RUSSIAN ACADEMY OF SCIENCES
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РОССИЙСКАЯ АКАДЕМИЯ НАУК
НАЦИОНАЛЬНЫЙ ГЕОФИЗИЧЕСКИЙ КОМИТЕТ

NATIONAL SEISMOLOGICAL REPORT OF RUSSIA

to the International Association of Seismology
and Physics of the Earth's Interior
of the International Union of Geodesy and Geophysics
2015–2018

НАЦИОНАЛЬНЫЙ СЕЙСМОЛОГИЧЕСКИЙ ОТЧЕТ РОССИИ

Международной ассоциации сейсмологии
и физики недр Земли Международного
геодезического и геофизического Союза
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In the National Seismological Report major results are given of research conducted by Russian geophysicists in 2015-2018 on the topics of the International Association of Seismology and the Physics of the Earth's Interior (IASPEI) of the International Union of Geodesy and Geophysics (IUGG). This report is prepared by the Section of Seismology and Physics of the Earth's Interior of the National Geophysical Committee of Russia.

В данном Национальном отчете представлены основные результаты исследований, проводимых российскими учеными в 2015-2018 гг., по темам, соответствующим направлениям деятельности Международной ассоциации сейсмологии и физики недр Земли (МАСФНЗ) Международного геодезического и геофизического союза (МГГС). Данный отчет подготовлен Секцией сеймологии и физики недр Земли Национального геофизического комитета Российской академии наук.

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Introduction

This report submitted to the International Association of Seismology and the Physics of the Earth‘s Interior (IASPEI) of the International Union of Geodesy and Geophysics (IUGG) contains results obtained by Russian geophysicists in 2015-2018. In the report prepared for the XXVII General Assembly of IUGG (Canada, Montreal, 8–18, July, 2019), the results are briefly outlined of basic research in seismology, geodynamics, in the studies of physics of seismic process and earthquake prediction as well as in some other directions.

The period from 2015 to 2018 was still difficult for Russian geophysics. 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 Assemblies, international projects and international centers. Russian geophysicists obtained a number of fundamentally important new results in the period under review. Many of them are presented in the following sections of this report.

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 2015–2018 are included in the report. At the same time it is hoped that authors may present these results at symposia of IUGG XXVII General Assembly.

1. The structure and results of seismic observations in Russia

1.1. Modeling and forecasting of aftershock processes of strong earthquakes.

The work is aimed at solving the fundamental problem of forecasting aftershock activity of strong earthquakes. Modeling of aftershock processes of strong earthquakes in areas with different seismogenesis (Svalbard Archipelago, Kamchatka, Altai-Sayan folded region, North Caucasus) with the help of relaxation models, trigger seismicity model and fracture mechanics model is carried out in order to find out the peculiarities and predict aftershock activity. The connection of deformations in the source of a strong earthquake with the presence of aftershock, comparable in magnitude to the main shock, is revealed. It is established that such aftershocks accompany earthquakes with non-double-dipole sources, because the main shock does not release the fully accumulated stresses. **(Federal Research Center United Geophysical Survey RAS,** see *Baranov S.V., Gabsatarova I.P.* The aftershock processes of strong earthquakes in the Western Caucasus // Izvestiya, Physics of the Solid Earth. 2015. V. 51. N. 3. P. 448-458)

1.2. Creation of spectral code-magnitude for earthquakes in Kamchatka.

The first variant of spectral code-magnitude for Kamchatka is developed. As calibration curves we used a family of decay curves of amplitude codes ("asymptotic envelope codes"), calculated for the Petropavlovsk cluster of stations on ~700 earthquakes. The curves are determined for a set of 2/3 octave frequency bands with 50% overlap on a logarithmic scale, in the frequency range [0.04; 40] Hz. Components of the spectral magnitude with binding of the values of the logarithm of the code amplitude A_{100} to the magnitude M_L are constructed. The first earthquake catalogue in the spectral magnitudes is calculated. The form of representation of the results is developed: the amplitude spectrum of earthquakes in relative calibrations (Fig. 1.1). Spectral magnitudes make it possible to study the source spectra of earthquakes and can be used to assess the tsunamigenic nature of an earthquake in the operational mode. **(Federal Research Center United Geophysical Survey RAS)**

1.3. The stochastic model of the seismic source proposed earlier by A.A. Gusev (Institute of Volcanology and Seismology FEB RAS) has been studied theoretically. The conditions under which the model implements the important properties of the seismic field in the far zone are found: the decrease in the displacement spectrum as a reverse square of frequency and the independence of high-frequency asymptotics from the position of the receiver. **(Institute of Earthquake Prediction Theory and Mathematical Geophysics RAS,** see *Molchan G.M.* Stochastic earthquake source model: the omega-square hypothesis and the directivity effect. *Geophys. J. Int.*, 2015, **202**: 497-513, doi:10.1093/gji/ggv158.

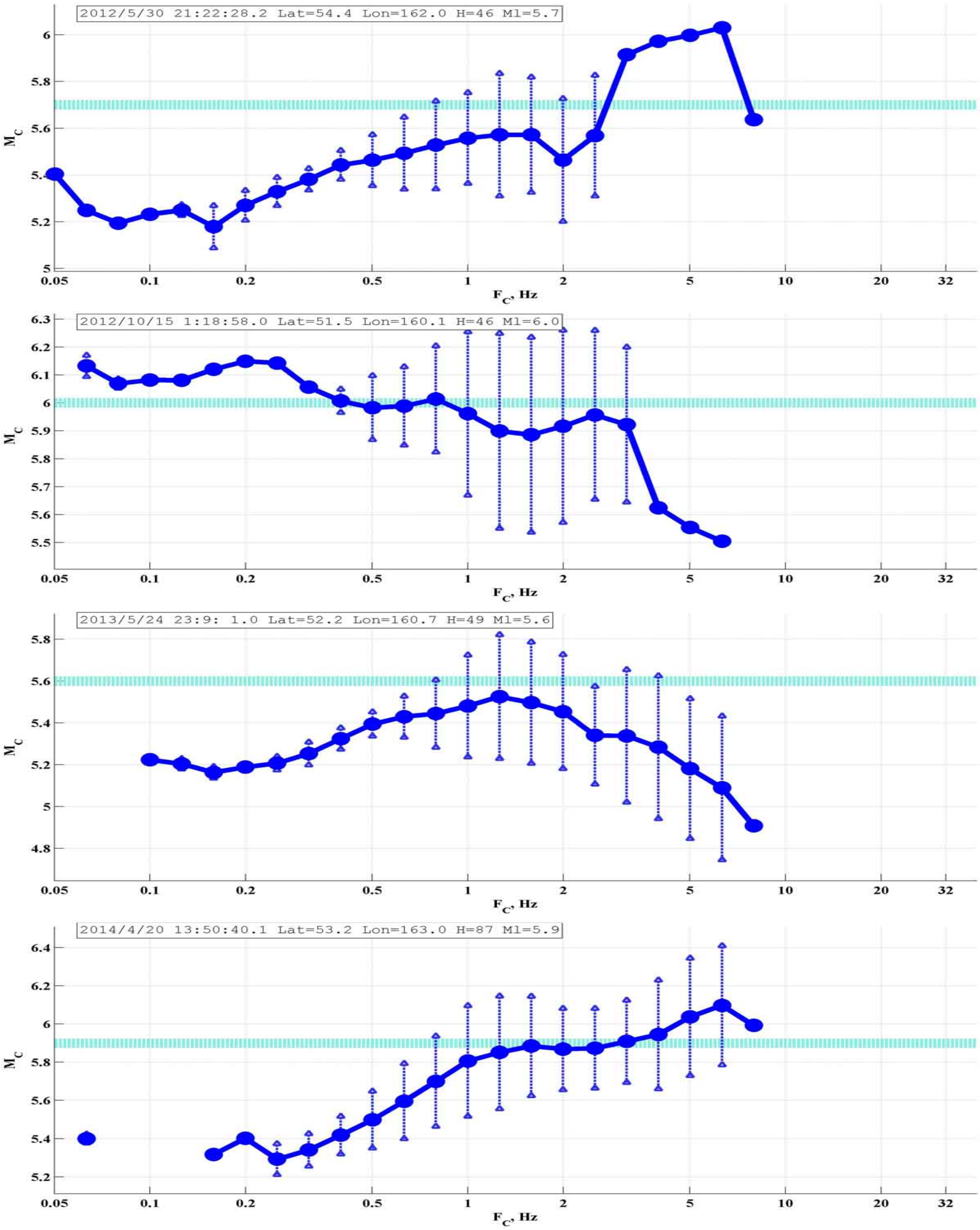


Fig. 1.1. Examples of smoothed focal spectra in relative calibrations. As a reference level the values of local magnitudes ML of corresponding earthquakes are applied. Standard deviations of the average network estimates of the magnitude components are applied. The absence of "mustache" for some points on the presented images means that the magnitude component was calculated from one station.

1.4. Study of the dynamics and structure of the processes of ice cover destruction and formation of icebergs at Svalbard Archipelago.

The possibility of continuous geophysical monitoring of ice tremors in the high-latitude Arctic has been experimentally proved for the first time. Using the seismic infrasound complex (SISC) with an innovative software package of data processing "SIM" installed in the Pyramida village on the island Western Svalbard, in the unloading area of the largest Lomonosov ice dome on the of Svalbard Archipelago was registered, localized and classified 108 earthquakes at a distance of up to 100 km from SISC PYR. A new method of remote control of the iceberg drift to the water area was proposed. Field tests at the edge of the Nordenskjöld outlet glacier flowing down from the Lomonosov Dome to the Is-fjord confirmed the reliability of the calving registration from a distance of 15 km in the near real-time mode (Fig. 1.2). **(Federal Research Center United Geophysical Survey RAS**, see *Vinogradov A., Asming V., Baranov S., Fedorov A., Vinogradov Yu.* Joint seismo-infarsound monitoring of outlet glaciers in the Arctic: case study of the Nordenskiold outlet glacier terminus near Pyramiden (Spitsbergen) // 16th International Multidisciplinary Scientific GeoConference SGEM 2016. Book 1. Science and Technologies in Geology, Exploration and Mining. Conference Proceedings. Vol. III. Hydrology, Engineering Geology & Geothechnics, Applied and Environmental Geophysics, Oil and Gas Exploration. Albena, Bulgaria, Sophia: STEF92 Tehcnology, 2016. Pp. 521-528. DOI 10.5593/SGEM2016B13; *Asming V.E., Baranov S.V., Vinogradov A.N., Vinogradov Yu.A., Fedorov A.V.* Using an Infrasonic Method to Monitor the Destruction of Glaciers in Arctic Conditions // Acoustical Physics, 2016. Vol. 62. No. 5. Pp. 583-592. DOI: 10.1134/S1063771016040035)

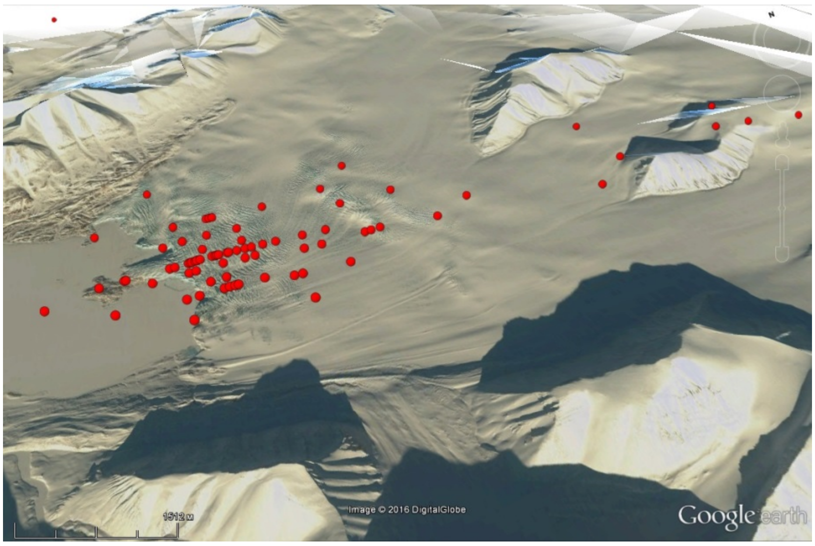


Fig. 1.2. Map of ice quake epicenter locations and calving (icebergs descending to the water area) registered by the seismic infrasound group PYR at the edge of the outlet Nordenskjöld Glacier (Svalbard) in 2016.

1.5. An experimental hardware-software complex for monitoring and detecting variations in seismic parameters was created to assess the seismic regime in the areas of exploration and production of energy resources in the area of Svalbard Archipelago and in the Western Arctic zone of the Russian Federation. The complex was created on the basis of new methods and allows to significantly improve the definition accuracy of earthquake parameters in this region of the Arctic. The use of modern equipment, developed technological approaches to its installation in the Arctic conditions of the Russian Federation has significantly increased the sensitivity of the method for determining the location of earthquake epicenters. **(Federal Research Center for Integrated Study of the Arctic named after Academician N.P. Laverov RAS)**

1.6. Qualitatively new magnitude scales Ms(40) and Ms(80) were created, using non-standard periods of surface waves - 40 and 80 seconds. For these magnitudes, experimental calibration functions were constructed using more than 1250 three-component records of earthquakes at 12 seismic stations in the region (Fig. 1.3). Unlike the usual magnitude of Ms20, the new magnitudes allow for a confident rapid assessment of the tsunami hazard even in those cases where such an assessment by magnitude Ms20 provides inaccurate, significantly underestimated estimates of the tsunami amplitude. The new methodology will make it possible to significantly increase the reliability of operational tsunami forecasting from a strong earthquake. **(Institute of volcanology and seismology of the Far East Branch of RAS,** see *Gusev, A.A., Chubarova O.S.* Regional long-period magnitude scales and their capabilities for tsunami warning // Izvestiya. Atmospheric and Oceanic Physics. 2016. Vol. 52, N 8. P. 797–805)

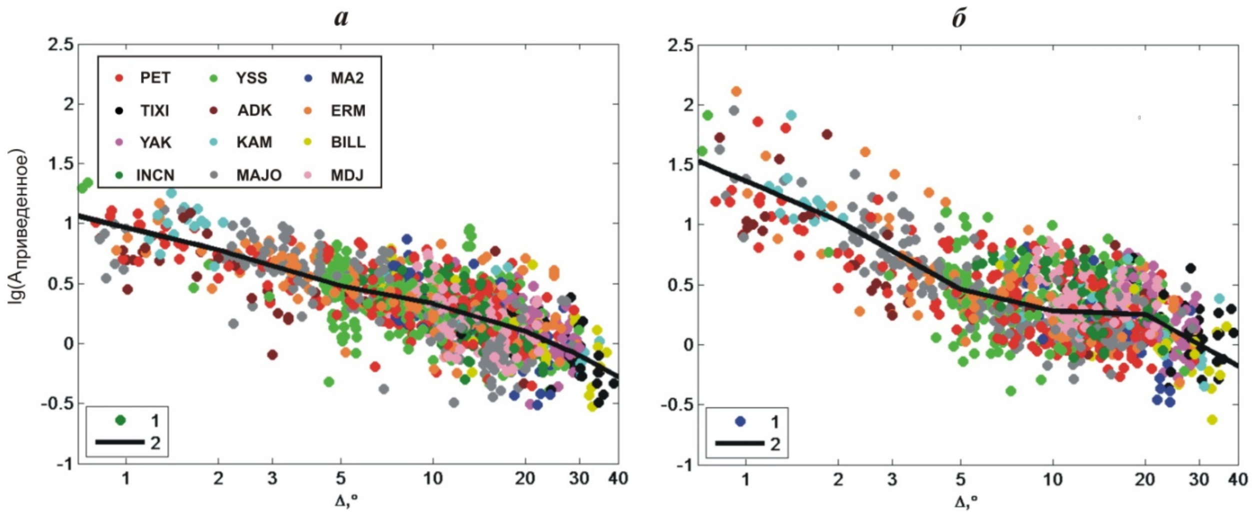


Fig. 1.3. Dependence of normalized station amplitudes on the epicentral distance and calibration functions for the magnitudes Ms(40) (a) and Ms(80) (b): 1 - observed data (RMS value of amplitudes of three components), the color of the circle marks the data of the seismic station; 2 - calibration functions for the magnitudes Ms(40) and Ms(80).

2. Strong earthquakes in Russia and abroad in 2015-2018

2.1. Unique records of the Nepal earthquake 2015 obtained near the site of the projected Ruppur NPP (Bangladesh)

The accelerometers of the seismic observation network in the vicinity of the projected Ruppur NPP in the People's Republic of Bangladesh, located at the site of the NPP and in the nearest settlement, received unique records of the main shock and aftershocks of the catastrophic earthquake in Nepal on April 24, 2015. (Mw=7.8) (Fig. 2.1). The spectrum of the registered earthquake was enriched with low-frequency fluctuations beyond the standard spectrum. This fact was taken into account in the formation of initial seismic data for design purposes. **(Institute of Physics of the Earth RAS)**

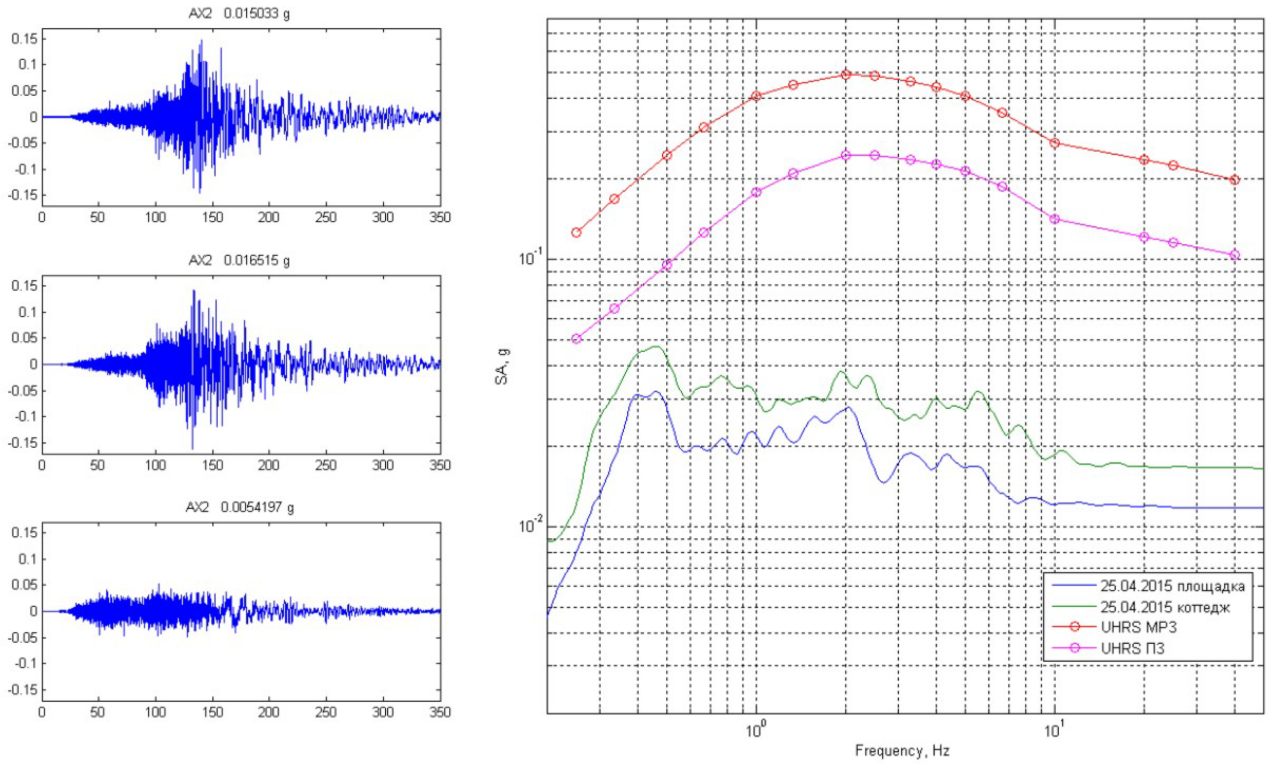


Fig. 2.1. Axlerogram of Nepal earthquake (Mw=7.8) obtained near Ruppur NPP site, People's Republic of Bangladesh (left); spectra of records at the site and near it (lower right curves) and calculated spectra of impacts at the level of design earthquake (DE) and maximum design earthquake (MDE) (upper right curves).

3. Seismogeodynamics

3.1. It was established that the migration of the maximum seismic activity throughout the latitudinal Olekmo-Stanovoy and Tukuringra-Dzhagda seismic zones from the meridional eastern frame of the Amur plate to the meridional Tukuringra-Dzhagda seismic zone occurs with a constant speed of 16.2 degree/year (2.5 km/day). In the ordered by longitude clusters, the maximums of seismic activity shift during the year from east to west and form spatial cycles (Fig. 3.1). The period of spatial synchronization of seismic activity is equal to 7.26 degrees and exactly corresponds to the doubled linear extent of tectonic inhomogeneities. **(Institute of Tectonics and Geophysics Far Eastern Branch of RAS)**

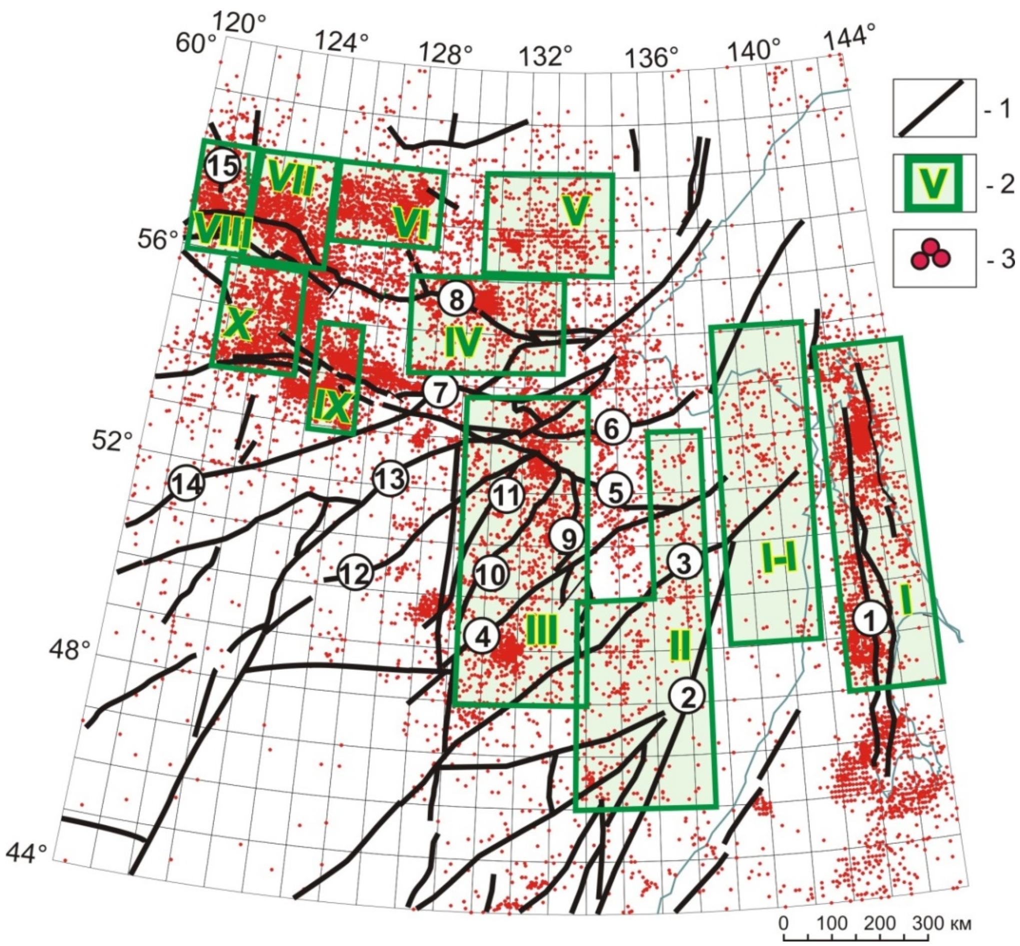


Fig. 3.1. Distribution of earthquake sources within the northern, north-eastern and eastern boundaries of the Amur plate: 1 - faults; 2 - conditional cluster boundaries; 3 - epicenters of earthquakes. Faults (figures in circles): 1 - Tsentralno-Sakhalinskiy; 2 - Tsentralno-Sikhote-Alinskiy; 3 - Ishu-Kharpinskiy; 4 - Khinganskiy; 5 - Paukanskiy; 6 - Tugurskiy; 7 - Severo-Tukurinskiy; 8 - Stanovoi; 9 - Tastakhskiy; 10 - Melginskiy; 11 - West-Turanskiy; 12 - Selemdzhinskiy; 13 - Busse-Norskiy; 14 - Sinlungou; 15 - Temulyakitskiy.

3.2. The key role of the Earth's crust type in the development of supervolcanic sources has been revealed. On the basis of the analysis of seismic tomography results under the Yellowstone caldera the conditions of formation of a multilevel source of supervolcanism over the mantle plume are revealed. The cases of continental (Yellowstone) and oceanic (Hawaii) crust were compared and it was concluded that the presence of a granite layer provides the conditions for the accumulation of a large volume of magmatic material (Fig. 3.2). **(Institute of Petroleum Geology and Geophysics of the Siberian Branch of RAS,** see *Shapiro N.M., Koulakov I.Yu.* (2015). Probing the underbelly of a supervolcano, Science, v. 348, p. 758-759)

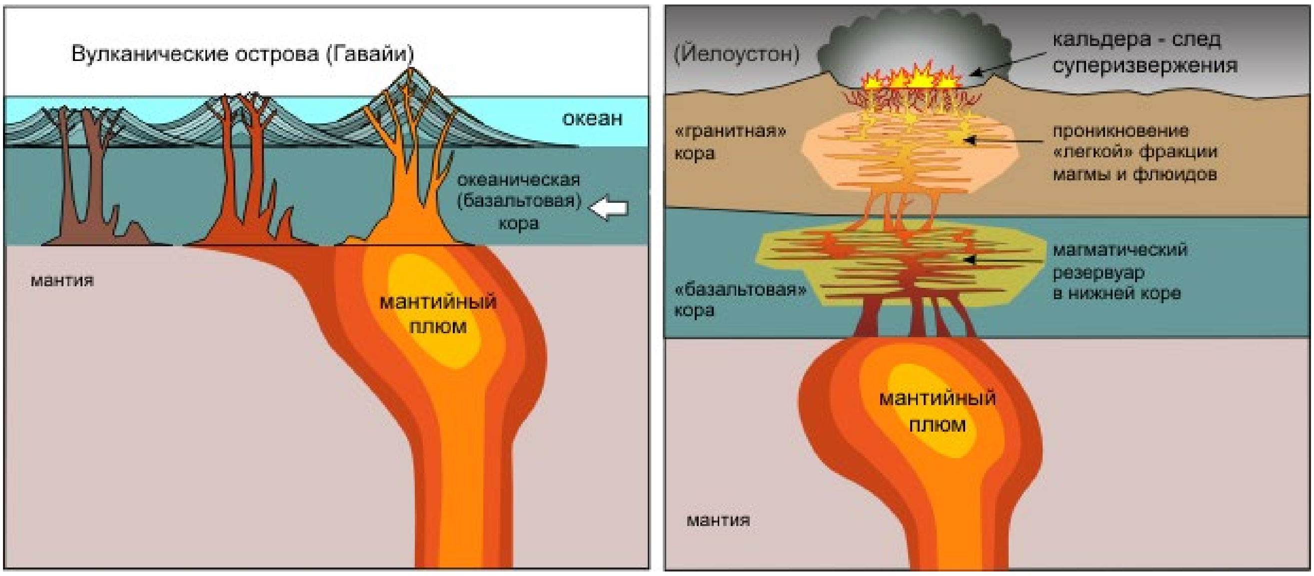


Fig. 3.2. Schematic comparison of volcanic activity caused by large plume under the ocean (left) and continent (right). In the oceanic crust, plume material can continuously penetrate the surface to form permanently functioning volcanic islands. On the continent, it takes time for the critical volume of light moving material to accumulate before it can pass through the low-density upper crust.

3.3. For the territory of Northern Fennoscandia, a seismic tomography was used for the first time to identify and map the horizontal velocity heterogeneities on both sides of the Botnia-Baltic Shear Mega-Zone in the upper part of the crust. The complex analysis of seismotomographic model of P-wave and focal mechanisms of earthquake sources showed the possibility of reactivation of this ancient Proterozoic structure in the postglacial period. This result calls into question the assumption about the connection of seismicity on the Baltic shield only with the glaciological leveling of the Earth's crust and provides the basis for the formation of a fundamentally new concept of development of tectonic processes of ancient shields. **(Institute of Geosphere Dynamics RAS,** see *Usoltseva O., Kozlovskaya E.* Studying local earthquakes in the area Baltic-Bothnia Megashear using the data of the

POLENET/LAPNET temporary array Solid Earth 7(4):1095-1108 July 2016. http://www.solid-earth.net/7/1095/2016/ doi:10.5194/se-7-1095-2016, DOI: 10.5194/se-7-1095-2016)

3.4. With the help of seismic tomography various feeding mechanisms of Kliuchevskoy, Bezymyanny and Tolbachik volcanoes were revealed.

A three-dimensional model of the crust under the Kliuchevskoy group of volcanoes, which is characterized by high activity and variety of lava compositions, has been constructed on the basis of data of time and constant seismic networks. Under the Kliuchevskoy volcano the earthquake traces a thin channel through which basalt magma is transferred from the mantle directly to the surface. Under the Bezimyanny volcano a seismic anomaly is observed in the middle crust, reflecting the zone of gradual accumulation of fluids, which is responsible for the explosive eruptions. Beneath Tolbachik volcano linear anomalies have been identified that coincide with the position of tectonic faults, which act as feed channels for basaltic magma feeding the fractured eruptions (Fig. 3.3). **(Institute of Petroleum Geology and Geophysics of the Siberian Branch of RAS,** see *Koulakov I., I. Abkadyrov, N. Al Arifi, E. Deev, S. Droznina, E. I. Gordeev, A. Jakovlev, S. El Khrepy, R. I. Kulakov, Y. Kugaenko, A. Novgorodova, S. Senyukov, N. Shapiro, T. Stupina, M. West* (2017). Three different types of plumbing system beneath the neighboring active volcanoes of Tolbachik, Bezymianny, and Klyuchevskoy in Kamchatka, J. Geophys.Res. Solid Earth, 122, doi:10.1002/2017JB014082)

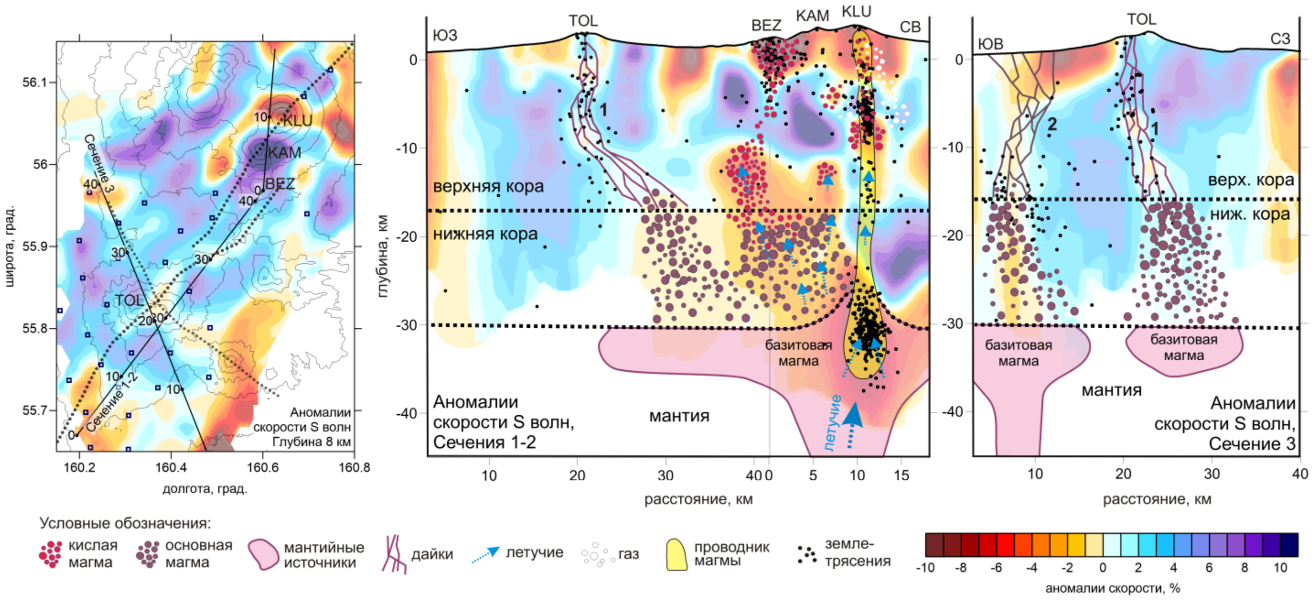


Fig. 3.3. Tomographic inversion results and possible interpretation. Left: map of anomalies at a depth of 8 km. Dotted lines - regional faults, points - seismic stations, isolines - relief. Volcanoes: TOL - Tolbachik, BEZ - Bezimyanniy, KAM - Stone, KLU - Kliuchevskoy. Right: two vertical sections of the velocity model with possible interpretation.

3.5. A new map of seismotectonics of the north-eastern sector of the Russian Arctic has been published, which reflects the classification of the geodynamic activity of the newest structures, structural and kinematic characteristics of active fault systems and parameters of seismotectonic deformations (Fig. 3.4). For the first time the gradation of the level of seismic hazard for the shelves of the East Arctic seas and the adjacent water areas of the Arctic Ocean was performed. This map will be used in the design and development of the Arctic shelf by large Russian companies such as ROSNEFT, GAZPROM and ALROSA. It provides an opportunity to assess the potential seismic and ecological risk of the study area. **(Institute of the Earth's Crust and Diamond and Precious Metal Geology Institute, Siberian Branch RAS,** see *Imaeva L.P., Gusev G.S., Imaev V.S. et al.* Neotectonic activity and parameters of seismotectonic deformations of seismic belts in the Northeast Asia // J. Asian Earth Sciences, 2017. V. 148)

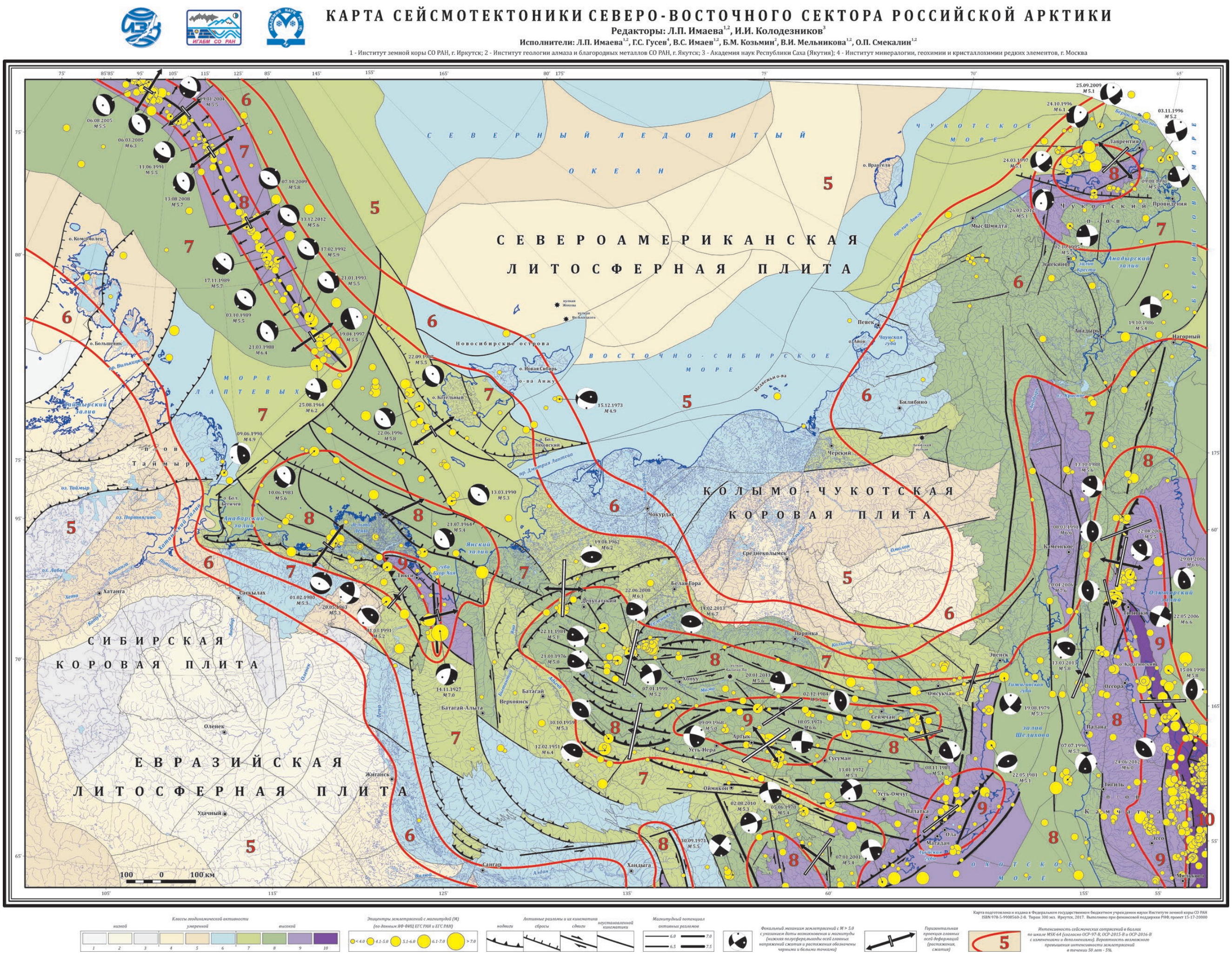


Fig. 3.4. Seismotectonics map of the north-eastern sector of the Russian Arctic.

4. Seismic risk assessment and management in the Russian Federation

4.1. The relationship between natural hazards and natural disasters has been explored. The impact of natural events is shown to be directly related to vulnerability. A new approach to integrated research of risk from earthquakes, volcanic eruptions, lava flows, tsunamis and other hazards based on joint transdisciplinary study of complex tasks (from problem setting to realization and implementation of their solutions) is proposed. The approach is aimed at in-depth study of natural hazard and vulnerability, risk assessment by means of systematic analysis, and implies preparation of a set of recommendations to reduce damage from natural hazards on the basis of research results. **(Institute of Earthquake Prediction Theory and Mathematical Geophysics RAS,** see *Cutter S.L.,* ***Ismail-Zadeh A.****, Alcántara-Ayala I., Altan O., Baker D.N., Briceño S., Gupta H., Holloway A., Johnston D., McBean G.A., Ogawa Y., Paton D., Porio E., Silbereisen R.K., Takeuchi K., Valsecchi G.B., Vogel C., Wu G.*, Global risks: Pool knowledge to stem losses from disasters. *Nature*, 2015, **522**, 7556: 277-279, doi:10.1038/522277a; ***Ismail-Zadeh A.,*** *Cutter S., eds.* (2015). Disaster risks research and assessment to promote risk reduction and management. Paris: International Council for Science / International Social Sciences Council. Available at: http://www.icsu.org/science-for-policy/disaster-risk/documents/DRRsynthesisPaper_2015.pdf)

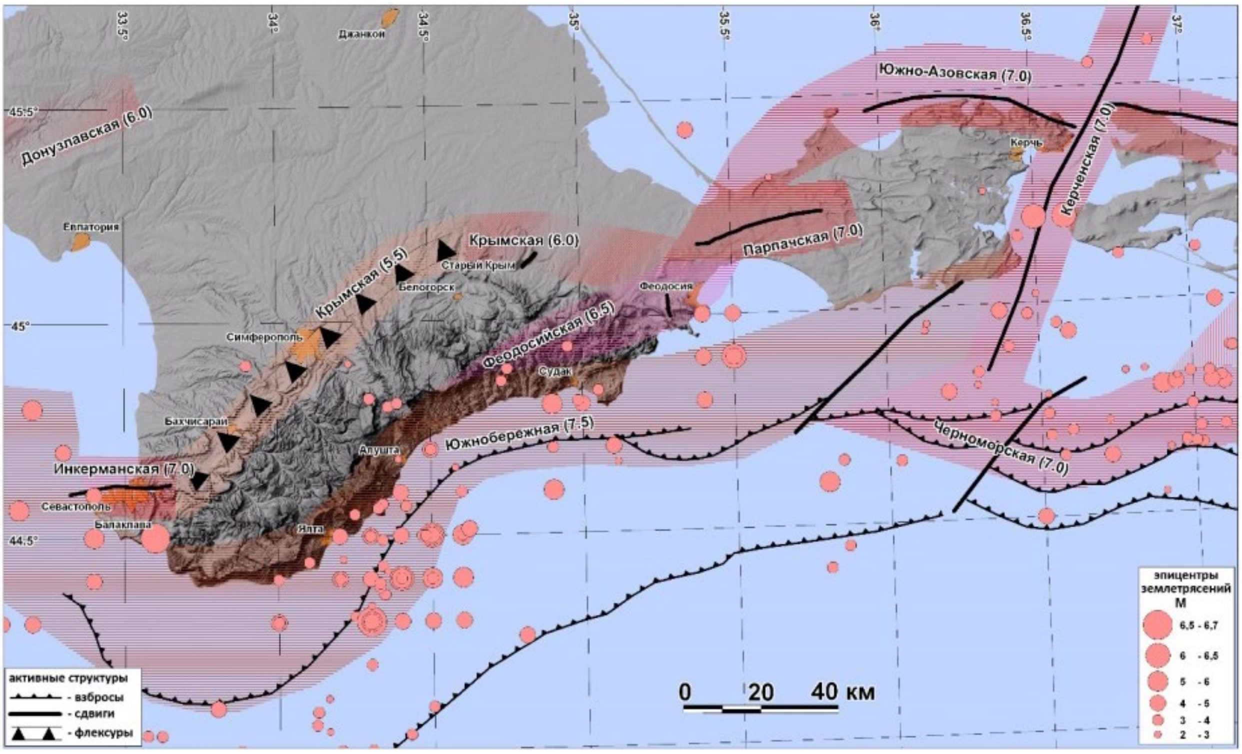


Fig. 4.1. Zones of probable expected earthquakes (zones of PEE) of the Crimea and adjacent water areas of the Black and Azov Seas with indication of predicted magnitude.

4.2. Clarification of Crimea's seismic hazard in connection with the development of transport and energy infrastructure. According to the results of complex seismotectonic researches and study of active faults of the Earth's crust a new map of zones of probable expected earthquakes of the south-eastern part of the Crimean peninsula and adjacent water areas of the Black and Azov Seas was made (Fig. 4.1). Relevance of the work is due to the extreme need to design and create the infrastructure of transport facilities and power supply of the Crimea. **(Institute of Physics of the Earth RAS)**

5. Physics of the seismic process and earthquake prediction

5.1. As a result of the analysis of multiyear series of observations of the Earth's natural pulsed electromagnetic field (ENPEMF) through a network of 10 recorders located from the Black Sea to the Caspian Sea within the seismodangerous regions of the North Caucasian region, characteristic images of regional anomalies (Fig. 5.1) were identified, which precede seismic events with a magnitude of more than 4 with a manifestation in advance from 0.5 to 15 days. An attempt is made to analyze the interrelation of the ENPEMF anomalies with the activation of seismicity of the most "hot" seismic regions of the Central and Eastern Caucasus. (**Geophysical Institute - the Affiliate of Vladikavkaz Scientific Centre RAS)**

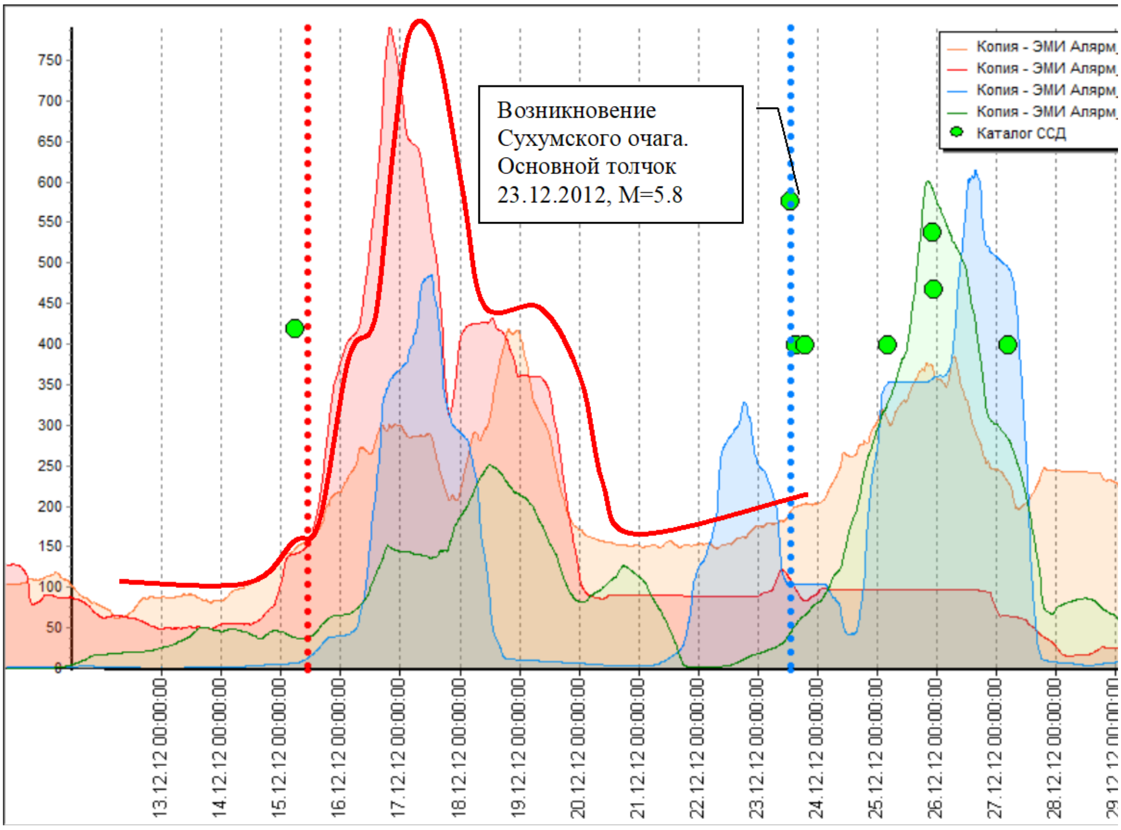


Fig. 5.1. Synchronous regional anomalies of electromagnetic radiation (EMR) at four stations before the occurrence of the Sukhumi earthquake source and during the period of maximum aftershock activity. A characteristic image of the anomaly is highlighted in red.

5.2. Systemic analysis method for the recognition of places of possible occurrence of epicenters of significant, strong and the strongest earthquakes.

The method of system analysis for recognition of places of possible occurrence of epicenters of significant, strong and the strongest earthquakes is offered. The method is invariant in relation to the scales of such seismic phenomena under study. For the first time, it makes the recognition of places of possible occurrence of epicenters of strong earthquakes by the procedure of system analysis. Its main characteristic that makes it a method of system analysis is the possibility of separating the system under study from the external infrastructure. With the help of the proposed method of system analysis the identification of places of possible occurrence of epicenters of the strongest earthquakes (M≥7.75) in the mountainous belt of Andes of South America and significant earthquakes (M≥5) in the Caucasus was carried out. **(Geophysical Center RAS,** see *Gvishiani A.D.*, *Dzeboev B.A.*, *Agayan S.M.* FCAZm intelligent recognition system for locating areas prone to strong earthquakes in the Andean and Caucasian mountain belts // Izvestiya. Physics of the Solid Earth. 2016, vol. 52, # 4, pp.461-491)

5.3. The poorly studied effect of low-frequency microseisms generation (with periods of about 50 and 100 s) by infragravity waves was revealed, which presumably influences the processes of stress accumulation/relief in the Earth's crust. Peaks in close periods were observed during storms in two different areas of the southeast coast of Sakhalin Island in different years, which suggests a reliable separation of this effect. The identity of the peaks seems to be determined by the similar character of the coastal relief (Fig. 5.2). **(Institute of Marine Geology and Geophysics and Pacific Oceanological Institute named after V.I. Ilyichev of the Far East Branch of RAS**, see *Kovalev D.P., Shevchenko G.V., Dolgikh G.I.* Generation of low-frequency microseisms by infragravity waves on the southeastern coast of Sakhalin Island // Doklady Earth Sciences. 2015, Vol. 461, # 2, pp.368-371)

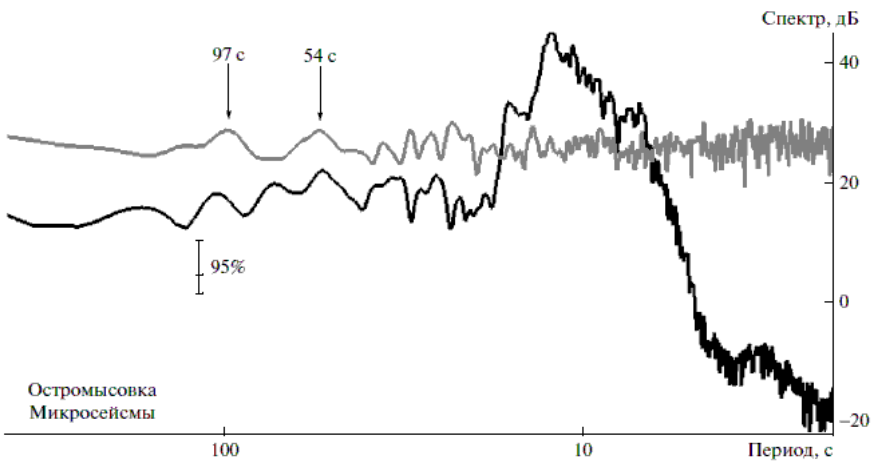


Fig. 5.2. Spectra of variations of near-bottom hydrostatic pressure (black line) and vertical component of the seismic signal (grey line), calculated from the one hour time interval of July 22, 2007. (number of degrees of freedom 6). Station "Ostromysovka".

5.4. Algorithm for sequential identification of possible earthquake locations. A principally new algorithm of system analysis SFCAZ (Successive Formalized Clustering And Zoning) has been created, which allows to carry out the recognition of places of possible earthquake occurrence for several magnitude thresholds in one and the same earthquake-prone region. It was possible to do this due to iterative narrowing of many recognition objects. Zones of possible occurrence of earthquakes for some magnitude threshold are recognized inside the zones already recognized as dangerous for a smaller threshold magnitude. Reproducibility of the study is ensured by the fact that the recognition algorithm remains unchanged at all stages. The algorithm has been successfully tested in the Baikal-Transbaikalia region. **(Geophysical Center RAS,** see *Gvishiani A.D., Dzeboev B.A., Belov I.O., Sergeeva N.A., Vavilin E.V.* Successive recognition of significant and strong earthquake-prone areas: The Baikal–Transbaikal region // Doklady Earth Sciences. 2017, Vol. 477, # 2, pp. 1488-1493)

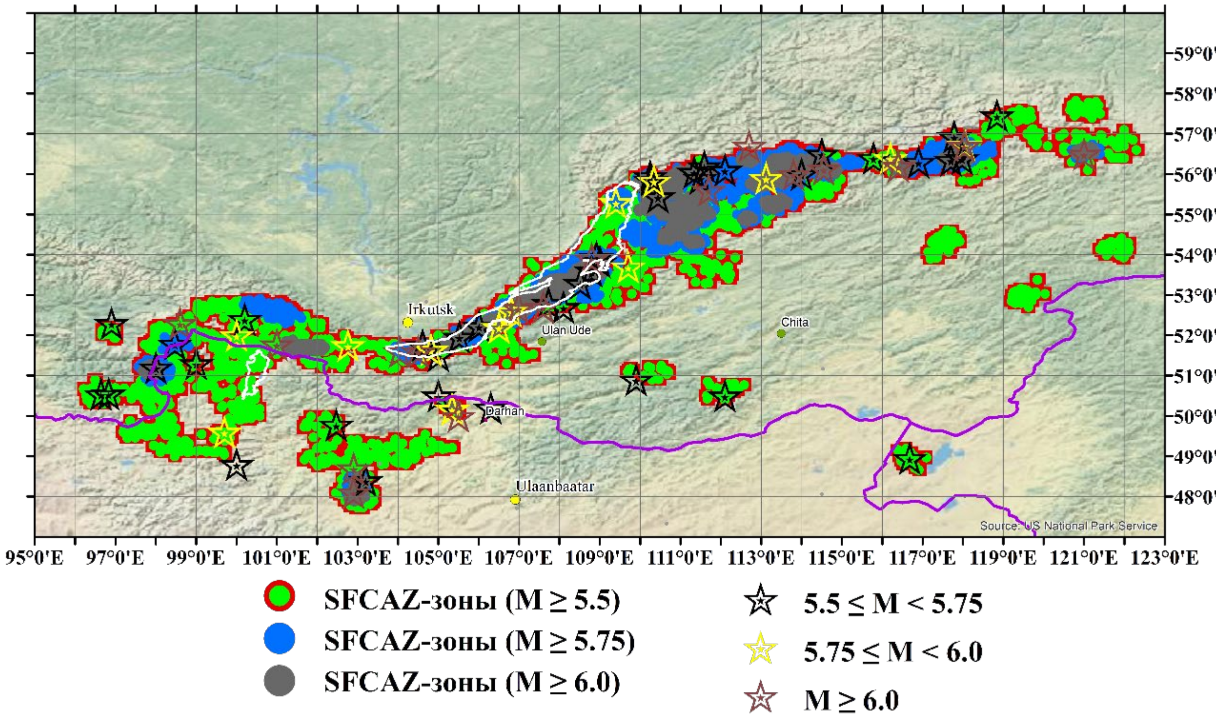


Fig. 5.3. Zones of possible occurrence of epicenters of earthquakes in the Baikal-Transbaikalia region.

5.5. Influence of the block structure of the Earth's crust on the seismic regime of the Northern Baikal Region. A detailed study of the nature of seismic activity in the Northern Baikal region in connection with the peculiarities of the block structure of the Earth's crust was carried out. The presence in the crust of structural elements of different scale levels and density inhomogeneities creates prerequisites for the clustering of earthquakes. Five clusters with the highest density of epicenters were identified (Fig. 5.4). It has been established that the character of stress discharge in the sources as far as it is from the axis of rift zone, which cuts a number of large Cenozoic rift troughs along the extension, in the direction to the south-east tends to monotonous attenuation. **(Federal Research Center United Geophysical Survey RAS**, see *Melnikova V.I., Gilyova N.A.* Relationship between seismicity in the northern Pribaikalye and the block structure of the crust // Doklady Earth Sciences. 2017, Vol. 473, # 2, pp. 386-389)

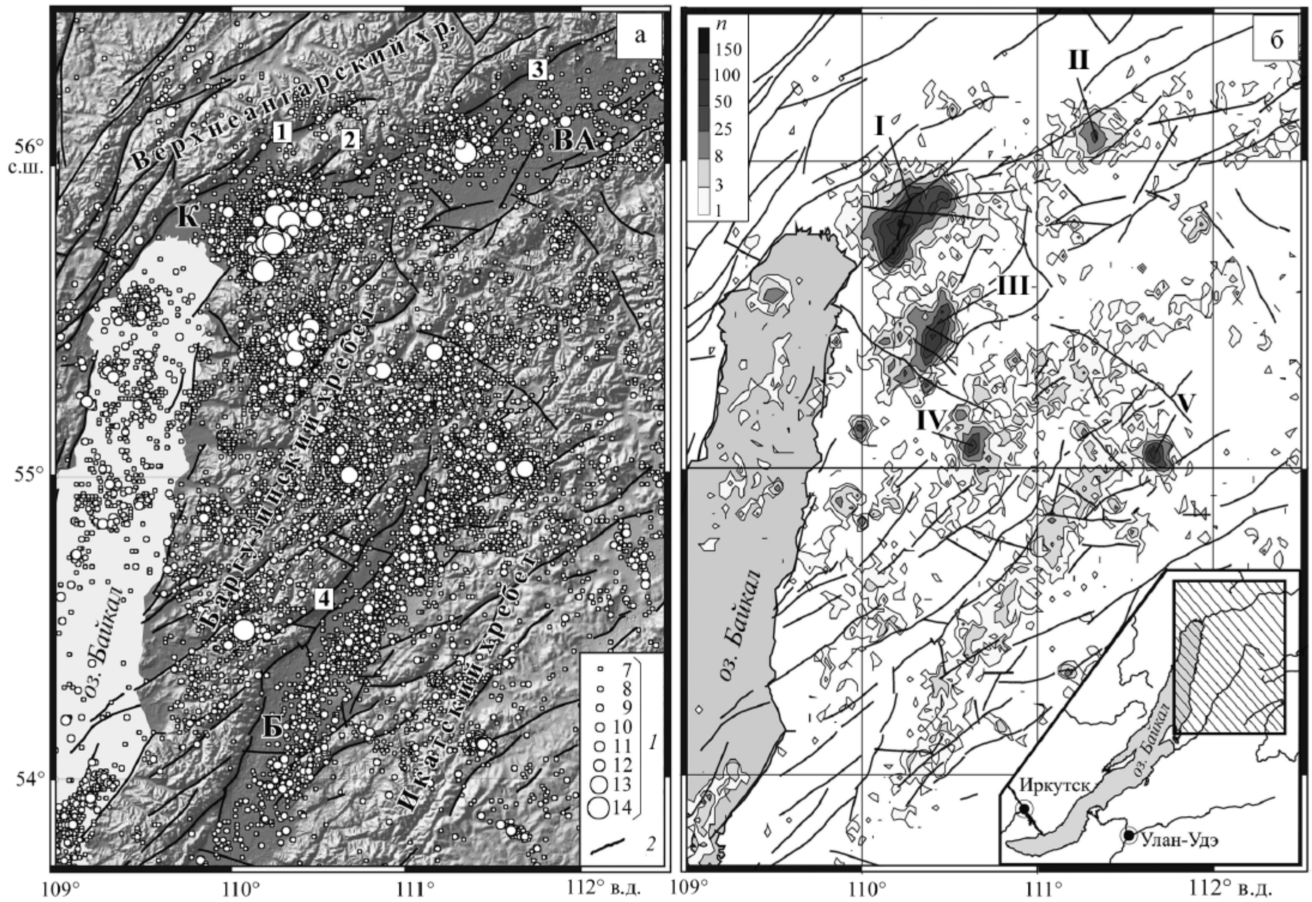


Fig. 5.4. Epicenter maps of the earthquakes (a) Northern Baikal Region and their density (b) for the period 1999-2013/

5.6. The effect of surface round-the-world seismic waves in the dynamics of repeated shocks of strong earthquakes.

The existence of the effect of round-the-world surface seismic waves is established and its manifestations in the dynamics of repeated shocks of strong earthquakes are analyzed. The effect is that the surface seismic waves excited in the source of the earthquake at the main shock, make a full turn around the Earth in about 3 hours and excite a strong aftershock in the epicentral zone of the main shock. The physical nature of the effect is that due to the superposition effect, the wave energy concentration occurs when the surface waves reach the epicentral zone (cumulative effect). The detected effect can be used to improve the reliability of the forecast of strong repeated shocks in determining the scenario of seismic process development in the epicentral zone of a strong earthquake.

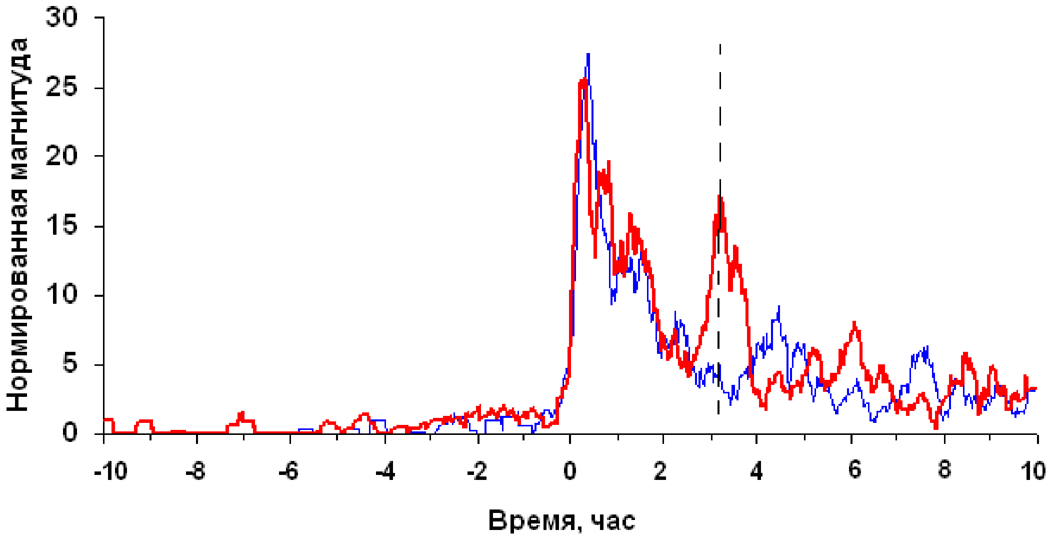


Fig. 5.5. Demonstration of the effect of round-the-world surface seismic waves ("round-the-world seismic echo").

Accumulated sequence of normalized magnitudes of repeated shockes for the main earthquakes with M ≥ 7.5. The result of detection of the round-the-world seismic echo effect (*red curve*) is shown in comparison with events in which the effect was absent (*blue curve*). The vertical dashed line marks the time of the maximum effect of the first round-the-world seismic echo. Selection of repeated shocks (aftershocks) was made in the epicentral zone with a radius of 1°. (USGS/NEIC catalog).

(Institute of Physics of the Earth RAS, see *Guglielmi A.V., Zotov O.D., Zavyalov A.D.* The Aftershock Dynamics of the Sumatra-Andaman Earthquake // Izvestiya, Physics of the Solid Earth, 2014, Vol. 50, No. 1, pp.64-72. ISSN: 1069-3513. DOI: 10.1134/S1069351313060037; *Zotov O.D., Zavyalov A.D., Guglielmi A.V., Lavrov I.P.* On the Possible Effect of Round-the-World Surface Seismic Waves in the Dynamics of Repeated Shocks after Strong Earthquakes // Izvestiya, Physics of the Solid Earth, 2018, Vol. 54, No. 1, pp. 178-191. DOI: 10.1134/S1069351318010159)

6. Induced seismicity and its monitoring

6.1. Criteria for revealing dangerous increase in activity of technogenic seismic phenomena in different regions of intensive impact on the subsoil are proposed. The criteria are justified by analyzing data on natural and technogenic seismicity in the extraction of hydrocarbons, solid minerals, construction of dams, use of geothermal energy sources. Application of the developed criteria to the analysis of seismicity in the vicinity of hydrocarbon fields on the shelf of Sakhalin Island has shown that there is a tendency to strengthen the technogenic component in the seismicity of the region, although there are currently no dangerous technogenic seismic events (Figures 6.1, 6.2). **(Institute of Geosphere Dynamics RAS and Institute of Marine Geology and Geophysics of the Far East Branch of RAS,** see *Turuntaev S.B., Konovalov A.V., Slinkova E.Y.* (2015) Seismicity in the region of Sakhalin offshore hydrocarbon fields. SEG Technical Program Expanded Abstracts 2015: pp. 5042-5047. doi: 10.1190/segam2015-5820937.1)

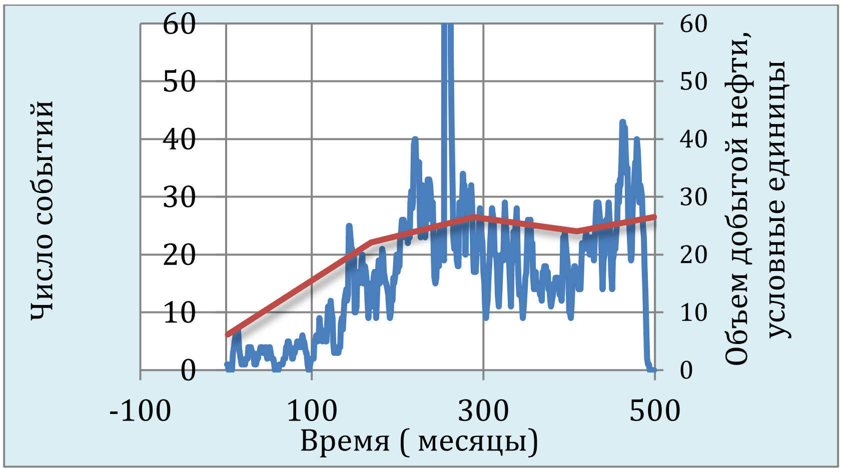


Fig. 6.1. Changes in seismic activity and oil production on Sakhalin Island during 1950-1991.

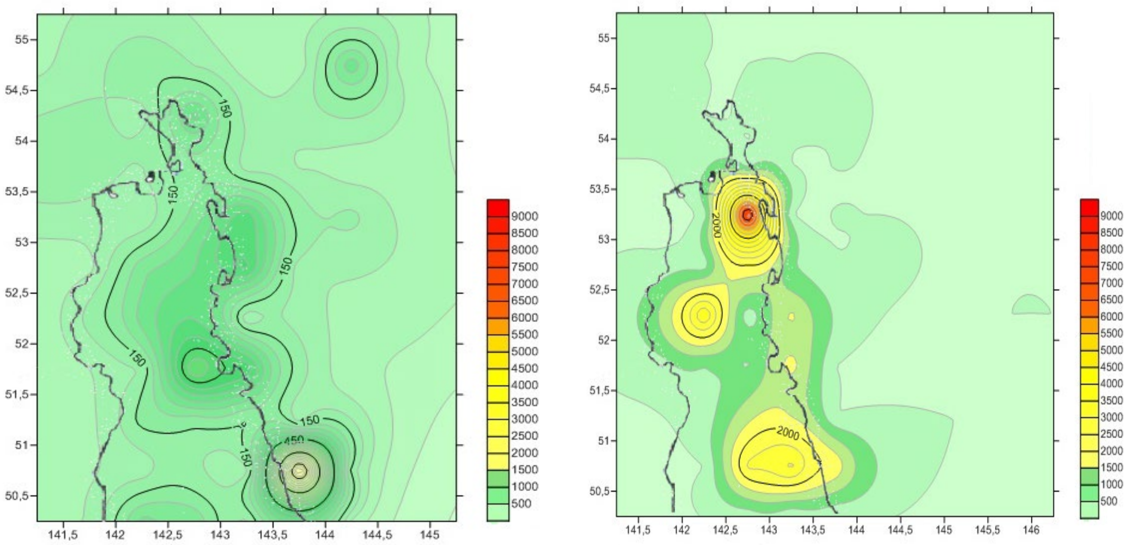


Fig. 6.2. Seismic Event Distribution Maps for the region of Hydrocarbon Fields of the Sakhalin Island shelf in isolines of equal activity: left - 1970-1991, right - 2011-2014.

6.2. A new mechanism for the formation and evolution of the gliding regime of tectonic faults has been proposed, according to which even small variations in the material composition of the fault filler can lead to a significant change in the fraction of the energy emitted in the form of seismic waves. It has been experimentally established that the sliding mode is determined by the ratio of two parameters, which can be found from the results of seismological observations - the fracture stiffness and the stiffness of the surrounding massif. The obtained result can be used to create technologies to reduce the risk of catastrophic technogenic earthquakes during the development of mineral deposits. **(Institute of Geosphere Dynamics RAS and Institute of Marine Geology and Geophysics of the Far East Branch of RAS,** see *Kocharyan G.G., Novikov V.A.* Experimental study of different modes of block sliding along interface. Part 1. Laboratory experiments // Physical mesomechanics. 2016, Vol. 19, # 2, pp. 189-199; *Kocharyan G.G., Ostapchuk A.A.* The influence of viscosity of thin fluid films on the frictional interaction mechanism of rock blocks // Doklady Earth Sciences. 2015. T. 463. № 1. C. 757-759; *Besedina A.N., Kocharyan G.G., Kishkina S.B.* Effect of deformation properties of discontinuities on sources of mining-induced seismicity in rocks. Part I: In situ observations // Journal of Mining Science. 2015, Vol. 51, # 4, pp. 707-717)

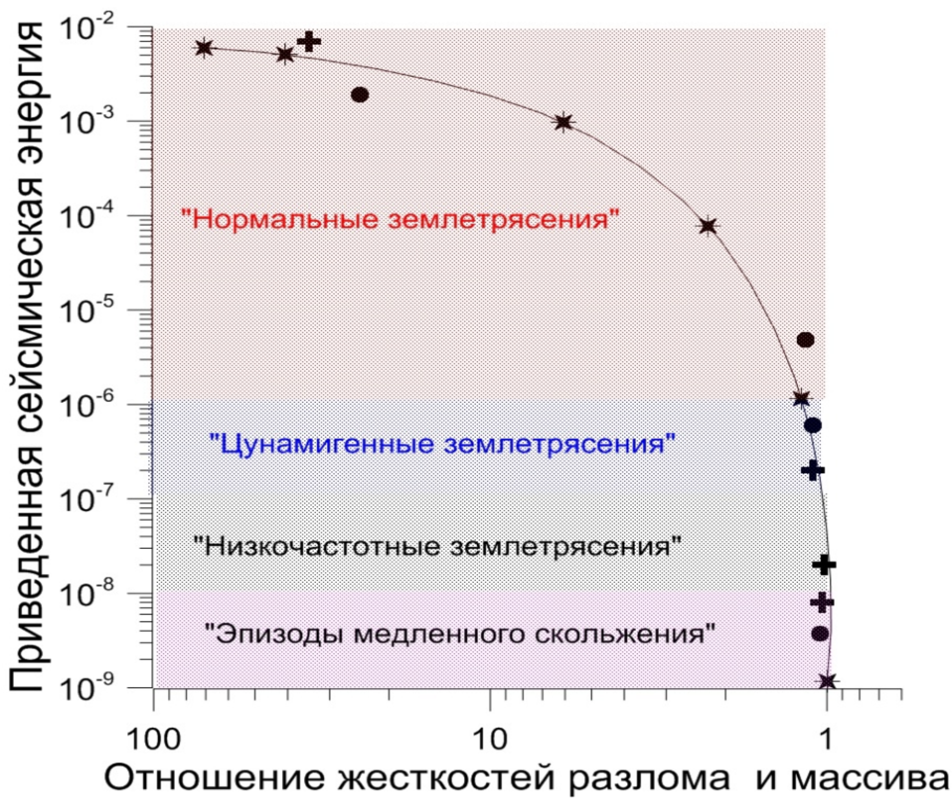
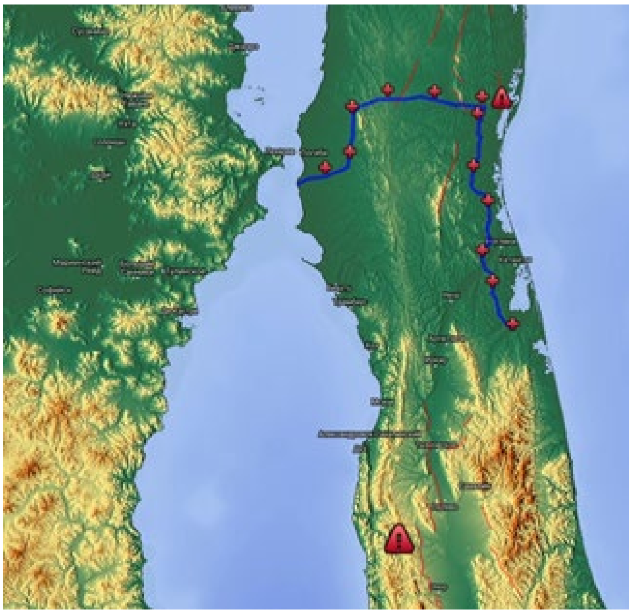


Fig. 6.3. Dependence of the value of the reduced seismic energy on the ratio of fault stiffness and massif. The points show the results of measurements in laboratory experiments.

6.3. Real-time seismic monitoring system for main fuel and energy facilities. Seismic monitoring system equipment was developed to transfer information to the central seismic data collection point (Fig. 6.4). The seismic monitoring system for the Sakhalin-Khabarovsk-Vladivostok gas pipeline was put into operation. For the first time in the practice of seismic hazard monitoring, a real-time seismic monitoring system is being introduced. **(Institute of Physics of the Earth RAS,** see *Tatevossian R., Bykova V., Mikhin A., Matveev I., Kalinina A., Ammosov S.* Seismic hazard assessment of the major pipeline "Yakutia-Khabarovsk", Russia // 26th IUGG General Assembly. Abstract: S07p-319. Prague. 2015)

Fig. 6.4. Equipment at the data collection point.

6.4. Seismic monitoring network on Sakhalin based on a broadband mobile seismometer. In 2016, a seismological monitoring system was put into trial operation near the Sakhalin-Khabarovsk-Vladivostok gas pipeline. The system consists of 12 registration points on the territory of northern Sakhalin and a data processing centre in Khabarovsk, connected by a fiber-optic network (Fig. 6.5). The system is capable of automatically identifying seismic events in the study area, determining the location of their hypocenters and energy characteristics, and assessing the impact on gas pipeline sections. **(Institute of Physics of the Earth RAS)**



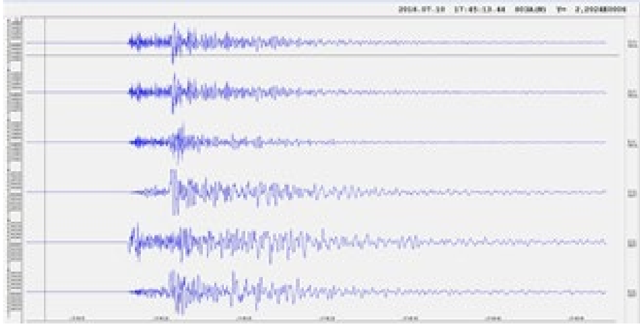
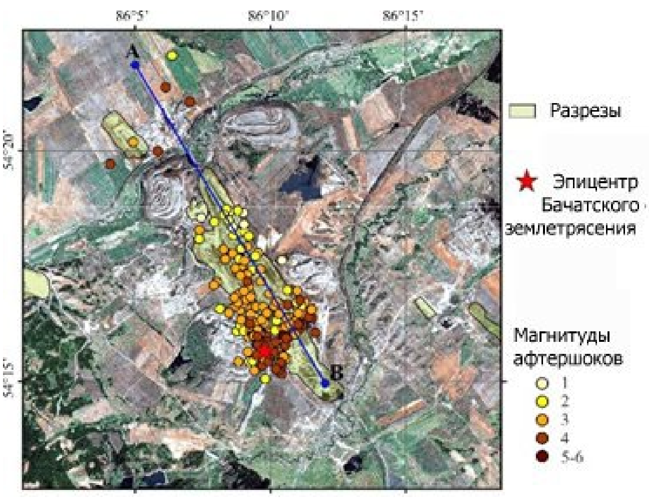


Fig. 6.5. Seismicity monitoring network on Sakhalin (crosses) and epicenters of significant earthquakes (red triangles) – *on the left*. Recording of local earthquake with magnitude 4 at a distance of 10 km from the epicenter; in the vicinity of the station one could feel 5-6 MSK (above - accelerogram) - *on the right*.

6.5. Structure of induced seismic processes in the origin zone of the world's largest technogenic earthquake. As a result of special seismological observations, the dynamics and structure of induced seismic processes in the source zone of the world's strongest technogenic earthquake, which was registered near the Bachatsky coal mine (Kemerovo region) on June 18, 2013, were studied in detail. This earthquake, which had magnitude 6.1, has happened within the limits of the largest in Siberia coal pit, which has the length of 12 km, width of 2 km and depth of 350 m. Continuous monitoring observations allowed to identify the main phases in the development of an intensive aftershock process, to assess the mechanisms of the strongest events, as well as to establish the features of the deep distribution of hypocenters of technogenic earthquakes. **(Altai-Sayan Branch of the Federal Research Center United Geophysical Survey RAS**, see *Emanov A.F., Emanov A.A., Fateev A.V., Leskova E.V.* (2017). The technogenic Bachat earthquake of June 18, 2013 (ML = 6.1) in the Kuznetsk Basin - the world’s strongest in the extraction of solid minerals. Seismic Instruments, 53(4), 333–355).



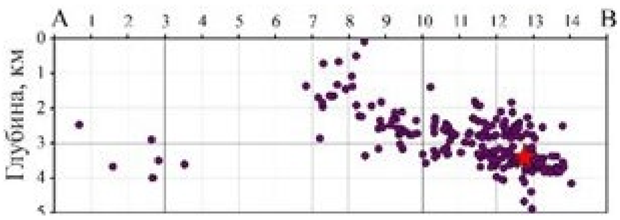


Fig. 6.6. Results of monitoring of technogenic seismic processes in the area of Bachatsky coal pit for the period 2013-2016: distribution of hypocenters of the main shock and aftershocks in the plan (*left*) and depth - along the profile of AB (*right*).