ORIGINAL RESEARCH ARTICLE

DOI: https://doi.org/10.18599/grs.2018.3.238-245

Emission seismic tomography – the tool to study fracturing and fluidodynamics of the Earth crust

I.Ya. Chebotareva

Oil and Gas Research Institute of the Russian Academy of Sciences, Moscow, Russiam Federation

Abstract. The article presents the results of seismotomographic monitoring of emission sources associated with fractured zone, tectonic faults and fluid filtration in the high permeable rocks. It is shown that the Earth's natural seismic noise recorded by surface array can be used to study the geodynamic processes caused by the presence of such inhomogeneities. The source of useful information is the extremely weak spatially coherent component of the seismic wave field – the seismic emission generated by background deformation in the energy-saturated volumes of rocks. Additional external technological and natural impact activates latent volumes of geophysical heterogeneity, which reveals new emission targets hidden in the background state. It makes to conduct additional exploration of the field within a radius of several kilometers during hydraulic fracturing.

The article also touches on the history of discovery of the seismic emission phenomenon and the mechanisms of generation of a low-frequency branch of emission as a result of amplitude instability of envelopes of high-frequency acoustic oscillations excited as a result of energetic impact on the medium. Low-frequency emission (1-100 Hz) provides the remote study of high-frequency (1-100 kHz) emission oscillations in the energy-saturated volumes located at a great distance from the seismic array.

Keywords: emission seismic tomography, seismic emission, structurally inhomogeneous media, oil and gas field

Recommended citation: Chebotareva I.Ya. (2018). Emission seismic tomography – the tool to study fracturing and fluidodynamics of the Earth crust. *Georesursy = Georesources*, 20(3), Part 2, pp. 238-245. DOI: https://doi.org/10.18599/grs.2018.3.238-245

Introduction

The phenomenon of endogenetic seismic emission was formally registered as an invention in the1980-s. Authors of this discovery are L.N. Rykunov, O.B. Khavroshkin, V.V. Cyplakov (Rykunov et al.., 1983), though experimentally-backed assumptions on existence of weak seismic energy sources associated with strain processes within the Earth's crust, had been previously published by other Authors as well starting from the century before the last one (Darwin, 1965; Golicyn, 1960; Gamburcev, 1960; Nanney, 1958; Zhadin, 1971; Gordeev, Rykunov, 1976; Naumenko, 1979; Leet, Leet, 1962). The Authors of the invention however have to be given credit for their firm pursuance of their scientific opinions and the existence of this effect itself. Results of the works by L.P. Rykunov, O.B. Khavroshkin and V.V. Cyplakov evoked a heated scholarly discussion. Their opponents attempted to overturn the existence of seismic emission, including experimental ways (Galperin et al.., 1987). Inconsistencies of the first experiments were associated with imperfections and differences in equipment, methods and technologies of investigations. It was also due to the fact that the phenomenon under examination is very complex in its space-time structure, and the intensity of endogenetic emission is very low. It was often on the threshold of used recorders' sensitivity readings. The very idea of existing seismic emission was completely out of classical continuum mechanics framework and the idea that natural noise of the Earth forms only due to multiple surfaces sources. The disputes gradually subsided along with the development of a new lithosphere model as a geo-environment which represents an open non-equilibrium non-linear dynamic structure, which shows variability of parameters, with hierarchy-block structure and energy saturation (Lukk et al.., 1996). As equipment was improved and processing methods were upgraded, new multiple test results emerged which confirmed existence of seismic emission, no longer possible to contest.

© 2018 I.Ya. Chebotareva. Published by Georesursy LLC
This is an open access article under the CC BY 4.0 license
(https://creativecommons.org/licenses/by/4.0/)

However at the first stage using single-point narrow-tape recorders, Authors of the invention managed to prove by experiments (Havroshkin, 1999) that low-frequency seismic noise (f > 1 Hz) was modulated by different strain processes, such as luni-solar tides, storm microseism, waves from remote strong earthquakes and explosions, Earth's own oscillations, etc. In seismo-active regions they found (Havroshkin, 1999) typical features of high-frequency noise which appear during preparation of earthquakes and during relaxation of stress in the Earth's crust after the earthquakes. Authors of this invention attributed this fact to existence of endogenetic sources of seismic emission which is a component of natural seismic background of the Earth. They suggested that sources of emission are associated with various-scale structural-geologic and energy (stress concentrations, thermal gradients) uniformities, whereas intensity of emission is controlled by external low-frequency strain impacts. Indeed, further direct borehole investigations did show that increase in the level of seismic and acoustic noise corresponds to intervals of fragmentation and higher fracturing, active micro-movements of the Earth's crust and tectonic faults and fractures (Diakonov et al.., 1989; Diakonov et al., 1991; Diakonov et al., 1990; Astrahancev et al., 2007). I

n particular, it was shown that increase in the level of noise and its variations relates to location of ore intervals and an oil reservoir (Diakonov et al., 1989; Atlas of Temporal Variations…, 1994). During seismic acquisition, appearance of induced geodynamic noise was encountered in up to 40 Hz frequency range near a hydrocarbon deposit (Maximov et al., 2015). A large number of test works established that recorded seismic emission activity was not stable in time and space, and possessed selective sensitivity to frequency of impact, however the emission response may differ from impact in frequency (Havroshkin, 1999).

Seismic emission signals may have various shapes (Havroshkin, 1999), but often they are represented by pulsed or noise-like temporal relations. Signals from multiple sources may superimpose during recording and interfere. Moreover, emission signals may be extremely low, completely buried in the noise on single records. Sources of such signals are impossible to localize by conventional seismological methods, based on establishment of seismic phase arrival time from microevents. For studies of seismic emission, a special method was suggested and patented which was later titled seismic emission tomography (Nikolaev et al., 1983). It enables to identify a spatially-coherent component of seismic noise, to localize its sources, to assess emission parameters (power, spectral composition) (Chebotareva, 2011; Chebotareva, 2012; Tchebotareva et al.., 2000).

Input data for emission tomography is represented by noise-like seismic records, recorded by a multi-channel sensors array. These may be recordings of natural seismic noise from the Earth, coda-waves from remote earthquakes and explosions, industrial noise. Recording sensors are placed on the surface or in holes. Even a small deepening of sensors, for first tens of meters is useful and allows to significantly reduce the level of local random noise and to increase sensitivity of the method. During implementation of algorithms, by introducing temporal signal delays, the seismic antenna is adjusted to amplify signals from different parts of the environment. This is followed by calculation of a functional which provides accumulation of information via channels and time. Location of emission sources corresponds to the location of the functional's maximum values which exceed the value of confidence interval of the purely noise field (Chebotareva, 2011; Chebotareva, 2012; Tchebotareva et al.., 2000). Therefore, if emission sources are absent, then we will gain an image with an even distribution of intensity. Statistical diversion of brightness values is established by the time of signal accumulation. If sources of seismic emission are present in the geo-environment, then a bright "cloud" will show up on the image and its contours are defined by geometry of the emission region.

Emission tomography was initially used for seismo-geologic surveys in geothermal, seismo-active and volcanic regions. Algorithms were developed, to be applied in time and frequency domain, for 1-component and 3-component recording, which enables to operate in a wide range of spatial scales up to the Earth's deep lithosphere (Chebotareva, 2011; Chebotareva, 2012; Chebotareva, 2017; Tchebotareva et al.., 2000). Adaptation of emission tomography for operations at hydrocarbon fields required to work out additional algorithms which make it possible to eliminate effects from intensive spatially-coherent industrial noise (Chebotareva et al.., 2008; Chebotareva, 2010a; Chebotareva, 2010). Approximate algorithms for ray tracing were also developed which enable to significantly speed-up calculation time for horizontally-layered, gradient velocity models and layered environment models with complex boundary geometry. The correct consideration of a velocity model allows to increase sensitivity of the method and to provide a more accurate 3D-adjustment of emission sources (Chebotareva, 2018).

Seismic emission tomography, despite its strong potential, is not sufficiently applied in hydrocarbons development. In our country there are some studies on application of different modifications of the method to monitor fracking jobs and to exercise methods for deriving geological information applying emission and scattered waves attributed (Gapeev et al., 2014; Alexandrov et al., 2015; Kuznetsov et al., 2016). In other countries emission tomography is also successfully applied by servicing companies to monitor hydraulic fracturing and high-activity fracture zones. Examples of such companies are MicroSeismic, Inc. and Global Geophysical Services, Inc.

Since emission tomography may operate with not only pulsed signal but with noise-like signals as well, it allows to extract more descriptive information than micro-seismic monitoring: to study not only microevents but also weaker in energy dissipative processes during formation of the environment, which are not accompanied by micro-earthquakes. This Article shows examples on identification and 3D localization of emission activity sources associated with tectonic faults, open fracturing, fluid filtering in highly-permeable rocks. All the images were generated applying seismic emission tomography algorithms.

Results and Discussions

Seismic records acquired at hydrocarbon fields during seismic acquisition often show intensive industrial noise associated with the field development processes. Random additive diffuse noise is easy to suppress, but since industrial noise sources are associated with some specific objects, industrial noise is spatially coherent. In addition, sources are not always located on the surface, for example, in case of a ‘noisy’ well. When using emission tomography, such noise may create shielding effect. This means that bright sources of strong industrial noise will show up on the images of the studied object, where weak deep sources will remain unnoticed against them. When adapting emission tomography methods for hydrocarbon fields, adaptive and rejector spatial filtering methods were developed, which allow efficient elimination of effects caused by coherent noise events (Chebotareva et al.., 2008; Chebotareva, 2010a, Chebotareva, 2010b).

But what turned out to be more interesting is that an industrial noise may be effective if used as a sounding signal. It creates an additional seismic ‘illumination’ of the geo-environment and allows to identify uniformities with strong scattering, reflective properties, or underground resonators. Fig. 1 shows two of such examples – image of a tectonic fault and a natural fracture (a side boundary of unstable block of rock). Image of the fault (Fig. 1a, b) has a complex spatial structure. It is known that the internal part of a fracture zone is characterized by a high level of fracturing (first tens and hundreds of meters). Towards the center of the fracture density of fracture rapidly grows, the central zone (centimeters – meters) becomes filled with crushed, fragmentized material. Seismic wave velocity of host rocks exceeds velocities inside the fracture by dozens of percent. In other words, the fracture represents low-velocity waveguide. If the source of industrial noise is located rather close to the fracture, then the low-velocity zone captures the energy of the industrial noise. Boundaries of the natural waveguide are not flat and not absolutely firm, therefore a significant part of seismic energy permeates through walls of the waveguide, and it becomes visible for emission tomography. Image of the fracture zone indicates that a large part of energy from industrial impact during development stops at deep horizons exceeding 6 km.

Fig. 1c shows an image of a natural fracture, whose internal part, as we can expect, is also filed with highly fragmented rocks. It showed up at the time of perforation blast. However the main energy from perforation blast lies in a higher frequency range than emission of the fracture. In other words, in this case we either observe a trigger effect, or non-linear transfer of energy from perforation blast to lower frequencies.

Fig. 2 shows horizontal slices of 3D images at the depth of the horizontal wellbore. They demonstrate how

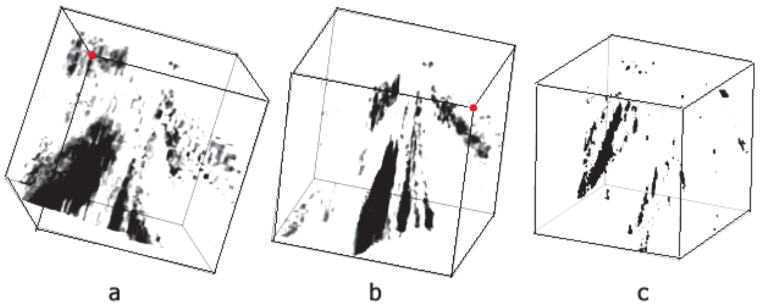

Fig. 1. Application of industrial noise to «illuminate» tectonic faults, a, b – images of a tectonic fault with turned isometric projection, c – image of a natural fracture. Size of the edge of studies objects is 6 km (a, b) and 3 km (c)

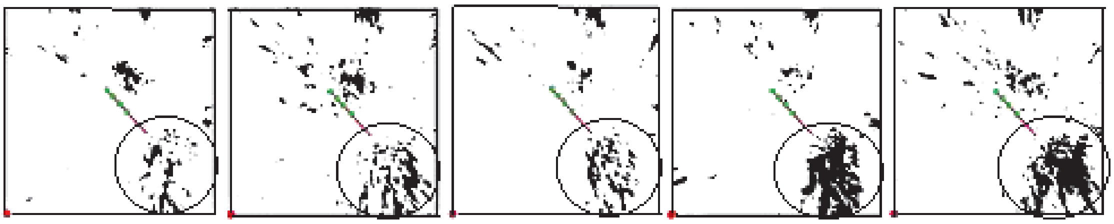

Fig. 2. Development of fluid outflow from borehole in high-permeability part of the rocks. Horizontal slices of 3D-images at the depth of a horizontal borehole. Time vector from left to right

fluid runs out of the well. Fluid spreads towards greater rock permeability. Radiated emission is associated with pressure fluctuations and micro-destruction of rocks when pore pressure grows behind the filtering front.

As mentioned previously, seismic emission response of rocks is enhanced by external effects. One of such industrial impacts comes from hydraulic fracturing. During fracking, by using microseism monitoring within first hundreds of meters they normally study characteristics of the breakdown, design of the disruption, absolute permeability of the bottomhole zone (Maxwell, 2010; Economides et al.., 2002; Rothert, Shapiro, 2007; Shapiro et al.., 2002; Alexandrov et al., 2015). Since emission tomography allows to study a thinner structure of the stress field, during emission seismo-tomographic monitoring it becomes possible to observe activization of open fracturing zones and tectonically unstable blocks in a much larger volume of the environment. Tests results show that in case of such local industrial effects, distribution of active emission clusters significantly changes within several kilometers radius from perforation zone, and in various ways in different frequency ranges (Chebotareva, Volodin, 2012; Chebotareva, 2017; Volodin, Chebotareva, 2014).

Images of the environment were computed in different frequency ranges within 10-100 Hz. It was established that micro-earthquakes, whose arrival amplitudes are clearly identified on single records, show up in the lowest frequency range. From the very start of formation impact, sources of micro-earthquakes are localized over the entire studied object which represents a hexahedron with 3 km edges (Chebotareva, Volodin, 2012). They can not be unambiguously associated with relaxation diffusion of disturbances in pore pressure. A better explanation is a trigger effect initiated by changes in stress-strain state of the rock mass.

Rocks fracturing zones show up on emission images in the medium frequency range. Partially they are visible prior to hydraulic fracturing (Fig. 3a). However, during growth of pressure in the environment during fluid injection the size of emitting cluster sharply increases (Fig. 3b), identifying latent fracturing zones inactive in background conditions. After completion of operations upon relaxation of stress in the geo-environment, distribution of emission clusters returns to previous shape (Fig. 3c).

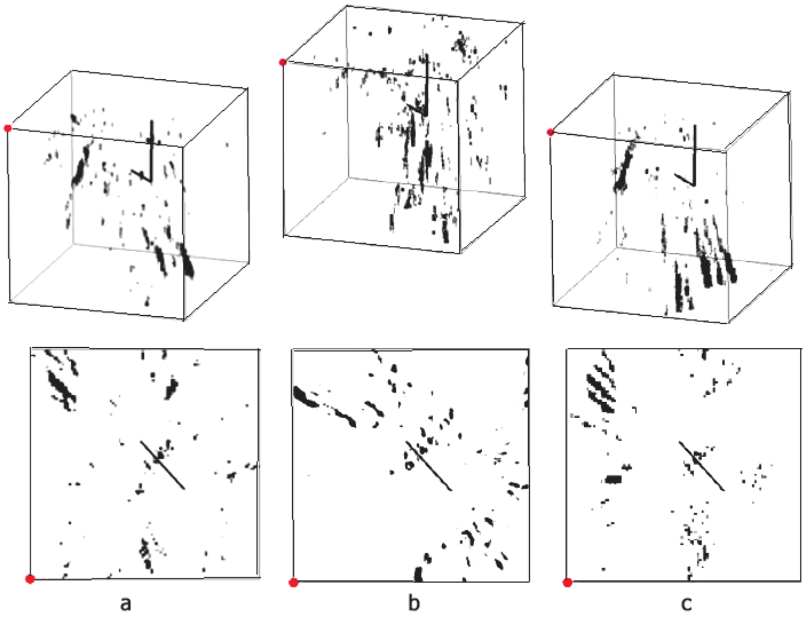

Fig. 3. Distribution of emission activity in zones of structural inhomogeneities (porosity, open fracturing) a – before, b – during (pressure growth interval) and c – after hydraulic fracturing. Size of the studied object's edge is 3 km

Behaviour of emission clusters in the upper frequency range has some distinctive features. In background state before and after hydraulic fracturing distribution of emission sources is similar in the medium and upper frequency ranges. The external impact however destroys the structure of high-frequency emission cluster. Distribution of image intensity becomes even (Chebotareva, Volodin, 2012). It is possible when environment in this frequency range does not emit or emits unevenly along the entire object. As pressure grows, emission «luminosity» is localized and drawn towards deformation strips, highlighting the location of unstable block, at which basement the strongest micro-earthquake occurs (Volodin, Chebotareva, 2014). Its source is at more than 2 km distance from perforation zone. After pressure release, distribution of intensity in the images becomes even again. It returns to initial background shape after relaxation of stress in the rock mass.

Fig. 4 shows emission image of the formation's disrupted area at the time between hydraulic fracturing in case of a multi-stage hydraulic fracturing. Emission signal is provided through relaxation energy of perturbed stress-strain state of the formation. Horizontal projection clearly shows the geometry of hydraulic disruption, non-symmetric in relation to the well. Since distribution of emission sources is essentially not flat, in this case we can observe a zone of bulk formation disturbance.

Conclusion

Results of emission seismo-tomographic monitoring at hydrocarbon fields under development demonstrate that zones of fracturing, tectonic and fluidal activity may be discovered and localized with background seismic noise records. However more substantial information, with further exploration of resources within a few kilometer radius, may be acquired with different types of external stimulation, such as hydraulic fracturing, strong industrial noise, seismic waves passing from remote earthquakes and explosions. Additional information may be extracted from seismic data re-processing, provided that the works are conducted with improved high-sensitivity seismic modules. Emission tomography and seismic acquisition are two complimentary methods. Seismic acquisition aims at identification of horizontally extending contrasting velocity boundaries. Emission tomography aims at identification of local non-uniformities which may not cause contrasting reflections. It applies different physical principles and utilizes seismic emission effects undetected by conventional seismic acquisition methods.

The studies of rocks' response to natural and industrial impacts is a fundamental scientific challenge. In order to develop emission seismo-tomographic technologies, which could be methodically available to servicing companies, it is necessary to carry out additional experimental and theoretical studies. Reliable data interpretation requires experimental statistics on the parameters of emission samples with an accurate connection to geological objects. It is also necessary to further develop the theory on seismic emission generation and propagation of seismic signals in structurally non-uniform environments. Despite the fact that 35 years have passed since seismic emission effect discovery was recorded, the mechanisms of seismic emission are still not clear.

Very often studies dedicated to seismic emission associate its appearance with a large number of micro-breakages, including those during relaxational diffusion of pore pressure perturbances. Conventional monitoring of hydraulic fracturing is conducted through borehole observations in order to record micro-earthquakes within hundreds – first thousand Hertz range. Presence of a continuous emission component is interpreted as superimposition of a large number of consistent pulsed signals from multiple shear fractures. The above results however show that emission effects enabling to visualize hydrodynamic processes associated with hydraulic fracturing are observed at much lower frequencies – tens of Hz.

By using resolution of the problem for a circular fracture which suddenly stops its development (Madariaga et al., 1976; Aki, Richards, 1983), we will

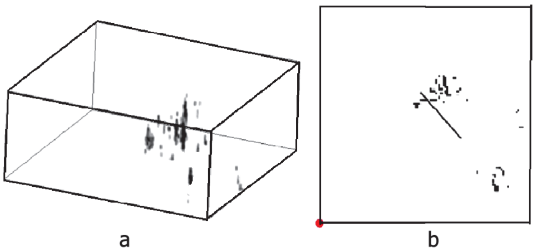

Fig. 4. Hydraulic breakage zone at a time between hydraulic fracturing during a multi-stage hydraulic fracturing. Horizontal edge is 3 km, a – isometrical projection, b – horizontal projection at the depth of a horizontal borehole

gain estimation of a typical radius of multiple fractures:

$$r = 0.32*V/f = 20 \text{ m},$$

where V = 3 km/s – seismic waves velocity, f = 50 Hz – emission radiation frequency. Such estimation is not true. Sizes of anticipated "multiple faults" are too large considering that normal sizes during hydraulic fracturing are only equal to first hundreds of meters.

A better approach to description of emission radiation mechanisms on the frequencies starting from first units to first hundred Hertz is based on non-linear properties of structurally inhomogeneous media. To present moment, there are several mechanisms developed taking into consideration non-linear nature and block discreteness of the geo-medium (Bovenko, 1987; Krylov et al., 1991; Dinariev, Nikolaevsky, 1997; Dinariev, Nikolaevskiy, 1993; Nikolaevsky, 1996; Garagash, 2002; Sibiryakov, Bobrov, 2008). They describe generation and transfer of emission radiation energy up and down the spectrum in the form of harmonics and sub-harmonics.

Recently a new mechanism of seismic emission generation was suggested on the frequencies enveloping the micro-oscillations elements of structurally inhomogeneous geo-medium (Volodin, Chebotareva, 2014). Movement equations were derived for a medium model in the shape of one-dimensional chains with Hertz nonlinearity. Modern geophysics commonly applies such models of granulated media not only for description of soft soils, but also for conventionally monolithic grainy and crystalline rocks. Experiments have proved that distribution of stress in volume is not uniform in granulated media during surcharge and vibration effect. Application of stress-optical material allows to visualize formation of a grid of power chains which bring all the load to the medium. The study (Volodin, Chebotareva, 2014) shows that when examining multi-scale movements, the chain movement equation has the shape of the nonlinear Schrödinger equation. We know that under certain conditions for nonlinearity and dispersion parameters, there appears modulational instability in solution of this equation which is expressed in a spontaneous amplitude modulation of radio-frequency carrier. When modulated wave propagates in nonlinear medium, its detection occurs (Zarembo, Krasilnikov, 1966), which results in only a low-frequency component remaining, which is recorded at large distances from the source. Correlation between the main and modulational frequency depends on structural parameters of the medium and is normally equal to several orders of magnitude.

For this reason on seismic frequencies equal to tens of Hertz it is possible to study remote areas of structurally inhomogeneous inclusion with micro-oscillations frequency from one to hundreds kHz. Physical simulations using core samples from oilfields show that during straining the core samples and vibrational impact, it is effectively possible to observe generation of dynamically bound radiation in 10-100 Hz and 5-20 kHz range, whereas the dynamics of intermediate frequency range is significantly different (Chebotareva et al.., 2017).

Conclusion

1. The emission seismic tomography method allows to identify tectonic faults, open fractures and porosity, to study geophysical processes in the zones of structural and fluidal inhomogeneity of the natural mass using multi-channel recordings of the Earth's natural seismic background recorded on the surface.

2. Industrial and natural external impacts on the geo-medium activate areas of structural inhomogeneity which are hidden in background state. This allows to conduct additional exploration in the field at the stage of development, to identify promising formations and missed deposits. In particular, during hydraulic fracturing it is possible to conduct follow-up exploration within a few kilometer radius.

3. To ensure reliable data interpretation and development of effective servicing technologies, it is necessary to conduct field studies of seismic effects observed at hydrocarbon fields, with an accurate geologic correlation of emission objects.

4. It is necessary to continue development of the theory on seismic emission generation and propagation of seismic signals in structurally inhomogeneous media.

References

Aki K, Richardson P. (1983). Quantitative seismology. Theory and methods. Moscow: Mir., v. 2, 831 p. (In Russ.).

Aleksandrov S. I., Mishin V. A., Burov D. I. 2015. Problems of well and ground microseismic monitoring of hydraulic fracturing. *Expozitciya Neft' i Gaz = Exposition Oil & Gas*, 6(45), pp. 58-63. (In Russ.)

Astrahancev Yu.G., Guberian D.M., D'yakonov V.P., Pevzner S.L., Troyanov A.K., YAkovlev Yu.N. (2007). Geoacoustic noise in the Kola superdeep well. *Vestnik MGTU*, 10(2), pp. 231-235. (In Russ.)

Atlas of temporal variations of natural processes. (1994). Project Man. N.P. Laverov. Ed. A.V. Nikolaev, A.G. Gamburcev. Moscow: Nauchnyy mir, v. 1, 176 p. (In Russ.)

Bovenko V. N. (1987). Self-oscillatory model of acoustoemission and seismic phenomena. *Dokl. AN SSSR*, 297(5), pp. 1103-1106. (In Russ.)

Chebotareva I.Ya., Kushnir A.F., Rozhkov M.V. (2008). Elimination of high-amplitude noise during passive monitoring of hydrocarbon deposits by the emission tomography method. *Izvestiya, Phys. Solid Earth*, 44, pp. 1002-1007.

Chebotareva I.Ya. (2010a). New Algorithms of Emission tomography for passive seismic monitoring of a producing hydrocarbon deposit. Part I. Algorithms of Processing and Numerical Simulation. *Izvestiya, Phys. Solid Earth*, 46(3), pp. 187-198.

Chebotareva I.Ya. (2010b). New Algorithms of Emission tomography for passive seismic monitoring of a producing hydrocarbon deposit. Part II. Results of Real Data Processing. *Izvestiya, Phys. Solid Earth*, 46(3), pp. 199-215.

Chebotareva I.Ya. (2011). Methods for passive study of the geological environment using seismic noise. *Acoust. Phys.*, 57(6), pp. 857-865.

Chebotareva I.Ya. (2012). Structure and dynamics of geomedia in noise seismic fields. Methods and experimental results. *Akustika neodnorodnyh sred. Ezhegodnik Rossijskogo akusticheskogo obshchestva*. Moscow: GEOS, 12, pp. 147-156. (In Russ.)

Chebotareva I.Ya., Volodin I.A. (2012). Images of Hydraulic Fracture in Seismic Noise. *Doklady Earth Sciences*, 444(1), pp. 621-625.

Chebotareva I.Ya. (2017). Emission tomography – basic tool for technologies for studies of hydrocarbon deposits. *Aknualnii problemy nefti i gasa = Actual problems of oil and gas*. DOI: 10.29222/ipng.2078-5712.2017-17.art8 (in Russ.)

Chebotareva I.Ya, Volodin I.A., Dryagin V.V. (2017). Acoustic Effects in the Deformation of Structually Inhomogeneous Media. *Acoustical Physics*, 63(1), pp. 84-93.

Chebotareva, I.Ya. (2018). Ray Tracing Methods in Seismic Emission Tomography. *Izvestiya, Physics of the Solid Earth*, 54(2), pp. 201-213. DOI: 10.1134/S1069351318020040

Darvin D.G. (1965). Tides and related phenomena in the solar system. Moscow: Nauka, 106 p. (In Russ.)

Diakonov B.P., Troyanov A.K., Nazarov A.N., Fadeev V.A. (1989). Seismoacoustic noise on deep horizons. *Doklady AN SSSR*, 309(2), pp. 314-318. (In Russ.)

Diakonov B.P., Karryev B.S., Khavrishkin O.B., Nikolaev A.V., Rykunov L.N., Seroglazove R.R., Trojanov A.K., Tsyplakov V.V. (1990). Manifestation of earth deformation processes by high-frequency seismic noise characteristics. *Phys. Earth Planet. Inter,* 63, pp. 151-162.

Diakonov B.P., Troyanov A.K., Kusonskiy O.A., Nazarov A.N., Fadeev V.A. (1991). Geological information of downhole surveys of high-frequency seismoacoustic noise. *Vulkanologiya i seysmologiya = Volkanology and Seismology*, 1, pp. 112-116. (In Russ.)

Diakonov B.P., Martyshko P.S., Troyanov A.K., Astrahancev YU.G., Nachapkin N.I. (2010). Isolation of periodicities of low-frequency deformation processes in variations of electromagnetic radiation in the Ural superdeep well. *Doklady RAN*, 430(1), pp. 105-107. (In Russ.)

Dinariev O.Yu., Nikolaevskij V.N. (1993). Creep of rocks as a source of seismic noise. *Doklady RAN*, 331(6), pp. 739-741. (In Russ.)

Dinariev O.Yu., Nikolaevskij V.N. (1997). Multiple period increase in the propagation of waves in elastic bodies with a dissipative microstructure. *Izv. RAN, MTT*, 6, pp. 78-85. (In Russ.)

Economides M., Oligney R., Valko P. (2002). Unified fracture design. Bridging the gap between theory and practice. Alvin. Texas: Orsa Press. 200 p.

Galperin E.I., Vinnik L.P., Petersen N.V. (1987). On modulation of high-frequency seismic noise by tidal deformations of the lithosphere. *Izv. AN SSSR. Ser. Fizika Zemli*, 12, pp. 102-109.

Gamburcev G.A. (1960). Izbrannye trudy. Moscow: AN SSSR, pp. 424-425. (In Russ.)

Gapeev D.N., Erohin G.N., Rodin S.V., Sedajkin R.D., Smirnov I.I. (2014). New possibilities of applying passive microseismic monitoring for revealing structural-tectonic features of oil and gas fields. *Vestnik Baltiyskogo federal'nogo universiteta im. I. Kanta*, 4, pp. 113-120. (In Russ.)

Garagash I.A. (2002). Model of dynamics of fragmented media with moving blocks. Fizicheskaya mezomekhanika, 5(5), pp. 71-77. (In Russ.)

Golicyn B.B. (1960). Izbrannye trudy. Moscow: AN SSSR, v. 2, pp. 411-413. (In Russ.)

Gordeev E.I., Rykunov L.N. (1976). Spectra of P-waves from remote earthquakes in the frequency range 1-10 Hz. *Izv. AN SSSR. Ser.Fizika Zemli*, 7, pp. 90-92. (In Russ.)

Havroshkin O.B. (1999). Some problems of nonlinear seismology. Moscow: OIFZ RAN, 286 p. (In Russ.)

Kouznetsov, A.A. Radwan, I.A. Chirkin, E.G. Rizanov, S.O. Koligaev. (2016). Combining seismic waves of different classes in exploration of hydrocarbon fields (new seismic exploration methodology). *Tekhnologii seysmorazvedki*. (3), pp. 38-47. DOI: 10.18303/1813-4254-2016-3-38-47. (In Russ.)

Krylov A.L., Nikolaevskiy V.N., EHl' G.A. (1991). Mathematical model of nonlinear generation of ultrasound by seismic waves. *Doklady AN SSSR*, 318(6), pp. 1340-1344. (In Russ.)

Leet L.D., Leet F.L. (1962). Cause of microseisms – a theory. *Geol. Soc. Amer. Bull.*, 72(8), pp. 1021-1022.

Lukk A.A., Deshcherevskij A.V., Sidorin A.YA., Sidorin I.YA. (1996). Variations of geophysical fields as a manifestation of deterministic chaos in a fractal environment. Moscow: OIFZ RAN, 210 p.

Madariaga R. (1976). Dynamics of an expanding circular falt. *Bulletin of Seismological Society of America*, 66(3), pp. 669-666.

Maksimov L.A., Vedernikov G.V., Yashkov G.N. (2015). Geodynamic noise of hydrocarbon pools and passive and active seismic CDPM. *Expozitciya Neft' i Gaz = Exposition Oil & Gas*, 6(45), pp. 55-57. (In Russ.)

Maxwell S. (2010). Microseismic: growth born from success. *The Leading Edge*, 29, pp. 338-343.

Nanney C.A. (1958). Possible correlations between earthquakes and microseisms. *Nature*, 181, pp. 802-803.

Naumenko B.N. (1979). On the phenomenon of partial elimination of tectonic stresses by storm microseisms. *Izv. AN SSSR. Ser. Fizika Zemli*, 8, pp. 72-75. (In Russ.)

Nikolaev A.V., Troickiy P.A, Chebotareva I.YA. (1983). Method of seismic prospecting: A. C. 1000962 SSSR. No. 3213796, declared 08.12.80; Publ. 28.02.83. Otkrytiya, izobreteniya, 8, 4 p. (In Russ.)

Nikolaevskiy V.N. (1996). Geomechanics and fluid dynamics. Moscow: Nedra, 448 p. (In Russ.)

Rothert E., Shapiro S. A. (2007). Statistics of fracture strength and fluid-induced microseismicity. *Journal of Geophysical Research*, 112 (B04309), pp.1-16. DOI: 10.1029/2005JB003959

Rykunov L.N., Havroshkin O.B., Cyplakov V.V. (1983). The phenomenon of modulation of high-frequency seismic noise of the Earth. Sertificate No. 282, Moscow (In Russ.)

Shapiro S.A., Rothert E., Rath V., and Rindschwentner J. (2002). Characterization of fluid transport properties of reservoirs using induced microseismicity. *Geophysics*, 6, pp. 7212-220.

Sibiryakov B.P., Bobrov B.A. (2008). Origin of acoustic emission under static loading of sands. *Fizicheskaya mezomekhanika*, 11(1), pp. 80-84. (In Russ.)

Tchebotareva I. Ya., Nikolaev A.V., Sato H. (2000). Seismic Emission Activity of Earth's Crust in Northern Kanto, Japan. *Phys. Earth Planet. Inter*, 120(3), pp.167-182.

Volodin I. A., Chebotareva I. Ya. (2014). Seismic Emission in Technological Impact Zones. *Acoustical Physics*, 60(5), pp. 543-554. DOI: 10.1134/S1063771014050145

Zarembo L.K., Krasilnikov V.A. (1966). Introduction to nonlinear acoustics. Moscow: Nauka, 519 p. (In Russ.)

Zhadin V.V. (1971). On the frequency composition of longitudinal wave records from remote earthquakes. *Izv. AN SSSR, Ser. Fizika zemli*, 5, pp. 99-101. (In Russ.)

About the Author

Irina Ya. Chebotareva – Chief Researcher

Oil and Gas Research Institute of the Russian Academy of Sciences

Gubkin st., 3, Moscow, 117971, Russian Federation

E-mail: irinache@inbox.ru

Manuscript received 14 June 2018;
Accepted 19 July 2018;
Published 30 August 2018