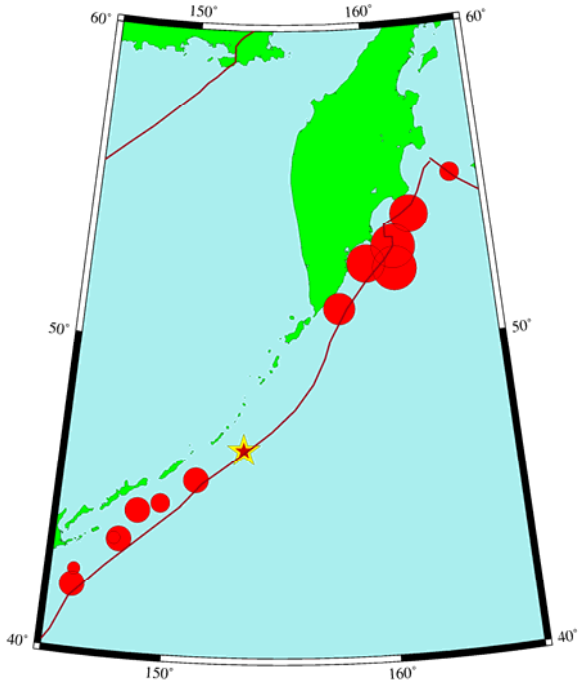


Fig.2.7. Earthquakes with magnitude M>8.0 on Kuril-Kamchatka arch.

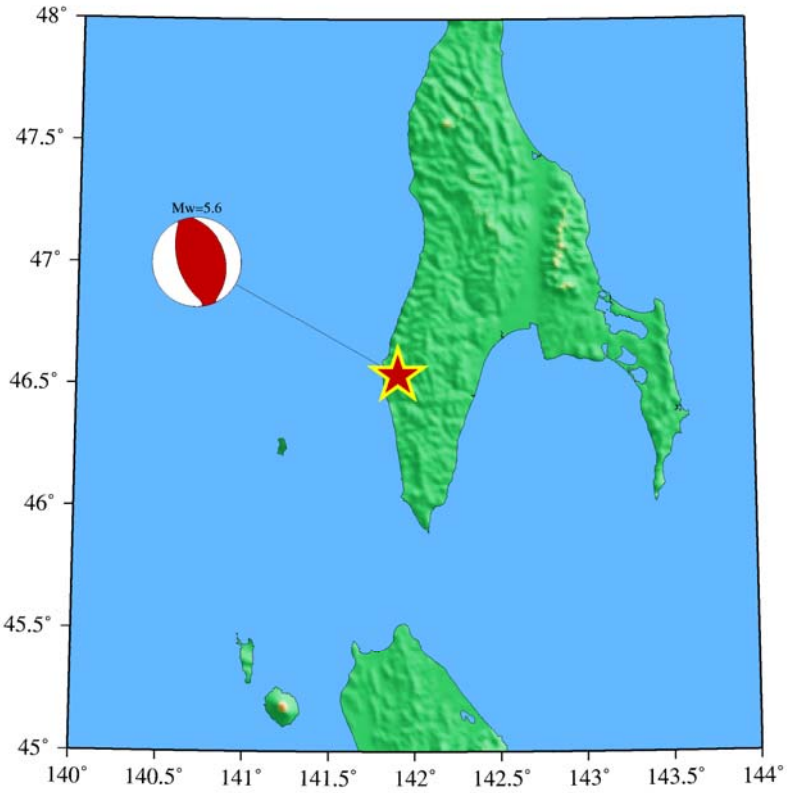


Fig. 2.8. Location and mechanism of the source of earthquake of 17 August, 2006

3. Seismotectonics of the zones of the strongest earthquakes in Russia in 2003-2006

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Introduction

Information on the results of seismic tectonic studies of the strongest earthquakes in Russia in 2003-2006 is given in the context of the achievements in this field of science in the world. It is the practice to investigate earthquake focal areas by several major directions. Epicentral field seismic tectonic observations in the focal area give information on seismic dislocations and tectonic position of the source. From the collected data the seismic source model is constructed which includes a reconstruction of the major movement planes, the amplitude and directions of impulse dislocations. The position and structure of the earthquake-generating zone is elucidated. In the report, the results are summed up of the combined studies of the zones of Altai earthquake (2003) and Oliutorskoye earthquake (2006, Kamchatka), which were the strongest earthquakes that occurred in different seismic tectonic conditions and geodynamic settings in the territory of the Russian Federation. This work allowed us to collect information on the tectonic position, geological, seismological and locally geodetic manifestations and to work out models of the seismic source for each event.

Seismotectonic research in the zone of Altai earthquake of 27 September 2003 in Gornyi Alyai

On 27 September 2003 in Altai a strong earthquake occurred that had magnitude M=7.3, intensity of 9 in the epicenter; the earthquake was felt in populated localities of the upland area of Altai with intensity of up to 6-7. The seismic shock did not result in considerable destruction or hu-

man life loss. Numerous aftershocks accompanied the earthquake. The strongest of them was only a little weaker than the main shock (M=7.0) and occurred three days later than the main shock. The Institute of the Physics of the Earth sent a team of specialists in seimotectonics who managed to reveal and map major seismic dislocations in October-November 2003 before winter and to establish the geological structure responsible for the earthquake generation [Rogozhin et al., 2004]. The work was continued in the summer of 2004 and 2005.

In 2004 and 2005 in the near zone of the earthquake, the telemetric network of seismic stations of IPE RAS was operated during summer months, which registered several thousands of seismic shocks weak and of moderate strength [Arefiev et al., 2004, 2006].

Knowledge on the structure of the source, its parameters (magnitude, seismic moment, focal mechanism, frequency characteristics of the main shock) as well as on the most intense aftershocks were obtained on the basis of prompt analysis of teleseismic data collected by the world seismological network, Russian national network and seismograph networks of some other countries [Starovoit et al., 2004].

Though the Altai earthquake occurred all of a sudden, it was predicted on the long-term basis [Reisner, 2004]. Combined seismotectonic research conducted in Gornyi Altai area in 1995-1998 involving extraregional seismic potential assessment method and paleo seismogeologic method (trenching) allowed us to establish that the south of Altai has a high seismic potential (Mmax = 7.5-8.0). Besides, it was revealed that earthquakes of magnitude of the order of 7.5 and higher had occurred in Chuisko-Kuraiskaya seismogenic zone in the Holocene [Rogozhin, Platonova, 2002]. Recurrency period was defined of these strongest seismic events of the past. Earthquake of September 27, 2003 showed that the assessments of seismic hazard of the region were correct. As a result these values of Mmax were accepted for Altai territory to compile a new map of the general seismic zoning of Russia (GSZ-97).

On the basis of epicenter research, data were collected that characterize different aspects of the earthquake source. These data were published as a collection of papers [Strong …, 2004] and in a number of papers [Arefiev et al., 2006; Rogozhin et al., 2007; Tatevosyan et al., 2006].

From teleseismic data obtained, the source is crustal and occurs in the upper and middle parts of the Earth's crust. According to data on the depths of aftershock hypocenters it was not deeper than at 17-18 km and reached the surface (Fig. 3.1). It is evident from seismotectonic data that the source was exposed on the surface as a linear system of seismic ruptures of the overall length of approximately 60 km. The length of the densest part of the aftershock epicenters field, which is oval in plan, is of the order of 100 km and its width is approximately 20 km. Such characteristics are typical of earthquake source of magnitude 7.3 [Wells, Coppersmith, 1994].

From the focal mechanism characteristics, configuration of isoseisms of 8 and 7 [Goldin et al., 2004] and seismic rupture zone kinematics on the surface, the movement in the source was on practically vertical plane of northwestern or west-northwestern orientation and took the form of a right-lateral fault. (Fig. 3.2). The amplitude of seimogenic displacement reached 2 m. The earthquake comparatively modest macroseismic effect and moderate gravitational seismic dislocations related to it are apparently associated with low-frequency spectrum of the main shock seismic oscillations and a thick layer of permanent frost in the near-surface part of young sediment section.

In the northern part of the focal area, one more seismic rupture was formed, which frames the Central Kuraiskaya anticlinal ridge in the south and crosses it diagonally in one location (Fig. 3.3). The rupture is not connected with the main zone of the seismogenic rupture; it has near latitudinal and locally northeastern orientation, its length is approximately 20 km and it shows upthrust morphological kinematics. The formation of this system of initial seismic dislocations may have been caused by a very strong aftershock of 1 October 2003, which had magnitude of 7.0.

Geodetic observations carried out by V.Yu. Timofeev [Timofeev et al, 2005] in the stationary GPS network of Gornyi Altai before and after the event of 27 September 2003 showed that the vast area of South Altai underwent irreversible horizontal movements. Displacements of amplitude of 15-30 cm were registered at a distance of approximately 50 km from the earthquake source. In this case, the surface to the northeast of the earthquake focal zone moved southeastwards or south-

wards and the block to the south of the focal zone moved to north-northwest. Generally it is in good agreement with deformations observed in the zone of main seismic rupture.

Fig. 3.1. Seismic rupture of Altrai earthquake (Photo by A. R. Geodakov)

Fig. 3.2. Right-lateral fault on the seismic rupture of Altai earthquake (Photo by A. N. Ovsyuchenko)

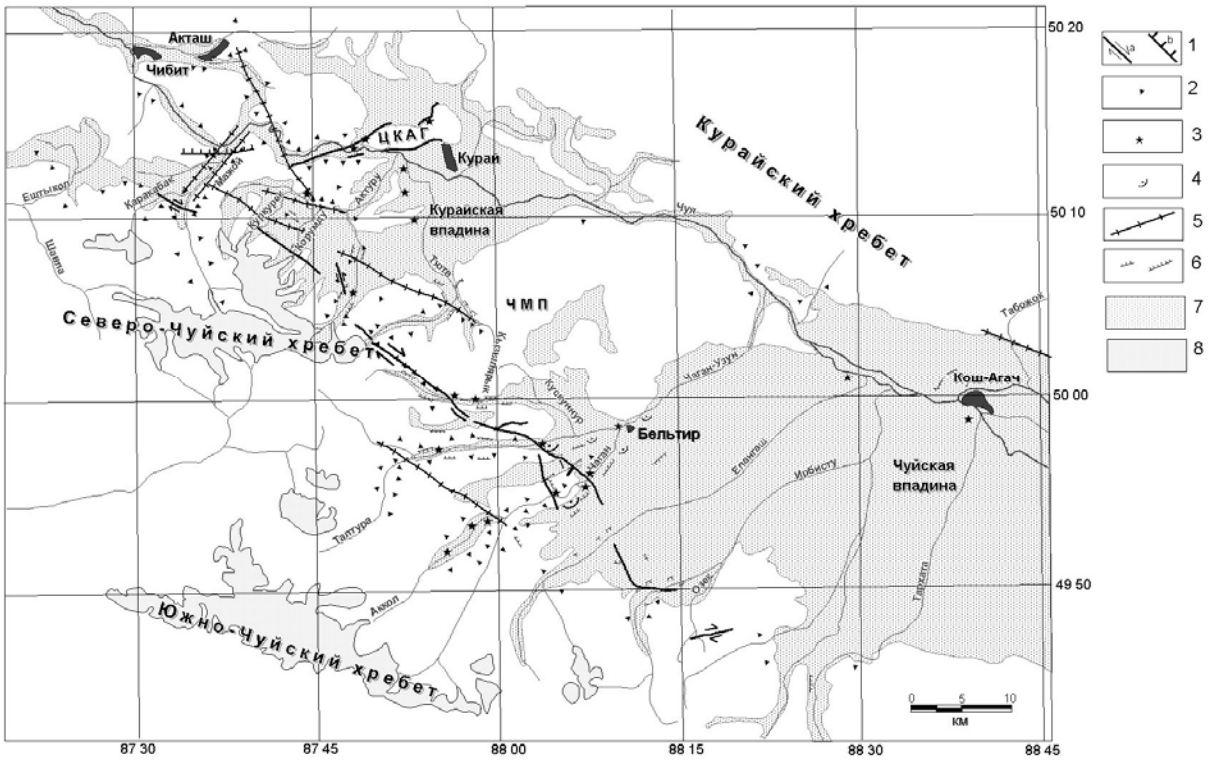

Fig. 3.3. The map of distribution of seismic dislocations [Rogozhin et al., 2004]
1 – seismic tectonic ruptures (*a* – right-lateral faults, b – faults); *2* – landfalls; *3* – soil liquefaction; *4* – landslides; *5* – seismic gravitational fissures of separation and slope settling; *6* – fissures of slope settling; *7* – faults rejuvenated in the process of resonance oscillations; *8* – Quaternary lake, river and glacial deposits *9* – largest modern glaciers. TsKAG – Central Kuraiskaya anticline ridge, ChMP – Chagan-Uzunskaya interbasin bridge.

Besides the main rupture, some less extended feathering disjunctive dislocations were formed on the surface, which were of reverse fault and fault displacement type with much more moderate amplitudes of seismogenic displacements.

From data on morphology and on distribution and size of secondary seismic gravitational and vibration deformations (landslides, landfalls, gryphons), the earthquake manifested itself in pleistoseist area with intensity of 9-10; horizontal and vertical accelerations may have reached the value of 1g [Rogozhin et al., 2004, 2007; Tatevosyan et al., 2006].

In the focal zone of the earthquake of 2003, numerous traces were found of strong earthquakes that had occurred before. According to radiocarbon dating of their formation time, primary and secondary paleo seismic dislocations testify to the effect that prehistoric earthquakes with magnitudes in the range from 7.0 to 8.0 occurred in the same source approximately 230-300, 1100, 1900-2000, 2500, 3200, 4000, 4600 and 7800-8000 years ago. Thus recurrence period makes 500-900 years. A long time-interval between seismic events that occurred 4600 and 7800-8000 years ago may be explained by incomplete knowledge on the ancient earthquakes of the first half of the Holocene.

Since the active fault that generated Altai earthquake of 2003 accumulates on the north a system of earthquake-generating faults of Northwest China and West Mongolia (Fig. 3.4) and has northwestern extension and for the major part right-lateral kinematics, it may be considered as typical of the whole Altai seismotectonic province. In this context, Gornyi Altai can be considered as a northern continuation of Mongol Altai and Gobi Altai where repeated earthquakes occurred with magnitude of 7 and higher [Earthquakes…, 1985] and thus all mountain systems of Bolshoi Altai can be united into one seismotectonic area with high estimates of expected earthquake magnitudes.

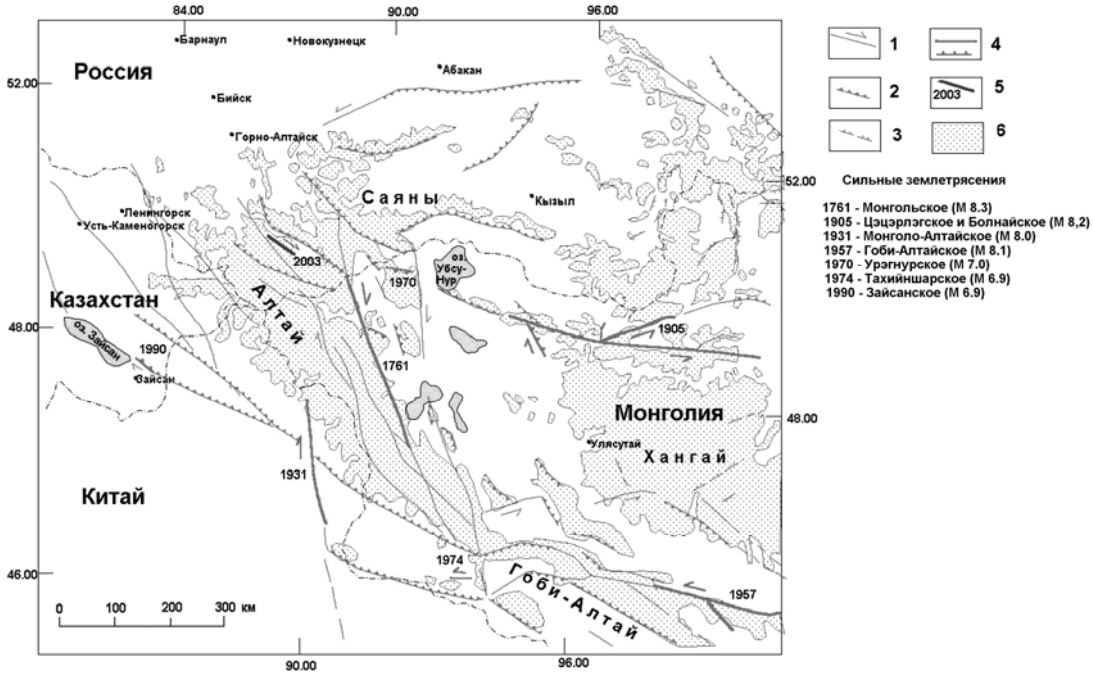

Fig. 3.4. The map of seismotectonics of Mongolia – Siberia region. The map was compiled with the use of data [Rogozhin et al., 2004]. 1-shifts; 2-reversed faults; 3-faults; 4-areas of seismogenic rejuvenation; 5-seismic rupture of earthquake of 27 September 2003; 6-rises higher than 2000 m.

Olyutorskoye earthquake in Koryakia (Kamchatka peninsula) of 20 (21) April 2006

On 20 April 2006 at 23.25 by Greenwich time or on 21 April at 12.25 by local time, a strong earthquake of magnitude Ms=7.8 (Mw=7.6) occurred at the territory of Olyutorskiy area of Koryak autonomous district (Kamchatka region). The epicenter area was located on the ridges of Koryak highland to the north of Goven Peninsula. The earthquake was the strongest event in the whole history of observations carried on in the territory of Koryak autonomous district and thus it attracted particular attention. It should be noted that strong Khailinskoe earthquake of magnitude 7.0 had occurred in the same source in 1991 [Lander et al., 1994].

The survey of the focal zone in populated localities Tilichiki, Korf and Khailino, which were in the focal area, allowed us to reveal and to document the system of the earthquake seismodislocations [Rogozhin et al., 2007]. A provisional network of seismic stations set up in the epicenter area registered repeated shocks. In the field research of 2006, initial and secondary seismic dislocations generated by a strong seismic event were revealed and mapped. Seismic source was exposed on the surface as an extended system of initial seismotectonic fissures (seismic rupture) of a length of approximately 140 km.

The detailed mapping of the source exposure allows us to outline three major areas of the seismic rupture that differ in the internal structure, morphotectonic position and displacement kinematics: southwestern, central and northeastern (Fig. 3.5).

The southwestern end of seismotectonic dislocation zone is an isolated rupture of a length of approximately 16 km with left-lateral shift kinematics. The shift amplitude measured from the displacement of torn out roots of cedar dwarf trees makes 1.3-1.8 m.

To the northeast of this area the seismic rupture is an echelon system of individual shift segments. All the segments show right-lateral shift kinematics and east-northeast orientation. Such a structure is typical of the seismotectonic rupture in its central area. The shift amplitude measured from the torn out road is 2.0 m (Fig. 3.6). Tension fractures of a length up to 50 m and width of 2 m play the major role in the segment structure; they are conjugated by swells of a height up to 1.5 m.

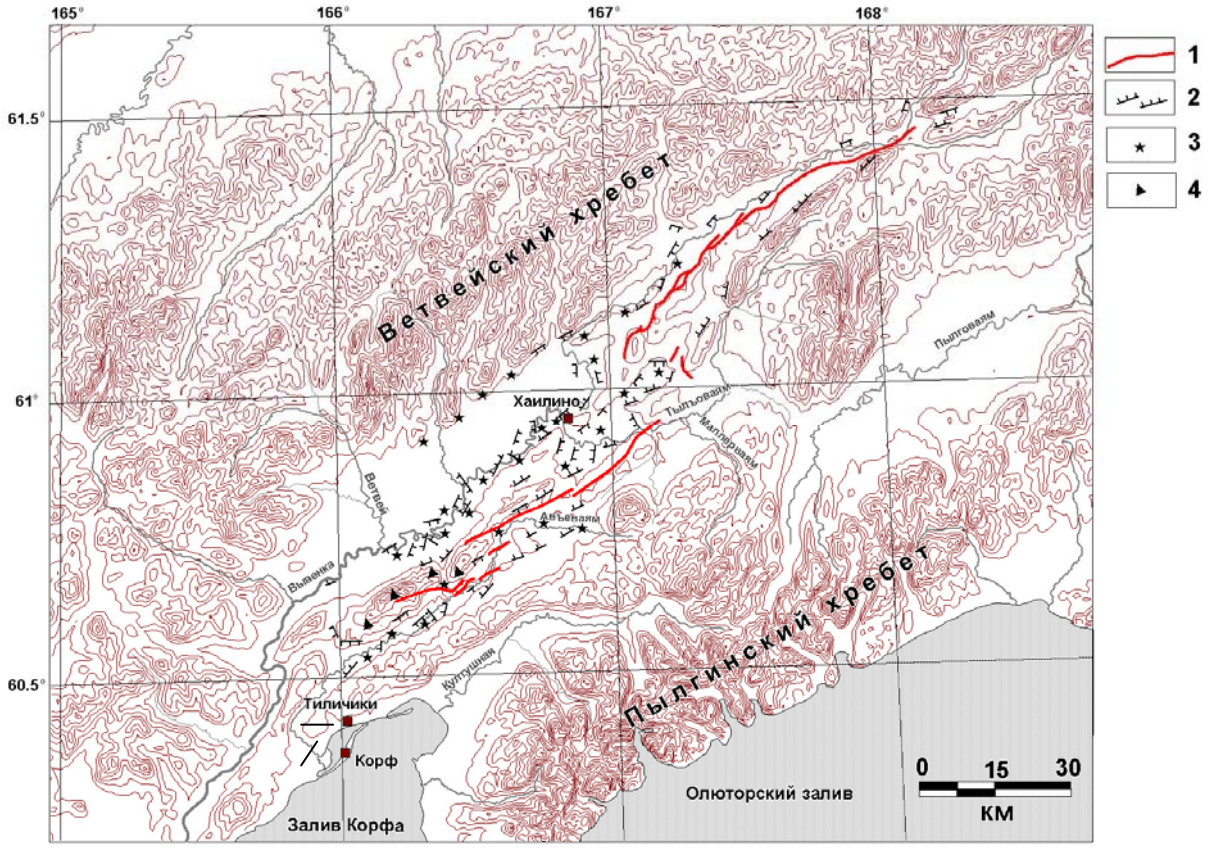

Fig. 3.5. The map of seismic dislocations of Olyutorskiy earthquake. Symbols: 1-seismic rupture route; 2-seismogravitation and vibration manifestations; 3-locations of abundant outbursts and flows of liquefaction ground; 4-large seismogravitational structures (landslides and landfalls). The relief contours drawn at 100 m.

The northeastern segment of the source exposure starts at the foot of a not very high mountain mass with peak Koldun and extends northeastwards along the left bank of the Vyvenki river valley. The segment length is approximately 75 km. The amplitude of right-lateral shift measured from deformations of water flow beds does not exceed 1-1.5 m. Upthrust-overthrust component prevails, which is especially pronounced at the sections where the seismic rupture has meridian or northeastern extension. The rupture branches off into branches that predominantly show either fault kinematics or upthrust-overthrust kinematics. However either upthrusts or anticline arches prevailing over tension structures (trenches) are characteristic of all the branches. The width of trenches is not more than 1 m. The amplitude of vertical displacement reaches 2 m.

Paleo seismogeological and morphotectonic observations allow us to state that the seismic rupture formation in 2006 is not coincidental but it is a link in the long seismic history of the source zone that generated strong seismic events before. Their traces are fixed in numerous deformed landforms and various seismotectonic ancient structures. It is frequently the case that such structures are found in sections opened by modern seismic dislocations or swells (Fig. 3.7).

In the earthquake epicenter area secondary seismic dislocations are abundant. Major dislocations of this type are structures of ground liquefaction: fissure eruptions of water-sand and water-gravel mixtures and gryphons. Large areas in the River Vyverka valley and in the shore area of Korf Bay have vibration fissures. Gravitation manifestations are not so abundant. Landfalls and landslides are noted on steep southeastern slopes of Ostantsovyi Ridge and Yakhtynyn M. in the initial rupture survey area. Generally the area covered by secondary dislocations is oval. The longer axis is extended northeastwards and its length is of the order of 160 km. The width is 50-60 km (Fig. 3.5).

Fig. 3.6. Displacement of four-wheel drive vehicle road with a right-lateral rupture. Displacement amplitude is approximately 2.0 m (Photo by A. N. Ovsyuchenko).

Fig. 3.7. Seismic trench and a bulging swell in the route of left-lateral rupture (Photo A.N. Ovsyuchenko)

Of the geodynamic models proposed earlier, the source structure is most consistent with the concept of [Mackey et al, 1997]. The extended zone of faults controlling crustal seismicity in Kamchatka can be traced as a system of active faults along Vostochnyi Range. To the northeast it runs as far as peninsula Ozernoy and Karaginskiy Bay. Epicenters of many small-focus crustal earthquakes of East Kamchatka are centered there (Fig. 3.8).

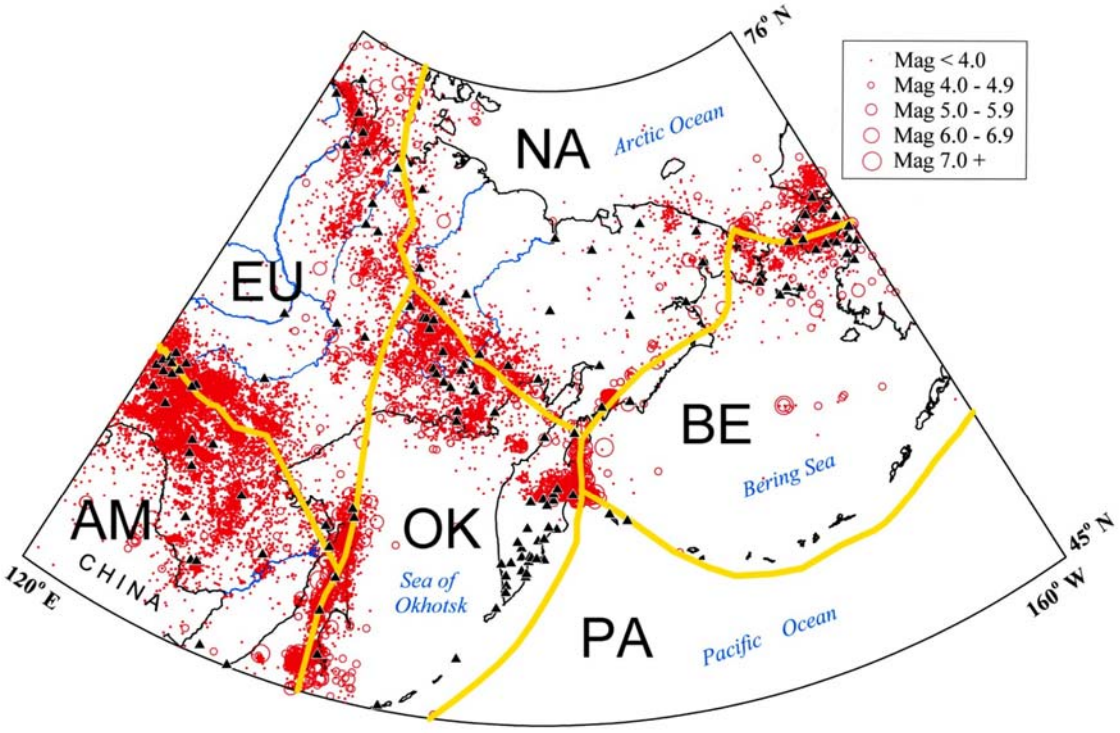

Fig. 3.8. The map of lithosphere plates margins and earthquake epicenters of the eastern Asia and northern Pacific [Gordeev et al., 2004] with epicenters of earthquakes of different magnitude values.

Significant right-lateral shift component with seismogenic displacement on seismic fault of Olyutorskiy shock gives grounds to join the both fault zones by “extending” them underwater to Litke Strait. This fault zone is so large and significant that it can be considered as northwestern margin of the Bering Sea micro plate as A.V. Lander and co-authors proposed [1994]. Vyvenksko-Vetveyskaya fault zone evidently extends underwater across Kichiginskiy bay and Litke strait to eastern Kamchatka almost to Kamchatskiy cape latitude where “Beringia”ends. Thus the marginal nature of the earthquake- generation structure between two lithospheric plates (the Bering Sea and North American) that generated Olyutorskoye earthquake seems to be realistic [Mackey et al, 1997].

Similarity of the focal mechanisms for the main shock of earthquake in 2006, Khailinskiy earthquake in 1991 and Ozernovskiy seismic event in 1969 (Fig. 22) allows us to combine all these strong seismic manifestations of East Kamchatka in a single earthquake-generating province.

Conclusion

Strong earthquakes in Altai and Koryakia are remarkable for the fact that their sources were exposed on the surface as echelon systems of seismic ruptures of the overall length of the order of 60 km and 140 km respectively. Values of vertical and horizontal displacements of the surface were revealed in the zones of seismic ruptures. In different sectors, primary dislocations of the type of upthrust, upthrust shear and fault represent seismic ruptures. In sectors with prevailing shear displacements; they are right lateral ones for the major part. In sectors where upthruths prevail, the

amplitude of vertical displacements in the rupture zone reaches 1.5 m for Altai seismic rupture and 4-5 m for Olyutorskiy seismic rupture and for horizontal shear displacements it is 1.5 and 3 m respectively.

In the epicenter area of both earthquakes, secondary seismic dislocations are abundant. Major dislocations of this type are structures of ground liquefaction, fracture flows of water-sand and water-gravel mixtures, and gryphons. Such seismic dislocations are a special factor strengthening macroseismic effect, because they increase the intensity of damage to buildings by 1 or 2. Vast areas are covered with vibration fractures. Gravitation phenomena are not so common. Landslides, landfalls are noted in steep mountain slopes.

In the both epicenter areas traces were revealed of repeated strong seismic events that had occurred before.

Geodynamic analysis of the settings in which the studied strong seismic events occurred and a comparison drawn with the tectonic settings of other earthquakes allowed us to reveal major features of seismotectonics of the south of Gornyi Altai and Koryak highland. The similarity between conditions of generating main shocks of earthquakes of 2003 and 2006 with shocks registered before in these seismically active provinces gives grounds to unite seismogenerating structures of Gornyi Altai with seismically active zones of Mongolian Altai and to combine seismogenerating Olyutorskaya zone with seismically active zones in East Kamchatka.

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4. Seismological research of the structure of the Earth's Interior

4.1. Method of receiver functions in structure studies

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Methods were developed to convert receiver functions of transversal waves into velocity models and the method of seismic tomography of receiver functions was elaborated that was based on combined conversion of receiver functions of latitudinal and transversal waves. With the use of receiver function method we revealed details of the upper mantle structure that were unknown before: a thin low-velocity layer immediately above "410-km" seismic boundary, positive seismic boundary at depths ranging from 130-170 km noted in hotspots; negative seismic boundary in the mantle transition zone at a depth of approximately 500 km. The rheological model to account for the character of Leman boundary at depths of 200-250 km proved to be false. Low-velocity layer above "410-km" boundary is associated with the effects of mantle plumes and in several cases it was revealed beneath large magmatism provinces of the age of 260 million years.

The displacement of lithospheric plates with respect to the position they occupied in the times of basalt flow reaches 2000-3000 km. Therefore from the fact of a relation between the low

velocity and Mesozoic magmatic provinces a conclusion should be drawn that there is a strong relation between horizontal movements in the continental crust and flows in the underlying mantle at depths down to 400 km.

With the use of the method of receiver function tomography, a 3D velocity model of Tien Shan was constructed from the day surface to a depth of 250 km. At depths in the range from 10 to 35 km a large area was revealed where transversal wave velocity is decreased by 15 per cent as compared to the abutting areas. The fact that strong earthquakes did not occur in this area testifies to mechanical weakness of low-velocity crust. This result is of great significance for seismic zoning and for understanding the dynamics of lithosphere processes. The deep structure of Iceland plume was studied and a number of features unknown before were revealed in it. Inelastic absorption anisotropy was revealed in the western hemisphere of the inner core of the Earth and isotropy of the eastern hemisphere was discovered. Absorption anisotropy was correlated with elastic anisotropy.

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4.2. Seismic tomography research in Kamchatka

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The studies of the velocity structure of Kamchatka with the methods of seismic tomography only began recently. The results of researches are various and are not always in agreement.

Generally the pattern of elastic wave velocity variation is as follows. The most significant variations are noted across the strike of surface structures. Thus high velocities of elastic waves are characteristic of the focal zone (from data by different authors longitudinal wave anomalies may reach 10-15% there; areas of decreased velocities are typical of continental block [Boldyrev, Kats, 1982; Gontovaya et al., 1995, 2003].

In one of well-known papers on tomography of Kamchatka [Gorbatov et al., 1999] a high-velocity zone (P-wave velocity variation was +4%) was arbitrarily preset in calculations with thickness of 80-90 km, that is the Pacific plate gently subsiding under the continent. With this variant of calculations, the high-velocity part of seismic focal zone (SFZ) appears homogeneous, which makes the interpretation of geophysical results difficult. However many researchers note that the high-velocity constituent of the focal zone is heterogeneous and associate this phenomenon either with non-uniform distribution of rays over the focal zone of with ruptures and structural heterogeneities of the plate, for example [Kuzin, 1998].

A new detailed spatial model of the structure of the crust and the upper mantle of Kamchatka peninsula was constructed from local earthquake data given by Kamchatka Branch of the Geophysical Survey RAS for the time period from 1971 to 2003.

Kamchatka network of seismic stations comprises stationary seismic stations, a network of strong movement stations and radiotelemetric seismic stations. To make calculations for the major part data were used that were obtained in radiotelemetric stations of the peninsula whose coordinates were improved with the use of GPS system. Data of 37 seismic stations of Kamchatka were used. Travel time of P- and S-waves was used for the calculations. For processing 6702 local events were chosen, the total amount of seismic wave phases was 96469; of them P-wave phases make 63515 and S-wave phases are 32954. After a series of tests the following parameters of the environment were chosen as optimum: rectangle blocks with rib length of 30 km x 30 km x 20 km. It is the first time that Kamchatka peninsula has been studied to such a great detail [Sanina et al., 2005; Nizkous et al., 2006].

From the calculations, two spatial models for P waves and for S waves were obtained. Horizontal sections of the model for P waves were made on the layers boundaries, which were defined in the environment parametrization and are shown in Fig. 4.1 and 4.2.

In structural layer-to-layer maps, from velocity anomaly pattern, fault zones can be clearly seen, which cut the lithosphere of Kamchatka, as well as their depths and extension. Fault structures established from geological and geophysical data were mapped, which were corroborated by the structure of velocity heterogeneities. A fault zone in the area of Avachinskii Bay may be easily followed: at the depths of 20-80 km the fault runs in the area of Shipunskii cape, and going deeper, it turns to the south; the fault zone goes deep down into the mantle for 140 km. Another fault zone, which is pronounced to the depth of approximately 140 km, is located in Kamchatskii Bay; the zone continues farther in the continental block towards Klyuchevskaya volcano group and was first established in the lithosphere velocity structure. Its existence is corroborated by other geophysical data, specifically by magnetotelluric sounding [Moroz, Nurmukhamedov, 2004].

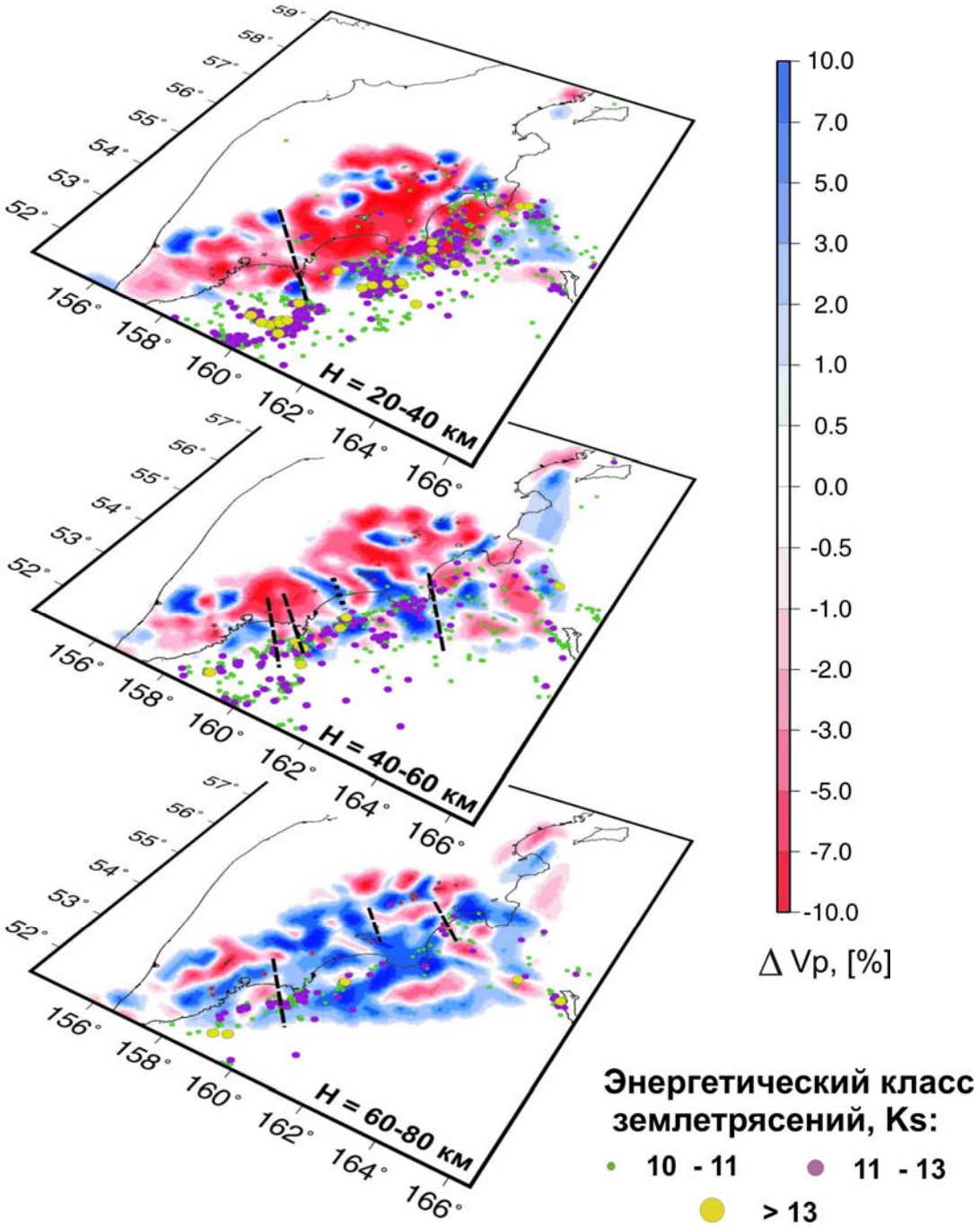

Fig. 4.1. Spatial image of horizontal sections of P wave velocity anomaly distribution for depths in the range from 20 to 80 km. Lines indicate tectonic faults according to [Silverstrov, 1998]. Ks – energy class of earthquakes.

The position of the deep tectonic fault located in the center of Kronotski Bay is also conrroborated by velocity anomaly pattern in the section of 40-60 km and deeper at a depth of 80-120 km. Supposedly it can be continued to the depth of 140 km, because it is the area where from section 120-140 km the boundary between two velocity anomalies of different signs is located.

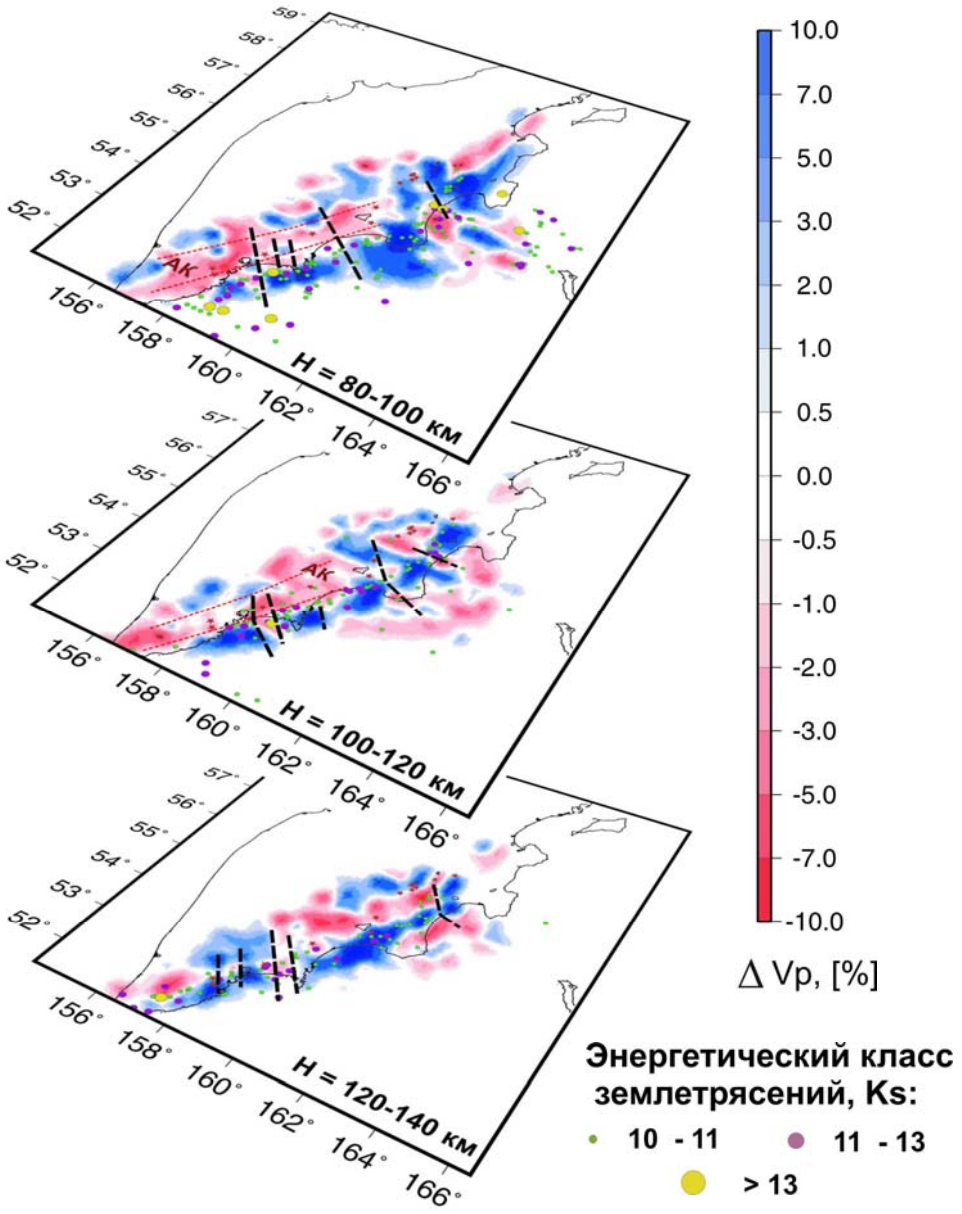

Fig. 4.2. Spatial image of horizontal sections of P wave velocity anomaly distribution for depths of 80 – 140 km. Lines indicate tectonic faults according to [Seliverstrov, 1998]. AK – asthenospheric wedge; Ks – energy class of earthquakes.

Besides tectonic dislocations, in structure charts the asthenospheric layer of sections 80-100 km and 100-120 km is pronounced. From these charts, interrelation is evident between seismicity and lithosphere heterogeneities, for example in the layer 20-40 km, where strong earthquakes cluster in the water area between peninsulas opposite bays or in the southern part of Kronotskii Bay and northern part of Kamchatka Bay with relatively low seismicity level if only strong earthquakes (Ks>12) are considered.

The analysis of the results of the new detailed spatial velocity model of Kamchatka can be stated as follows:

1. The velocity structure of the Earth's crust and the upper mantle of Kamchatka region is considerably layered and the layering character varies along the strike of seismic focal zone and major tectonic structures of the peninsula.

2. The lithosphere of East Kamchatka transverse to the extension of transition zone "ocean-continent" shows considerable heterogeneity and it equally applies to the whole area of subduction

including the continental block and the oceanic plate. It is shown that in most cases such velocity heterogeneities are interrelated and are controlled by seismicity level variation at different depths.

3. In the upper mantle of Kamchatka, the asthenosphere wedge was revealed for the first time (at the depth of 80-120 km), which can be followed beneath East Kamchatka volcanic belt and has velocity structure markedly associated with the depth and near-surface tectonics. Evidently magma supply of active volcanoes is related to this mantle layer and its features determine the character of deep seismicity (Fig. 4.3).

4. Sloping high-velocity anomaly was revealed, which is interpreted as the Pacific plate. Its angle of slope varies along Kamchatka from approximately 50° in the southwest to 20° (not more) in the northeast. The area of maximum seismicity runs on the upper boundary of the assumed plate. It is characterized with considerable velocity heterogeneities and layering. In this case velocity heterogeneities of the asthenosphere wedge area continue into the plate zone, which may testify to the single state of mantle physical matter at the depth. Absolute values of velocity within the plate vary as well; they are higher in the junction area of island arcs, which may be a consequence of high deep stresses (Fig. 4.4). This plate does not show up as a reasonably homogeneous high-velocity block. In this regard, the results obtained by us sufficiently differ from the results published before [Gorbatov et al., 1999].

5. By the character of velocity structure, Kamchatka may be divided into three parts: southern, middle and northern, which though they have some similarities caused by their location in the transition zone "continent-ocean" have a number of individual features. It appears that the most vivid of these differences is an intense practically aseismic low-velocity anomaly revealed in the upper mantle at a depth of approximately 150 km beneath Central Kamchatka, which evidently is related to near-surface structure, specifically Central Kamchatka depression.

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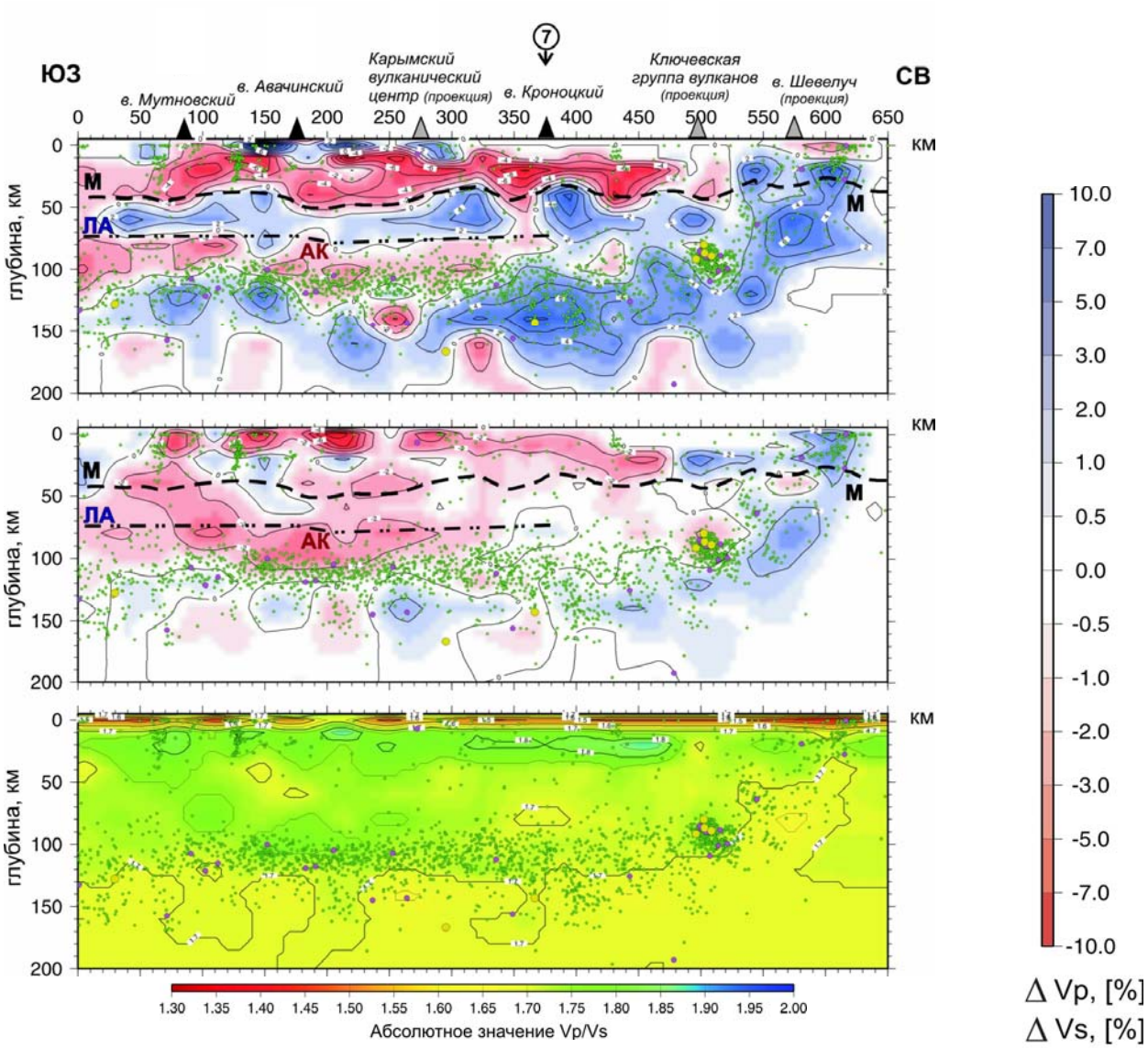
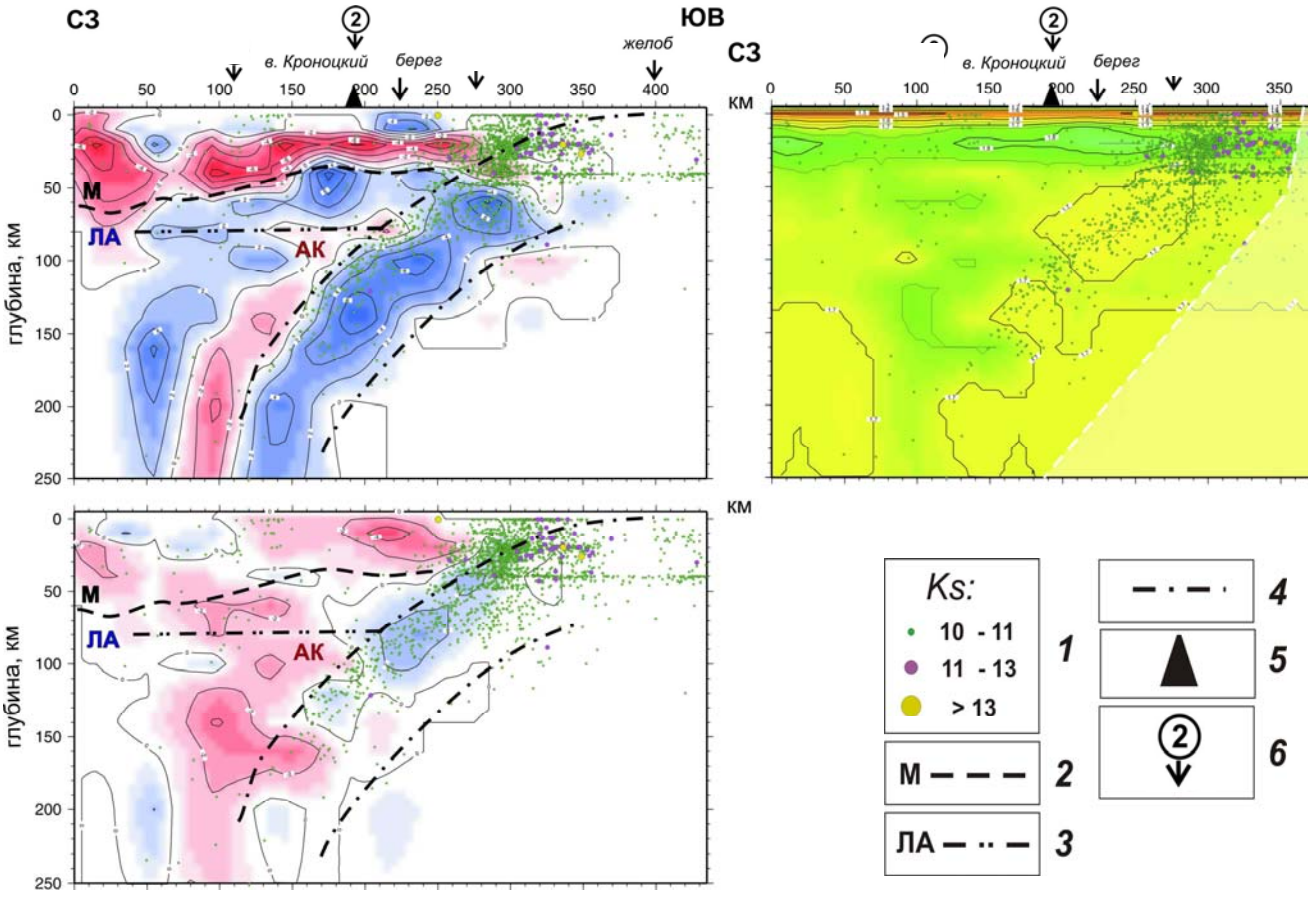


Symbols:

1 – energy class of earthquakes, Ks; interpretation: 2 – Moho boundary, 3 – boundary of lithosphere and asthenosphere, 4 – border of a prospective immersing Pacific plate; 5 – положение вулканов, спроецированное на профиль position of volcanos, projected on a profile; 6 – area of crossing with the specified vertical profile AK - astenosferic wedge.

Fig. 4.3. Relative change of speeds P- and S-waves and absolute value Vp/Vs for a profile 7 which are taking place along extension of Kamchatka through the East volcanic belt.



Symbols:

1 – energy class of earthquakes, Ks; interpretation: 2 – Moho boundary, 3 – boundary of lithosphere and asthenosphere, 4 – border of a prospective immersing Pacific plate; 5 – положение вулканов, спроецированное на профиль position of volcanos, projected on a profile; 6 – area of crossing with the specified vertical profile AK - astenosferic wedge.

Fig. 4.4. Relative change of speeds P-and S-waves and absolute value Vp/Vs for a profile 2 which are taking place transversely to a focal zone through volcanos Krotsky, Kizimen and others which are located in the field of displacement of East volcanic belt to northwest, in the central part of Kamchatka.

4.3. Seismic research in structural characteristics of the transition from outer to inner core of the Earth

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In the context of modern concepts, the inner core composed of iron was formed at the expense of gradual solidification as the Earth was cooled. The model describing this process of adiabatic cooling presumes that the adiabatic curve crosses the iron-melting curve at the inner core boundary. It is there in the transition zone from the inner core to the outer core that freezing of light

fractions takes place and the inner core grows. In this case, first, thermal energy is released that sustains thermal convection in the inner core and, second, gravitational energy (latent heat of solidification) is released, which results in structural convection formation. These two mechanisms are considered to be major sources that sustain magnetic geo-dynamo. A relative contribution of thermal and structural convection in the inner core was discussed in a number of papers as well as different scenarios of processes going on in the boundary layer between the inner core and the outer core when the temperature drops lower than solidus temperature with suspension formation complicating the fractionation process and rapid cooling leading to dendritic growth of the inner core. Some of the proposed dynamic models predict the formation of fragments floating up from the surface of the inner core, which take the form of thin flat plates of sizes ranging from tens to several hundreds of kilometers. Other dynamic processes are possible as well, for example plume formation or simple accretion. It is apparent that constructing dynamic model of the transition from the outer to the inner core of the Earth is possible on the basis of combined interpretation of researches into material composition and seismological measurements. The latter provide direct measurements of seismic wave velocities, density, modulus of elasticity and others necessary for theoretical models of dynamic processes in the Earth's core.

Among commonly used types of seismic data to study the core (inner core oscillations, waves PKP (DF) refracted in the inner core and waves PKiKP with supercritical reflection) at present short-period waves with sub-critical reflection came into use, which are one of the best means to study structural characteristics of the transition from the outer core to the inner core owing to their sensitivity to density jump when observed at small distances (<300) and to transversal wave velocities in the inner core when observed at distances from 300 to 900 km. In spite of the fact that first publications on sub-critical reflected waves appeared at the beginning of the 1970s, it only became possible in the last decade to conduct more detailed research in the inner core with the use of subcritical reflected waves PKiKP owing to developing digital devices of seismic observation.

In the Institute of the Dynamics of the Geospheres RAS, first results on PKiKP waves characteristics were obtained in 1977 from seismograms of underground nuclear explosions registered at a distance of 60 [Adushkin et al., 1997; Ovchinnikov et al., 1998]. At present the collected database on PKiKP waves caused by nuclear explosions and earthquakes contains more than a hundred measurements made by several tens of seismic stations. Projections of reflection points on the Earth's surface for the major part are centered in the area of Central and South-East Asia, in the North Pole area and in the northern Russian platform. These data allow us to obtain results that are of interest for understanding the physics of processes going on at the boundary between the inner and the outer core of the Earth.

Our research conducted on the basis of these data show that PKiKP waves have three characteristics [Adushkin et al., 2000; Adushkin, Ovchinnikov, 2004; Krasnoshchekov et al., 2005].

1. The spectrum of PKiKP wave is shifted to high-frequency area as compared to waves P and PcP. Maximum of spectrum density falls on frequency of 1.3-1.5 Hz.

2. The epicenter distance dependence of the wave maximum amplitude shows that in the range of epicenter distances of 700-900 the measured amplitudes exceed amplitudes predicted for epicenter distance range of 700-900 the measured amplitudes exceed for more than an order the magnitudes predicted for model PREM.

3. Wave PKiKP is accompanied by a coda including high-velocity waves with duration of 200 s and frequency in the range of 2-4 Hz. The coda has either an arc form with slow rise and slow drop or is in the form of individual pulses. PkiKP wave coda of arc type testifies to heterogeneities in the upper part of the inner core on which scattering takes place and the coda is formed. A coda in the form of individual impulses is the result of reverberation in the thin layer.

Researches on the characteristics of PKiKP waves conducted in the Institute of Dynamics of the Geospheres allow us to conclude that the boundary between the outer and inner cores is an area whose structure has thin plates as major elements located either in the top of the inner core or in the base of the liquid, which accounts for the character of amplitude variation with distance, the coda spectrum and coda formation in the form of individual pulses. In the upper part of the inner core,

heterogeneities are noted as well, on which scattering of PKiKP waves takes place and the coda of arc type is formed.

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5. Seismogeodynamics and seismic hazard prediction

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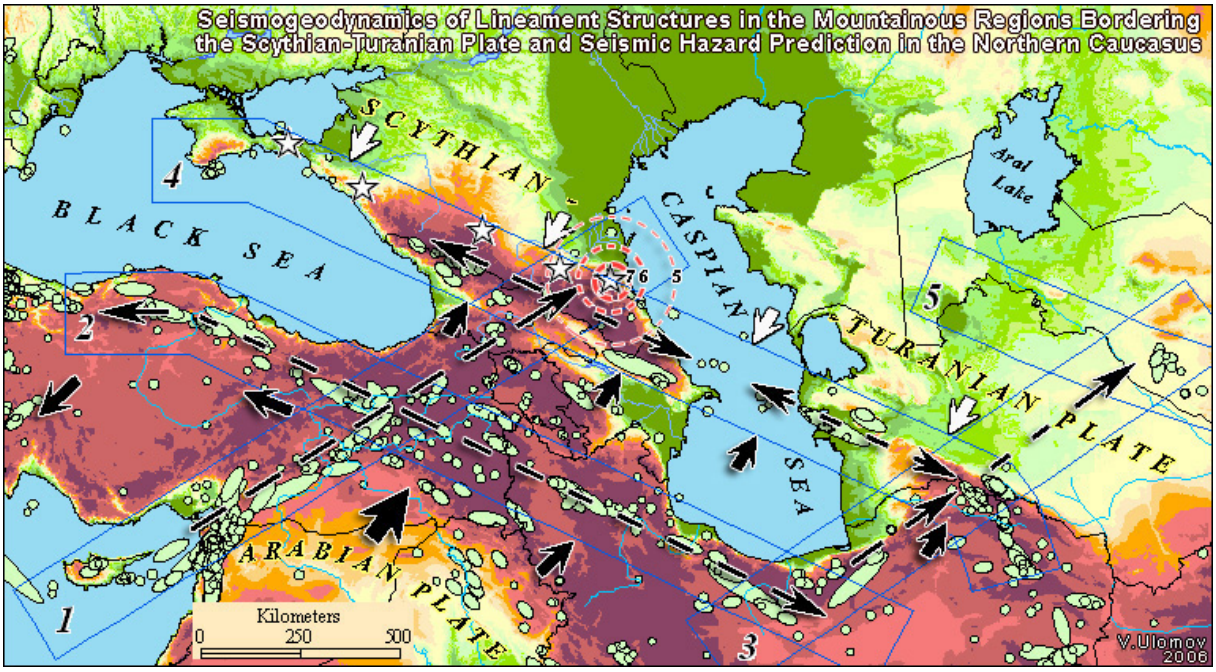

Fig. 5.1. Position of profiles (bands) covering seismic lineaments along which time-space and energy evolution of seismic geodynamic processes was studied. Profiles: 1 – Cyprus – Caucasus, length 1870 km; 2 –Anatolia – Elburs, 2270 km; 3 – Elburs – Turan, 1520 km; 4 – Crimea – Kopet-dag, 2500 km; 5 – Southern Tien Shan, 2520 km. Short black arrows show the direction of geodynamic effect, white arrows show the reaction of the Scythian-Turanian platform on compressive force from the Arabian lithospheric plate (large arrow) and the Alpine structures of the Iran-Caucasus-Anatolia region. Dashed-line arrows show the direction of seismic activation migration along profiles. Stars indicate the location of earthquake potential sources of M = 7.0±0.2 in North Caucasus. Isoseismal lines are shown around one of them.

This reseach continues the work on dynamic zoning of seismic hazard in North Eurasia including the territory of Russia and abutting seismically active regions (See Loom V.I., 1999-2002).

The major object at this stage is the Iran-Caucasus-Anatolia region, which is seismically hazardous for the south of the European part of Russia. Abutting territory of the Central Asia, which is tectonically associated with the Iran-Caucasus-Anatolia region and Scythian and Turanian platforms, was considered as well (Fig. 5.1).

The research to reveal potential sources of strong earthquakes in North Caucasus and Ciscaucasia is based on new concepts of seismic geodynamics of seismically active regions and space-time and energy degree of order of earthquake generating structures. The term "seismic geodynamics" (SGD) proposed by V. I. Ulomov in the middle of 1960s came into active use in seismological practice. As distinct from seismotectonics, which for the major part studies the statics and the spatial relation between seismic sources and tectonics, seismic geodynamics treats the nature of seismicity as a result of movements of the Earth's crust and of the whole lithosphere with account for their deep structure, strength characteristics, hierarchic fault-block structure, stress and strain at various scales from local sources of individual earthquakes to structures generating regional and global earthquakes. Time-space and energy evolution of seismic activation along seismic lineament structures (deformation waves, earthquake source migration and others) play a key role in this case.

It is demonstrated that transition areas from mountain structures of North Caucasus and the west of Central Asia to Scythian and Turanian platforms are a single geodynamic system that determines the features of seismic conditions on the whole area under studies. The research in time-space and energy evolution of seismic geodynamic processes along major lineament structures revealed regularities in the position of earthquake sources, in the processes of seismic activation migration and in the rate of gradual accumulation of seismic events registered by magnitude intervals. Besides, it was revealed that the development of seismic processes along the profiles under investigation is determined by their position and orientation with respect to geodynamic effects from Arabian and Indian lithospheric plates. Seismic activation migration manifests itself most vividly and in single direction on profiles that are longitudinal in relation to acting forces and in different directions on transversal profiles. Profile Cyprus – Caucasus is grouped with the former and the Crimea – Kopetdag profile belongs to the latter. The both profiles are most interesting for assessing seismic danger in North Caucasus and in the south of Russia. Vertical sections of the crust and the upper mantle of the Earth constructed along these profiles offer a clearer view of the nature of anomalous sections with deepened sources of earthquakes.

From the analysis of the accumulation process of seismic events in different intervals of magnitudes, time-intervals (years) are defined along each profile when the next large earthquake of a corresponding magnitude is most likely to occur (Fig. 5.2). On the basis of the elaboration of the primary epicenter distances method, the locations were determined of five potential seismic sources with M=7.0±0.2 in North Caucasus. The time interval from 2013 to 2036 when they are most likely to occur was defined and the expected seismic effect was calculated that might be caused by one of them located in the eastern North Caucasus (Fig. 5.1).

A close relation was revealed between the geodynamics of the central area of the Caspian Sea represented with an active fragment of an old subduction zone and the seismic geodynamics of the whole Crimea-Cacasus-Kopetdag lineament. On the basis of the studies of the deep structure features, the lithosphere dynamics, regional seismicity and modern tectonic movements, a 3D seismic geodynamic model of the Caspian Sea region (Fig. 5.3) was proposed that accounts for the relation between the Caspian Sea level variation and local seismic geodynamics. For example, it was established that the warping of the South Caspian basin floor and the coming of water "excess" in the sea preceded the seismic activation of the Caspian Sea area. On the contrary, after large earthquakes and subsidence of crustal areas in subduction zone the general drop of water surface is noted. Assessments were obtained of the geodynamic deformation values of the southern Caspian Sea oceanic lithosphere, which cause the accumulation of elastic stresses in the lithosphere and the preparation of local earthquakes.

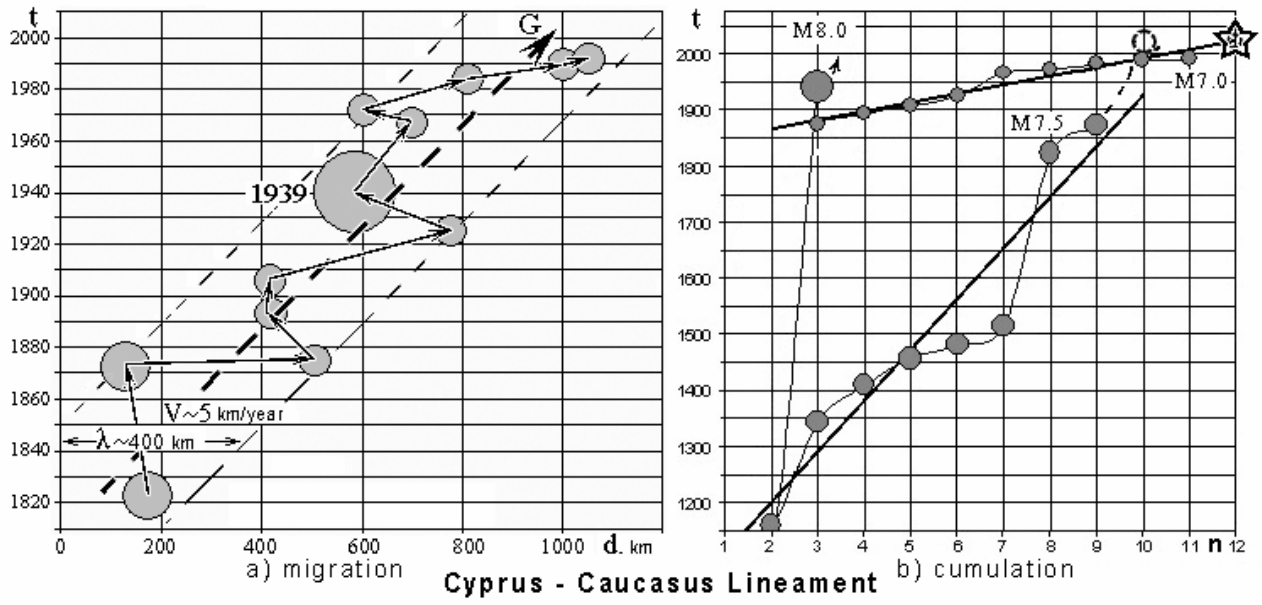

Fig. 5.2. Migration of seismic activation (on the left) and sequence of seismic events occurrence in magnitude intervals M=7.0±0.2, 7.5±0.2 and 8.0±0.2 along the profile Cyprus – Caucasus. Each interval of magnitudes has a respective circle of smaller, medium or maximum diameter. Thin arrows connect events in the sequence of their occurrence; the heavy dashed-line arrow shows the generalized direction of seismic sources migration going on with velocity of approximately V=5km/year within deformation wave of a length of about 400 km. Heavy arrow is the hodograph of deformational G-wave travel. With a knowledge of velocity V of G-wave travel, it is possible to make long-term earthquake prediction in a given magnitude interval as well as to predict the most likely area of occurrence.

A sequence of seismic events accumulation in time along the profile Cyprus – Caucasus (on the right). The star shows the time of likely occurrence of the next earthquake with M=7.0±0.2, and dashed-line circle shows events with M=7.5±0.2.

Thus the Caspian basin being isolated from the oceans of the world is sensitive to the smallest regional deformations of the lithosphere and is a kind of indicator of local geodynamics and seismicity.

Combined research in seismic geodynamic and hydro-geodynamic phenomena offer new possibilities for earthquake long-term prediction on both regional and global scales. We revealed the correlation between the world ocean level variation and global variations of seismic conditions that testifies to this. Thus on the basis of new methods, considerable changes in seismic conditions were revealed in the time period of 1965-2005. These changes involve a threefold and more than threefold decrease in recurrence of large earthquakes (M≥7.0+/-0.2) in the 11-year interval of time from 1982 to 1993 with subsequent intense activation on the total depth range of seismic source occurrence. These correlated phenomena are explained by the features of seismic geodynamic conditions in the subduction zones of lithospheric plates on the periphery of the Pacific and Indian oceans.

Conclusions

Traditional views on seismic regime in one or other region or in the Earth on the whole based on seismic event recurrence integral plots and concepts of seismicity developing with time based on summing up the total amount and the energy of all earthquakes that occurred make information flat and hamper the studies of seismic process nature. The results obtained by us are based on a radically new approach to seismic regime studies, in which the current of seismic events is

analyzed by magnitude intervals reflecting the hierarchic nature of the geological environment block structure.

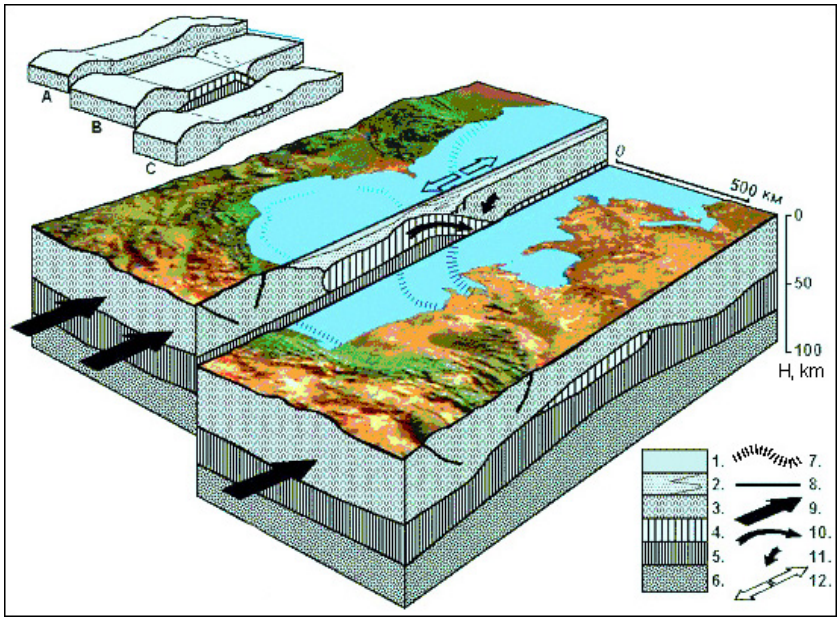

Fig. 5.3. 3D seismic geodynamic model of the Caspian Sea region (scaled up vertically). 1 – water mass; 2 – sedimentary bed and dislocated sediments in the central area of the Caspian Sea; 3 – continental crust; 4 – oceanic crust relics; 5 – sub-crustal layer of the lithosphere; 6 – asthenosphere; 7 – maximums of isostatic anomalies gradient; 8 – large tectonic dislocations (faults); 9 – pressure direction from Iranian and Arabian lithospheric plates; 10 – the direction of the oceanic lithosphere subduction of the Southern Caspian Sea under Scythian-Turanian plate; 11 – the direction of drawing in the subsidence of the northern Caspian Sea lithosphere; 12 – local horizontal extension in the bending lithosphere of the northern Caspian Sea. The upper figure is a conventionalized model of the dynamics of three blocks: A – Caucasus – Talyshskii, B – Elburs – Caspian, C – Kopetdag – Turanian.

Self-organization is characteristic of the Earth, which develops in strongly non-equilibrium conditions. Global oscillation regimes of the lithosphere are caused by the processes of the geological environment volumes adjusting to prolonged force effects of planetary scale. In this context, the alternation of elastic stresses and their subsequent discharge in the form of small deformations and rapid decrease of stress in earthquake sources is the most economical self-organization regime of geodynamics because it involves successive repetition of an event of the same type. Though geodynamic system is changing continuously, the Earth on the whole is in dynamic equilibrium and the observed periodicity contributes to it.

Processes of accumulation and release of geodynamic stresses alternate and thus reflect discrete and continuous nature of the dynamics of the Earth's crust and the whole lithosphere. These processes and phenomena are reflected in both global and regional seismic geodynamics. They should be taken into account in research in strong earthquake long-term prediction.

Acknowledgements

The author is grateful to his colleagues T. I. Danilova, N. S. Medvedeva, T. P. Polyakova and L. S. Shumilina for their participation in this research.

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6. Seismic Risk Assessment and Management in the Russian Federation

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In the Russian Federation more than 20 million peoples live in the regions characterized by moderate and high level of seismicity. Earthquake prone areas, where earthquakes with intensity 7 (MMSK-86 scale) and higher may occur, occupy about 20% of the Russian Federation territory. The most seismically active regions are the Northern Caucasus, Altaj, Sayany, the Baikal area, Yakutiya and the whole Far East, including Kamchatka, Sakhalin and Kuril Islands. In order to secure the population safety in earthquake-prone regions the assessment of seismic risk level and possible consequences due to scenario events should be carried out in advance.

During the past years much attention was paid in Russia to seismic risk assessment and reduction. New approaches for seismic hazard, vulnerability and risk assessment were developed under the Russian Federal Programs "Safety of Population, Buildings and Structures against Natural

and Technological Hazards", "Federal System of Seismological Observations and Earthquake Prediction", "Natural and Technological Risk Reduction and Management in the Russian Federation up to 2005 and 2010". GIS-based tool "Extremum" assigned for loss assessment due to strong earthquakes was improved by joint efforts of the Emergency Research Center and the Seismological Center, Institute of Environmental Geosciences, Russian Academy of Sciences. During 2003-2006 different tool versions were applied for seismic risk assessment and mapping at different levels: national, regional, urban, as well as for loss estimations due to scenario events for some earthquake prone regions.

In the Russian Federation as in many earthquake-prone countries the studies on estimating seismic risk and expected loss due to scenario events are based on the general methodology accepted and described in UN Guidelines and Manuals, as well as proceedings of international and European conferences on earthquake engineering [Karnik and Algermissen, 1978; Fournier d'Albe, 1982, 1986; Karnik, 1984; Manual, 1991, Guidelines, 1997]. According to this procedure, seismic risk is obtained as superposition of seismic hazard and vulnerability of different elements at risk (population, buildings and civil engineering facilities, economic activity, public services, utilities and infrastructure, etc.). In Russia one of the first procedures for loss and risk assessment were developed in 1990-th in the Military Engineering Academy named after Kujbyshev and then updated in the Emergency Research Center [Larionov, 1992, 1999; Larionov et al., 2000; 2003a; 2003b; 2003c; 2005; Frolova et al., 2003a, 2003b, 2005, 2006]. The recent version of "The Methods of Earthquake Consequences Assessment" [Methods, 2000] was developed by joint efforts of the Emergency Research Center, Seismological Center of IGE, Russian Academy of Sciences and VNII GOChS, Emercom of Russia. "The Methods" were approved by the Interdepartmental Coordination Scientific Council on Civil Defence and Emergency Problems on September 19, 2000 and was certified by the Interdepartmental Commission on Emergency Situations Management on January 19, 2001.

"The Methods" allow the principle indexes of loss due to earthquakes to be determined. They are the following: number of buildings and structures classified according to MMSK-86 scale, which survived different damage states during the earthquake with intensity I; number of fatalities and injuries with different level of impact under the condition that buildings survived the definite damage state; number of homeless. "The Methods" may be also used to estimate debris volume and their characteristics, square of settlement destroyed part, areas where buildings survived various damage states, length of blocked roads, number of fires and accidents at life line systems etc. According to "the Methods" mathematical expectation of social losses M(Nj) for the considered settlement taking into account inhabitant migration in the buildings of j type during the day and night may be determined by equation

$$M(N_j) = \sum_{j=1}^{n} \iint_{S_c} \int_{0}^{24} \int_{I_{\min}}^{I_{\max}} P_{Cj}(I) \cdot f(x, y, I) \cdot \Psi_j(x, y) \cdot f(t) dI dt dx dy \qquad (1)$$

where $I_{\min}$ и $I_{\max}$ – maximum and minimum possible earthquake intensity; S_c – settlement area; n – number of considered building types according to MMSK-86 scale; $P_{Cj}(I)$ – probability of fatalities and injuries under the condition of damage to buildings of j type due to earthquake with intensity I; $\psi_j(x,y)$ – density of population distribution within the considered area in buildings of j-type; $f(x,y,I)$ – density function of earthquakes' intensity probabilities within the unit area with coordinates x, y; $f(t)$ – function obtained on the basis of statistical analysis of data on population migration during 24 hours.

The computations of $P_{Cj}(I)$ are carried out by formula

$$P_{Cj}(I) = \sum_{i=1}^{5} P_{Bi}(I) \cdot P(C_j | B_i) \qquad (2)$$

where PCj (I) - probability of people to be impacted during the earthquake with intensity I; PBi(I) — probability of definite i damage state of buildings providing the given value of earthquake intensity; P(Cj|Bi) — probability of people to survive j level of impact under the condition that the building survived the damage state i. The computations are done for buildings and structures types classified according to MMSK-86 scale: buildings' types A1, A2 (from local materials); buildings' types Б, Б1, Б2 (brick, hewn stone or concrete blocks); buildings' types B, B1, B2 (reinforced concrete, frame, large panel and wooden); buildings' types C7, C8, C9 (designed and constructed to withstand the earthquakes with intensity 7, 8, 9).

The individual seismic risk Rs or the probability of death (or injuries) due to possible earthquake within one year in a given territory may be determined through mathematical expectation of social losses M(Nj) taking into account the number of inhabitants N in the considered settlement and probability of seismic event H

$$R_s = H \cdot V_s\ (I) = H \cdot M(N\ ) / N \qquad (3)$$

where Vs(I) – vulnerability of population for the considered settlement; H – probability of seismic event per one year; N – the number of inhabitants in the considered settlement.

In 2003-2006 the above-described procedures was used for seismic risk assessment for the whole country, some earthquake-prone regions and cities. Different “Extremum” system versions were developed for computations. The proper databases on population and building stock distribution were updated taking into account the end user requirements about the details of expected results. For seismic risk computations at national and regional levels the information about seismic hazard was taken from the review maps of seismic zoning of the Russian Federation territory GSZ-97 A, B, C. The maps show the seismic intensity I which may occur in a given area within the time interval equal to 50 years with probability of exceedence equal to 10% (GSZ -97A), 5% (GSZ -97B) and 1% (GSZ -97C). For seismic risk computations at urban level the information about seismic hazard was taken from the maps of seismic microzoning. The detailed inventory data obtained during last years by the Extreme Situations Research Centre and data on built environment provided by the Regional Departments of Emercom of Russian Federation was used to develop the building stock models for the whole country, separate regions and cities’ districts. The averaged models, characterized by percent of buildings of different types and their height, were also used for those settlements where detailed inventory data was not available.

Estimation of individual seismic risk for the population of the country, regions and cities was carried out for the worst scenarios when earthquakes occurred during night time. In order to estimate expected social losses within cities and their districts, they were divided into unit sites. Then indexes obtained for each unit site were summed up. The map of seismic risk zoning for the Russian Federation (Fig. 6.1) includes two elements: risk for settlements with number of inhabitants less than 50,000 and risk for settlements with number of inhabitants more than 50,000. The hypsometric scale is used to represent both elements on the map. When constructing isolines, the value of risk was computed in the points which are the geometric centers of settlements and then the risk values were averaged within the unit sites. The method of bilinear interpolation was used to construct the isolines and identify the colour of corresponding zones.

For 366 cities and towns in the Russian Federation with number of inhabitants more than 50,000 the values of risk are presented by signs: circles of different size and colour. Size of circle stands for the number of inhabitants, colour defines the risk level (Fig.6.1). Obtained values of seismic risk for the Russian Federation (Fig. 6.1) vary from negligible values up to rather high ones equal to $50.0*10^{-5}$ and higher. The following risk Re, 10^{-5} 1/year categories are identified: extremely high (> 50); rather high (20-50); high (10 – 20); average (5 – 10); moderate (1 – 5); insignificant (0.5 –1); low (< 0.5). The highest values of risk are typical for settlements in Sakhalin, Kuril Islands, Kamchatka, near Lake Baikal, Altai-Sayan region and Northern Caucasus. In these regions the special measures should be implemented to reduce the risk level.

Fig. 6.1. Zonation of the Russian Federation territory according to the level of seismic risk R_e , 10^{-5} 1/year categories: 1- extremely high; 2 – rather high; 3 - high; 4 – average; 5 - moderate; 6- insignificant; 7 - low. Values of risk for the cities with population more that 50 000 people, R_e , 10^{-5} 1/year: 8 – 20 up to 50; 9 – 10 up to 20; 10 – 5 up to 10; 11 – 1 up to 5; 12 – 0.5 up to 1; 13 - less than 0.5. Number of inhabitants: 14 –1 000 000 and more; 15 - 500 00 up to 1000 000; 16 – 200 000 up to 500 000; 17 – less than 200 000

Fig. 6.2 shows an example of seismic risk assessment and mapping at regional level. For 764 cities and towns in the Krasnodar region with number of inhabitants more than 1,000 the values of risk are presented by signs: circles of different size and colour (Fig. 6.2). Obtained values of seismic risk for the Krasnodar area (Fig. 6.2) vary from negligible values up to ones equal to $40.2*10^{-5}$. The high values of risk are obtained for the Novorossijsk city, Tuapse and Lazarevskoe towns, as well as for Krasnodar city, Sochi and Adler towns. On the whole for more that 30 % of the Krasnodar region territory the value of seismic risk computed taking into account direct damage to buildings exceeds value equal to $1.0*10^{-5}$.

Computations of seismic risk for the Krasnodar region taking into account the secondary technological processes trigged by earthquakes showed that in this case the value of risk equal to $1.0*10^{-5}$ will be exceeded for more that 50 % of the region territory. High level of individual seismic risk for the Krasnodar region results from relatively high seismic activity of the region under consideration and lack of earthquake resistant measures of the existing building stock.

Fig. 6.3 and 6.4 show examples of seismic risk assessment taking into account technological accidents at fire hazardous and chemical facilities triggered by strong events at urban level.

Comparison of risk values for settlements obtained as a result of computations at different levels: national, regional or urban, shows definite scatter. Multiple estimations of seismic risk for various territories taking into account input data with different details allowed to reveal the interesting peculiarity that the probability of risk anomaly values for small areas are rather high relatively to averaged values. It means that the risk for the whole settlement may be estimated as acceptable one, but for some districts within the settlement the risk value may many times exceed the average one. Anomalous risk values are smoothing when changing the level of risk computations.

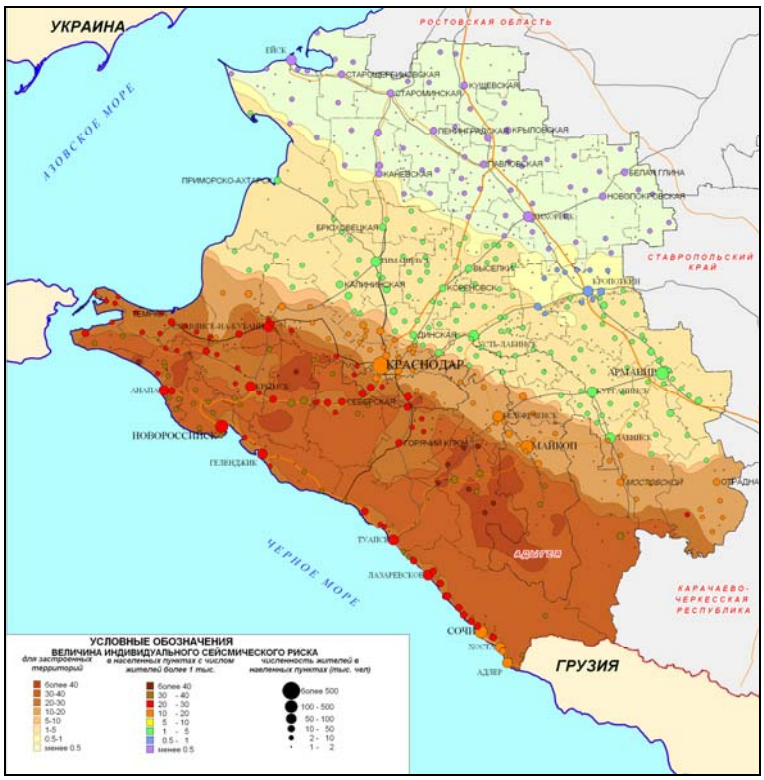

Fig. 6.2. Krasnodar region zoning according to the level of seismic risk

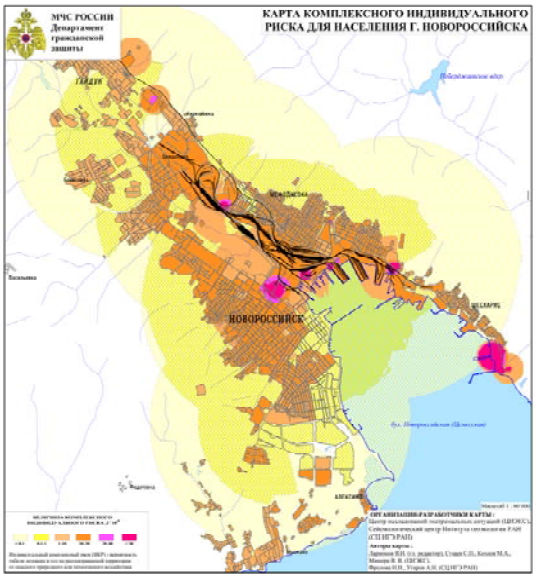

Fig. 6.3. Novorossijsk city zoning according to the level of seismic risk

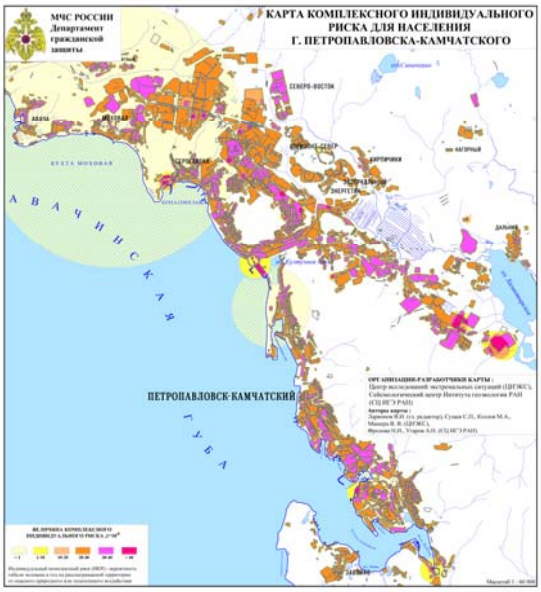

Fig. 6.4. Petropavlovsk-Kamchatcky city zoning according to the level of seismic risk

In 2005-2006 scenario earthquakes consequences were estimated for the Northern Caucasus by joint efforts of the Seismological Centre of Institute of Environmental Geosciences, Institute of Physics of the Earth, Russian Academy of Sciences and Extreme Situation Research Centre. The most dangerous scenario events for the considered area were identified taking into account the possible sources zones for the Krasnodar and Stavropol regions, as well as historical moderate and strong events occurred in the area under study.

According to the map of possible sources zones (Fig. 6.5) for the Stavropol region [Sobolev et al., 1996] the earthquakes with Mmax from 3.5±0.2 up to 7.0±0.2 may occur in the region. Table 6.1 shows the parameters of scenario events.

Table 6.1

Parameters of scenario events for possible source zones

No. of event (Fig.6.5)	Epicentre location		Source depth, km	Magnitude
	φ^0 N	λ^0 E		
№ 1	43,75	43,08	20	7
№ 2	43,92	42,49	15	6
№ 3	43,98	43,22	15	6
№ 4	43,71	42,44	20	7
№ 5	44,98	41,97	10	5

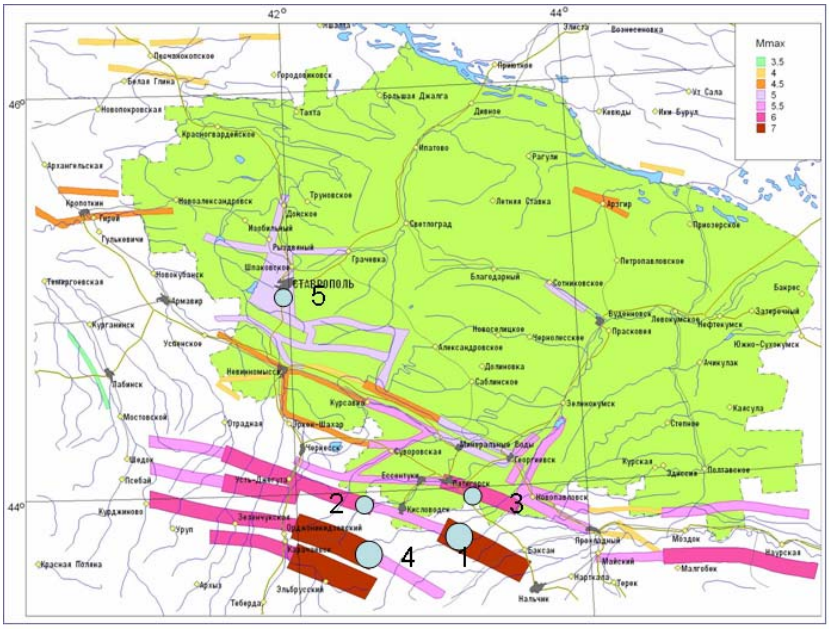

Fig. 6.5. Map of possible earthquakes source zones for the Stavropol region according to the Institute of Physics of the Earth report [Sobolev et al., 1996]: scenario events location (Table 6.1) is shown by signs and figures

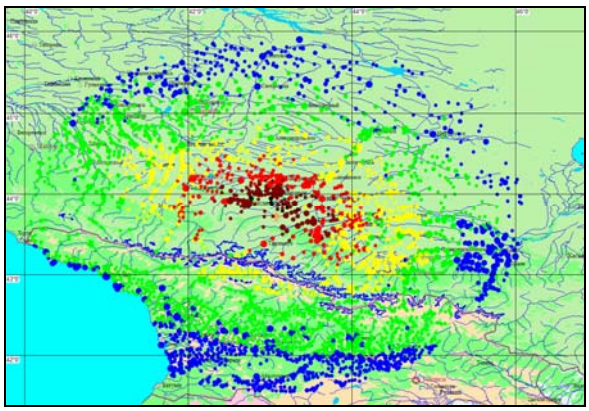

Fig.6.6. Results of possible losses assessment due to scenario earthquake no. 1 (Table 6.1) with *M*=7.0, *h*=20 km in the Stavropol region**;**

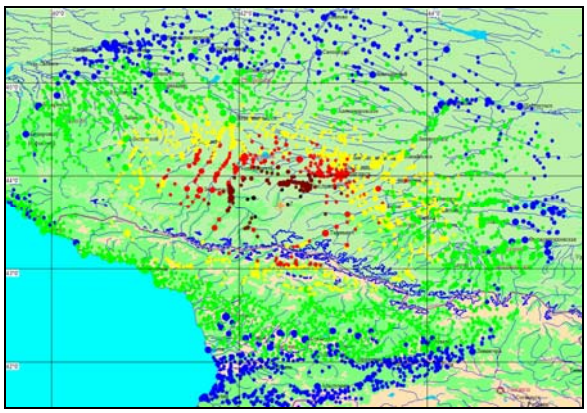

Fig.6.7. Results of possible losses assessment due to scenario earthquake no. 4 (Table 6.1) with *M*=7.0, *h*=20 km in the Stavropol region**;**

Distribution of average damage states: black colour -total collapse, brown - partial collapse, red - heavy, yellow -moderate, green - slight damage, blue - no damage

Estimation of possible consequences due to chosen scenario events was carried under the assumption that 95% of inhabitants are inside buildings. Theoretical isoseismal maps were computed taking into account active tectonic faults and regional parameters of macroseismic field. Different orientation of ellipse axis was also taken into account through orientation of ellipse large axis (angle of inclination) and according to source mechanism. Fig. 6.6, 6.7 show distribution of averaged damage states in settlements of the Stavropol region due to scenario event no.1 and no.4 (Table 6.1) with M=7.0, for which the most severe damage to existing building stock may be expected. On the maps the settlements are shown as circles of different size and color. Circle size depends on the number of inhabitants, its color stands for average damage states of existing building stock in the settlement under consideration. Black color means total collapse (d=5), brown color – partial collapse (d=4), red – heavy damage (d=3), yellow – moderate damage (d=2), green – light damage (d=1), blue – no damage. For the most part of settlements located at the distance of 30-40 km from epicenter the buildings and structures will survive on average partial collapse (d=4), at the distance of 50-100 km – heavy damage (d=3).

Damage to buildings of different vulnerability classes (according to MMSK-86 scale) in settlements located at different distance from epicentre may vary from total collapse (d=5) to light damage (d=1). Table 6.2 shows expected damage distribution for some large towns of Stavropol region.

Table 6.2

Probable damage to existing building for settlements of Stavropol territory in a case of scenario events of №1 and №2 (tab. 1)

Settlement	Scenario event no. 1 (Table 6.1)							Scenario event no. 4 (Table 6.1)						
	Δ, km	Percent of buildings survived different damage state					d_{av}	Δ, km	Percent of buildings survived different damage state					d_{av}
		d=1	*d*=2	*d*=3	*d*=4	*d*=5			*d*=1	*d*=2	*d*=3	*d*=4	*d*=5	
Essentuki	36	4	10	18	27	38	4	52	10	19	27	24	14	3
Pyatigorsk	30	4	10	18	27	38	4	61	13	23	28	20	8	3
Lermontov	41	6	13	22	28	28	4	62	13	23	28	20	8	3
Kislovodsk	33	2	8	15	24	50	4	31	4	10	18	27	39	4
Cherkessk	98	15	31	30	16	5	3	64	8	26	32	22	9	3

Macroseismic effect in epicenter zone due to scenario event no.5 (Table 6.1) with M=5 and h= 10 km may reach 6-7 grades of MMSK-86 intensity scale. In 14 settlements of the Stavropol region buildings and structures may survive on average d=1 (light damage). According to computations the effect of this event may be felt in 99 settlements of the region. In Stavropol City located at 5 km distance from the epicenter the intensity of shaking may be equal to 6.5-7. Within the city about 30% of buildings may survive moderate damage (d=2), about 20% - heavy damage (d=3) and 2% - partial collapse (d=4).

In 2006 joint study by Seismological Center, Institute of Environmental Geosciences, Russian Academy of Sciences and Geophysical Survey of Russian Academy of Sciences was undertaken in order to reveal the influence of regional attenuation laws' peculiarities on reliability of damage and risk estimations with "Extremum" system application. The events occurred in the Northern Caucasus on April 19, 1926; July 22, 1966; October 2, 1971; May 22, 2001 and November 9, 2002 were chosen for the study. The parameters of past events are listed in Table 6.3.

Table 6.3

Parameters of past earthquakes used as scenario events for the Krasnodar and Stavropol regions

Date	Origin time	Epicenter location		Source depth, km	*M*	I_0
		φ^0 *N*	λ^0 *E*			
April 19, 1926	07:49:58±10 s	45.37±0.2	39.3±0.2	50 33-75	5.4 ±0.5	6-7 ±0.5
July 12, 1966	18:53:08±5 s	44.7±0.2	37.3±0.2	55 36-85	5.8 ±0,1	7 ±0.5
December 4, 1970	01:59:25±1 s	43.84±0.1	39.34±0.1	7 5-10	5,1 ±0.3	7-8 ±0.5
October 2, 1971	10 56 41±1 s	44.8±0.1	42.1±0.1	2.5 1-4	4.5 ±0.3	>7
May 22, 2001	19:13:22.8±1.36 s	46.381	42.181	33.0	- mb4.6	6
November 9, 2002	02:18:15.0±0.03 s	45.05±0.03	37.7±0.03	33	-- mb5.2	6

For the computation of expected shaking intensities due to past events the Shebalin equation [Shebalin, 1968] was used.

$$I = bM - \nu \lg \sqrt{\Delta^2 + h^2} + c \qquad (4)$$

where Δ — epicentral distance, km; h — source depth, km; M — magnitude. The coefficients in the equation are estimated taking into account the empirical data. If there is no enough statistical data in the area under consideration the following coefficients b =1.5; ν= 3.5; c=3.0 are used as default ones. In the present study the computations were made for default values, as well as for regional coefficients obtained for the whole Northern Caucasus territory b =1.6; ν= 3.1; c=2.2; and for some separate seismic zones: Sochi zone - b =1.48; ν= 3.0; c=2.73; Crimea zone - b =1.5; ν= 3.45; c=3.42. The obtained circular isoseists were stretched along the active tectonic faults in order to take into account the anisotropy of the medium and source line extension. Theoretical isoseismal maps due to past earthquakes were computed taking into account various regional coefficient of macroseismic field and different orientation of ellipse axis. The empirical data about ratio of ellipse major and minor semi-axis, which varies from 1.2 up to 2.0 for the Northern Caucasus, was also taken into account. The comparison of theoretical and observed macroseismic fields for 6 past events showed the great influence of regional peculiarities and source depth on computed shaking intensities. Fig. 6.8-6.11 show the results of simulation of expected consequences due to four past events, for which the good agreement between theoretical and reported shaking intensities was observed.

For the event in Sochi zone on December 4, 1970 the good agreement between reported and simulated shaking intensities values was observed for the regional attenuation laws coefficients obtained by Lutikov for this zone b=1.48; ν= 4.0; c=2.73 and ratio of ellipse minor and major semi-axis equal to 1:2. It should be noted that for the event in Sochi zone the isoseists' extension coincides with orientation of tectonic faults along the Black sea shore line. In this case the observed angle of isoseists' inclination was used for computations of expected shaking intensities.

For the event in Anapa zone on July 12, 1966 the good agreement between reported and simulated shaking intensities values was observed for the regional attenuation laws coefficients obtained by Shebalin [Shebalin, 1968] for the Northen Caucasus b=1.6; ν=3.1; c=2.2; ratio of ellipse minor and major semi-axis equal to 1:1.5; and angle of large axis inclination equal to 38° obtained through the source mechanism constructed by Pustovitenko [Pustovitenko et al., 1989]. For the recent Nizhnekubanskoe earthquake occurred on November 9, 2002 the best agreement with observed values [Tatevosyan et al., 2003] was for the regional attenuation laws coefficients obtained by She-

balin [Shebalin, 1968] for the Crimea b =1.5; ν= 4.0; c=3.42; ratio of ellipse minor and major semi-axis equal to 1:1.5; and angle of large axis inclination equal to 47° obtained through the Harvard source mechanism [http://www.seismology.harvard.edu]. For Kubanskoe earthquake on April 19, 1926 good agreement was observed for the parameters of macroseicmic field similar to the Nizhnekubanskoe event. In the case of the Kubanskoe earthquake the comparison of simulated shaking intensity values with observed values published by Ananin [Ananin, 1977] and Nikonov [Nikonov et al., 1996] showed good agreement in both cases. It should be mentioned that isoseists of three considered events in Anapa – Kubanskaya zone are stretched counterwise to the main Caucasus direction.

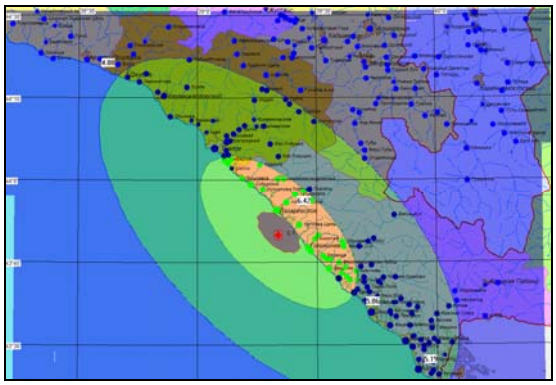

Fig. 6.8. Results of possible losses assessment due to scenario earthquake on December 4, 1970; *M*=5.1; *h*=7 km; in the Sochi zone;

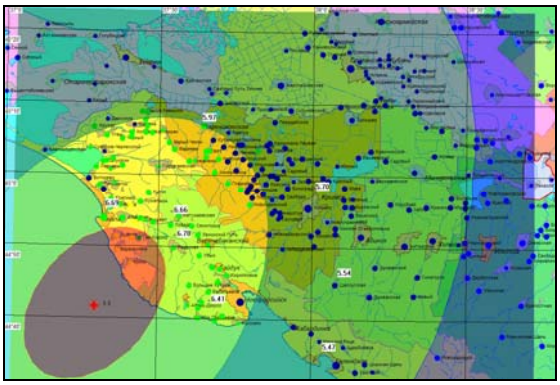

Fig. 6.9. Results of possible losses assessment due to scenario earthquake on July 12, 1966 in the Anapa zone; *M*=5.5; *h*=11 km;

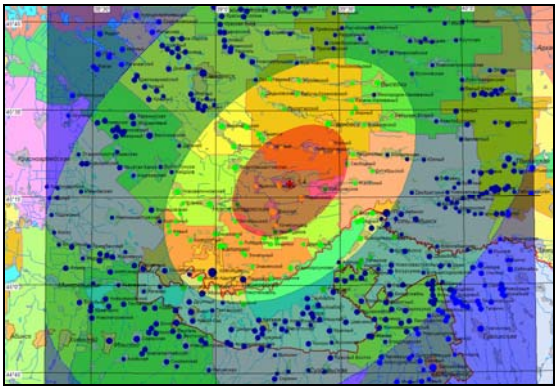

Fig. 6.10. Results of possible losses assessment due to Kubanskoe earthquake April 19, 1926 earthquake, *M*=5.4, *h*=10 km;

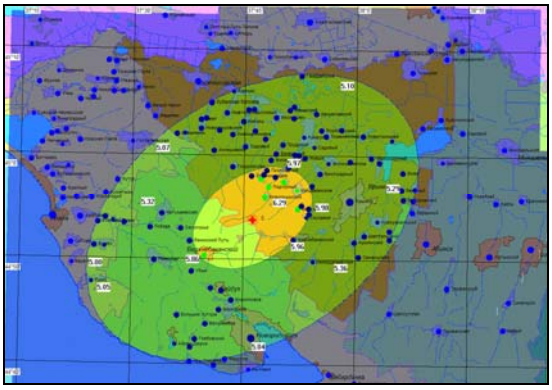

Fig. 6.11. Results of possible losses assessment due to Nizhneubanskoe earthquake on November 9, 2002; *M*=5; *h*=14 km;

black colour -total collapse, brown - partial collapse, red - heavy,
yellow -moderate, green - slight damage, blue - no damage

Fig. 6.12 shows histogram of simulated and reported shaking intensity values for the Nizhnekubanskoe earthquake, which occurred on November 9, 2002. The observed values of shaking intensity are shown by green colour; theoretical values are shown by blue and orange colours. The theoretical values are obtained for the same ratio of ellipse minor and major semi-axis equal to 1:1.5, and for different ν and angle values: ν=4.0 for the variant shown by blue colour and ν=3.45 – orange one; inclination angle is equal to 47° for the variant shown by blue colour and 55° for orange colour. For the worst variant shown by orange colour the average difference $\overline{\delta}$ between theo-

retical and simulated values of shaking intensity may reach one grade of intensity scale; for the variant shown by blue colour $\bar{\delta}$ will not exceed 0.3 grade of intensity scale. The corresponding values of dispersion $D=\sigma 2$ are equal to 0.21 and 0.10.

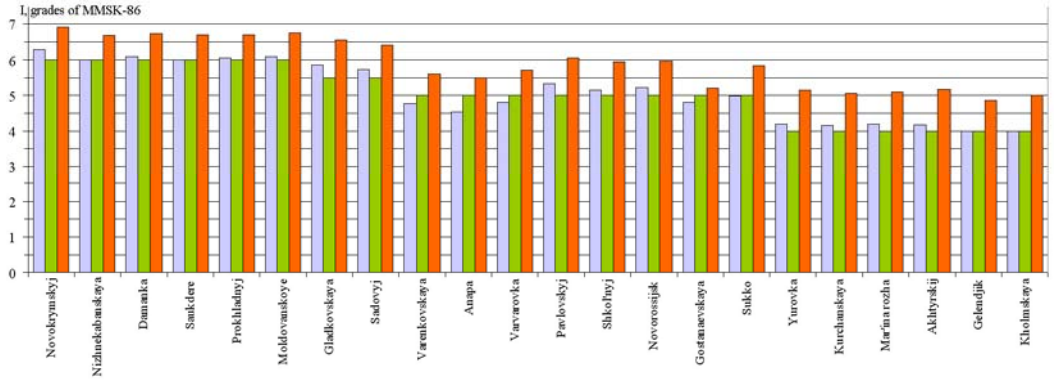

Fig. 6.12. Comparison of theoretical and observed shaking intensities for the Nizhnekubanskoe earthquake on November 9, 2002

The obtained results on possible shaking intensity, damage distribution and expected number of casualties due to scenario earthquakes were delivered to the local authorities for taking measures aimed at earthquake preparedness and seismic risk reduction.

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7. Researches in seismic process physics and earthquake prediction

7.1. Earthquake physics and precursors

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In 2003-2006 in Russia combined research into earthquake physics was conducted to impove the methods of prediction of location, time and energy of natural disasters of this kind. Laboratory research included experiments on deforming environment block models to create the source of inner destruction and to obtain and analyze seismograms and 3D catalogs of seismic emission with the use of new devices. Research in the trigger mechanism of external effects on the source being formed was conducted as well. Stable regularities revealed in laboratory experiments, which can be repeated, were verified from the analysis of earthquake catalogs and observation data on

stress and strain variation of the Earth's crust and geophysical fields of terrestrial and outer space origin. As a result, earthquake source physical models were improved; new algorithms to predict earthquakes were elaborated; with the use of GIS technology, a map was compiled of potential sources in Russia with estimates of time and expected magnitude of strong earthquakes originating in them. When necessary the results were given to the Ministry for Emergencies of RF.

In 2003-2006, we obtained the following important results.

Field data analysis:

A new type of medium-term precursor was revealed. As a result of studying Kamchatka earthquake catalog, we discovered the effect of hidden periodic oscillations of seismic flow appearing before strong earthquakes with M more than 7. Oscillations appeared 3-5 years before an earthquake in the areas of linear size of the order of 100 km encompassing the earthquake sources. Maximum oscillations periods are in the range from 0.6 to 1.8 years. A regular shift of spectrum maximums was revealed towards lower periods as the moment of a strong earthquake approaches. The universal character of the discovered effect was verified from laboratory modeling data.

With the use of GIS technology, a map version was compiled of potential earthquake sources with magnitude more than 7 for Northern Caucasus. Distance regularities of sources locations in the lineament structure of the Earth's crust were taken into account to compile the map.

Methods were elaborated that allow us to assess the destruction cycle duration of the Earth's lithosphere material from earthquake catalogs data. The duration is assessed on the basis of the generalized recurrence law in the area of the size equal to the earthquake source size, which allows us to reduce the results of seismic statistics to environment volumes actual in destruction physics. Using the elaborated approaches we obtained the assessments of destruction cycle duration of the Earth's lithosphere at two levels of detail: planetary level for the major seismic belts of the Earth and regional level for a number of seismically active regions (Kamchatka, northeastern China, and Greece). Values of obtained assessments vary with region from hundreds of years to tens of thousand years, which is in agreement with paleo seismological assessments. It appears that, on the average, the duration of destruction cycle has only a weak dependence on the size of source. This feature is vividly manifested in displacement areas for the most part. In the areas of prevailing tensions (rift structures), the duration of destruction cycle somewhat increases with the increase of the source size, whereas in the areas with prevailing compression (subduction zones) it decreases.

As a result of studying the representative character of the Kuril island arc earthquake catalog, a series of expected earthquakes maps were calculated for this region. The analysis of the total amount of obtained maps of expected earthquakes for Kuril island arc for the time period from 1970 to 2001 showed that the efficiency rate of MEE method used for retrospective prediction is not worse than similar rates for seismically active regions of the world studied before. It appeared that about 68 per cent of strong earthquakes occur in the zones with conventional probability of $P(D1|K) \geq 70\%$ with the mean time of strong earthquake expectation equal to $Texp=3.40\pm1.27$ years, and in this case the average area of alarm zones makes about 30 per cent of the observation area.

Potentialities of MEE method (Map of Expected Earthquakes) were studied to predict earthquakes in real time (by the example of Greece) and strong dynamics events in the settings of an operating mining enterprise (by the example of PO "Apatit", Kola peninsula). Formalized methods were elaborated to study the process of seismicity localizing in the areas of strong earthquakes preparation. With the use of these methods this phenomenon was revealed in the preparation process of a number of strong earthquakes in Kamchatka. In the conditions of seismically active regions of Kamchatka and the Caucasus, it was established for the first time that destruction process goes on from one scale level to another, which was only observed in laboratory before.

Comparative research was conducted in the effects of magnetic storms influence on seismic activity in the regions having different geological structure. It was established that the same time interval of activity delay for 3-5 days after a storm was characteristic of the Caucasus, Middle Asia and South California.

In seismically active regions, research was conducted into the time structure of geophysical fields variations of different nature: volume deformations, apparent resistance, radon concentrations, inclinations and relative vertical displacements. The structure description is given in terms of rhythmic variations and random component. Assessments show that the observed chaotic variations can be grouped with processes caused by variations of a small number of physical factors that interact in non-linear way. It is shown that the studied time series can be classed into two groups by their fractal dimension (dimension of realization). The first group is characterized with dimension values of 1.5-1.9 and contains geophysical fields that directly of indirectly reflect the deformation process in the lithosphere. The second group series are of various physical characters (electrical conductivity, radon concentrations and others). They are characterized with dimension values of 2.7-3.5. We can use the obtained results to study the nature of geophysical fields variations and to develop approaches, methods and algorithms to reveal prognostic anomalies.

In the area of Altai seismological test site, new data were obtained on the structure of the zone of an active dislocation with a break in continuity (Karaiskii fault branch area). The research results testify to variation of a number of physical characteristics (elastic wave velocities, electrical specific resistance) associated with Chuiskoye earthquake, the strongest in Russia in 2003. A representative picture of seismicity was obtained beginning with M-1.5 in the radius of up to 40 km and with M-0.5 in the radius of up to 100 km, which is lower by 2-3 than the representativity characteristic provided by the regional seismological network of the Geophysical Survey of the Siberian Branch RAS.

Records of high-band stations IRIS Petropavlovsk-Kamchatskii, Yuzhno-Sakhalinsk, Magadan, Yakutsk, Obninsk were studied before Kronotskoe earthquake in Kamchatka with the use of different programs of processing and analyzing time series. Intervals are noted of stable manifestation of one or several periods of microseisms (synchronization intervals). Asymetric oscillations of relaxation type were revealed before Kronotskoe earthquake; they appeared 5 days before the earthquake and 3 days before the intense foreshock activation. The amplitude of oscillations at this station exceeds for an order of magnitude the level noted at other stations, which testifies to the source location in the seismically active Pacific area. One hour before the earthquake, the period of 37 minutes is pronounced. Intervals of oscillations synchronization as well as foreshock activation are indicative of unstable conditions of the seismically active area.

From satellite altimetry data, it was shown that the linear trend of the ocean surface in the area, where disastrous Sumatranskoe earthquake of 2004 had been prepared, had undergone changes several years before the event. It was proposed that this effect might have been related to the geoid variation caused by the deformations of the Earth's crust in the earthquake preparation.

The evolution of views on the concentration criterion for solid body destruction was discussed in relation to the use of the criterion in the physics of earthquake source to predict strong seismic events. We analyzed results obtained from testing of many years the parameter of seismogenic faults density Kav as an earthquake precursor in different seismically active regions of the world and thus we obtained experimental data on its efficiency to predict earthquakes. Possibilities of using parameter K_{av} to predict rock bursts and volcanic eruptions were demonstrated.

On the basis of kinetic views on solid bodies strength and constructed models of earthquake preparation, criteria of the formation of the process source stage were formulated and experimentally tested. Three major indicative features of macro rupture preparation were distinguished: acoustic (seismic) lull in the zone outward the source; foreshock activation in the inner zone; growing share of clustering events (foreshock clustering). Significant features of seismicity were revealed in the near-fault (inner) zone and in the neighbouring zones. One of them is as follows: with lull developing in the near-fault zone it is not noted in outer (lateral) zones. The other feature is the fact that with foreshock activation in near-fault zone the lull is noted in outer (lateral) zones.

Spectra were analyzed of geophysical series variation of different nature registered in a seismically active region (Northeastern China). Factual assessments of time variation spectrum density were obtained in a wide spectrum range, which in some cases amounted to frequency range of up to 7 orders. Flicker-noise character (piecewise in twofold logarithmic scale) of the geophysical

fields variation spectra was corroborated. Spectral density scaling ranges (linear fall in twofold logarithmic scale) were established for series of different characters.

To study the physics of earthquake source we analyzed parameters based on correlating values of the moment of earthquake beginning (determined from data on first arrivals) and results of defining seismic moment characteristics, which describe "mass center" of the source process. On the basis of this analysis new empirical correlations were revealed that characterize differences of source process features in different PT conditions. Thus it was revealed that as the depth of source was going deeper, the characteristic duration of the source process and a relative contribution of more low-frequency components in seismic emission increased. Such changes correspond to depth ranges of assumed solid-state transformations of matter and in doing so these depth ranges are also distinguished for a relative growth of earthquakes number.

Records made by wide-band stations IRIS Petropavlovsk, Yuzhno-Sakhalinsk, Magadan, Yakutsk, Arti and Obninsk before Kronotskoe earthquake of M=7.7 in Kamchatka on 05.12.1997 and before Neftegorsk earthquake with M=7.0 in Sakhalin were studied with the use of interactive program "Spectra_Analyzer" to analyze the characteristics of scalar time series. It was discovered that stations nearest to the sources of the earthquakes registered pulse oscillations several minutes long and divided with intervals of several tens of minutes 5-10 days ahead of shocks. As the moment of earthquake was approaching, the asymmetry of impulse form characterized by different amplitude of phases of positive and negative polarity was getting more pronounced and frequency and regularity of pulse sequence were increasing as well. Besides, microseism fluctuations were analyzed with the use of the evolution assessments of their multifractal spectra of singularity. Values of alfa that is the generalized Herst indicator, which realizes singularity spectrum maximum, were taken as an indicator characterizing background features in the current time window. Transition was made from the analysis of initial high-frequency seismic records to combined analysis of low-frequency time series of alfa-variations at several stations. By assessing the evolution of the spectral measure of alfa-variation coherent behavior in sliding temporal window of 5-day duration, we revealed hidden effects of variations of microseism field synchronization before a seismic event for various combinations of stations. It is assumed that the nature of phenomena is related to self-organization of seismic process in metastable lithosphere and to synchronizing oscillations in the inner and outer spheres of the Earth whose dynamics has both random and quasiperiodic constituents.

Microseism records were studied of 5 wide-band stations IRIS located at a distance of 1-2 thousand kilometers from the earthquake source of 26 December 2006 in Sumatra. To reveal hidden periodicities, signal coherence at different stages, asymmetry in oscillation amplitudes specially adjusted programs were used. Sixty hours before Sumatra earthquake in the records of some stations periodic oscillations were revealed in the period range from 20 to 60 minutes, which had appeared after Makkuori earthquake and had lasted twenty-four hours. Fifty-three hours bafore Sumatra earthquake synchronization of oscillations started at the stations and went on until the moment of earthquake, and in this case prevailing period gradually lengthened from several minutes to tens of minutes.

We put to the test algorithms and programs elaborated by the authors to reveal stages that are of prognostic significance before a strong earthquake such as seismic lull, foreshock activation and clustering of sources. Before the strong earthquake with M 8.2 of 15 November 2006 in Curil Islands, the seismic lull anomaly appeared in 2002. Information about a likely earthquake in the anomaly area was sent to the Russian Expert Council for earthquake prediction at the Ministry for Emergencies of Russia beforehand. After the stage of seismic lull was completed, foreshock activation started. Finally, 1.5 months before the earthquake in the source area, clusters were formed of weaker earthquakes with magnitudes ranging from 4 to 6. Program developed in 2006 to calculate the time and magnitude of a future earthquake on the basis of formalizing critical acceleration of seismicity had an error of one week in the definition of main shock time and of 1.3 in the definition of magnitude. Similar results were obtained with the use of retrospection before Kamchatka and Sakhalin earthquakes with magnitudes more than 7. Thus it is demonstrated that the earthquake

preparation process is not purely random and there is a possibility of separating a determined component that may be described with analytical equation. This fact strengthens physical grounds for earthquake prediction.

It was proposed that time factor should be included in the maps of general seismic zoning. As a possible approach to putting this idea to practice, we propose using algorithm MEE (map of expected earthquakes) accepted for medium-term prediction of earthquakes.

Applicability of RTL algorithm for different regions was studied by the example of Iran, Northeastern China and Northwestern India). It was shown that in different regions and with initial data catalogs that are not equally detailed the algorithm is efficient even if a standard set of parameters is given. A more precise adjustment of the algorithm allows us to improve the contrast range and in some cases to make anomalies more detailed but the general pattern does not change.

Theoretical studies

A phenomenological theory of the earthquake formation process was proposed for the case of earthquake preparation outside the zone of existing fault. In this case, by the area of potential source of an earthquake Ws the area is meant where the process goes on of self-organization of destruction. It was believed that it was in the area Ws that fissures interaction resulted in the growing probability of the environment fissuring development as compared to it in random process, all other things being equal. The theory describes the environment evolution averaged over time and space.

General models of the generation of exponential (self-similar) distributions typical of the seismicity case were considered and statistics research of recurrence plot character was conducted to reveal deviations of recurrence empirical plots from Guttenberg-Richter law. The presence is shown of weak log-periodic variations of earthquake number of unknown character and recurrence plot deviation from Guttenberg-Richter law was corroborated in the area of uncommon strongest events. Methods were proposed for robust parameterization of such deviations and the significance is discussed of taking such deviations into account to assess values of long-term seismic danger.

Research was carried out in the variations of seismogenesis character in relation to thermal dynamic conditions with the use of new factual data (earthquake moment catalogs) and source parameters that had not been used before (differences of time moment and source depth from first arrivals data and seismic moment solution); the depth dependence of mean parameters of the source was considered. New correlations were revealed between the source parameters; in particular, the obtained correlations suggest the presence of fluidal phase of low density in the source.

The model matching multiracial fields scaling was studied. The results show that the methods of classical correlation analysis may prove to be inapplicable to the studies of interactions between real multiracial structures (for example fault and seismic structures) first because correlations between structures are realized in points that do not form coherent sets and second because in the structures of fields with matched scalings these points can form fractal sets with different fractal dimensionalities. It is demonstrated that in the general case the relationship between singularity indexes of one field and singularity indexes of the other field is non-monotonous and ambiguous.

In the frame of the theory that considers an earthquake as a critical point, a new precursor of strong earthquake preparation is proposed on the basis of the analysis of weak earthquakes correlations in the area of strong earthquake preparation.

The model of matching multifractal fields scalings is extended to the case of arbitrary number of natural self-similar fields that characterize the area of tectonic earthquake preparation. Thus the model of matching scalings took the character of the model of structural organization of multifractal fields of the Earth's crust in the focal area of the earthquake under preparation.

New approaches to the analysis of time geophysical series were elaborated from the viewpoint of the theory of non-linear dynamic systems. The emphasis on the use of non-linear dynamics approaches to the analysis of combined geophysical fields is for the major part associated with clear physical sense of the assessed dynamic parameters. Their values allow us to estimate model regularities of behavior of the phenomena under investigation. Dimensionality of dynamic system phase

space belongs to parameters of this kind. The possibility of assessing it from the single time realization of geophysical field is considered at the present stage by an example of prolonged observations of apparent electrical resistance and relative vertical shift of the surface. The method of parameter assessment is based on the concept that the assessment may be obtained from the analysis of dispersing velocity variation of close phase tracks in the space of various dimensionalities of embeddings. The assessment of equivalent phase space dimensionality makes 7-8 for variations of apparent electrical resistance and it is 6 for shift variations. These values can serve as the assessment of independent variables forming the pattern of the field behavior. To assess the coherence degree of resistence and shift dynamic systems we calculated phase space dimentionality of variation pairs: apparent resistence in different directions measured at the same point and apparent resistance and vertical relative shift measured at observation points set up at a distance of approximately 150 km. The obtained assessments suggest a single dynamic system describing the behavior of apparent electrical resistance in two perpendicular directions. The elaborated methods and obtained results can be used to construct models of complex geophysical processes and develop new approaches and methods to distinguish prognostic characteristics of the behavior of physical fields of different nature.

The model of Self-Similar earthquake-generating Structure of the Earth's crust (SSS model) was elaborated that is intended for the studies in the structural organization and interrelations of different geophysical fields in seismically active regions. The model is based on the concept published before concerning matched scalings of real scale-invariant fields among which fault, seismic and seismic energy fields are major. However the model is open for including new fields of unlimited number and of different physical character (for example permeability fields or vertical shifts of the Earth's surface), for which representative experimental data are nor available for the present. Real seismotectonic structures are modeled with multifractal fields with matched scalings, which allows us to reveal the common structural organization of different physical processes going on in earthquake-generating environment. Three-dimensional analytical apparatus of the model was constructed and a program package was written to analyze digitally the cases that cannot be solved analytically. With the use of the model the nature was explained of the interrelations between fault, seismic and seismic energy fields which are not described with Euclidean geometry but with fractal geometry methods and it was shown that exponential relationship (Guttenberg-Richter law) is noted not between the earthquake finite sample and their energy but between seismic field and seismic energy field. In a more general case, exponential dependencies with fractional exponents are evidently noted in relations between any self-similar fields in seismically active regions, which may be considered as a feature of the common structure of non-equilibrium physical processes being elements of one natural system and resulting in earthquakes no matter what their specific nature is. Owing to this fact, the charactertistics of local self-similarity of different physical fields in seismically active regions (indexes of singularity) may have a linear relation, whereas statistics characteristics of fields i.e. their spectra of singularity may be transformed into one another with the use of affine transformations of the argument. Model SSS allows us to interpret actual data by fields of different physical charactertistics with the generality level greatest at present.

We began to develop a model of seismic macro rupture formation from large numbers of microfissures appearing in rocks under mechanical stresses, high temperatures and prolonged deformation. With fractal spatial distribution of microfissures and if the concentraion criterion for enlargement of fissures (Zhurkov-Kuksenko criterion) is met, conditions may be formed in which multiple hyerarchic enlargement of fissures occurs, which may result in a macro rupture formation. The deduced formulas allow estimating such parameters of rock destruction as correlation of lengths of emerging fissures and fissures formed as a result of their one-stage emerging; the number of fissures emerging into one at one hierarchic stage of emerging; the number of hierarchic stages of emerging from micro fissures to macro rupture; relation between concentration criterion and fractal dimensionality of fissure class, which is required for avalanche-like multiscale emerging of fissures and others. The model of seismic macro rupture formation from fractal set of micro fissures at the expense of their hierarchic large-scale emerging shows that conditions of avalanche-like

emerging of fissures might be fulfilled even if the total length of starting-point micro fissures of the initial scale-level tends to zero, i.e. in undisturbed material.

Stochastic model of multiplicative cascade was used to model seismic conditions treated as a sequence of episodes of avalanche-like processes relaxing conditions of systems that are non-equibilibrium in thermodynamic sense. The model includes a number of parameters and is described in the output as a set of values of events (earthquakes) at successive time intervals. It was shown that in the frame of this model, the variation of the system parameters leading to the probability increase of strong events occurrence at the same time leads to a decrease of the recurrence plot inclination. To compare modeling results with empirical data an averaged vicinity of a strong earthquake was formed from Harvard catalog data. It was demonstrated that anomalies revealed in such vicinity and related to moments of strong events formation are of long duration and persist even after the moment of a strong earthquake. Thus empirical data apparently give a result similar to the result obtained with the model. We study the obtained data to see if deterministic and stochastic approaches to earthquake prediction could be used successfully.

Analysis of laboratory experiments data

Regularities of seismic regime relaxation were revealed from full-scale and laboratory data. The analysis of laboratory modeling data on relaxation process with destruction of rock samples showed that the same statistical regularities of relaxation are observed with other methods for disturbing destruction conditions when the source of major event is lacking. Timing and location of acoustic event sources in the experiments allowed us to study the features of acoustic events successions. They appeared to have the same features as aftershock successions of earthquakes: decrease of activity according to Omori law, increase of b and decrease of d. The obtained results suggest that the presence of the main event is not a necessary condition of forming relaxation processes similar to aftershock successions.

Experiments were made on deforming a model of quartz sand, granite crumb, and cement with two-axial compression. During the experiment of several months, with quasistatic layer of applied stress, the model was periodically subject to elastic impulse irradiation and water injection. It was established that the both types result in sharp activation of acoustic emission. The form of seismograms and recurrence plots of acoustic signals registered before and after affecting the model do not differ significantly, which suggests the trigger character of the phenomenon. The distribution of acoustic signals energy after affecting the model is similar to the activity in earthquakes swarms in qualitative sense, and in this case the influence of these factors on seismicity is not ruled out. Different types of distribution in time of the induced acoustic activity are described with the equation known from the kinetic theory of strength if activation energy and acting stresses are time-dependent.

Features of acoustic emission generation were studied in rock samples with all-round compression of 160 MPa and deformed with constant velocity of 10^{-7} l/c by uniaxial load, which is modulated by sinusoidal oscillations. Samples with preliminary formed surface of inner destruction were used on which unstable stick-slip phenomena are realized. The external force application period was 160 and 570 s and the amplitude reached first hundredths with respect to maximum load. Catalogs of acoustic events were analyzed that contain tens of thousands events in the energy range of three orders. In the first approximation the experiment is considered as a model of changing seismic conditions under the effect of natural periodic processes.

To analyze time characteristics of acoustic emission in laboratory samples we used algorithms for searching hidden periodicities. As the first result, it is shown that periodic synchronous response AE is formed in the samples the intensity of which dramatically varies with time. It was revealed that the most marked reaction of the environment on the external force is observed in the period immediately after stick-slip phenomena. We assume that it is caused by greater strain-sensitivity of the environment during “aftershock” acoustic activity, when the environment is in unstable and metastable state.

The analysis of mine seismicity data

Major regularities were established of time and space development of anthropogenous seismic processes in Verkhnekamskoe deposit of potassium salts. We studied the influence of the method of processing and filling worked-out areas on the level of anthropogenous seismicity for potassium mines conditions. Correlation was established between microseismic activity in underworked massifs of potassium mines and surface subsidences. Time-delay value between seismic processes and processes of the earth surface subsidence was determined.

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7.2. Studies in the influence of small perturbations of stress and strain of the Earth's crust on the evolution of deformation processes

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One of the lines of research, which traditionally attracts interest in Russia beginning with pioneering work of Academician M. A. Sadovskii, is aimed at the studies of possibilities of remote control of deformation processes in a rock mass.

In the last fifteen years, convincing facts were collected about earthquakes and other dynamic events initiated by seismic waves, which makes seismological community less sceptical to such a possibility.

In 2003-2006, several teams of researchers carried out work in this field in Russia.

Scientists of the Siberian Branch of RAS and first and foremost of the Institute of the Earth's Crust RAS and the Institute of Strength Physics and Materials Technology RAS study the dynamics of movements in active fault zones with the use of deformation-measuring monitoring and technogenic effects on the fault zone [Ruzhich et al., 2003; Psakhie et al., 2007].

The most interesting results were obtained in field experiments conducted on a fragment of Angara fault zone in 2004. As a result of local effects on the fault with the use of small explosions in boreholes, vibrations and artificial flooding, continuous displacements of banks were initiated of the amplitude up to 10 mm (Fig. 7.1) accumulated during two weeks, which is many times over the average rate of creep. Experiments on a larger scale were carried out in mining enterprises where the process of initiating displacements in faults and fissures with high-volume industrial explosions was studied.

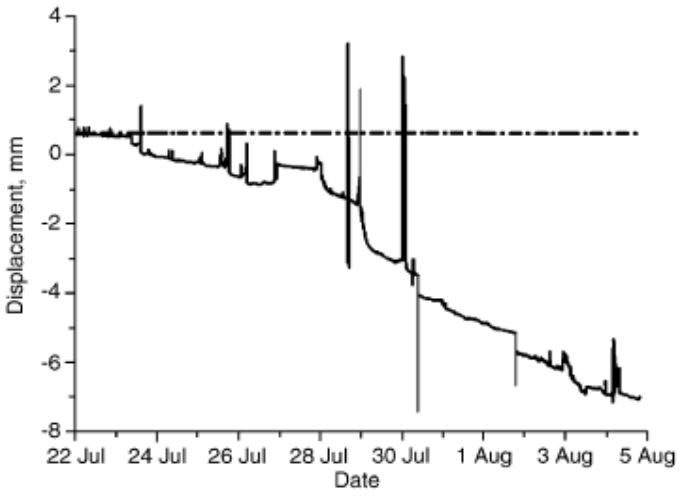

Fig. 7.1. Strike-slip faults registerd in Angara fault zone in experiments in 2004. Dot-and-dash line showes averaged data on the previous two years [*Psakhie, Ruzhich, Shilko et. al., 2007*].

The general result of the experiments is the demonstration of the possibility of continuous increase of fault zone deformation velocity under technogenic effects, which, as the authors believe, results in the release of a part of energy accumulated in the rock massif. It is noted that after the experiments carried out on a fragment of Angara fault in 2004, this section has remained discharged for a long

time, which is supported by its considerably weaker response to effects of different types and intensity, that were used in 2005-2006.

Regularities of formation, development and interactions of boundaries between blocks were studied by the same team on the example of the ice cover of Baikal Lake, which is a hierarchic block medium [Psakhie et al., 2005; Dobretsov et al., 2007]. It was shown that relative displacements of blocks might be initiated or speeded up in the direction determined by local field stress, which probably suggests that the obtained results are common for block media of different character. In 2006, a Patent of the Russian Federation was obtained for the method of controlling displacements regime in fragments of seismically active tectonic faults [Psakhie et al., 2006].

In model experiments carried out in the Institute of the Geodynamics of Geospheres RAS, we demonstrated the possibility of macro displacements on the boundaries of structural blocks with weak vibration affecting block medium. It is shown that either the regime of dynamic breakdown or the regime of gradual accumulation of deformation, which are two possible regimes of deformation, is realized according to stress-strain state of the environment and time and amplitude characteristics of the vibration. In the former case, weak vibrations play the role of trigger mechanism, whereas in the latter case considerably large levels of displacements may be reached with almost constant velocity of deformation [Kocharyan, Spivak, 2003]. The mechanics of initiating interblock displacements with dynamic impulses is studied in detail in the experiments. It is shown that in strained block medium the relative movement of blocks is observed during rather a long time, which is many times as long as the initiating vibration time. The contribution of "slow motion" into the integral value of accumulated deformation can be considerably large. In weak-strain contacts, dynamic component prevails, and as static load is approaching the contact ultimate strength, the amplitude of slow motion may greatly exceed initiating dynamic displacements [Kocharyan et al., 2004].

Results obtained in experiments invite elaboration of mechanical models explaining low-amplitude effects of the conditions of rock mass deformation. In Coulomb's criterion for strength, the necessary condition of residual displacement appearance is the excess of static and dynamic stresses total over ultimate strength of continuity break. Otherwise deformation accumulation in interblock contact does not take place and this is the most common case.

One of the key moments in the description of small deformation accumulation process is adequate description of interblock contacts deformation process. In a number of papers devoted to research in characteristics of the Earth's crust continuity break, a new non-linear model of block medium was elaborated on the basis of laboratory and field experiments. According to this model, both normal and shift rigidity of faults and fissures decreases as the amplitude of dynamic effect increases [Kocharyan, Spivak, 2003].

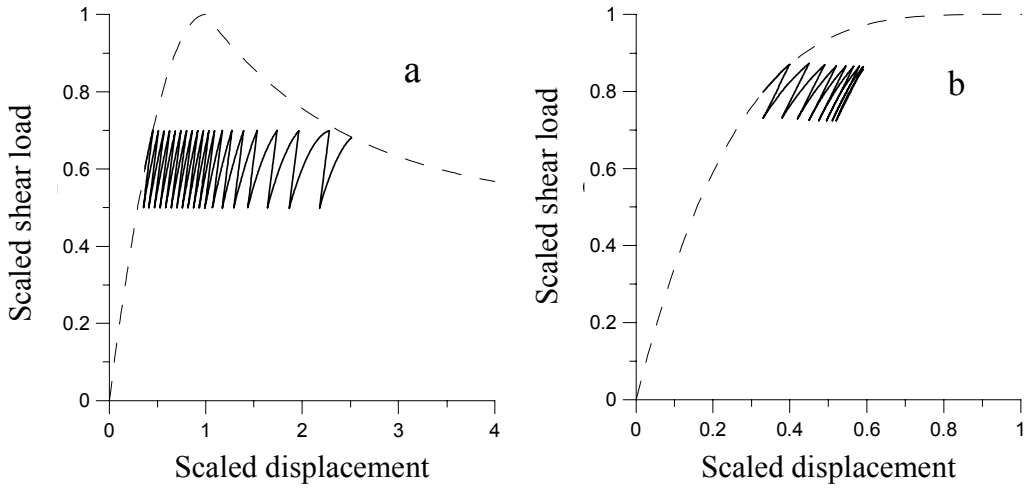

Fig. 7.2. Examples of computation of cycle loading of contact with dynamic impulse.
a – after cumulative value of accumulated displacement exceeds limit value, the after-displacement value gradually grows;
b – computation with account for rigidity growth with repeated loading. Residual displacement decreases wuth each following cycle of loading [*Kocharyan et al., 2006*].

The elaborated model shows that accumulation of interblock deformations in stressed contact is possible with any amplitude of dynamic effect, which is a direct consequence of stress-deformation non-linear characteristic. The account for gradual growth of contact rigidity with repeated cycles of loading and unloading results in the fact that the contact "gets accustomed" to the level of dynamic effect (Fig. 7.2). By this is meant that the threshold of effect on block medium is apparently oscillations with amplitude considerably exceeding the level of microseismic background in the corresponding frequency range [Kocharyan et al., 2005; Kocharyan et al., 2006; Kocharyan et al, 2006].

Digital modeling of fault deformation processes with the use of method of mobile box automated devices [*Psakhie et.al., 2007*] and theoretical description of the process [Filippov et al., 2006] allowed us to substantiate the possibility of shift stick-slip regime transfer into viscous flow regime, i.e. to change the statistics of generated earthquakes, so that the number of weak shock increases instead of high-energy earthquakes.

Some authors believe that another kind of geophysical field disturbances that can affect the character and structure of seismicity is powerful electromagnetic impulses affecting the Earth's crust.

It is noted that strong electromagnetic impulses by magnetogas dynamic generator (MGD generator) show statistically significant influence on seismic conditions of Pamir and Northern Tien Shan. MGD generator was used as a source to work on deep electric sounding of the crust in Garm and Bishkek test sites. Detailed studies of seismicity of Northern Tien Shan showed that electromagnetic impulse effect of MGD generator results in deep and prolonged change in the seismic process of the area under investigation and abutting areas. During a series of experiments with impulse MGD generator, the relative share of weaker seismic events, seismic activity of the area and clustering increase. [*Tarasov, Tarasova, 2004; Avagimov et al., 2006*].

At present in Bishkek geodynamic test site, electromagnetic monitoring is carried out with the use of specialized strong-current source, that is electrical prospecting generator (EPG) giving current of 600 A in dipole. Preliminary results show that we observe in these experiments the electrical sounding initiating influence on weak seismicity increase (Fig. 7.3) [Bogomolov, Sychev et al., 2005; Velikhov et al., 2006].

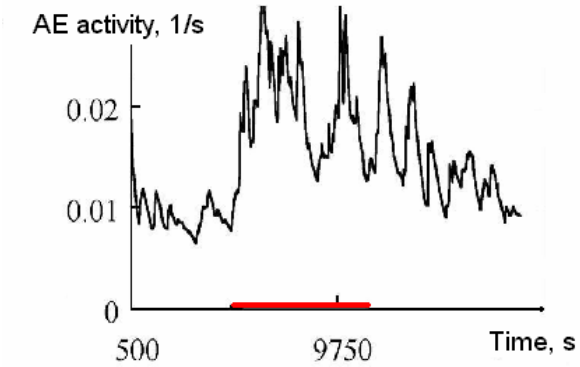

Fig. 7.3. Variation in acoustic emission of halite sample under the effect of electrical impulses during 6000 s. The affected area is shown with a segment in the axis. [*Bogomolov et al., 2004*].

It is suggested that electromagnetic impulses generated by MGD generator result in the release of energy accumulated in the crust in the form of small seismic events. To study likely mechanism of this phenomenon laboratory experiments were carried out in which electromagnetic influence on the velocity of defect formation in rock samples and model materials was studied. Load ranges were defined experimentally, in which the stimulation of acoustic emission (AE) with electric impulses appeared efficient. Thus in samples without piezoelectric properties, this range corresponds to dilatancy stage of deformation. In piezoelectric samples AE electrical excitation is observed beginning with smaller levels of stress. It was revealed that the effect of combined electrical and magnetic fields leads to greater increase of AE than in case of activation with either electrical or magnetic field. It was demonstrated that the structure of induced acoustic response could be changed or formed if we vary parameters of energy action [Sobolev, Ponomarev, 2003; Bogomolov, Il'ichev et. al., 2004, Bogomolov, Zakupin et al., 2004].

While physical model of the phenomena is to be developed, the obtained results nevertheless provide the ground for the studies of seismic acoustic and electrical interactions and development of algorithms of controlling such processes including seismicity regime change and release of elastic energy accumulated in the medium.

As for the prospects of developing methods of controlling deformation processes in a rock mass, we note that in spite of apparent difficulties in technology and management, when working on such projects, progress in ideology that was made in the last few years gives hope for further development of this line of research. Specifically it seems promising that radically new technologies be developed involving prolonged influence on a rock mass and combining high energy saturation characteristic of explosion and possibility of repeated actions as in vibration systems. [Kostyuchenko et. al., 2003].

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8. Study of Induced Seismicity and its Monitoring

8.1. Study of Induced Seismicity

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The problem of «Induced Seismicity» was investigated mainly in the institutes of the Russian Academy of Sciences and the Ministry of Natural Resources of Russia, dealing with basic researches on impact on seismicity of technogenic factors and mutual impact of natural processes, proceeding in the Earth's shells - lithosphere, hydrosphere and atmosphere. A part of these researches is focused on prediction of earthquakes, monitoring processes of oil and gas production, fossil minerals, impact of the tanks formed as a result of creation of high-altitude dams, pumping of liquid industrial waste in layers-collectors. Alongside with studying the influence of separate technogenic and natural impacts on seismicity and processes of preparation of strong earthquakes, last years of research in many respects are focused on studying of cumulative impacts of initiating factors of various physical nature on a discharge of tectonic pressure by earthquakes.

Let's consider the results of research of technogenic impact on seismicity, natural factors and natural-technogenic influences.

Technogenic impact on seismicity

Let's consider the impact of the following technogenic factors: construction of large dams and water reservoirs, oil, gas and solid fossil minerals recovery; seismic impacts, impact of vibrations and impulses.

Large dams and reservoirs impact on seismicity. Gravitational load of water on a bottom, canyon edges and body of a dam creates constant loading and deformations in a vicinity of a dam, provokes increasing infiltration of water in the field of an arch dam inlets in a canyon. Constant deformation, seismic and acoustic monitoring of the Chirkeyskaya dam and Sayano-Shushenskaya hydroelectric power station helps to estimate stability and safety of operation of dams, to appreciate the danger of occurrence of strong earthquake in the dam's area and water reservoir, to estimate the danger of occurrence of a large landslip threatening by appearance of a seiche and water inrush over the dam. Such observations are going on at the Chirkeyskaya dam and Sayano-Shushenskaya hydroelectric power station, where on the basis of data registration of geodeformation processes and seismoacoustic emission the condition of the dam is examined; according to seismic and complex geophysical and hydrogeodynamic data the danger of occurrence of strong earthquake in the vicinity of the dam and water reservoir is also estimated.

The Institute of Physics of the Earth has elaborated the method of estimating danger of occurrence of induced strong earthquake on the basis of complex geophysical, geodetic and hydrogeodynamic measurements data processing. Such system is designed and during 5 years is carrying out continuous observations at the Sayano-Shushenskaya hydroelectric power station. Thus, complex geophysical and geodynamic monitoring solves the two tasks: controls the dam's condition and environment, estimates seismic danger and in accordance with these estimates provides recommendations concerning the choice of optimal safe regimes of the reservoir's exploitation.

Oil and gas production. Oil and gas production activates dynamic processes in the field of deposits and in the nearest part of the medium. Exploitation of fields, artificial impacts on a rock bed with the purpose of oil recovery increase is reflected in sharp amplification of seismoacoustic emission, redistribution of pressure and deformations both in a body of a deposit, and in the environment - above a deposit, under a deposit, especially near to a sedimentary layer's border and the crystal base, in the top part of the Earth's crystal crust. The study of induced earthquakes has shown that the strongest of them have occurred in the upper part of the Earth's crust, their preparation took 10-30 years from the moment of the start of deposits recovery. Presently the investigation of the strongest induced earthquake of the last years continues – of the Neftegorsky earthquake in 1995. Strong induced earthquakes, occurring in the upper part of the Earth's crust, are prepared as natural tectonic events and most probably obtain the same number of precursors.

The experience of research indicates that the most considerable loss is related to induced geodynamic processes, connected to oil and gas extraction – by slow movements alongside the faults, crossing the wells and destroying them. The task of mitigating loss, related to induced geodynamic processes requires continuous monitoring of the seismoacoustic emission, accompanying tectonic faults activation and deflected mode redistribution.

At present time the research of seismicity, induced by oil and gas recovery is concentrated in the institutes of the Russian Academy of Sciences – the Institutes of Physics of the Earth, of Oil and Gas Problems, Dynamics of Geospheres, and in a number of companies, dealing with oil production in Tatarstan. Besides the nature observations, theoretical research and laboratory modeling are being carried out.

Artificial seismic impact. Artificial seismic impacts on seismicity and strong earthquakes centers embrace a wide range of impacts intensiveness and their character (spectral distribution, other inducing signals parameters). Inducing impact of nuclear explosions was investigated by the group of scientists of the Institute of Physics of the Earth and the Institute of High Temperatures RAS. It was discovered that during the period starting from 1964, the beginning of nuclear tests, up to 2005, the number of earthquakes with magnitude exceeding 8.3 has decreased dramatically: the first strong earthquake after the moratorium (1988) was the Sumatra earthquake on 26 December 2004, with magnitude more than 8.5, followed by gigantic tsunami. This experimentally established fact indicates that nuclear tests, taking place during almost 25 years in testing areas of Nevada, Semipalatinsk, Novaya Zemlya, Lobnor have dramatically diminished the tectonic tensions and decreased the seismicity level of strongest earthquakes on the globe. It was established that earthquakes and nuclear explosions considerably differ in their capability to induce immediately (in 24 hours) a strong earthquake. The character of initiating impact of powerful electric impulses of MHD generator on medium and weak earthquakes was investigated. It was established that electric impacts entail the increase of seismicity level, continuing during a week and occurring on the 2-3rd day after the impact. The range of effect is about 300 km. Research of influence on seismicity of mass bombings during the local wars in Yugoslavia, Afghanistan, Iraq has revealed their initiating influence on the weak and moderate seismicity, long-range action of effect more than 500 km (Institute of Geoecology of the Russian Academy of Sciences).

Weak continuous vibrations, produced by seismic vibrators, acting on the oil pool from surface, induce the seismoacoustic emission, that in its turn induces processes, related to oil recovery. These effects were investigated by several groups of researchers of the Russian Academy of Sciences and oil companies of Russia – the Institute of Physics of the Earth, Institute of Oil and Gas Problems, Institute of Geology of Siberian Branch of RAS, Institute of the Russian Gas.

Natural processes impact on seismicity

Let's consider the impact of the following factors: terrestrial tides, change of the Earth's rotation velocity, strong earthquakes, storm microseisms, ionospheric phenomena, extreme weather phenomena – storms, typhoons.

Much attention is usually paid to terrestrial tides' influence on seismicity. This research is mainly fundamental, partly belongs both to applied studies and to practical matters – earthquakes prediction and seismic danger.

Inducing of strong earthquakes and seismicity by a terrestrial tide. A big number of works is devoted to the problems of inducing earthquakes by vertical and horizontal tides. These works were held in the institutes of RAS and in educational institutions. The main results obtained after a detailed investigation of the problem, come to the following conclusions: induced seismicity reveals both in the increase and in the decrease of seismic activity, in the probability of a strong earthquake; seismic activity deviation from its mean value is mainly determined by a tense earthquake center; character of seismic activity response varies with time, this variety reflects natural variations of stress field and shows in the earthquake center specific variations anticipating strong earth-

quakes; depending on the frequency, acoustic emission reacts to lunar and solar component differently, it reveals both in intensiveness and in seismoacoustic response to the tide influence.

Inducing of earthquakes by typhoons. The observations in the area of Kamchatka – the Kurile Islands - Japan have established that typhoons initiate an increase of seismic activity of earthquakes of medium and weak magnitudes (the Institute of Geotectonics, Far Eastern Branch of RAS). This fact, viewed by seismologists with mistrust, was confirmed by the observations of storm microseisms impact on activity of earthquakes with medium magnitudes in the Kuriles area.

Directed influence of earthquakes zones with the purpose of decreasing the earthquakes magnitude. Observations of earthquakes, induced by natural and technogenic influences, show that anticipatory impact leads to occurrence of an "immature" earthquake of lesser magnitude, than a natural earthquake, which would occur later, had there not been a strong enough influence on it or a sum of influences. Actually, seismic, electrical impact can discharge by small foreshocks a part of tectonic energy, accumulated in the earthquake center and thus diminish the main impulse energy and the magnitude of destructive earthquake. Magnitude decrease by 0.3 leads to 1.5 reduction of loss in the magnitudes range of 0.65-0.75 of the earthquake center. The qualitative scenario of artificial impact on the center of incoming earthquake and combining technogenic and natural impact has indicated the feasibility of organizing special field and model investigations. The Institute of Lithosphere RAS has started the first experiments of seismic impact on seismically active area of the southern part of the Baikal rift zone. The program of artificial impacts by electrical pulses by MHD generator was developed by the group of institutes (Institute of High Temperature RAS, Institute of Physics of the Earth RAS, Institute of Oceanology of Far Eastern Branch of RAS), oriented on application of electric pulses impact on the seismically active zone of the Far East.

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8.2. Monitoring of Mining Seismicity

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In 2003-2006 the detailed study of technogenic seismicity was implemented in Russia at three mining enterprises – at the Verkhnekamsky potassium salts deposit, located in the Western Urals, and at the Khibinsky apatite-nepheline and Lovozersky rare-earth deposits, located on the Kola Peninsula. The researches were held by, correspondingly, the Mining Institute, Ural Branch RAS (Perm) and Mining Institute, Cola Scientific center RAS (Apatites).

Seismicity research at Verkhnekamsky potassium salts deposit

The Verkhnekamsky potassium salts deposit (VKPSD) is located on the territory of the Permsky Krai, 1200 km to the east of Moscow. Six mines are working on productive horizons (in sylvinite and carnallite zones), located at a depth from 140 to 420 m below the Earth's surface. All mines use room and pillar system of mining with the following parameters: length, width and height of rooms, correspondingly, 150-180 m, 3-15 m and 10 m, pillars width 3-18 m. Seismological observations on mines are carried out since 1995. [Malovichko *et al.*, 2005] using the monitoring sys-

tems, representing areal arrays of vertical seismographs SM3-KV, set in mines excavations and connected by cable telemetric lines with ground registration modules. Altogether in the VKPSD mines there are 34 seismic pavilions, monitoring the total mining area of about 150 km^2.

The operating monitoring systems regularly detect small local seismic events. The records of events, as a rule, contain P-waves packages and more intensive S-waves packages (Fig. 8.1a). The frequency range of signals is from 8 to 30 Hz. Seismic records processing includes detecting the centers location of events of P- and S-waves, estimate of the liberated seismic energy E_S, and also identification of type of event (technological explosion in a mine, natural event).

The processing results indicate that the centers of all events are located within the mining area. Given the fact that the seismic monitoring systems configuration at the VKPSD mines is close to the planar (the seismographs are set up in the horizontal mines), direct estimate of vertical coordinate of events of spatial mode is difficult. However, some parameters of wave forms (low amplitude of P-waves compared to S-waves on vertical seismographs, absence of high apparent velocities of seismic waves distribution through the seismographs' setting) give every ground to assume that the events are dated to excavations level.

On average, during a year in all VKPSD mines about 350 events with seismic energies from 100 J to 30 kJ are registered. Based on the data catalogues of events the seismic mining regime is examined, active zones are detected and dynamics of their development is analyzed. These data are taken into account at the planning of mining (in particular, it allows to correct the order of carrying out stowing operations).

An interesting peculiarity of seismicity, detected in the VKPSD mines, is the presence of a group of so-called *"low-frequency" events*, characterized by intensive surface waves of Rayleigh type(R) in the frequency range of 0.5–2 Hz (Fig. 8.1b).

Study of the events data has shown that their seismic wave forms would be problematic to describe in the framework of the classical mode of the center looking like a growing shear crack. For example, at Fig. 8.2 the results of seismograms modeling for a source looking like a flat round crack (the Sato-Hirasawa model) [Aki, Richards, 1983]. Calculations were made with the help of numerical integration method in the wave number area for the medium model as vertically heterogeneous stratified half-space, constructed according to geological-geophysical data. The lumped source, corresponding to the Sato-Hirasawa model, was placed at a depth of 280 m (over the excavations level). Fig. 8.2a shows the synthetic recordings of vertical components of shift velocities at the level of excavations (at a depth of 300 м) located at different distances from the source (1000 m, 2000 m, …, 5000 m), obtained for one of the center's variants (vertical crack with radius of 3 м, speed of growth – 2500 m/sec, shear tension fault – 5 MPs). Fig. 8.2b shows the amplitude spectra of these records.

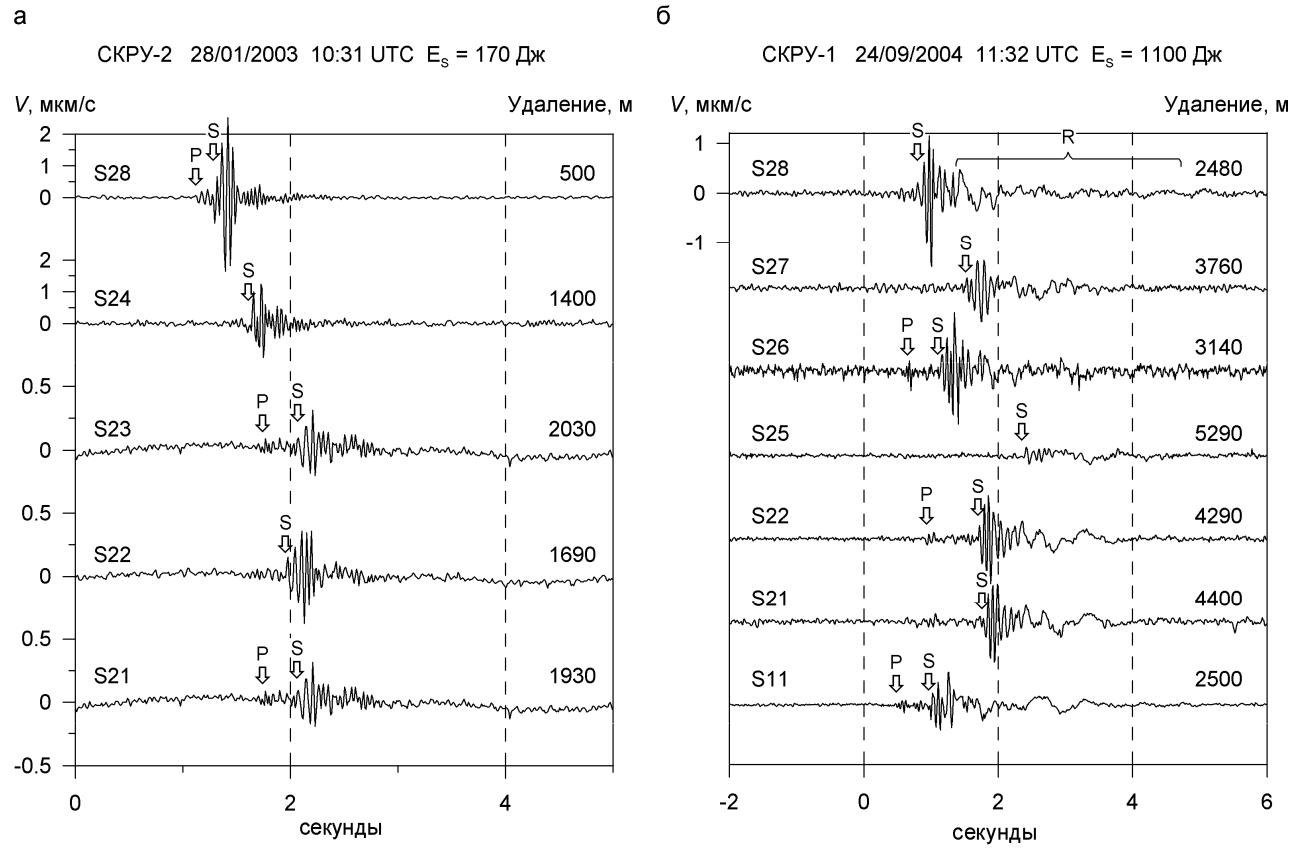


Fig. 8.1. Seismic events, recorded by seismomonitoring systems at VKPSD mines

As we can see, spatial mode records are domineering. The complex interferential character of these waves is caused by the presence of numerous horizontal contrasting borders in the medium model. The amplitude of surface waves is insignificant, they are detected only in the frequency band (at a range of 1-2 Hz). Similar features of synthetic records are kept at a wide variation of parameters of shift model of the center - orientations of the motion plane, of the radius (up to 10) and speeds of the crack growth (from 100 up to 2500 km/s). Thus, *the classical shift model of the center does not reproduce a wave picture, characteristic for "low-frequency" events on VKPSD*.

As the potential centers of "low-frequency" events the following dynamic phenomena detected in potash mines [Malovichko, 2005] also have been examined:

- fragile pillar failure (Fig. 8.3a);
- local roof rock failure(Fig. 8.3b);
- dynamic roof rock or sole failure (Fig. 8.3c).

For these dynamic processes the seismograms modeling was also implemented. As a result, the greatest similarity to "*low-frequency*" events records has been detected on model siesmograms, received for local rock failure. For example, Fig. 8.4 shows the synthetic records and their spectra corresponding to 50 tones rock failure in the room 6 m. high.

Thus, the carried out modeling of seismic radiation of potential source processes in the in VKPSD mines has shown that the most probable source of "*low-frequency*" events are local rock failures, occurring in the mines.

For the investigation of centers of "*low-frequency*" seismic events another method was applied, based on the reconstruction of parameters of centers on surface waves. This method is widely

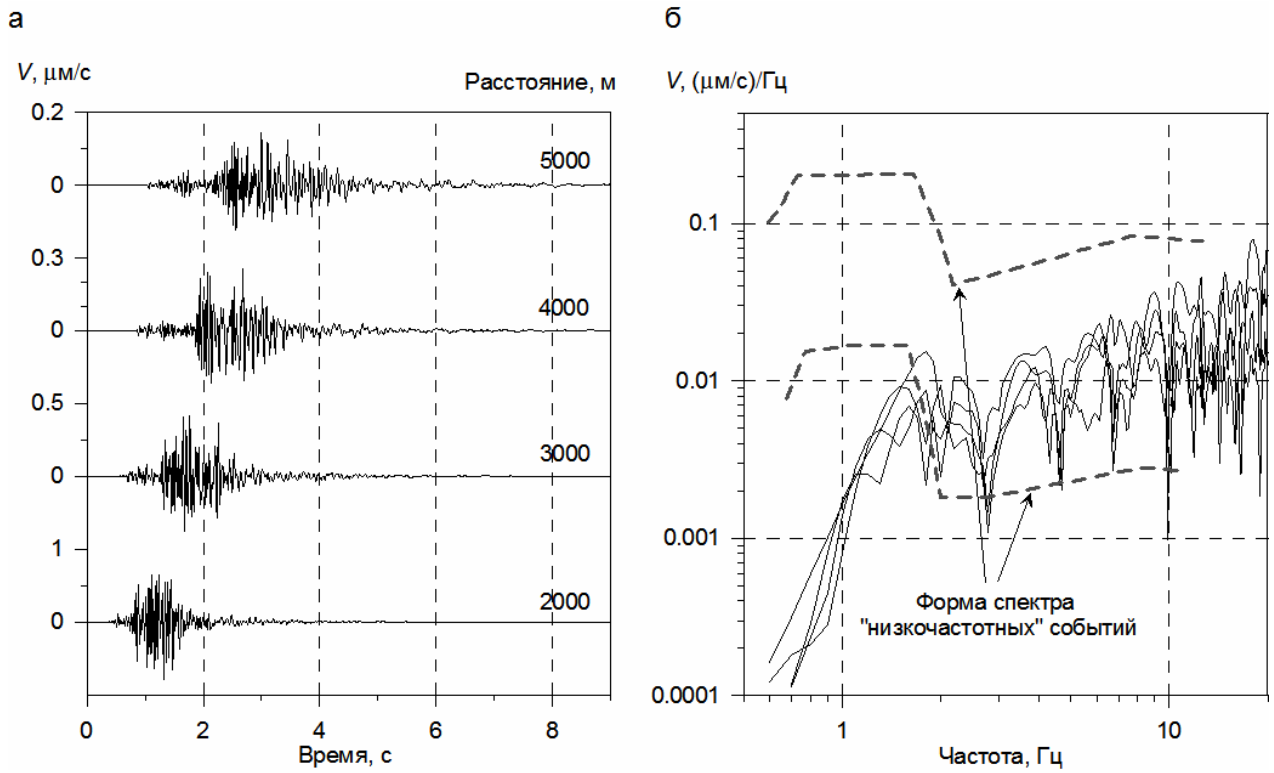


Fig. 8.2. Syntetic records (a) and their amplitude spectra (b) for shear crack growth over excavations

used in general seismology, but in seismology of mines its application experience is considerably limited. We might only mention the coal field Midlothian, where higher harmonics of surface waves were used for the study of local seismic events [McBeth, Redmayne, 1989]. Similar limitation of use of surface waves in mine seismology is caused mainly by specificity of the conditions providing formation of a steady package of surface waves on records of local events: small depth of a deposit and seismic centers, stratification of a profile with insignificant lateral variability.

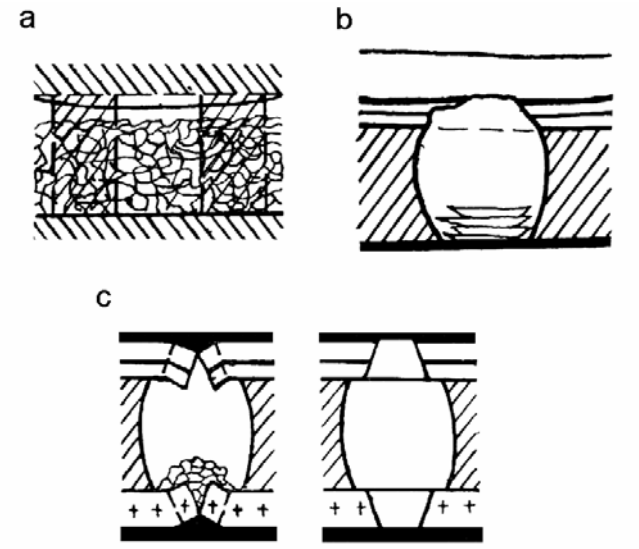


Fig. 8.3. Dynamic processes, recorded in potassium mines [Dolgov, Polyanina, Zemskov 1976]

At VKPSD the present conditions are implemented and, as a result, we confront an unique situation, when oscillations on 0.6-1.0 Hz frequency band detected on "*low frequency*" events records are well described by basic harmonic of Rayleigh wave for horizontally stratified medium model. This provides us the opportunity by minimizing the discrepancy between the real and model seismic traces to determine the alternative source type and its time function at range of 0.6-1.0 Hz. Fig. 8.5 shows the example of the procedure realization. On the left side (Fig. 8.5a) the records of one event are shown, on the right (Fig. 8.5b) the low-frequency (0.6–1.0 Hz) part of the present records and corresponding model seismic traces of the main Rayleigh wave harmonic are shown, cal-

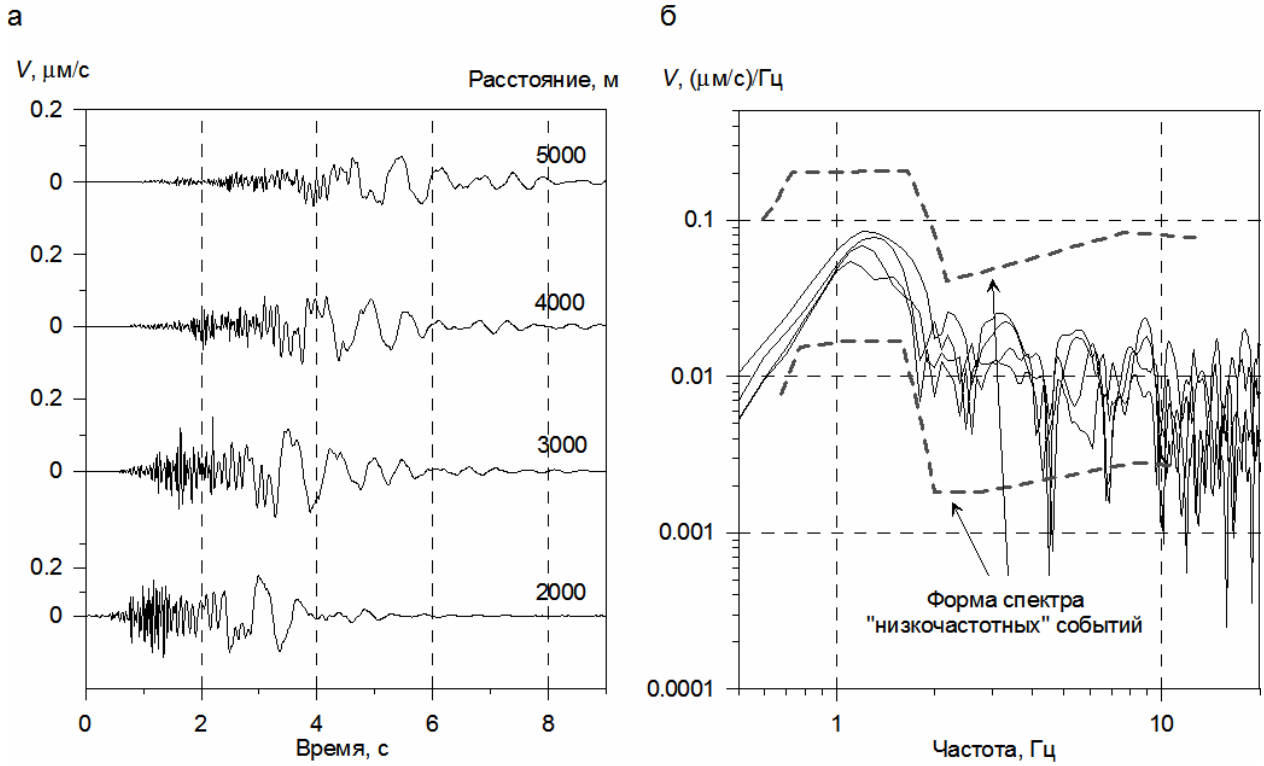


Fig. 8.4. Syntetic records (a) and their amplitude spectra (b) for local roof rock failure

culated for the source as vertical force. The correlation coefficient between real and model seismic traces is sufficiently high – 0.96.It is worth mentioning that, using the abovementioned procedure of inversion in conditions of VKPSD there is an ambiguity of definition of type of a source. The given ambiguity is connected with seismic monitoring system configuration parameters.

As the seismographs are installed approximately in a horizontal plane (in a plane of mining excavations) the field of Rayleigh surface waves, symmetric to a vertical axis can be equally generated by various axissymmetric sources (vertical force,vertical dipole, the center of expansion). For example, presented on Fig. 8.5b real seismic traces can be described by a source in the form of a vertical dipole with the same degree of accuracy, as vertical force.

The given ambiguity can be eliminated by the phase characteristics analysis of the source time functions. Time function behaviour at a zero moment of time (increase, decrease) indicates the source's correlation with a concrete dynamic process (roof rock failure, pillar failure).

Procedure of surface waves inversion also provides an opportunity to estimate the physical-geometrical parameters of a central process by a low-frequency part of time function spectrum. For example, for cases of failure the multiplication value of precipitated rock mass m by excavation height H can be obtained.

Using the abovementioned method of inversion the processing of materials of seismological monitoring of two mines in 2004 was implemented. Total for this period 70 most significant "low frequency" events were selected. As it turned out, all these events are satisfactorily modeled by axissymmetrical source. At this time average correlation coefficient of real and model records of sur-

face waves was 0.81. Phase characteristics analysis of time functions led to the conclusion that the overwhelming majority of the selected events (66, or 94 % of the total number) present local roof rock failures. For the present events the estimate of integral parameter of the central process $-m \cdot H$ was prepared. This value turned out to be within limits from $5 \cdot 10^4$ to $3 \cdot 10^6$ kg*m (pic.8.6).

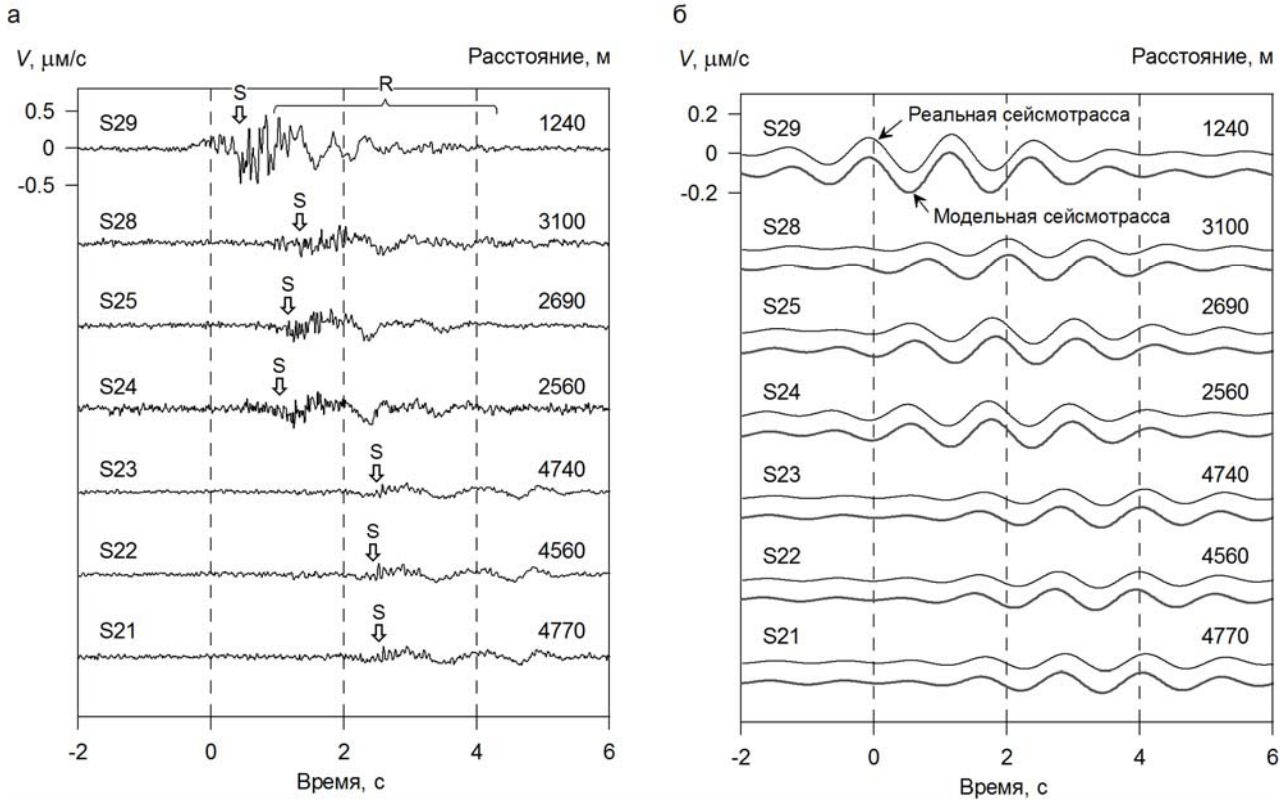


Fig. 8.5. Records of a seismic event at SKRU-2 mine, on 18 May 2004 at 19:08 UTC (a). Surface waves modeling of the event by vertical force source(b).

Using the abovementioned method of inversion the processing of materials of seismological monitoring of two mines in 2004 was implemented. Total for this period 70 most significant "low frequency" events were selected. As it turned out, all these events are satisfactorily modeled by axissymmetrical source. At this time average correlation coefficient of real and model records of surface waves was 0.81. Phase characteristics analysis of time functions led to the conclusion that the overwhelming majority of the selected events (66, or 94 % of the total number) present local roof rock failures. For the present events the estimate of integral parameter of the central process $-m \cdot H$ was prepared. This value turned out to be within limits from $5 \cdot 10^4$ to $3 \cdot 10^6$ kg*m (Fig. 8.6).

Thus, the results of study of "low frequency" events at VKPSD with the help of both direct and reverse methods (modeling of seismograms for potential sources and inversion of registered wave forms) testify to the fact that their center's mechanism can be described as a local roof rock failure. Given the fact that "low frequency" events comprise a considerable part (30-50%) of registered events, one can draw the conclusion that, local roof rock failure processes are the important component of siesmicity at the VKPSD mines.

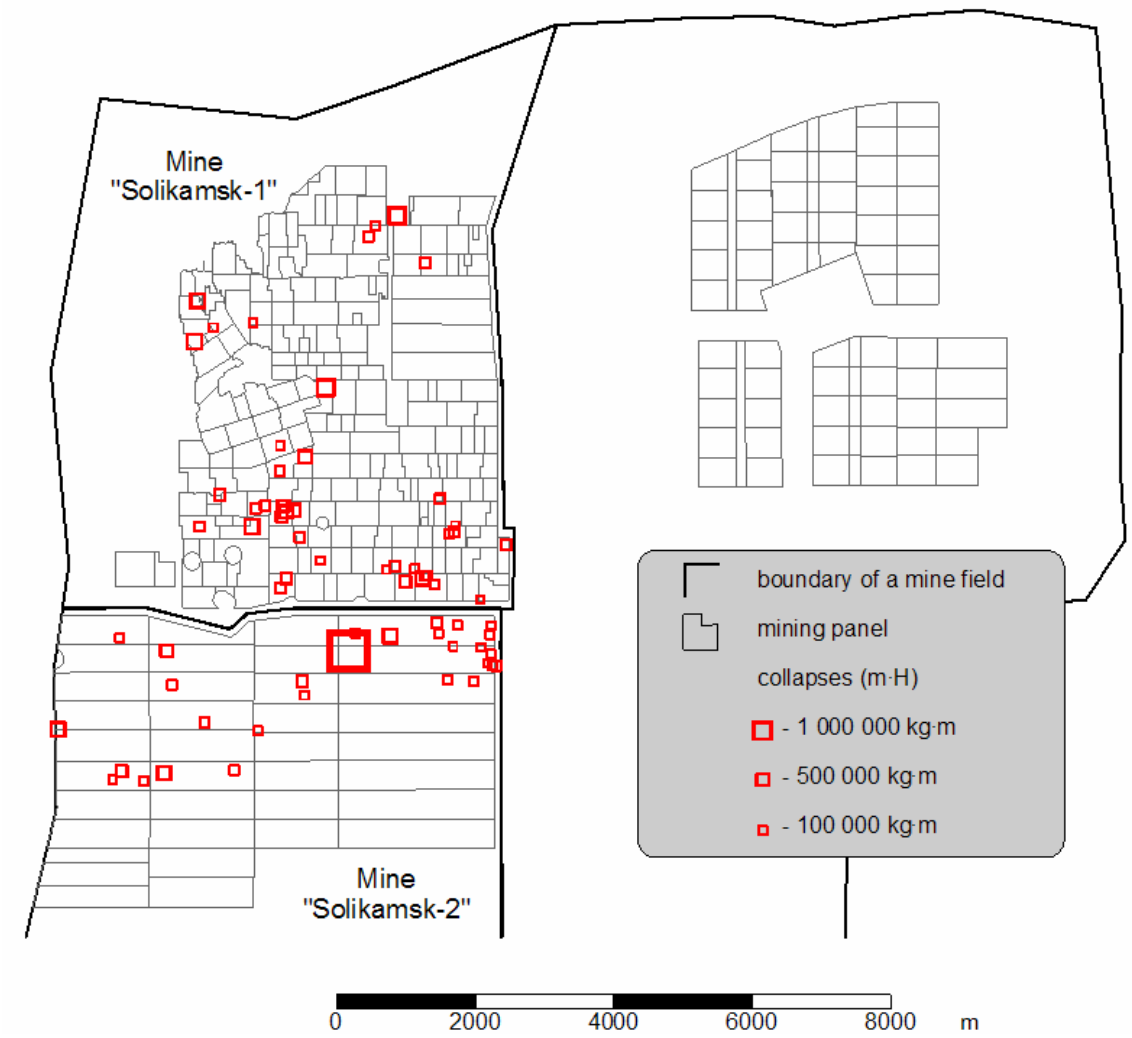


Fig. 8.6. Space distribution of local failures at mines SKRU-1 and SKRU-2 in 2004 according to results of "low frequency" events records processing.

Study of seismicity of the Khibinsky and Lovozersky massifs on the Kola peninsula

The Institute of Mines of the Kola Scientific Center RAS in the period of 2003-2006 was dealing with databases support on seismicity and other methods of control of the state of the massif, analysis of current and reverse data on seismicity of massifs of underground apatite and rare-earth mines on the Kola peninsula was carried out. The results of the earlier research are published in [Seismicity at mining, 2002].

In 2003 the observations on the complex of conjugate monitoring of the entire region was Khibinsky apatito-nepheline mines were completed. As a result of the work the system of complex geomechanical monitoring of high-stress hierarchical-block rock massif, based on seismicity parameters and rock deflected mode registration and hardware-software means of processing and the analysis of results of observations was proved and realized.

The deformation pattern of high-stress of block geological medium induced by dynamic pressure from strong industrial explosions was established. The first results of geodynamic monitoring of the bordering zone between the underground Rasvumchorrsky mine and Central Public Corporation "Apatit" mine were obtained, using the new seismoacoustic subsystem [Kozyrev et al., 2003]. The mechanisms of centers of several technogenic earthquakes and mining, registered in the Lovozersky massif, were calculated. Comparative analysis of the results obtained of reconstruction of centers' mechanisms with geological and geomechanic data on fissuring and stress was carried

out.In 2004 on the basis of experimental and analytical research of deflected mode of the rock, analysis of low-energy seismicity centers the model of technogenic earthquakes at large-scale open mining was proved, confirmed by the practical work of Public Corporation “Apatite” mines. The most probable mechanism of technogenic earthquakes is the mechanism is the mechanism of strike-slip type on available surfaces of slackening tension due to removal of vertical loading at minerals extraction.

As an example of analysis of a strong technogenic earthquake in the Lovozersky massif the energy model of forming and realizing dynamic rock massifs phenomena was verifiedд [Fedotova et al., 2004]. Development and verification of this model was continued according to the data of non-linear effects of rock deformation and failure in the process of evolution of scientific-technical systems of mining. Seismic precursors efficiency of strong dynamic phenomena in mining areas was estimated. Search of new approaches to estimating seismic danger was carried out [Kozyrev et al., 2004].

In 2005 the method of geodynamic risks monitoring at mining in high-stress rock mafssifs was developed. Its main feature is that it predicts and provides prevention not of a single dynamic event but a whole critical area, dangerous by its dynamic parameters like rock bumps and technogenic earthquakes, that makes geodynamic forecast more reliable and increase the safety of mining. Based on the proposed and earlier verified model of geological medium evolution in mining natural-technical system according to the geodynamic monitoring data critical areas of geomechanic space of a mine are contoured (dangerous by geodynamic risks like like rock bumps and technogenic earthquakes) and the risk value is estimated, equal to the probability value of these events realization multiplied by the value of expected loss. In cases of unacceptable risk corresponding precautions are taken. By tectonophysical analysis of high-energy areas of geological medium and comparison of its results with the data on deciphering the mechanisms of seismic events centers it was established that, the overwhelming majority of these events were provoked by mining, and events with the central mechanism of strike-slip type turned out to be the most dangerous. Development of the method of estimation of critical areas of geological medium according to seismic process parameters (including criteria of the fractal size of seismic events distribution; skew of recurrence curve; concentration criteria taking into account the borders of open face space and fault zones) was continued. The program software for complex method of geodynamic danger estimate was developed the program was tested on the local seismic stations database, working at apatite

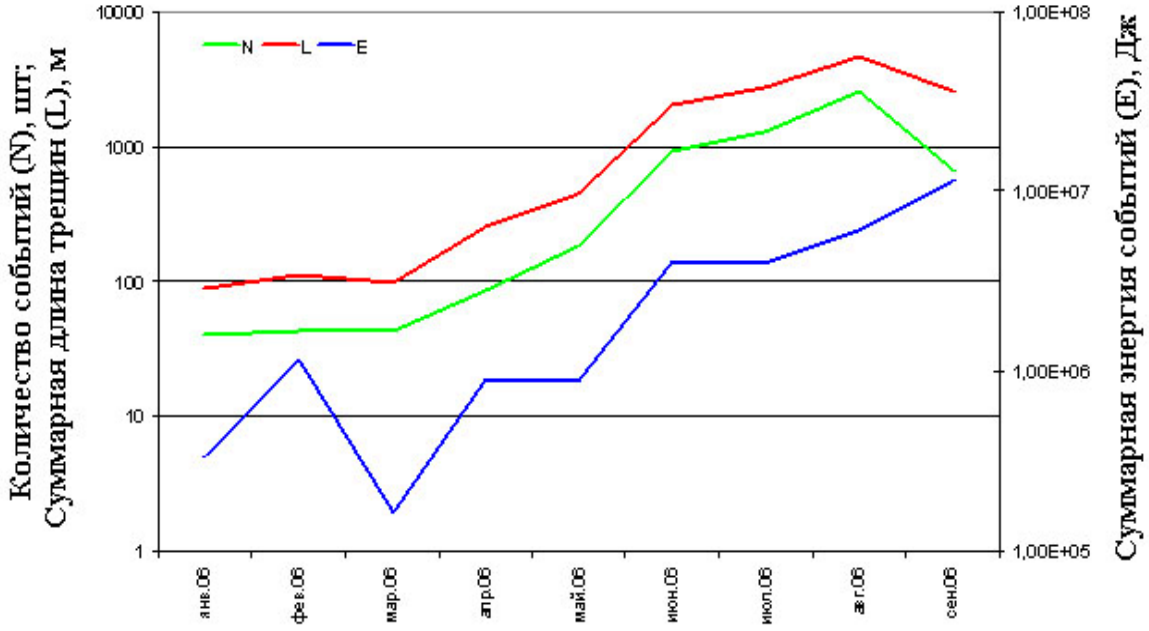
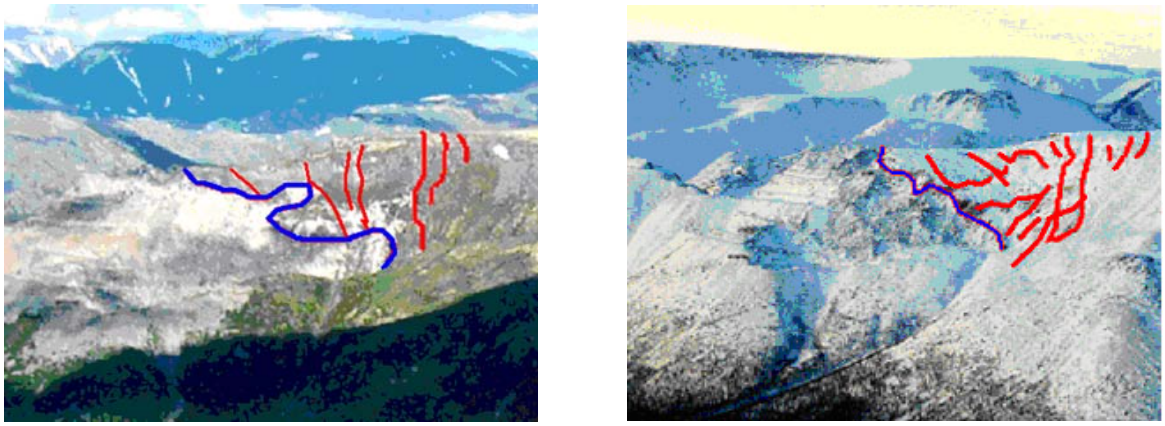


Fig. 8.7. Change of seismicity parameters on Uksporsky wing of OKM by months of 2006. N – number of events; L – total cracks length; E – energy of events.

mines. Thus, strong seismic event probability for different bases is equal to 0.55–0.82 (6 months before the event), 0.29–0.37 (for 1 month) and 0.27–0.35 (for 1 day) [Kozyrev, 2005a, b, c, d].

In 2006 the analysis of spatio-temporal dynamics of massif seismicity in geomechanic space of apatite mines was implemented. Fig. 8.7 shows as an example the monthly change of seismic parameters of the Uksporsky wing of the United Kirov mine in 2006.

The picture shows four obvious peaks of maximum values of cumulative energy of registered events (in February, April, June and September). At this time the number of events and total length of cracks increase till August was observed. These tendencies could be explained by the fact, that the process of cracks formation by August has passed from the system of new cracks formation and the stage of interfission barriers destruction to the process of formation of the main rupture with its probable wedging out to the surface of the massif. Mining works "actively facilitate" to the process of intencification of the main rupture wedging out in the area. This is confirmed in October by emerging necessity of choosing the variant of creation of cutting slit, ensuring the most secure mining conditions at increased seismicity at removing the pillar block of 9/13 hor. +410 m of the Yuksporsky wing of OKM. Fig. 8.8 shows the dynamics of development of cracks growing on the surface on 27.06.2006 and 30.10.2006. The photos show the development of the process of cracks opening at the Yuksporsky mineral deposit, change of the failure configuration and appearance of new cracks on the massif's surface, confirmed by the data on Fig. 8.7.



27.06.06 30.10.06 (Photo by V.F.Yegorov)

Fig. 8.8. Visual observations data of the Yuksporsky failure area. Blue line – failure edge, red lines – crack of rupture.

Fig. 8.9 shows the change of seismicity parameters at Rasvumchorrsky mine by months in 2006, with three maximum peaks of total energy values of registered events (in January, May and August).

This is probably connected to the fact that at that time in the zone of failure the processes of opening of ruptures already formed were going on accompanied by continuing formation of the main ruptures in the bordering zone of the underground mine with the Central mine pit. The process of mining has aggravated the state of the north-western edge of the pit in the bordering zone. This process was confirmed by visual observations (Fig. 8.10, on 27.06.2006 and 13.11.2006).

The method of geological medium state estimate by the kinetics of technogenic seismic process, allowing to follow clusters formation on time and carry out qualitative estimate of induced seismicity parameters of stress massif under dynamic pressure from mass and technological explosions. On the basis of the data of geology and deposits tectonics and mines stress modifications results geomechanic models of mines and pits were designed. On their basis methods of geomecanic processes monitoring at underground and open mining were prepared, with the purpose of diminishing geodynamic risks, including the massif's relief with the help of special cracks, periodical dynamic impacts by explosive works, decrease of the massif's elastic parameters etc.

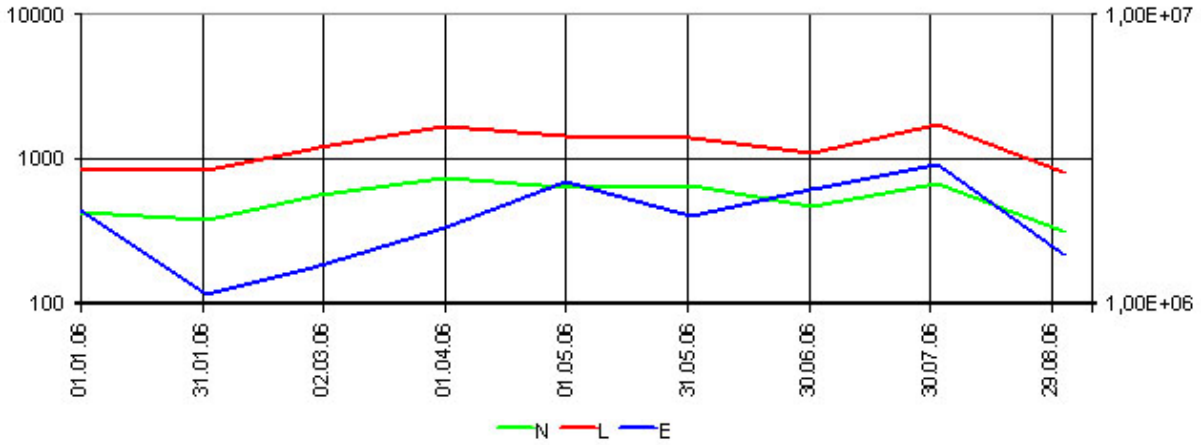
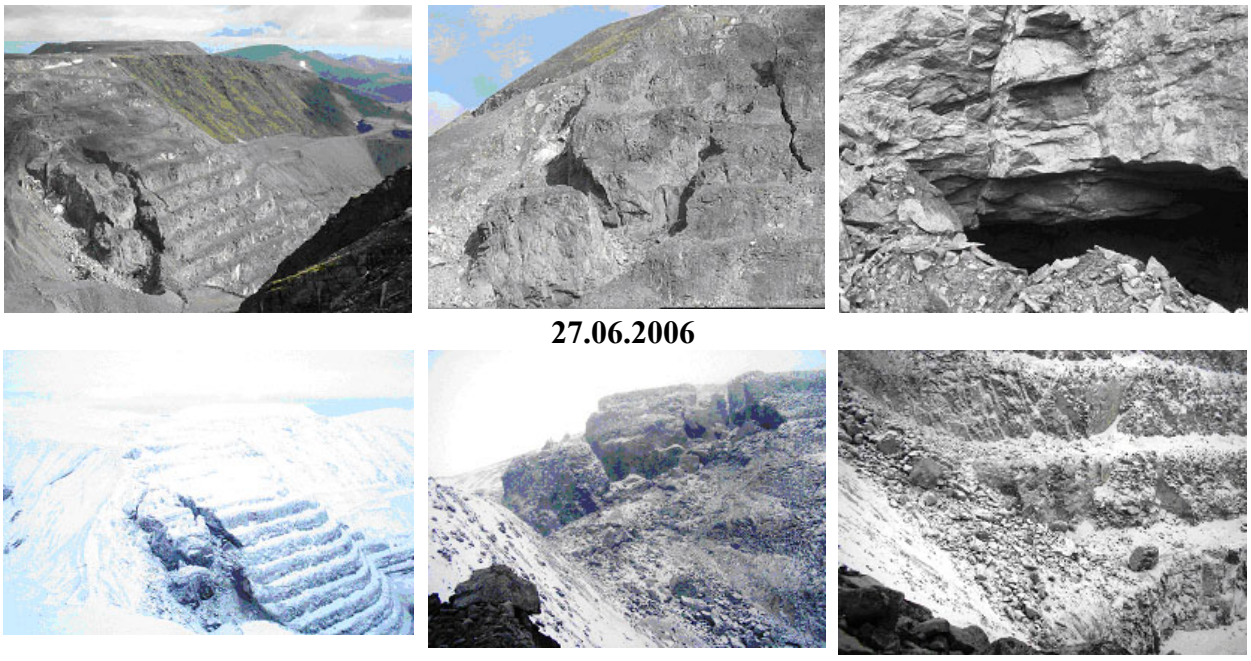


Fig. 8.9. Change of seismicity parameters at Rasvumchorrsky mine by months in 2006. N – number of events; L – total length of cracks; E – energy of events.



27.06.2006

13.11.2006

2 photos below (compared to the upper ones) show change of failure configuration

Upper photo shows a windhole, presently covered by caved material

Fig. 8.10. Failure of north-western edge of the Rasvumchorrsky mine.

The results of research were reported at the All Russia Conference "Risk-2006", held in April 2006 in the Center of Strategic Research of Civic Defense of the Ministry of Emergencies of Russia [Kozyrev and others, 2006].

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8.3. Technogenic Induced Processes in the Earth's Crust

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It was noted repeatedly, that engineering activity and emerging deformation processes, including technogenic earthquakes, led to disastrous consequences, bringing tremendous material losses and human casualties. Some cases are known, related to occurrence of "dam" earthquakes with magnitude up to 6.0-6.3, earthquakes occurring at developed mineral deposits, mining and tectonic rock bumps are usually accompanied by numerous casualties [Seismicity at mining, 2002]. Technogenic earthquakes were detected at the time of underground nuclear explosions and large-scale explosions of chemical highly explosive materials [Adushkin, Spivak, 1996]. Trigger impact

of remote seismic events (natural earthquakes, explosions) is described in some works by A.V.Nikolayev.

Complexity of construction of a complete geomechanic model of a block massif, taking into account correlation of mechanic and fluid dynamic processes, entails generalized approaches to description of complex systems, presently developed in the non-linear dynamics domain [Malinetsky, Potapov, 2002]. The monograph [Adushkin, Turuntaev, 2005] has analysed various types of technogenic seismicity and on the basis of the created database on induced and triggered earthquakes of different genesis (including the data on more than 200 technogenic seismic phenomena) the parameters of occurrence, development and dissemination of technogenic seismic phenomena were described. Method of kinetic analysis of technogenic seismicity development in time and space was offered, based on the dynamic systems theory.

The main feature of this method is the phase coordinates input, such as seismic activity and velocity of activity change. A point in such phase space gives the parameters of the seismic process at the present moment and velocity of change of this state, the trajectory describing the seismic process development in time. The analysis of phase portraits with the purpose of revealing their type and definition of existence of steady parameters (reconstruction of attractors) is set as the primary goal. For the analysis of phase portraits the Grassberg-Prokacchia method based on calculation of correlation integral is used.

The developed method of technogenic seismicity analysis was applied for seismic analysis in the area of the Romashkinsky oil deposit and the northern Ural bauxite deposits. For the Romashkinsky deposit it was established that to the obtained phase portrait the limit cycle is rather close, found from solution of Duffing equation, describing oscillator's behaviour under the impact of driving force. It was established that the time series, characterizing technogenic seismic activity in the Romashkinsky deposit area, belongs to the system with attractor of fractal size 2.7, with six variables used for its description.

Phase portraits were also constructed for the ratio of the monthly volumes of obtained liquid to volumes of pumped water within the limits of the four most seismically active areas of the Romashkinsky oil deposit. Calculations were made for two periods: before and after first increase of seismic activity. The attractor's size in the first period is equal to 1.5. The attractor's size in the second period is of the same value as the attractor's size, obtained from seismic activity data.

Comparison of change of seismic activity with efficiency of pumping, and also with the volumes of recovered and pumped liquids and pumping disbalance shows statistically important connection between seismic activity variations and regimes of pumping and recovery. Importance of this connection is 99%. The correlation of seismic activity of seismically active areas of the Romashkinsky deposit with operation parameters is characterized by high values of correlation coefficients (up to 0.8). The synchronism of disbalance variations and seismic activity can be explained by the fact that the change of these values are caused by the same process, for example, by change of the medium's permeability during preparation of seismic events. In the period of increase of seismic activity the pumping efficiency considerably decreases.

Analysis of seismic kinetics in the area of mine fields of the Northern Urals Bauxite Basin. It was found that the trajectory in the phase space is close to external limit cycle of one mine field, and at the same time phase portrait of another mine field looks like internal limit cycle. In the first half of the period under review activity oscillations are to some extent synchronized; in the second half the growth of activity on one mine field corresponds to almost synchronized decrease of activity on another, the reviewed areas seismicity experiences antiphase oscillations.

A complex of experimental laboratory works on technogenic seismic deformation phenomena modeling at a pore pressure change was implemented [Zenchenko et al., 2005, Turuntaev et al., 2006]. Correlation between seismic emission and change of pore pressure change in the collectors with different permeability was established (Fig. 8.11), which differs with growth and drop of a pore pressure. The impact of stress on discovered dependencies was analysed. It was discovered that the approaching values of maximum and minimal main compressure stresses leads to seismic emission front dissemination velocity increase, significant for predicting time of development of technogenic seismic consequences at mining carbohydtates. It was shown that experimental results can be satisfactorily described in pore elastic approximation by pore pressure diffusion taking into

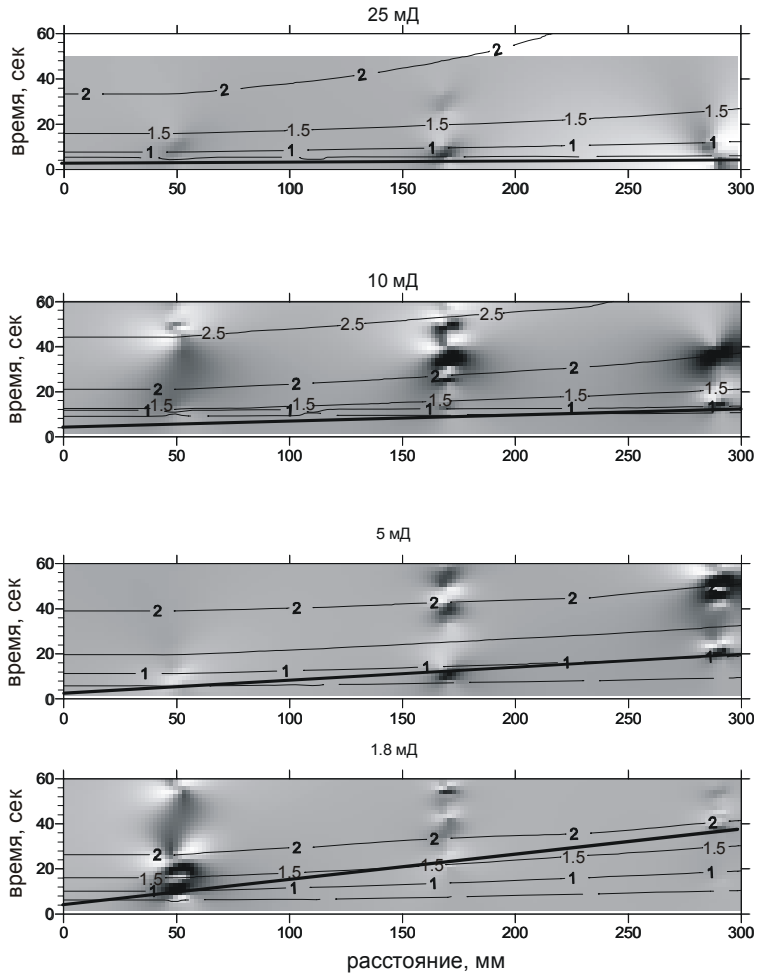

Рис. 8.11. Активность акустической эмиссии в опытах по нагнетанию воды в коллектора с разной проницаемостью. Жирная линия аппроксимирует распространение фронтов эмиссии, тонкие линии – изолинии давления, нормированного на прочность материала на одноосное сжатие.

account the stress type [Eremeeva, Turuntaev, 2006].

The seismicity analysis method, described above, was applied for the study of acoustic emission in laboratory experiments. Time dependencies changes of AE at pressure release in samples with various permeability were examined. Fractal dimensionality of attractor, that can be detected by the data, obtained in the experiment with low permeability comprised 2.8. In case of higher permeability the fractal dimensionality was indefinitely high. Thus two time dependencies of AE were established, for the samples with different permeability.

Fig. 8.12 show the technogenic seismicity distribution on the territory of Russia. The absence of correlation between spatial distributions of technogenic and natural earthquakes is obvoius. The regions, where technogenic seismic phenomena were noted, are, on one part, the regions of active industrial development, on the other part, seismic construction works are usually absent there, leading to serious consequences even of relatively weak technogenic seismic events. The most considerable technogenic seismicity phenomena in Russia are presently related to mineral deposit recovery.

The data on almost 50 cases were collected and analyzed, when mining of minerals led to the tangible change of seismic regime of the area of works. It was found out that the deposits, which exploitation has led to the escalation of seismic activity, are characterized by higher values of depth and capacity of mines with relatively lower values of porosity and permeability of collectors rocks compared to average values of the parameters under consideration.

Fig. 8.13 shows that seismic activity reveals, on average, in 10–20 years after the mining begins, and the strongest eathquakes, on average, occur ten years later, i.e. in 20 – 30 years after the works start. Partly such delay of seismic events occurrence is related to dynamics of the drop of strata pressure and by the measures aimed at strata pressure support by flooding. Related to the beginning of pumping of liquid, appearance of seismicity lags 5–10 years behind, and maximal earthquakes – 10–15 years. Time period before seismic events occurrence tend to diminish at the increase of the initial pore pressure and values of vertical and horizontal stress components, that is usually observed at the increase of depth of mines.

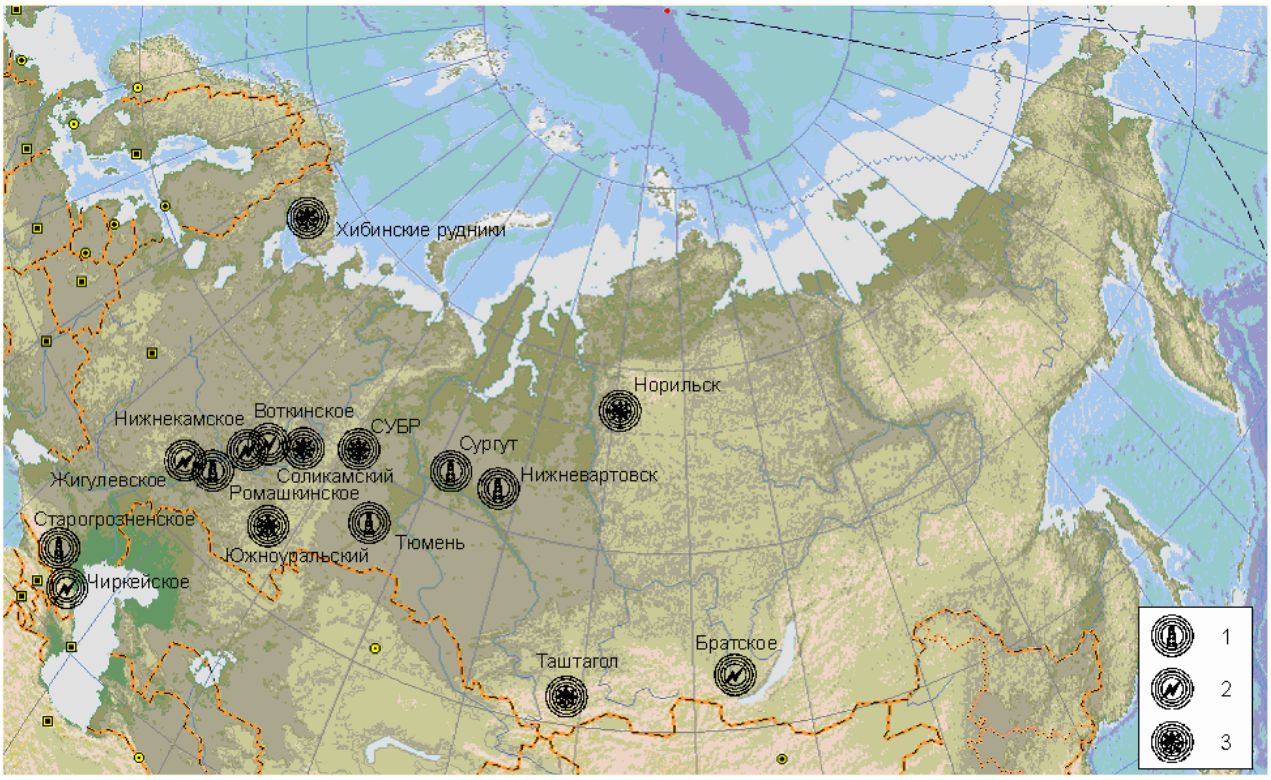

Fig. 8.12. Map of seismic centers, induced by engineering activity on the territory of Russia: 1 – by mining of carbohydrates, 2 – by reservoirs fillup, 3 – by mining ore minerals.

Unfortunately, there are practically no long-time observations of seismic regime, starting from seismic background registration to beginning of mining and till the late stage of operation and after the end of the works. Recovery of hydrocarbon offshore deposits on the Sakhalin Island according to the projects Sakhalin-1, Sakhalin-2 was an exception from this rule. Due to the productive collaboration between the Russian State surveillance services, the Russian Academy of Sciences (Institute of Marine Geology and Geophysics, Far Eastern branch of RAS, Institute of Dynamics of Geospheres RAS (IDG RAS), Institute of Physics of the Earth RAS) and the companies administrations the local seismic monitoring network was established before the beginning of mining.

Seismic phenomena related to mining are observed on more than a half of mines in our country. The problems of labour security combined with mineral resources recovery depreciation, examined in the works by A.A.Malovichko, A.A. Kozyrev, A.V. Lovchikov and others, are very important.

For the solution of these problems the collective of scientists from IDG RAS, Institute of Problems of Comprehensive Exploitation of Mineral Resources RAS (IPKON RAS) and Mining Institute, Siberian branch of RAS headed by V.V.Adushkin has suggested, examined and realized the new mining technology. The technology is based on considerable increase of scale of explosive preparing works before mining. It was suggested to carry out explosions with capacity up to 700 tons using vertical concentrated bombs from 20 to 60 tons each, placed into the rock massif. The number of mass explosions at an enterprise has reached 1-2 a year, considerably saving the costs of work. The manifold decrease of the mass explosions number has diminished the risk of emergence of negative geodynamic phenomena.

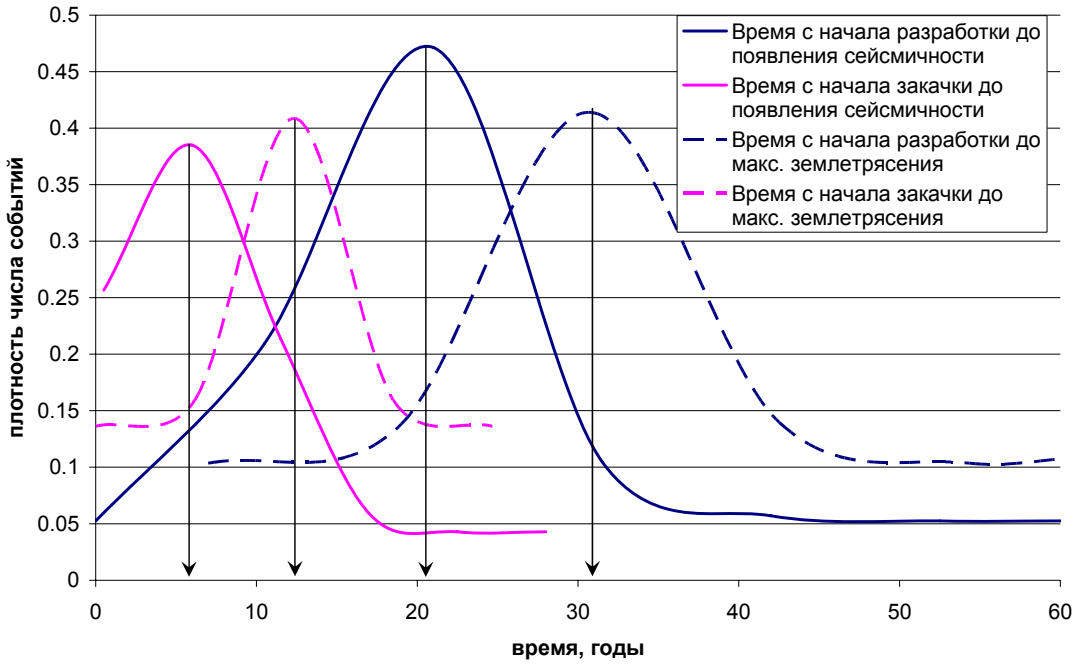

Fig. 8.13. Time intervals distribution, from beginning of hydrocarbon deposits recovery to seismic events occurrence and to maximal earthquake, from liquid pumping beginning and to maximal earthquake.

Development and approbation of the new technology began on the Siberian iron ore mines in Sheregesh, Abaz and Tashtagol. At the present time the new technology mass introduction began on iron ore mining enterprises in Siberia.

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9. Researches in the physical properties of rocks and minerals under high pressures and temperatures

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In the studies in physical properties of rocks under high pressures and temperatures, three directions of research are noted: (1) traditional, (2) with the use of microstructure methods, (3) a new direction associated with the use of nanostructures.

The first direction

Density characteristics of rocks that underwent hydrothermal alteration (tuffs) from deep boreholes core (Iturup Island) were determined under pressures of 1.5-17 GPa and temperature of 400°C in the device of "lens" type [1]. It is established that tuff density change under high p-T parameters is for the major part associated with irreversible deformations of pore space. After the experiment, the difference between mineralogical density and tuff density showed that a part of porosity recovers after stress release. High-temperature processes in natural conditions affect tuff, decreasing solidification effect under high p-T conditions of the experiment.

Data on elastic characteristics of dacitic tuff samples were obtained in the process of heating in a closed system in isobaric conditions under pressure of up to 7hPa and temperature up to 300°C [2]. From experimental data on samples deformations, density alterations were calculated in the process of compression and heating. Obtained data on samples density alteration in the process of isobaric heating showed that the volume of rocks that occur at the depth of more than 600 m showed linear variation with temperature with both its rise and drop, whereas younger near-surface samples have a section that shows non-linear volume variation when heated at temperature with marked minimum in the range from 150-250°C. With further isobaric heating and cooling, longitudinal waves velocity variation after initial isothermal compression to pressures of 0.7 hPa occurred for the major part linearly with temperature. To study the nature of sealing empty spaces we conducted research in micro porosity with the use of nitrogen vapors adsorption and desorption on their surface in initial and tested samples. Experiments were carried out in both open and closed systems. In initial samples, cylindrical, slit-like, wedge-shape (with an open end) forms of empty spaces prevailed; after temperature and pressure affected them, the range of forms narrowed and slit-like forms and wedge-shape forms with an open end became prevailing and in this case their specific pore surface considerably decreased. Obtained results suggest that processes of tuff volume variation under simultaneous effects of temperature and pressure for samples with large porosity go on at temperatures about 200°C at the expense of plastic deformations and redistribution of stresses in the sample volume, and porosity decrease manifested in the elastic wave velocity variation under the influence of high pressures and temperatures.

The influence of stress state on the acoustic emission (AE) character in rock samples of volcanic origin was studied under uniaxial load with the use of press "INOVA" [3]. Rock samples with the same texture, porosity and fissuring were tested with constant velocity of deformation or constant velocity of loading. In this case, we did not reveal significant differences in AE at initial stages with different kinds of loading. A small increase of the acoustic impulses amount with subsequent drop to zero is observed. This activity is associated with porosity sealing. Elastic deformation zone is characterized by small acoustic activity. Samples of weak porosity and having no fissures pass this stage practically without acoustics. A distinct increase of acoustic activity is noted when the sample passes from elastic deformation zone to plasticity zone and micro destruction beginning. Increased activity is noted when the regime of constant growth of load is used. As distinct from it, with constant velocity of deformation no energy is added to the sample with local relief of individual zones. The analysis of signal energy distribution against their number for samples with different porosity showed that in the general case in logarithmic coordinates they have a form simi-

lar to recurrence plot in seismicity. In this case the slope of curves varies according to the stage of stress and strain.

Pressure influence on temperature memory of induced magnetic anisotropy (IMA) of magnet-containing rocks is presented in [4]. It was demonstrated that pressure with which induced magnetic anisotropy was created in magnetic minerals made it difficult to subsequently determine temperature to which the rock had been heated.

Thermal conductivity of sedimentary rocks was studied; combined influence of layer temperature, pressure and fluid (gas, oil and water) in the range 293-573°K and hydrostatic pressure up to 150 MPa [5] on core material samples was investigated.

Besides the influence of chemical composition of saturating environment on thermal conductivity as well as the influence of increasing and decreasing pressure and temperature were studied. It was established that thermal conductivity of sedimentary rocks in conditions modeling deep occurrence of layers depends on combined influence of layer temperatures and pressures and saturating fluid composition as well. Fluid physical and chemical characteristics influence on thermal conductivity variation significantly exceeds thermal conductivity variation caused by layer pressures and temperatures. Rock thermal conductivity decreases with the increase of sedimentary cover temperature. The extent of such decrease depends on both saturating fluid and lithological composition. Thermal conductivity decrease of oil-saturated collectors is greater in magnitude than of gas-saturated collectors. As pressure is increasing the thermal relationship is shifting towards thermal conductivity increase and is domineering within the parameters of the experiment.

Geoelectrical characteristics of phlogopite were studied in the range 100-1000°C [6]. The major feature of specific electrical conductivity σ relation to absolute temperature T in coordinates $\lg\sigma = f(1/T)$ is the presence of three major areas: area of extrinsic conductivity related to crystal lattice defects associated in complexes; beginning with approximately 800°C the area is noted where those complexes are completely dissociated; the third area is related to the intrinsic mechanism of ion electrical transfer and begins with temperature of the order of 900°C. Values of energy activation, electrical conductivity and pre-exponential factor for all the areas were determined, which is very important owing to a significant role of associated defects in minerals and rocks in metamorphic processes. A relation is established between electrical conductivity variation, dehydroxylation in octahedral layer of phlogopite and isomorph cation in mica structure. Phlogopite electrical conduction regularly decreases as the degree of iron oxidation state increases in octahedrons and fluorine increases in samples, which suggest a relation between these factors. This regularity can serve as a criterion for endogenic vertical zonality of mineralization in sampling phlogopite area, where fluoride content increase in the vertical section from bottom to top is one of zonality factors.

Experiments on deforming rocks in different conditions of stress and strain were conducted with external and internal loadings [7]. We used hydraulic press and high-pressure device as external source and nonexplosive destructing mix as internal source. Loading rocks, we registered deformations, elastic wave velocities, acoustic emission. It was established that irrespective of stress source it was characteristic that elastic wave velocities increased up to several percent at the elastic deforming stage and a decrease was noted in non-linear deformations. Research in ruptures formed under uniaxial compression and with splitting at constant deformation velocity demonstrated that samples of dolomite marble and calcite limestone showed more intense acoustic emission under compression than with splitting. В результате численного моделирования распределения напряжений внутри исследуемых моделей до разрушения и после образования первой трещины было описано трехмерное поле напряжений. As a result of numerical modeling of stress distribution inside models under investigation before destruction and after the first crack formation, 3-D stress field was described.

Permeability of more than 50 rock samples typical of continental crust was studied under temperature up to 600°C and pressure up to 200 MPa [8]. Pressure increase always results in permeability decrease with depth. Temperature rise may result in both increase and decrease of perme-

ability on the whole temperature range and in rocks permeability trend inversion owing to competing effects of temperature and pressure. On the basis of statistical processing of experimental data the generalized trend of permeability with depth was constructed. Average values of permeability vary from $2.82x10^{-13\pm1.5}$ m^2 at the Earth surface to $1.17x10^{-20\pm1.5}$ m^2 at depth of 40 km. Against the general background of permeability decrease, local water-bearing horizons may also be formed at great depths.

In paper [9] the task is solved of assessing the parameters of ore-bearing fluids in the process of formation of useful mineral deposits in which ore bodies are located in dense crystalline rocks with low-permeability veinstones. To do this a new high-temperature unit was developed and methods of measuring permeability under high-temperature conditions were elaborated.

Neutral and acid fluids influence on elastic characteristics of sandstone was studied under fluid pressure of 300 MPa and temperature up to 850°C [10]. In the presence of acid and neutral fluids (H_2O; H_2CO_3; HCL) elastic waves velocity increase by 0.3-0.5 km/s is noted in temperature range of 400-600°C. By silicification of rocks is meant the process of metasomatic substitution or filling of empty spaces and fissures by quartz or silica. It is known that rock silification may result from two causes: solution acidity increase and solution temperature decrease. Experiments showed that intense silification of rocks took place under the effect of acid solutions at temperature of 590°, when amorphous silica precipitated from solution that filled micro fissures of rocks and as a result elastic characteristics of rocks increased.

Elastic waves velocities in hyaloclastic material of Iceland were determined in the process of hating in isobaric conditions in a closed system under pressure of 0.7 GPa and temperature up to 300°C [11]. Major results of work are as follows: Основные результаты работы: (1) samples mass does not change; (2) density varies with compression in cold conditions, it is inelastic in the first cycle and elastic in the second cycle; in the third cycle with isobaric heating large plastic deformations are observed. Additional research of derivation charts of samples (up to 700°C) showed that in hyaloclastic samples mineral transformations took place at low temperature of 80-150°. Registering acoustic emission experiments with heating and without external pressure corroborated that in temperature intervals revealed in derivation charts intense ultrasound signals of acoustic emission are noted, thus suggesting processes of fissure formation.

Amplitude dependences of velocities and attenuation of P and S waves in dry consolidated sandstones [12] were studied experimentally under all-round pressure. Anomalous behavior of kinematic and dynamic parameters of acoustic waves was revealed in deformation amplitude range ɛd ~ (0.2–2) $x10^{-6}$. As the amplitude increases, wave velocity weakly increases (0.6%) or remains constant, whereas attenuation decrement considerably decreases (up to 18%). (Attenuation decrement hysteresis is observed in the first amplitude cycle (Amin – Amax - Amin), and it is missing in following cycles. A conclusion is made that attenuation parameter is sensitive to amplitude variation as compared to wave velocity. It is proposed that amplitude characteristics are promising as a criterion for search in the tasks of geological section prognosis.

In paper [13], the results are given of research into pressure influence on temperature memory of induced magnetic anisotropy (IMA) of magnetite-containing rocks. It is manifested not only in formation of new local extremums on relationship A3/A5=f (T), but in the fact that distortion of the dependencies related to IMA extend to larger temperature range. Besides, with IMA being formed under pressure, the value of stretching is for the major part as lower as Px is higher and in this case the amplitude of harmonics related to IMA effects grows less. However, the temperature of IMA formation determined from extremums in plots A3/A5=f (T) differs only slightly from the true temperature even in the case when IMA is induced under pressure close to the pressure under which the sample is destructed. Thus even with deep occurrence the rocks apparently fix temperature that is very close to the temperature of their heating and it is much more difficult to determine it than for rocks that occur close to the surface.

Longitudinal and transversal waves velocities were measured in containing-elite basalts and basalts that do not contain elite [14], in dry conditions in six-punch device (with 600 Map and tem-

perature up to 700°C) and in gaseous unit with internal heating in dry and water-bearing conditions (300 MPa and temperature up to 900°C) with different effective pressure (Peff). It means that Peff=Pconf and Peff=Pfluid=0, respectively. Temperature dependencies of velocity variation reflect the effects of hydration and dehydration processes. In the conditions of effective pressure zero values, zeolite formation shows significant increase in elastic waves velocities in the area of 200°C in basalts that first did not contain zeolite with filling pores and fissures by newly formed minerals at grains surface. Dehydration reaction in some zeolite-containing basalts with initial high effective pressure in dry conditions shows an abrupt decrease of P and S waves values at temperature close to 350°C. In the presence of fluids reverse variation of velocity is noted. Velocity deviation is associated spontaneously with the decrease of effective pressure owing to the appearing internal pore pressure, which causes opening pores and reconstructing pore geometry. Under pressure 300 MPa and temperatures in the range from 20 to 850°C, elastic wave velocity variations in sandstone depend on fluid composition: neutral, alkaline or acid. Results of experiments with pressure of water dramatically differ from ones with pressure of gas. Analysis of temperature relations of elastic characteristics of fluid-saturated rocks shows that they all depend on the physical characteristics of matrixes of fluids and rocks as well as on the changes in rock structure caused by chemical reactions owing to fluid presence under high temperatures and pressures. Mineral reactions going on in rocks in the presence of fluid result in dissolving under pressure of mineral formations and formation of new ones. Changes in microstructure cause changes in porosity and permeability values. And elastic properties of rocks change in their turn as well. Temperature relations of elastic characteristics of rocks in dry and fluid-saturated conditions can be used for geochemical interpretation of seismic anomalies.

Elastic waves velocities on monocrystals of natural quartz and sandstone samples were determined under hydrostatic pressure up to 80 MPa and at room temperature [15]. Results of experiments show waves velocities decrease and absorption coefficient increase with stress increase in natural quartz monocrystal. Decrease of P and S wave velocity is observed in sandstone with pore pressure variation and fixed hydrostatic pressure. Open loops of wave velocity hysteresis and absorption coefficient are found in full cycle load-unload

The second direction

Research was conducted to study relations between layered structure and rock deformation mechanism in complex stress and strain conditions. [16, 17]. In the conditions of non-uniform three-axial compression deformation-strength and structure characteristics of biotite gneiss sample were determined that were oriented at the angles of 0°, 30°, 45°, 90° to schistosity. Schistosity is provided by subparallel orientation of biotite and chlorite scales and turn in the same direction of rhomboid plagioclase porphyroclast. Preliminary deformation-strength characteristics of samples were determined in the conditions of non-uniform volumetric compression under constant all-round pressure of 200 MPa and deforming stress that makes 60-70 percent of destructive stress. In the course of the experiment, all round pressure, uniaxial compression force, and longitudinal and transversal deformation of the sample were measured. Micro structural characteristics were determined before and after the experiment with the use of electron microscope. In this case, several chippings were studied for each of them. Structure research was conducted with the use of scanning electron microscope JEOL-35-CF. Vacuum sputtering of splits is carried out with aluminum. Experimental data analysis showed that with the increase of orientation angle to schistosity and correspondingly to the direction of deforming load, the structure defects accumulation of different kind goes on, which is accompanied by plasticity growth and volumetric deformation increase. In the sample cut out at an angle of 90° to schistosity, plastic deformation prevailed, the number of defects increased and defects of special kind appeared, i.e. lens-shaped breakings on crystal surface with shattering zones in dying away edges, traces of breaking foliated mineral of biotite, and step formations. Such accumulation of structure defects without discontinuity in layered rocks and in the crust

may lead to the critical size and as one of likely consequences to destruction under stress effects oriented at angle of 45° and 90° to schistosity.

Samples of amphibolites and gneiss from Kola super-deep borehole were studied in the three-axial compression unit [18]. Special design of the unit allows measuring velocities of longitudinal waves (VP) and shear waves of orthogonal polarization (VS1, VS2) in three perpendicular directions of samples having cubic form. Measurements were made in a wide range of pressures up to 600 MPa at room temperature and in the temperature range from room temperature to 600°C with all-round pressure of 600 MPa. Then crystallographic texture of mineral components of rocks was measured of the same samples with the use of neutron diffraction method. The data on texture were used to model spatial distribution of elastic waves velocities. Experimental results were correlated with model calculations. Calculated values of velocities provide important information on the different contribution of minerals textures (hornblende, plagioclase and quartz) into the anisotropy of volumetric samples elastic properties and on the relationship between crystallographic texture and seismic features of rocks (elastic waves velocities anisotropy, splitting and shear waves polarization). Directions of maximum and minimum of velocity values of longitudinal and transversal waves as well as shear waves splitting are controlled for the major part by prevailing crystallographic orientation of minerals. Comparison of model velocities and velocities measured in three directions of samples not coinciding with linearity and foliation show that with shear waves propagation in anisotropic environment the direction of particles vibration in S wave has a role that is no less important than the direction of the wave propagation. It is established that reliable measurements of shear waves splitting with the use of two perpendicular units (emitter and receiver) are only possible if shear wave propagation directions are parallel to foliation and perpendicular to linearity.

The dynamics of α–β transition was studied in quartzite sample with the use of neutron diffraction and acoustic emission [19, 20]. It was shown that the transition took place in temperature range of 540-573° and when the temperature reached 600°C, the sample almost completely was comprised of β-quartz. Variation of crystal framework interplanar distances was measured in the course of α–β transition and values of framework stresses were assessed on this basis, which were several times as much as external mechanical stress applied to the sample. It was established that after α–β transition acoustic emission (AE) outbreaks appeared, which exceeded by two orders of magnitude the intensity of AE level caused by thermal cracking under heating. A relation of relaxation type describes the dynamics of AE outbreaks and its structure is somewhat similar to sequences perceptible in seismology, that is main event and aftershocks.

To study the relation of elastic and micro structure characteristics of rocks with different orientation to schistosity, biotite gneiss samples oriented to schistosity at angles of 0°, 30°, 45°, and 90° were tested under quasi hydrostatic pressure [21, 22]. Schistosity is given by subparellel orientation of biotite and chlorite scales and the turn in the same direction of plagioclase rhomboid porphyroclast. Experiments were conducted under high pressures up to 1 GPa with the use of piston-cylinder device and by well-known methods. Micro structural characteristics of samples before and after the experiment were determined with the use of scanning electron microscope JEOL -35-CF with vacuum deposition of aluminum. Several chippings were studied for each sample. Elastic waves velocities under atmospheric and high pressures correspond to elastic waves velocities obtained before by other researchers and are in the range from 5.5 to 6.0 km/s under atmospheric pressure and from 5.8 to 6.2 under 1 GPa. In the initial pressure range, the increase of elastic waves velocities occurs, which is characteristic of majority of rocks. However further increase of elastic waves velocities after 200 MPa is noted only in a sample cut off at the angle of 45° to schistosity. In other oriented samples insignificant decrease of elastic waves velocities is noted up to 1 GPa. Maximum decrease of velocity up to 5% (after 200 MPa) is noted in a sample of zero orientation. It is evident from the analysis of structural characteristics of this sample after the experiment that this decrease of velocity is associated with the formation of micro structural faults in a sample in the course of quasi-hydrostatic compression. In the sample, curved bent of biotite porphyroclast is ob-

served with breaking lines beginning to show on the bent and some sections show lines of plagioclase breakings. Individual fractures of closely foliated biotite porphyroclast are filled with fragmental material. Apparently it is these segments of worn out materials that contribute most to the decrease of elastic waves velocities.

As it is known from literature, as the pressure increases, defects contribution to the crystal elasticity variation decreases and the role of reciprocal position of atoms in crystal framework increases. The extent of high-pressure influence on the elastic parameters variation related to the crystal framework elasticity is not the same not only for different minerals but also in different crystallographic directions in one and the same mineral. In this case, as the pressure rises, the anisotropy of transverse waves velocities shows a greater decrease along schistosity plane than perpendicular to it. Elastic waves velocities in biotite gneiss samples obtained under pressures of up to 1 GPa are considerably lower than in rock-forming minerals of corresponding crystallographic directions. Apparently we deal with cumulative contribution of rock-forming minerals defects that is found not only under atmospheric pressure but is also added with new defects formed under pressure.

In paper [23], temperature gradients and heating velocity influence on fissure-formation process as well as the behavior of elastic waves velocities and attenuation were studied in quasi-isotropic samples of marble with the use of acoustic emission registration. Crystallographic textures of marble and sandstone were measured by neutron diffraction method. It was shown that temperature gradients up to 52°C/cm did not result in texture variation. It was established that temperature dependence of acoustic emission in sandstone samples differs with different velocities of internal heating. Acoustic activity maximum of sandstone samples coincided with maximum temperature gradients in the samples. Temperature dependence of marble acoustic activity considerably differs from temperature dependence established for sandstone. Marble samples show acoustic activity maximums at temperatures from 30 to 60°C and more than 200°C. In the interval between those temperatures an area is registered where acoustic activity decreases. Such behavior suggests the domineering role of the surface defect structure in the process of fissure-formation in marble. All samples show similar behavior on cooling. Maximum acoustic activity is noted at the moment when heating element is turned off; emission intensity of different samples is comparable.

Results of combined use of neutron diffraction and mechanical spectroscopy to study physical characteristics behavior of monocrystalline quartz and quartz powder in the temperature range of α–β transition are given in paper [24]. From the registered diffraction spectra, the lattice parameters are calculated of quartz powders with different grain size in the temperature range from 540 to 620°C and atom coordinates in elementary cell are calculated as well. Temperature dependencies of internal friction value and resonance frequency in phase transition temperature vicinity on exciting oscillations in planes parallel and perpendicular to Z-axis of quartz. In the studied samples, different temperatures of phase transition are registered in the range from 560 to 620°C. Acoustic and neutron research results testify to the fact that α–β quartz phase transition has inherent features, which are of both the first and the second type of transitions. Internal friction maximum at temperatures of 350-450°C is revealed. The blurred character of this maximum and its asymmetry suggest that it is a complex peak, which is a superposition of maximums with close times of relaxation. A likely cause of this effect is the sample surface influence.

The third direction

Research into nanostructures in rocks and minerals to study processes going on in them under high pressures and temperatures.

Academician O.A.Bogatikov [25] noted the abundance of nanostructures in nature as a global characteristics and the necessity of studying them. At present the research is at exploring stage as far as the problems of the physics of the Earth are concerned. As it was noted in [26], one of such directions in the physics of the Earth can be studying processes of rock and mineral formation under high p-T parameters. For this purpose a number of tasks should be fulfilled:

- selecting methods of revealing nanoparticles at various natural objects under normal conditions;

- establishing presence or absence of nanoparticles in natural materials under different p-T conditions and deformation regimes;

- making a list of minerals in which nanoparticles are found and drawing correlation to mineral formation genesis;

- revealing features (objects) that initiate nanostructures appearance in natural materials;

- establishing the time influence and duration in the changes of nanostructures characteristics in natural materials;

- developing instrumental techniques of registering physical characteristics variation in nanoscale.

For the first time, research in this direction was conducted by scientists of Schmidt Institute of the Physics of the Earth RAS and Ioffe Physical and Technological Institute RAS in the frame of program No. 5 of Earth Science Department RAS "The deep structure of the Earth, geodynamics, magmatism, interactions of the geospheres". To find nanocrystals in rocks and to assess their size Raman scattering spectroscopy was used [27, 28]. Experiments were conducted on thin-laminated arkose sandstone PV-364 from Riphean turbidite beds of Srednii Peninsula. The rock contains 60 % of quartz and feldspar, 15 % of mica and 5 % of zircon ore and titanium dioxide (TiO_2). Chemical composition of the rock components was studied with the use of microprobe SX-100 in the Institute of Geochemistry RAS (operator N. N. Konankova). To register Raman scattering, spectra plates of thickness 3-4 mm were cut out from rock samples along shcistosity and across slickensides. Their surface was polished to diminish Rayleigh scattering of light. To obtain spectra the plates were set on microscopic stage Ramalog 5. The spectra were excited with argon laser Ar++ 16508 (Spectra Physics), line 488.0 nm. The laser ray focused on the sample surface made a spot of the diameter of ≈ 30 μm. Accuracy of defining maximum frequency and the width of bands under investigation are not less than 0.2 cm^{-1}. For the purpose of reliable classing of observed bands, monocrystal spectra of anatase, quartz and plagioclase were recorded coincidently with rock samples spectra. In all the spectra of a rock, the bands are shifted towards high frequencies as compared to their position in monocrystal spectra and they are widened on the same side. These results show that in all the investigated parts of the sample, particles of anatase, quartz and plagioclase are of nanometric size. The size of nanocrystals of anatase and quartz vary in different places from 5 nm to 9 nm, whereas plagioclase crystals have for the major part constant value of the order of 20 nm. Besides in different sectors of the sample not only the form and position of the bands under investigation vary but also their intensity, which is proportional to nanocrystals concentration. The research demonstrated that Raman scattering spectroscopy allows us to reveal nanocrystals and to assess their size, concentration and interatomic relations in them in different sectors of the rock surface layer with resolution equal to the diameter of light beam (in our case it is of the order of 30 nm).

The research of nanocrystals on the slickenside surface of arcose sandstone PV-364 was conducted by the method of atomic microscopy [29]. In this case, on "undamaged" and polished surfaces of the rock slickenside, formations resembling intensely rugged "mountain ridges" and "hills" were discovered. Their height on "undamaged" surface varies in the range of 3-40nm and on the polished surface it varies from 1 to 500 nm.

The efficiency of Raman scattering for the purposes of revealing nanocrystals is also corroborated in [30], which sets up the tasks of obtaining information on the structure and composition of magmatic basite melts containing ore elements. The authors studied incrustations of hardening from mid-oceanic ridges. It is shown that this experimental method allows us to identify crystalline or amorphous state of the material. It is revealed that the decrease of effective velocity of material hardening with moving away from the outer edge of the sample results in the appearance of crystal phase impregnations. The assessment of glass structure nanometric heterogeneities was obtained, which amounts to 2 nm.

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10. Researches in the physics of the Earth and geothermy

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New assessments of rheological characteristics of the mantle and the value of liquid core compression with account for electromagnetic relation were obtained from the results of recent high-precision data on amplitudes and phases of the induced nutation of the Earth. Assessments were obtained of the effective dynamic compression of the solid core of the Earth from data on its induced nutation. Areas of possible values of the set of three indicating parameters were defined: low mantle inelasticity coefficient and values of effective dynamic compression of the inner solid and outer liquid cores of the Earth.

The theory of free and induced nutation of the Earth with liquid core of non-uniform chemical composition (with non-zero frequency of Brendt-Viaisil) was constructed. A new type of free six-day nutation of the Earth was revealed which is only characteristic of planets with liquid core of nonuniform composition. Three-dimension solutions were obtained that define tidal displacements and gravitation field variation in the liquid core, Love numbers and constants of induced nutation for the model of the Earth with liquid core having non-homogeneous chemical composition.

The most recent model of the polarity magnetic scale of the Early Paleozoic was elaborated. It was proved that in the Early-Middle Ordovician inverse polarity superchron of duration of about 20 million years existed for about 20 million years (superchron Moiero). It was shown that as the Ordovician superchron is approached the frequency of polarity reversals gradually decreases and in the Middle Cambrian, Late Cambrian and Tremadocian makes 6-8, 2.5-3 and 0.5 reversals per 1 million years respectively. The obtained result corroborates the hypothesis that reversal process is non-stationary and with approaching superchons the geomagnetic reversal frequency decreases.

As a result of combined paleomagnetic and isotope-geochronological studies of dykes and sills of western Prianabar'e, for the first time paleo Proterozoic basic paleomagnetic pole has been obtained and substantiated for inner areas of Siberian platform, which supports the hypothesis that Siberia and Lavrentia were in single supercraton in the period of time at least from 1.9 to 0.95 Ga.

On the basis of biomagnetostratigraphic data, the general scale of the Paleozoic of north-eastern Russia was compiled, in which 18 normal-polarity magnetozones were established against predominant inverse polarity. Magneto zones of normal and inverse polarity are located in concrete biostratigraphic intervals, which allow us to identify magneto zones in other sections of the same age.

The scale is correlated with the general stratigraphic scale, general magnetostratigraphic scale of polarity and isotope age scale.

Three-dimension numerical model of hydromagnetic dynamo in the outer core of the Earth was elaborated. The model takes into account the influence of solid core capable of rotating under the effect of viscous and magnetic forces and allows us to reproduce a number of phenomena well-known in the geophysics, such as eastward rotation of the solid core with respect to the mantle, reversals and digressions of magnetic field, magnetic energy prevailing over kinetic energy characteristic of magnetostrophic equilibrium of forces in the core.

With the use of a combination of various methods of analysis we studied the nature of a layer at Cretaceous–Paleogene boundary, which is associated with evidence for biota changes approximately 65 million years ago. It formed in two stages. In the lower part of transition layer, anomalous concentrations of iridium, lead, chrome, copper, titanium were formed under the influence of volcanic activity of plume nature. The origin of micro particles of nickel, diamond and awaruite discovered in the upper part is associated with the impact event.

Methods were elaborated of mathematical modeling of two-dimension stress fields in the elastic lithosphere, using experimental data on major stresses orientation as input information. The methods do not require presetting boundary stresses and in defining stress deviator fields do not require presetting horizintal mass forces caused by non-uniformity in thickness and density of the lithosphere.

On the basis of numerical modelling of gravitation effects caused by the Earth's surface deformations and stress accumulation in the lithosphere of closed zones of subduction it was shown that satellite system GRACE data can be used to monitor seismogenic structures.

A set of maps was compiled of velocity vectors of modern horizontal movements of the Earth's crust in southern shore of Gulf of Finland, Karelia, Cola Peninsula and North Caucasus defined from space geodesy data (GPS and GLONASS measurements).

For the territories of Tien Shan, Western Altai and Central Mongolia, quantitative assessments of modern horizontal deformations of the Earth's crust were obtained from GPS measurements data and calculations of seismotectonic deformations in the epicenter areas of strongest earthquakes in the last hundred years. Zones where horizontal compression, extension or shear prevails were separated. It was shown that total deformations of block locked between Jungaria and North Eurasia are close to seismogenic ones in both directions of compression and extension axis and velocity values. It gives us grounds to believe that the major part of load applied to this block is realized at the expense of displacements with strongest earthquakes (M>7.5) in its periphery, which occur repeatedly.

On the basis of quantitative interpretation of data on gravitational anomalies, we constructed a 3D model of Khangaiskii batholith (Transbaikal region), a series of geological and geophysical sections across the batholith, and the chart of isolines of its thickness. Three-dimension modeling data allow us to make a conclusion that Khangaiskii batholith is characterized by flat form vertically: on the average the mass thickness is 5-7 km and locally it reaches 12 –15 km. Such areas coinciding with zones of large faults crossings most likely were granite magma feed channels.

A new mechanism of formation of large deep sedimentary basins (the Barents Sea basin, the Caspian Sea basin and others) with the initial stage of formation on the crust of continental type was proposed. Downwarpings of considerable amplitudes occur with small values of the crust extension at the expense of thickening low-crustal rocks in phase transitions related to infiltration into the crust of surface-active fluids from the mantle.

A new geodynamic model of formation of the system orogen – piedmont depression was elaborated, which shows that piedmont depressions are formed for the major part under the effect of small convection in the asthenosphere that forms as a result of mechanical and thermal unbalance in the process of continental collision. Digital modeling of the process of continental collision zone formation with parameters corresponding to the Bolshoi Kavkaz and Northern Caucasus troughs was carried out.

Methods of combined processing of surface and satellite electromagnetic data were elaborated. With the use of the methods, 3D model of electric conduction of Elbrus volcanic center was reconstructed. At a depth of 40 km, a body is revealed that shows a relatively good conduction of more than 0.04 S/m (vertical extension is 20 km, latitudinal and longitudinal extension makes 35 km and 15 km respectively), which may be a magmatism source.

On the basis of seismic data interpretation and temperature and heat flow variation, we developed 3D models of the geothermal field of sedimentary basins of different types: evaporite (The Caspian Sea basin) and shelf (Western Arctic region basin).

From the results of quantitative interpretation of magnetotelluric (MT) and magnetic variation (MV) data we revealed anomalous distribution of electric conduction of the Earth's crust in the zone of Talass-Fergana fault (TFF). It is established that two crustal conductors gently subsiding towards southwestern and northeastern Tien Shan rise to near-surface structures in the zone of Talass-Fergana fault and form an arc-form structure in plan. Deep geoelectric structure of the Talass-Fergana fault zone studied in eight sections of the fault with the use of MT and MV sounding profiles is a combination of high-resistence core in the center and conduction zones of listric zones gently subsiding southwestwards from TFF zone to depth of 40-45 km and northeastwards to depths of 25-30 km.

On the basis of mathematic modeling, the assessment was made of underground heat accumulated by magmatic sources of volcanoes Mutnovskii and Gorelyi (of the order of $10^{19} \div 10^{21}$J). The conclusion was made that at the expense of underground water heating, the heatflow given away by magmatic sources is several times as much as known reserves of energy of heat-transfer agent in the geothermal reservoir of Mutnovskaya geothermal electric power station.

The theory was forwarded of sealing cracks system in a rock mass owing to solid-phase precipitation from hydrothermal solution. It is shown that a critical value of the initial width of cracks exists, which is defined by the distance between cracks closest to each other, thermal physics processes and parameters characterizing the kinetics of deposition. According to the relationship between the initial width of a crack and the critical value different scenarios of crack sealing may be realized. If the initial width of a crack does not exceed the critical value, uniform sealing prevails. Otherwise the process has the character of progressive sealing beginning with periphery cracks. On the basis of this theory, assessments were made of the life of oceanic floor high-temperature hydrothermal systems.

From the results of isotope research in samples taken from thermal sources of seismically active area of Eastern Tuva, mantle helium content was determined and heat flow values were calculated. It was established that helium isotope relation value in all points where sample were taken is several times as much as the continental background of Paleozoic crust, which suggests additional supply of mantle helium. Variability of the value of helium isotope reltion was defined in areas of volcanism of different age: for the Quaternary it is 54.2-1257.0 (Ush Beldyr, Khoito-Gol, Maimalysh); for the Late Oligocene it is 37.1 (Kara-Charyk); for the Paleozoic-Cenozoic it is 43.5-45.3 (Tarys, Saldam, Naryn). Calculated values of the heat flow testify to the excess of conductive heat flow over background continental level, which is a result of convective heat addition to the crust from the mantle. Prognostic estimate is given of the Earth's crust temperarture at different depths. The thickness of thermal lithosphere varies from 62 to 97 km, increasing from north to south at the eastern side of Tuva.

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11. Research in comparative planetology

11.1. Planetary and satellite geophysics

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Research in planetary and satellite geophysics for the major part were conducted in IPE RAS. Below we discuss major publications.

The book [1] has 5 chapters. In Chapter 1 the features of the Earth modern model are considered. In Chapter 2 models of giant planets are given and the role of Jupiter in the formation of the Solar system planets is discussed. In Chapter 3, the importance of studying the Moon is emphasized in order to understand better the Earth origin. In the same chapter, the potentialities of the proper oscillations method are discussed for constructing the Moon's inner structure model and the problem of the Moon orbit evolution. Chapter 5 deals with the problem of constructing the model of Mars inner structure. Models, figures and gravitational moments of Galilean satellites of Jupiter are treated in Chapter 5.

In [2], research conducted in the Institute of Physics of the Earth RAS (IPE RAS) on modeling planets' interior is summed up. In [3], based on the chemical model of Mars proposed by German researchers H.Wanke и G.Dreibus, a new set of global models of the planet inner structure was

constructed. The model comprises four sub-models, i.e. outer porous layer, the crust, the mantle and the core. The first layer of 10-11 km is considered as a transition zone from regolite to consolidated rocks. Mineralogical composition of crustal basalts varies with depth owing to phase transition gabbro-eclogite. The starting point of modeling the mantle was experimental data [4] for the mantle minerals along the areotherm. Sulfur and hydrogen content varied in the core model. In mantle silicate, iron content varied. It was taken into account that a considerable amount of hydrogen might have got into the core in the formation of the planet [5]. Modeling revealed the following features:

1) hydrogen presence in the core leads to the increase of weigh ratio Fe/Si and decrease of the mantle ferruginosity Fe# (atomic ratio Fe/(Mg+Fe) owing to the core radius increase;
2) increase of sulfur and hydrogen content in the core makes the occurrence of perovskite layer in the mantle floor less likely;
3) in order that the ratio Fe/Si reach the value of 1.71, which is characteristic of chondrite, the planet's core should contain more than 50 mol. % of hydrogen.

In the second part of [3] on the basis of estimated values of Mars seismicity and sensitivity values of modern devices, amplitudes were calculated for different types of proper oscillations of the planet. The depth was defined to which proper oscillations may sound Mars's interior. Thus Mars quake with seismic value moment of 10^{25} dyn*sm is capable of exciting detected spheroidal oscillations of degree. Such spheroidal modes are capable of sounding outer layers of Mars down to depths of ~700-800 km.

Paper [6] is a further development of [3]. It was initiated by [7], in which the value of Love tidal number k_2 was determined from observations. This value of k_2 number combined with the value of inertia mean moment imposes a new strong limitation on the planet model. The constructed models of Mars internal structure are elastic, whereas observed k_2 contains both elastic and inelastic parts. In this paper, the problem of dividing k_2 into elastic and inelastic parts is discussed and such division is carried out.

In paper [6], prognostic value of Chandler's period for Mars is calculated, which is equal to 199.5 days including 1 day owing to inelasticity.

In IPE RAS, theoretical research in giant planets is conducted. In [8], the spectrum of Saturn proper oscillations is calculated for a new set of the internal structure models. Global acoustic frequencies are calculated for radial (overtone) order up to 20 and degree (number) of oscillations up to 15. Especially interesting are diagnostic abilities of discontinuous gravitational modes associated with density jumps in molecular shell of Saturn and in the interface of molecular and metallic shells. These two modes show displacements, which are not equal to zero, on the planet surface and their periods may be in resonance with orbital periods of rings D and C of the planet. Much attention was given to the theory of Galilean satellites of Jupiter.

All the Galilean satellites of Jupiter are close to hydrostatic equilibrium, therefore data on their figure and gravitation field allow imposing limitations on density distribution in the interior of these bodies and thus to foster constructing models of their inner structures.

In [9] the theory of equilibrium figure and gravitation field of Galelean satellite Io was constructed with accuracy up to second order members by small parameter α ($\alpha = \frac{\omega^2 S_1^3}{G_m}$, ω is angular velocity of the satellite rotation, G, S_1, m stand for *gravitation* constant, mean radius and Io mass respectively). It is shown that in order to describe all the effects of the second approximation, formulas for the satellite figure and its gravitation potential should contain not only components of the second spherical harmonic (first approximation) but also components of the third and fourth spherical harmonics. Love's number of the third degree h3 determines the third harmonic contribution. Measuring gravitation moments of the third degree and order would allow us to reveal the degree of detail to which hydrostatic equilibrium condition is fulfilled for Io. The conditions are as follows: $J_3=C_{32}=0$, $C_{31}/C_{33}= -6$. Errors are calculated at the expense of the second order infinitesimal for gravitation moments J_2 and C_{22}. A conclusion is made that when constructing models of Io inner

structure it is better to make them subordinate to the known k2, than to go fromчем переходить от k_2 and inertia moment meaning. The theory is applicable to the rest of Galilean satellites.

Papers [10, 11] are devoted to theory elaboration and application. In [11] trial three-layer models of Io and Europe satellites of two types are constructed. In the first type models (Io1 and E1) it is assumed that the core is composed of eutectic solution Fe-FeS, which in satellite core conditions has density $\rho 1 = 5.15$ g/cm^3 (Io1) and 5.2 g/cm^3 (E1). In models of the second type (Io3 and E3), the cores are composed of FeS with nickel admixture and have density $\rho 1 = 4.6$ g/cm^3. The approach in this paper differs from those used before in both selection of chemical models of these satellites and imposing boundary conditions on the model. The most important question to be answered by the models of Galelean satellites inner structure is the composition of condensate at the time of Jupiter system formation. Jupiter's core and Galilean satellites were formed of condensate. Ganymede and Callisto were formed at a considerable distance from Jupiter in zones, where temperature was lower than water condensation temperature; water in total amount was in their composition and model construction showed that ice component/ heavy component ratio is IC/HC~1. Models of satellites Io and Europe will define the heavy component composition. Models of the second type (Io3 and E3), in which the cores are composed of FeS, give for core masses (in weight percent) 25.2 (Io3) and 22.8 (E3). In the discussion of HC, it is noted in the paper that theoretically the matter of which the core of FeS + Ni may be composed has in HC component ~25.4 weight percent of the satellite mass. In this case, such an important parameter as mantle silicate ferruginosity is equal to Fe# =0.265. Models Io3 and E3 are in good agreement with this theoretical prediction. Models of the first and second type differ noticeably in the core radius size, and in principle, from geophysical research in Io and Europe, we can hope to obtain an answer as far as HC composition in the zone of Jupiter system formation is concerned. The other problem discussed in this paper is the error that is made in the construction of Io and Europe models with the use of formula Rado-Darwin in transition from Love's number $k2$ to dimensionless polar moment of inertia C. In the case of Io, Rado-Darwin formulas reduce the true value of C by one and a half unit in the third sign. In the case of Europe, this effect is about three times as small, which approximately testifies to small parameters ratio of the satellites under consideration αI0/αEuropa ~ 3.4. In the model construction of satellite inner structure, the core radius strongly depends on both the inertia mean moment value I and value k_2.

In [12] the models of inner structure of completely differentiated satellite Europe and partially differentiated satellite Callisto are constructed on the basis of data on gravitation field obtained by spacecraft "Galileo", geochemical limitations on the composition of ordinary and carbonaceous chondrite and thermal dynamics data and equations of water state, ice high pressure phases and meteorite materials.

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11.2. The formation and early evolution of the Earth and planets

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A book and a number of papers on the formation of the Earth and planets were published from 2003 to 2006. The monograph [Dorofeeva, Makalkin, 2004] sums up the results of combined researches in physical and physical-chemical processes going on in gaseous dust protoplanetary disk around the young Sun that influenced the chemical composition of the planets most and significantly affected their inner structure. Numerical models of protoplanetary near-sun disk at sequential stages of its evolution are constructed. The behavior is considered of the most important chemically active volatile elements and compounds that caused impoverishment of the Earth group planets, parental meteorite bodies and Galilean satellites of Jupiter. In Chapter 1, composition and thermal dynamic conditions of matter differentiation in the near-sun protoplanertary disk are discussed on the basis of cosmochemical data. In Chapter 2, the results are given of numerical modeling of physical and physical-chemical conditions in protoplanetary disk at sequential stages of its evolution beginning with the formation stage and ending with dissipation stage. Chapter 3 is devoted to the studies of various physical processes and kinetic limitations influence on the volatile matter accumulation in parental bodies matter of meteorites and the Earth group planets. Among physical processes discussed in the Chapter is the growth of dust particles, their sedimentation to the equatorial plane of the disk, radial drift towards the Sun, the formation and growth of planetesimals and their interaction with dust particles. In Chapter 4, new thermodynamic models of protosatellite disk of Jupiter and the conditions of Galilean satellites formation are discussed.

The results of numerical modeling of the early thermal evolution of the Earth are presented in [Makalkin et al., 2003]. Calculations showed that the major source of the planet heating at the accretion stage were large bodies impacts, which gave approximately 75 % of the total heat production. The heating source that was the second in significance (about 15 %) was energy release with sinking metal inclusions through mantle matter in the process of the Earth's core formation if we assume that the Earth's core formation went on simultaneously with the planet formation according to timing data by Hf-W system. At the same time as it follows from calculations, owing to convection the temperature in the mantle averaged by lateral and times over 1 million years did not significantly rise above the temperature of mantle matter solidus. The calculated evolution of averaged radial distribution of temperature in the Earth's mantle at the planet formation stage is shown in Fig. 11.1.

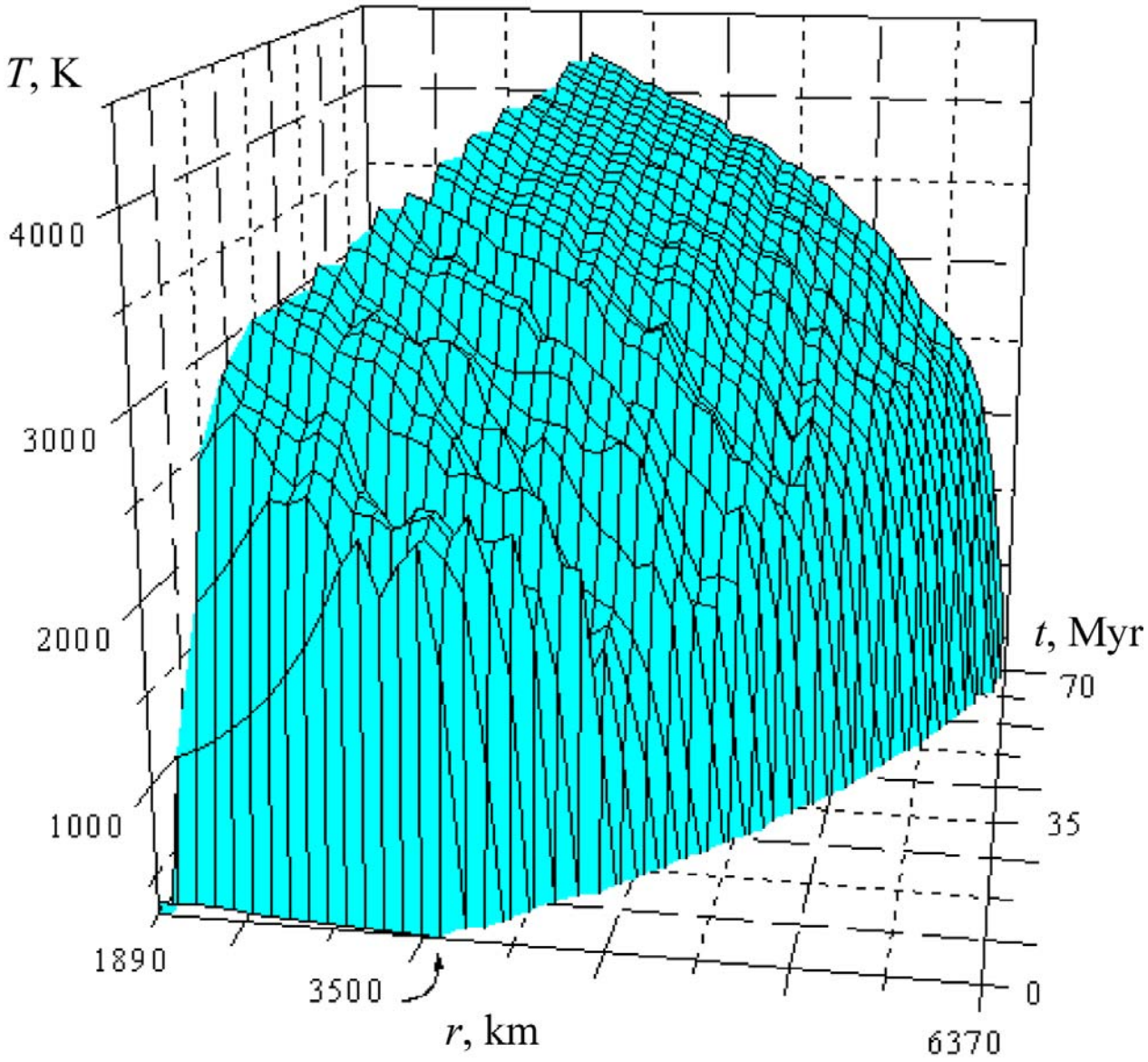

Fig. 11.1. Early thermal evolution of the Earth's mantle. Considered sources of energy: impacts of falling bodies, gravitation dissociation, adiabatic compression, impacts of falling bodies, gravitation differentiation, radioactive decay. Mechanisms of heat transfer: convective, impact mixing, thermal conductivity. теплопроводность.

In [Pechernikova, 2005] the role of large bodies falling down on the Earth in the process of its accretion is refined and it results in a considerable increase of the calculated velocity of the planet mass increase at an early stage of its formation. According to the estimates, one thousand-kilometer embryo of a planet is formed during several million years and the Earth grew for 17 million years to reach Martian mass, i.e. about two times earlier and faster than the theory assumed before. Shortened scale of the planet growth at an early stage of the planet accretion is in agreement with Hf-W geochronometer indications.

Three-dimensional numerical modeling was carried out of the impact dynamics of large space bodies with radius from 100-200 to 1000-2000 km falling on the Earth in the first several hundred millions of its existence [Teterev et al., 2004]. Density variation in the Earth's interior before and after a large body impact, the evolution of the planet surface form, shock wave propagation inward the planet and its reflection from the core, which undergoes strong attenuating vibrations were calculated. In the calculations of the body impact of lunar size, the following features were shown: the formation of a large impact crater, throwing out up to 60% of the body mass outside the

planet and the formation of gaseous dust cloud revolving around the planet; propagation of a very powerful wave on the Earth surface

The process was studied of thermal anomalies formation around localities where large space bodies fell on the Earth [Ivanov, 2004]. In this paper, digital calculations were conducted in the frame of complete 2D modeling of the impact event including both dynamic and thermal aspects. The parameters of thermal anomalies with impacts of bodies of different scale from 1 to one hundred kilometers in diameter are compared. Rocks cooling time is estimated under impact craters of different scale. These estimates were used to model heat addition by the impacts of small (less than 500 km in diameter) planetesimals at the late stage of the Earth accretion. With the use of combined studies on impact thermal anomalies sizes and the masses model spectra of falling planetesimals, boundary conditions were improved to calculate thermal evolution of the early Earth.

Numerical modeling of largest meteorite craters formation on the Earth was conducted [Ivanov, 2005]. Geological and geophysical data accumulated in the past decades were used as limitations in order to select correct values of parameters in the available mechanical models for the reaction of the planets' crust to a large body impact and to improve initial diameters and morphology of four terrestrial craters partially eroded with the use of numerical modeling.

Computer modeling of dust particles and small bodies migration from the periphery of the Solar system to the area of the Earth and Earth's group planets was carried out [Marov, Ipatov, 2005]. It was shown that the contribution of comet and trans-Neptune dust particles to the total amount of dust delivered to the planets might have been significant. By the assessment obtained, dust particles contribution to the delivery of volatile matter to the Earth's group planets is less than the contribution of small planetesimals by three or four orders. However dust particles could have been the most efficient carriers of organic and even bioorganic matter to the Earth owing to less heating when going through the atmosphere.

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12. Artificial intelligence in geophysical researches

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Using algorithms based on artificial intelligence, recognition of images and fuzzy logic methods to analyze data in earth sciences is not common practice in Russia, and papers treating this line of research are few in number. Nevertheless such research shows diversity of both fields of geophysics and methods applied. We may note purely applied research with the use of well-known algorithms of artificial intelligence, first and foremost neuron nets, and the development and use of new approaches as well [Gvishiani et al., 2003; Mikhailov et al., 2003; Gvishiani, 2003; Kedrov et al., 2003; Makarenko, 2003; Makarenko, 2004; Zlotnicki et al., 2005; et al.].

Among paper series where both new fundamental lines of processing and analysis of data and geophysical applications are elaborated we note the following [Makarenko et al., 2001; Akkulov et al., 2003; Makarenko, 2003; Makarenko, 2004; Mordvinov et al., 2004]. In these papers, new concepts of data series analysis are considered to restore major characteristics of the attractor describing the behavior of the system under investigation. To analyze data different approaches are used that are based on the methods of image recognition and neuron nets. Elaborated approaches are used in analysis tasks 1-D (number series) and 2-D (map sets of geophysical data arrays). Mapping data are analyzed to search for indications of useful mineral deposits. There are examples of successful use of such an approach for Kazakhstan territory. The behavior of number series describing various aspects of solar-terrestrial relations is considered as 1-D data.

The authors of these papers set the major task of modeling and prediction of cosmic weather with the use of deterministic chaos and stochastic dynamics methods on the basis of dynamic invariant assessments derived from scalar time series. Such approaches are used together with methods of neuron nets and image recognition.

One of the results of work, which was partially realized and partially stated by the authors, is creation of the methods and model of computer programs for Markovskii predictors of geo- and solar-indexes behavior.

Research cycle combining elaboration of new algorithms and approaches and their application to solving different geophysical problems is the cycle of research based on the original algorithms of clustering and morphological analysis developed on the basis of fuzzy logic and statistics [Mikhail et al., 2003; Grissini et al., 2003; Zlotnicki et al., 2005; Soloviev et al., 2005; Agayan et al., 2005; and others].

Authors of these papers believe that approaches based on artificial intelligence methods and fuzzy logic are required in the studies of geophysical objects that are unique and especially complicated because the role on expert intuitive estimates is often great in such research. However a large amount of factual information makes expert processing of data difficult. Besides, formalization of the process of obtaining expert estimates and identical data processing for the total data array, which is often very large, seems to be necessary, which is actually impossible with expert processing of data.

The cycle of clustering algorithms elaborated before [Gvishiani et al., 2003; Gvishiani et al., 2003a; Mikhailov et al., 2003; and others] was used to analyze data of detailed geomagnetic observations, relief characteristics and in the analysis of space interferometry SAR. On the basis of algorithms, data were aggregated to distinguish stable characteristics of series for further interpretation.

In the analysis of geomagnetic data for Sent Malo bay (France) and massif Akhkhagar (Algeria), the task was to reveal system features of anomalous field and separating stable characteristics of the field, which allow us to obtain its tectonic interpretation. We used clustering algorithms "Kristall" and "Rodin". To analyze geomagnetic data and the relief for Nizhne-Kanskiy massif near Krasnoyarsk we used alghorithm "Monolit" as well.

One more significant line in this research cycle is the analysis of geophysical monitoring data. An alternative to visual identification of signals by an expert is proposed that is convenient for use and quick reprogramming. A number of algorithms to analyze large 1-D data arrays were elaborated and used to recognize anomalies of various types in the data. The algorithm of morphological analysis was used to analyze of electrotelluric monitoring data of La Fournese volcano (Reunion Island, France). Earlier, algorithm DRAS was used to analyze these data, which allowed automating the separation of anomalies in the data. But this algorithm did not allow us to analyze the character of signal morphology, which made it difficult to distinguish anomalies with different character of morphology. It is well known that various causes like heavy rains, hydrothermal processes, and magmatic masses approaching the surface may generate electrotelluric anomalies. In this case, different physical mechanisms generate anomalies that differ in the character of morphology. To distinguish anomalies corresponding to different agents we used the algorithm of morphological analysis. Anomaly samples corresponding to different types of effects were preset and morphological search for anomalies of the required type was made. An example of such data processing results is given in Fig. 12.1. Using morphological analysis algorithm allowed us to separate anomalies of different morphology corresponding to different types of natural agents.

We compared the results obtained with the use of morphological analysis method and traditional statistics approaches. To solve the problem in terms of classical statistics it seems reasonable to calculate the coefficient of current correlation r between selected segment of the initial record and current segment of the analyzed record. Other variants of comparison are also possible on the basis of wavelet or SWAN analysis. Comparison of different methods with model and real examples showed that the morphological analysis method is more stable than methods based on more traditional approaches with record segments given as anomaly that are relatively shorter and less specific in character. For example, in these conditions, stable selection of the required segment with the use of correlation analysis is only achieved with considerable increase of the record segment length.

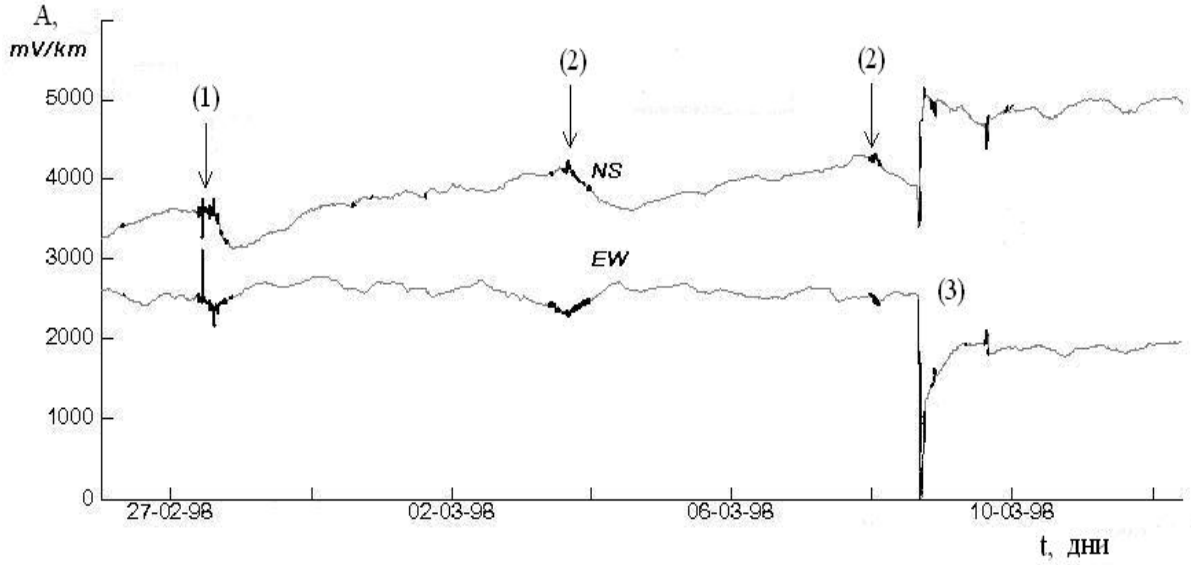

Fig. 12.1. Example of combined morphological analysis results from electrotelluric sounding data in La Fournese volcano. Anomalies of different morphology were revealed that were associated with shower rainfall (1), hydrothermal activation (2), and eruption (3).

Besides, the method of image recognition is used in geophysics in Russia to identify underground explosions and earthquakes from seismic data [Kedrov, 2003; Kedrov, 2006]. In [Kedrov, 2003], the new method to calibrate criteria of underground nuclear explosions (UNE) identification was proposed, and in [Kedrov, 2006], the results obtained with the use of this method are given for areas where calibration explosions were not made. Explosion identification is carried out with the use of data on earthquakes of a given area by adapting data on the area for base area that has sufficient amount of records of both earthquakes and explosions. As base area we used the stable platform region of Eurasia including Semipalatinsk test site (STS); assessments of regional identification criteria in STS were obtained from large samples of UNE and earthquakes. Taking into consideration the pressing problem of dynamic calibration of the International monitoring system global network stations under the Comprehensive Test Ban Treaty, research is conducted in Russia with the use of records of UNE from STS in Kazakhstan and earthquakes from Talgar station (TLG). After route correction is made, 100 percent of UNE and approximately 85 percent of earthquakes are identified correctly from recognition functions that had been obtained before for the base area.

One more line is the use of fuzzy logic methods to analyze borehole and other geological data on oil-producing areas to assess hydrocarbon resources [Kovalevsky, Kharchenko, 1992; Kovalevsky et al., 1997; Kovalevsky, Gogonenkov, 2004; Senilov, Lyalin, 2005 and others]. First geological models of deposits did not have uncertainty assessments. Such models are called determinate. Uncertainty, which was considerable, was given by expert assessments. To obtain probability assessments geostatistics models are commonly used. The use of geostatistics allows a better adequacy of geological models. Geological environment category character and qualitative estimate of significant characteristics hamper successful use of geostatistics. Geostatistics model is not always adequate with category assessments of the parameters and we may note from experience that it often overestimates uncertainty. As a variant of assessment method an approach was elaborated on the basis of fuzzy sets of L. Zade, which appears to describe more adequately the uncertainty of 3D parameters in a geological model of oil and gas trap than geostatistics commonly used now to say nothing of determinate modeling. The result of fuzzy modeling is improving the accuracy of reserve amount of prospected and exploited deposits. Arguments are put forward [Kovalevskii, Gogonenkov, 2004] that the method of fuzzy modeling gives a better base to calculate procedure parameters of mining deposits than determinate or geostatistics models.

Note that this analysis is not complete because a large amount of applications, for example in oil geology and geophysics, is not considered to a full measure in major specialized publications.

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13. Web geoinformation media to analyze space and time-space data

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In the last few years, a significant result in geoinformatics is the elaboration of web geoinformation medium to analyze space and time-space data. This project is being implemented in the frame of RAS Presidium program "The development of principles to create scientific distributed information-computation medium on the basis of GRID technologies", line "Electronic Earth: scientific information resources and information-communication technologies". About 20 institutes

affiliated to RAS departments for earth science, mathematics and informatics are involved in the project.

The aim of the project is to create an integral information field to fulfill tasks related to earth sciences and to provide the user with it. At present base version of geoinformation media has been elaborated and it is being experimentally operated.

The information field of web media comprises resources (publications and geological and geophysical time-space data) means of analysis (program systems including GIS), computation devices (servers, supercomputers, users' computers) and system facilities to search for and integrate resources and analytical means. Personification principle is employed to carry out search and integration. Resources of the web medium as well as programs may be distributed in Internet servers and user's computer. For example, the core of the web geographical information system (GIS) realized in Java applet architecture is at a certain server. In this case, resources and GIS plug-in can be distributed in both any sectors of free and limited access and in user's computer. Storing a part of data in user's computer works for better protection from unauthorized access. GIS-applet and XML file generated from user's requests with addresses of resources and plug-ins are downloaded into user's computer. Then the applet collects resources and plug-ins indicated by the user and the user starts doing the task.

This web media gives the user an access to geoinformation resources of the Project participants as well as to world network and vector geodata including prompt catalog of earthquakes NEIC USGC. Analytical means comprise web-map viewers, web analytical GIS GeoProcessor 1.7, KOMPAS V and GeoTime II, and a number of analytical and computation programs developed by project participants; some of them use computation capacities of the super-computer center RAS. The search for, integration and the analysis of distributed resources and programs use the infrastructure of metadata and headings. Resources selected by user are individualized, i.e. in server's portal; a unique repository of initial data addresses and stored results is formed for each user.

Solution of a number of problems to analyze time-space processes is based on combined processing of data. Most commonly three features cause it: (a) interaction of processes under investigation; (b) impossibility of direct measuring of their key characteristics; (c) insufficient amount of observations and noise effects comparable to useful signal level. For example, seismic manifestations in the Earth's crust are associated with processes going on in the mantle, the lithosphere, ionosphere and planetary interactions. In the studies of seismic tectonic processes, for the major part measurements are used that are made on the surface: seismograms, earthquake catalogs, time series of geodetic, geophysical and geochemical monitoring, geological and geophysical fields, fault tectonic interpretations and others instead of energy and structure parameters of the Earth's crust.

In the analysis of such data, principle problems arise of obtaining unambiguous interpretation of processing results. To search for stable solutions methods that allow complex use of all available multidisciplinary data and expert knowledge are required.

The web medium analytical means support solution of the following types of tasks of combined geoinformation analysis:

- Estimating relations between geological environment features (for example, mapping research in mutual position of elements of several informational layers, estimation of statistics parameters of the geological environment time-space characteristics, estimation of direct economic losses caused by earthquakes, estimating useful mineral reserves).
- Estimating relations between geographical objects (for example, estimating the extent of relation between natural processes or geographical objects, specifically indirect losses caused by earthquakes).
- Prediction, detection and identification of unknown features of the geological environment and unknown geographical objects (for example, prediction of maximum magnitude of expected earthquakes from the complex of geological and geophysical data, prediction of deposits, detection of earthquake precursors).

- Prediction of the evolution of time-space interacting processes (for example, modeling scenarios of the disaster following an earthquake).

Information medium is realized in the form of a system of several portals.

The portal of the All-Russia Institute of Scientific and Technical Information RAS (*http://eearth.viniti.ru/*) is central. It supports remote authorized user's access to distributed repository of metadata describing publications, georesources, geoinformation systems, organizations and personalia in Earth's sciences, access to analytical GIS, super computer center RAS and GRID-calculations and provides personification of user's data and metadata. The central portal contains medium metainformation base, base of publications, repository of geoinformation resources, repository of personal data of authorized users, client program of search for and integration of metadata on all distributed resources of the web medium, means of GIS project monitoring, means of interaction with GRID and of data reservation.

The portal of the State Geological Museum RAS (*http://earth.jscc.ru*) contains geoinformation resources including data in ESRI formats on modern geodynamics, movements and strain of the Earth's crust, global and regional models of the structure of the major types of the Earth's structures, on the geology and metallogeny of the Early Pre-Cambrian, the mechanism of large and super-large deposits of useful minerals, geological structure of the floor and mineral resources of the oceans of the world.

The portal of the Geophysical Center RAS (GC RAS, *http://eearth.wdcb.ru/*) contains retrieval systems located inside informational and computational-algorithmic geological and geophysical resources, navigator of georesources on seismology, internet application to collect and visualize messages by services of urgent communications on earthquakes, information resource "International polar year (2007-2008); GIS resource, which is a map of horizontal constituent of the major geomagnetic field of the Earth, database on rare-metal carbonatite and world kimberlite with diamond content, resource "Dissemination and use of GRID in earth sciences (*Degree*)» (*http://www.eu-degree.eu/*).

The portal of the Institute of the geology of ore deposits, petrography, mineralogy and geochemistry RAS (IGEM RAS, *http://eearth.igem.ru/ru/*) contains a number of databases on useful minerals of the world and Russia. The databases are "Geology of ore deposits", "Geology of non-metalliferrous deposits", "Geology of caustobiolith deposits subdivided into gas, oil, gascondensate, coal", "Underground water", "Mineral deposits of Russia", "Placer deposits of Russia and CIS countries" and others. Besides the portal contains information for distributed information-computation medium that is set on analyzing ecological conditions in Moscow districts, the analysis of geodynamic settings in Russian regions, analysis of natural hazards and risks, natural hazards in Altai, Asia and Russia.

The Portal of the Institute of Geography RAS (GI RAS, *http://igran.ru/*) contains a viewer to view electronic geographical maps of "virtual" library as well as geoinformation resources on glaciology, ecosystems of world regions, on land resources of Russia and others.

The portal of the Institute of Information Transfer Problems RAS (IPPI RAS, (*http://www.geo.iitp.ru/*) provides remote users with technological means and GIS projects to conduct complex research of geodata, reveal empirical regularities and predict stationary and dynamic characteristics of geological environment. Web geotechnologies having powerful instrumentation are very expensive and intended for "advanced" specialists in geoinformatics (*ArcIms-ESRI, MapXtreme-2005-MapInfo)* and web systems either inexpensive or free, the so-called GIS-viewers *ArcExplorer, ArcReader, MapViewSVG,* have limited instrumentation.

IPPI RAS portal provides a new information technology for the user, regulated access to web geoinformation analytical systems to carry out complex studies of data, to reveal empirical regularities and to predict stationary and dynamic properties of the geological environment as well as free access to GIS projects presented in the portal. The systems allow us to integrate information resources in GIS project (geodata layers) distributed in different servers and user computers, which makes unnecessary storing data only in applet server and protects data from unauthorized access and for the most part it is the major demand of data owners.

The portal core is three original web GIS in Java-applet architecture for complex analysis of geodata: GIS GeoProcessor 1.7 for work with vector and network data, GIS GeoTime II, (β-version, http://geo.iitp.ru/geotime/all.html) for work with time-space vector and network data and GIS KOMPAS (versions 3 and 5) for work with vector data.

Geoinformation resources on seismotectonics and geodynamics of Northern Caucasus, Central Asia, Greece, China, Central Europe and others are presented in the portal.

The first stage of the scenario of registered user work with the medium is to make GIS project description. To do this the user is given on-line access to publications, to searching for data and required plug-ins as well as to enriching personal repository of information. Then from task metadata XML-document of GIS project is formed in automated mode, GIS-applet or GRID calculations are launched, data and plug-ins are loaded; the solution of the task (formulating cause-and-effect model of prognosis, discovering rules of prognosis and compiling prognosis map, constructing logical rule to explain the prognosis) and the result obtained are stored either in personal repository of the central portal or in user's computer.

The work has two principle results:

- We transferred from web GIS to distributed analytical geoinformation medium.
- Integral information field was created to do tasks in earth sciences; complex analysis technology was elaborated available for users that were not professionally trained in info.