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Seismic studies of the unevenness of open fracturing and inhomogeneity of the fluid saturation in the geological environment for optimal development of oil and gas fields

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Abstract. The distribution of fracturing and the type of fluid saturation in the geological environment, along with its structure, is the most important information for optimal development of oil and gas fields, including their search, exploration and development. Integrated use of seismic information about fluid saturation, fracturing and the structure of sedimentary strata helps to choose the optimal locations for the discovery of wells in order to obtain the maximum possible inflow of hydrocarbons into them. This approach drastically reduces the drilling of dry wells while performing prospecting and exploration works, significantly reduces the capital costs for their implementation and accelerates the commissioning of fields. In the development of the field, continuous seismic monitoring of fracturing and fluid saturation of the productive strata in real time allows the operative optimization of oil displacement schemes and operating modes of wells, choosing the optimal location and time for performing geological and technological measures, and controlling the geological and technical efficiency of their implementation, etc., the rate of recovery and the completeness of the oil extraction from the deposit while reducing capital and operating costs. To study the 2D-4D distribution of fracturing and fluid saturation in the geological environment by scientists and specialists of the "Scientific School of Oil and Gas Seismoacoustics by prof. Kuznetsov O.L.", innovative seismic technologies are created: "Seismic side-view locator", "Seismolocation of foci of emission" and "Acoustic low-frequency survey", in which for obtaining this information, waves of diffuse reflection and microseismic emissions are used, not mirror reflection, as in traditional seismic surveys. As a result of experimental laboratory, well and field studies, the regularity of the amplitude-time parameters of seismoacoustic emission was determined depending on the type of fluid saturation of rocks and physical impacts, which was also used in the technologies of "Logging of seismoacoustic emission" to isolate oil-containing intervals in a section of wells and "Wave treatment of the reservoir" to increase the oil inflow into the well, including hard-to-recover highly viscous oil.

Examples of the application of seismo-acoustic technologies for solving a wide range of applied problems in the development of oil and gas fields are given.

Keywords: seismic studies, fracturing, fluid saturation, oil and gas fields

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Uneven and non-uniform fluid saturation (oil, gas, water) of reservoir formations and uneven distribution of open fracturing in the geological environment are extremely important information that is currently not fully or completely used in prospecting, exploration and development of oil and gas fields, which in turn significantly reduces the efficiency of oilfield development. Optimization of exploration, when the discovery of an oilfield and the selection of drilling sites is carried out using a complex of structural seismic information, data on fluid saturation and fracturing, can significantly increase the "success" of drilling, resulting in drilling of wells with the highest possible flow rate of hydrocarbons. This optimization reduces drilling costs, speeds up the oilfield commissioning and makes them attractive for investment. In confirmation of such opportunities, one can refer to the world statistics of well drilling "successfulness", which is 30-35% when

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searching for (discovering) an oilfield, and 65-70% when exploring, which indicates on "hidden" reserves to improve efficiency of prospecting surveys.

When developing oil and gas fields, information on reservoir's fracturing and fluid saturation in the interwell space is obtained from discrete seismic observations or continuous seismic monitoring, which provides real-time results and unlimited in time. In the first case, the information can be used for optimal placement of production and injection wells, which is especially important for fields with a fractured-porous and fractured (usually carbonate) reservoirs. According to our data, at such fields, 10-15% of wells produce 85-90% of oil. This shows that consistently high flow rates in such a reservoir can be obtained if a well accidentally successfully drilled into the zone of intense fracturing (Akselrod, 2013). If these "oilfield's good places" can be determined from seismic data in accordance with distribution of oil content, fracturing, fluid (oil and water) flows, etc. within the reservoir, then the number of producing wells can be significantly reduced. In the second case, the information obtained in real time continuous monitoring allows quickly optimize reservoir drive mechanisms and well production conditions, select the optimal place and time for performing well stimulation operations and monitor the geological efficiency of their implementation, identify areas of high oil content in the water-saturated part and behind the extent of the reservoir, etc. Solution of these and other development optimization problems allows to significantly increase production and oil recovery rates at an oilfield as well as reduce capital and operating costs.

Innovative seismic technologies such as "Seismic Locator for Lateral Survey" (SLBO-technology, Kuznetsov et al., 2004), "Seismolocation of emission centers" (SLEC, Kuznetsov et al., 2007b) and "Acoustic Low-Frequency Prospecting" (ANCHAR, Arutyunov et al., 1997), as well as acoustic technologies such as "Seismoacoustic emission logging" (SAEL, Kuznetsov et al., 2007b) for identifying oil-saturated intervals within the well section, including identification through the iron and cement columns, penetration zone, and the "Wave Reservoir Stimulation" (WRS, Kuznetsov et al., 2001, Kuznetsov et al., 2007b) increasing the flow of oil (including hard-to-recover and highly viscous) into the well were developed by scientists and specialists of the "Scientific School of Oil and Gas Seismic Acoustics of Prof. Kuznetsov O.L." to study the 2D-4D distribution of fractures and fluid saturation in the geological environment. Creation and improvement of these technologies was carried out in accordance with the results of theoretical studies and numerous laboratory experiments, well operations and field surveys. The research data allowed to study in detail the processes of fractures formation and seismoacoustic emission waves occurrence, as well as to establish the pattern of changes in seismoacoustic emission amplitude-time parameters related to the type of rocks fluid saturation and physical impacts. For the first time, there were discovered the sub-vertical zones of intense open fracturing (geodynamic pumps for vertical fluid transfer), it was identified the mini-block structure of the sedimentary sequence, as well as were revealed the lunar-solar phases of the geological environment compaction and decompaction, etc. All the identified phenomena and patterns can be used to improve the efficiency of oil and gas fields development. For example, diffuse reflection and microseismic emission (MSE) waves, rather than specular reflection, as in traditional seismic exploration, are used in such seismic technologies as SLBO, SLEC and ANCHAR in order to increase the geological efficiency of studying fracturing and fluid saturation of the sedimentary sequence. This made it possible to significantly increase the reliability of the obtained seismic information on fracturing and fluid saturation of the geological environment. Below we briefly describe the basics of the scattered reflection and MSE waves generation, and then the most important information about the process of fracturing and the space-time (4D) distribution of fracturing in the geological environment.

Scattered reflection waves

Diffuse seismic waves (or scattered waves) are formed in the geological environment on irregularities with sizes comparable and smaller than the length of the incident seismic wave. In acoustic terms, an open fracture filled with fluid (gas, water, oil) act as the most contrast heterogeneity. Scattered waves arise on the totality of open fractures (within the 1st Fresnel zone). The amplitude of this wave is dominantly dependent on the intensity of rock fracturing in the area, where this wave was formed. Considering that fracturing exists everywhere in the geological environment ("... there are no non-fractured rocks in nature ..." (Dorofeeva, 1986)), so the scattered waves also occur everywhere. Therefore, the location survey should be used for observing and positioning scattered waves, and the location survey should be lateral to exclude (suppress) the influence of the interference of specularly reflected waves. The energy of scattered waves is in 1-2 orders less than the energy of specularly reflected waves, which determines the need for in-phase scattered wave signals stacking with a multiplicity of 10^4. In order to get such a stacking, the emitting and receiving antennas of the locator should each contain at least 100 emitting and receiving points, respectively. The kinematics of the scattered wave corresponds to a hodograph of a point emitter, which is individual for each viewpoint. This makes it possible to determine the energy of scattered reflection, which corresponds to the intensity of open fracturing, at a lateral location survey at each scanned point of the geological media. Thus, using Seismic Locator for Lateral Survey and always presenting scattered waves, as well as specularly reflected waves in an artificial seismic wave field, we can obtain information on the spatial (2D and 3D) intensity of open fracturing distribution in the geological environment. Fig. 1 shows an example of such information obtained using the SLBO-technology at the Kuyumbinskoye field in Eastern Siberia

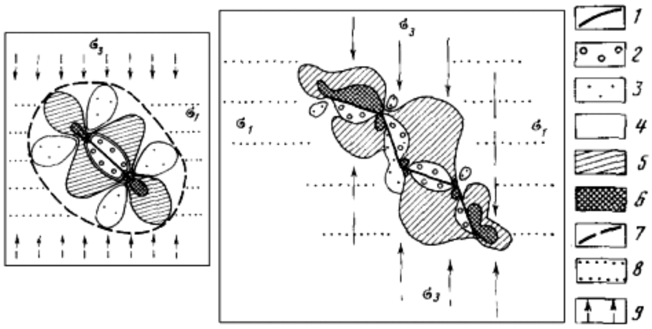

Fig. 2. An example of stress state modeling in the region of a single linear (a) and group zigzag (b) fractures (according to M.V. Gzovskii (Gzovskii, 1975)). 1 – fracture (cut in the model); zones: 2 – the highest decrease in stress, 3 – a slight decrease in stress, 4 – unchanged initial stress, 5 – a slight increase in stress, 6 – the highest increase in stress; 7 – conditional boundary of the signal emission zone; 8 – directions of maximum principal stresses σ_1; 9 – directions of the minimum principal stress σ_3

MSE waves

MSE and acoustic emission waves exist everywhere and every time in the geological environment. These waves arise due to transformation of elastic energy from a potential form (stressed state of rocks) into kinetic form (elastic waves emitted by these rocks). This transformation occurs in an open fracture (Fig. 2), when the lateral expansion and formation pressure forces stretching the fracture cavity in width begin to exceed ultimate tensile strength of the rock. Then, a discontinuity of the rock occurs at the ends of the fracture, the fracture lengthens closing its banks together and pushing fluid out of the cavity. At this moment, the following two main acoustic waves are formed: the first wave is formed when the cavity collapses and the wave propagates within the rock matrix with a negative (dilatation) first phase, the second wave propagates in a fluid with a positive (pressure increase) first phase. These waves propagating in the nearby space (at a distance of 2-3 wavelengths) provoke adjacent fractures prone to stress relaxation. New waves (together with the previous ones) provoke the adjacent fractures to discharge, etc. A "chain reaction" effect is created when sets of fractures co-operatively form elastic seismic waves in a wide range of energies (from 10^{-16} to 10^{18} J) and frequencies (from 10^{-1} to 10^{8} Hz) in the geological environment. The intensity of seismic waves is determined by the density of "mature" fractures located in the area of wave formation, while the frequency range is determined by the size of these areas (from 10^{-6} to 10^{3} m). Under natural conditions of the geological environment, acoustic waves are formed in areas of up to one meter, while microseismic waves are formed in areas of up to hundreds of meters.

It is also important to note that each MSE wave emitted in the geological environment has its own individual hodograph on the observation surface. This hodograph corresponds to the wave from a point source located in the hypocenter of the MSE wave generating zone. This relation makes it possible to unambiguously position MSE waves in the geological environment by their kinematic parameters, and make assumptions on the intensity of the fracturing in accordance with their dynamic characteristics.

The time variation of microseismic emission in a discrete volume ("point") of the geological environment corresponds to a random multiplicative process (Fig. 3), in which the amplitude-time characteristics

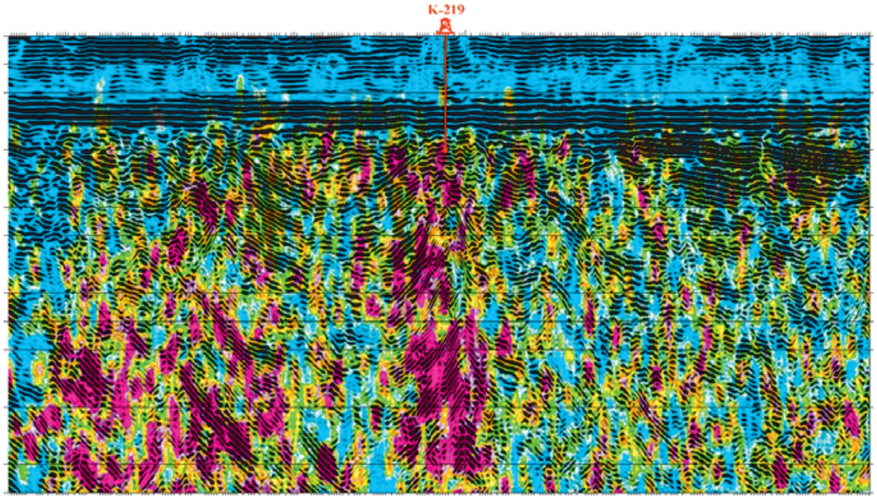

Fig. 1. Vertical sections of the open fracturing field with non-uniform intensity (high is indicated in red, low is indicated in blue) in comparison with the structural factor (black) obtained by scattered and reflected waves, respectively. Kuyumbinskoye field, Eastern Siberia

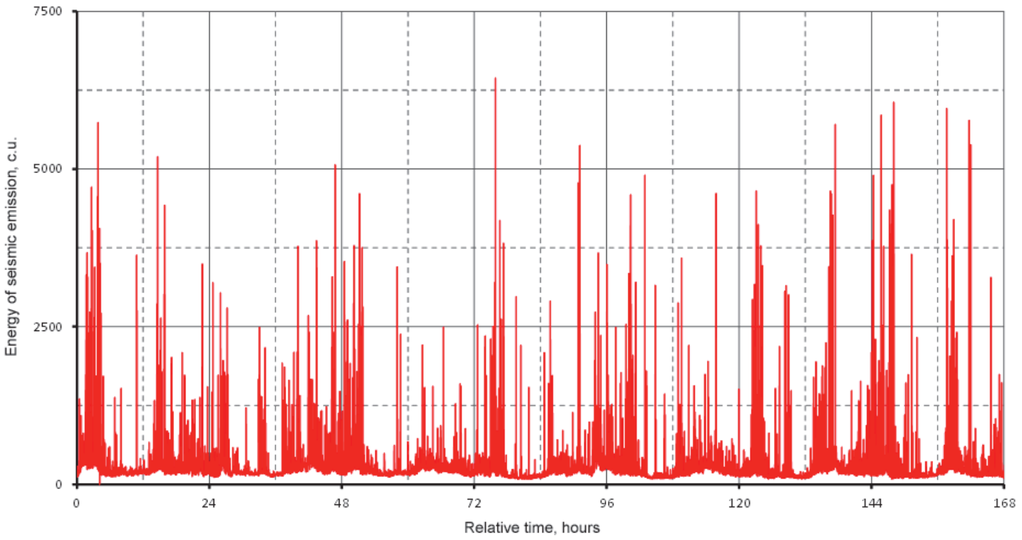

Fig. 3. Random multiplicative process of changing the intensity of microseismic emission in a discrete volume ("point") of the geological environment for 160 hours of continuous observation using the SLEC technology. Duration of discrete processing intervals is 10 s; total number of intervals (emission values) is 5760

of emitted elastic waves discrete signals correspond to the Gutenberg-Richter law or the seismic law of earthquake recurrence (Richter, 1963). This law defines an inverse linear relationship (on a logarithmic scale) between the energy of an emitted signal and the frequency (repeatability) of its emission with a given energy (following the logic of the physical process it can be concluded that the more energy is emitted, the more time it is required to accumulate it). For MSE, this pattern corresponds to signals the amplitude of which exceeds the level of seismic noise caused mainly by technogenic and natural sources generating near-surface interference waves. The lower threshold of the MSE waves intensity is determined by the sensitivity limit of the equipment used for seismic observations. The use of the Gutenberg-Richter law in analyzing the results of seismic monitoring materials processing allows estimation the accuracy of MSE waves identification in the resulting seismic wave field, which is required at the initial stage of interpretation.

In addition to the above pattern, it was found that the amplitude-time parameters of microseismic and acoustic emission vary depending on the type of rocks fluid saturation as well as on physical impact (Kuznetsov et al., 2007a). In case of natural occurrence of rocks with oil saturation, the average energy of a random MSE process is minimal and the dispersion and autocorrelation interval are characterized by maximum values relative to gas saturation, where the average energy is maximum and the dispersion and autocorrelation interval are minimal, as well as relative to water saturation, where these statistical parameters have average values. In case of physical impact (natural and technogenic), the MSE activity increases dramatically in oil-saturated rocks, where the average energy increases multiplely. The energy increases in water-saturated rocks by the first tens of percent and remains almost the same in gas-saturated rocks

These changes in the amplitude-time parameters of seismoacoustic emission (SAE) process, depending on the type of rocks fluid saturation and physical impacts, were experimentally studied in laboratory, downhole and surface conditions. Fig. 4 shows the results of accumulated AE energy laboratory studies for oil-, water- and gas-saturated core samples-clones before and

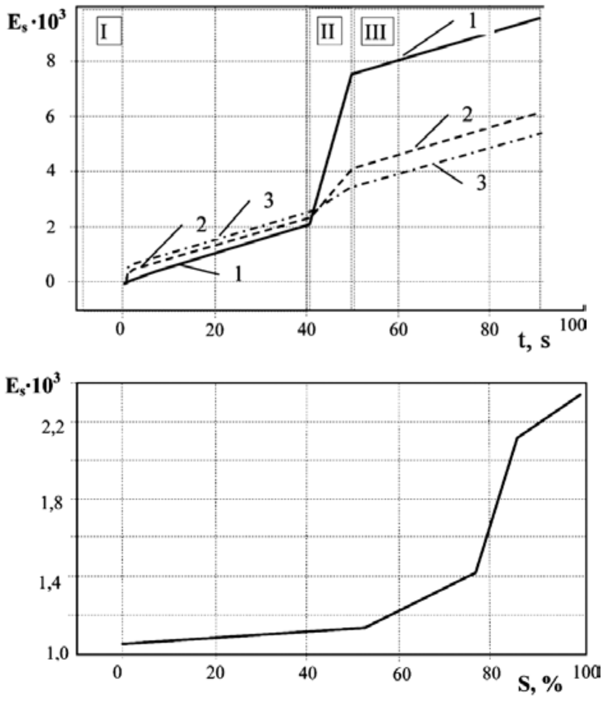

Fig. 4. Results of accumulated AE energy laboratory studies for oil-saturated (1), water-saturated (2) and dry (3) core samples-clones under load (top) and changes in AE energy from sample's oil saturation (bottom). I – when applying a mechanical load, II – when applying an impulse-wave impact, III – after impact

after its loading, as well as changes in AE energy from the uneven oil saturation of the sample.

The following main factors and conditions define the pattern of change in the amplitude-time parameters of elastic energy emission. In case of natural occurrence of the reservoir in statically uniform conditions, when identical rocks with a single reservoir pressure occur at the same depth, the nature of the emission is determined by the type of saturating fluid, the viscosity of which for the gas-water-oil sequence increases from 10^{-5} Pa·s (for gas) up to 10^{2} Pa·s (for high-viscosity oil). If the reservoir is saturated with oil, then there is rare emission of signals with relatively high energy and low-frequency spectrum, if the reservoir is saturated with water, the emission is more frequent, but its energy is lower and spectrum is more high-frequency, and if the reservoir is saturated with gas, then emission frequency and spectrum of discrete signals are even higher however its energy is minimal. Such an amplitude-time characteristic of discretely emitted signals determines the above statistical parameters, their gradation depending on the type of saturation.

At the event of geological environment activation, in case of tensile forces increase (for example, when reservoir pressure increases due to hydraulic fracturing) and/or in case of fluid viscosity decrease (for example, under acoustic or thermal effects), the SAE process in oil-saturated rocks is also gets activated/ This process is characterized by increase in frequency of discrete elastic signals emissions and also by increase in their energy. This in turn changes the value of probabilistic average of a random process for oil-saturated rocks, which becomes maximal in relation to emissions in case of water and gas saturation. It should be noted that the effect of SAE enhancing under wave impact on oil-bearing formations and oil fields (there is no such an effect for gas fields) is used in some seismic acoustic methods of "direct prospecting". For example, in SAEL and ANCHAR, the wave impact is used to reduce the time of emission observation (monitoring). In the method of G.V. Vedernikov (Vedernikov et al., 2011) the appearance of MSE waves on CDP seismograms is used as a sign of the presence of an oil reservoir; The "Bright Spot" and "Adaptive Vibroseismic Prospecting" methods (Zhukov et al., 2011; Zhukov, Schneerson, 2000) use a concept, where oil reservoir can be identified by the effect of a significant increase in the reflected wave amplitudes from the productive strata due to MSE energy.

Thus, MSE waves are a reliable indicator of the type of fluid saturation, as well as an indicator of geological environment open fracturing in case of long-term continuous passive seismic wave field monitoring. However, the intensity of the MSE waves is low. It is 1-2 orders of magnitude less than the intensity of surface interference waves. This fact determines the need for the in-phase scattered wave signals accumulation with a multiplicity of more than 10^{4}. The principle of passive seismic locator is used to implement such accumulation stacking. The receiving antenna (aperture) of such locator should contain at least 400 receiver channels, and the duration of the discrete processing interval should be more than 100 estimated MSE wave periods, i.e., about 6-10 seconds. Thus, given that the MSE occurs everywhere and constantly in the medium, the procedure of wave field localization in a large time window makes it possible to determine the average intensity of the elastic energy emission at the focal points in a given time interval. All these methods of seismic wave field observation as well as the identification of MSE waves and their positioning in geomedia are implemented in "Seismolocation of emission centers" (SLEC) technology.

In the SLEC technology, an increase in the signal-to-noise ratio (SNR) occurs not only n0.5 times, where n is the number of receivers in the locator antenna (surface monitoring array), but also due to stacking in time of m0.5 times, where m is the number of MSE waves with a period T in the time window Δt, which is m = Δt/T. In general, SNR = (n×m) 0.5. For example, in case of antenna with n = 400, Δt = 8s and T = 0.08s, we obtain SNR = 200. Similar MSE waves accumulation at each observation point at one iteration (duration of Δt) and subsequent statistical processing of the MSE process on the total duration of monitoring (t), i.e. with representativeness of the sampling k = t/Δt, which is more than 105 discrete values of the average (for iteration) MSE energy, makes it possible to calculate average value, variance and autocorrelation function (ACF) in the field of statistical parameters of the random emission process, while the random noise is almost absent. In this case, the average MSE energy field is identified with open fracturing distribution, and the field of the normalized ACF parameters is identified with the oil-saturation distribution in the geological environment.

Fractures distribution in the geological media

The distribution of fracturing in the geological environment is determined by its stress-strain state. In any area of the geological environment there is a large variety of multi-scale deformations and sources of stress. The main ones can be considered as:

- *global* caused by oscillations of poles and speed of the Earth's rotation;
- *regional* caused by the movement of lithospheric plates (plate tectonics);
- *local* caused by crystalline basement blocks movements and deformation of the sedimentary sequence.

These numerous stress-strain state sources create their own specific fracture systems in various parts of the environment, which, interfering with each other, form a fracturing distribution corresponding to "organized chaos" (Kuznetsov et al., 2004). At the same time, "tendentious organizers" are the main stress vectors that deform the geomedia and form the main spatial structures of fracturing widely represented and described in tectonophysical models (Gzovskii, 1975; Kuznetsov et al., 2004). For example, global stresses create a fracturing system in the Earth's crust, widely known in geology as diagonal, when orthogonally intersecting linear fracturing zones with azimuthal orientation from southwest to northeast and from southeast to northwest form mini-block or platy structure in a layered sediments. Fig. 5 shows an example of a productive sedimentary strata mini-block structure identified on SLEC data.

Regional and local fracturing systems formed by local stresses and strains are superimposed on this global diagonal structure. Thus, in the presented example, the radial fracturing system is identified from the local stress source formed by the sub-vertical fracturing zone. These zones, which are often found in the geological environment (for example, in Fig. 1), are usually formed due to the interference of linear, ring-shaped, and other zones as well as due to formation of local highly intense open fracturing anomalies. Further, this zone develops (during geological time) in the direction of the main stress vector, the rock pressure, i.e. in the vertical direction. The high significance of subvertical zones in the geological environment is that they act as geodynamic pumps causing convective thermodynamic mass transfer of fluid. Through these subvertical channels, hydrocarbons from oil source rocks migrate into overlying reservoirs. In this regard, it is extremely important to identify these zones to create a geological reservoir model and the reservoirs recharge in the development process.

Another important aspect of information on the distribution of fractures in the sedimentary layers is the ability to detect structural traps by matching the obtained distribution with tectonophysical models. For example, an anticlinal fold can be formed in the sedimentary layer due to the vertical uplift of the basement block. The radial and concentric (in horizontal plane) as well as fan-shaped divergent (in vertical plane) zones of anomalously high and low geo-media fracturing are formed within this fold (Kuznetsov et al., 1981). An example of a tectonophysical model representing the total 3D distribution of open fracturing within an anticline structure formed by a crystalline basement block uplifting is shown in Fig. 6. Based on this model, an anticline fold can be identified in the 3D fracturing field along vertical fan-shaped diverging linear and horizontal radial-concentric fracturing zones. Such structural studies are qualitative and insufficiently detailed in comparison with seismic structural information obtained by reflected waves. However in case of difficult seismic and geological conditions (salt domes, dikes, faults, etc.), the amplitude of fold-traps is extremely small (10-15 meters or less), the reliability of structural seismic maps becomes low, and in this situation additional independently obtained information about the trap becomes extremely important.

The combination of diverse stresses and strains, as well as the effect of vertical and lateral changes in the physical and mechanical properties of rocks and their fluid saturation, create a rather complex picture of the natural open fracturing distribution in the geological environment. However on the basis of the obtained open fracturing distribution comparable to tectonophysical models, as well as information about the geological environment structure (deformation), we can estimate the main geodynamic situation in the study area, identify the main stress vectors and determine their directions.

Another important pattern of fracturing distribution is that the azimuthal directions of the linear zones correspond to the main directions of the main horizontal stress vectors. This pattern is also observed for vertical

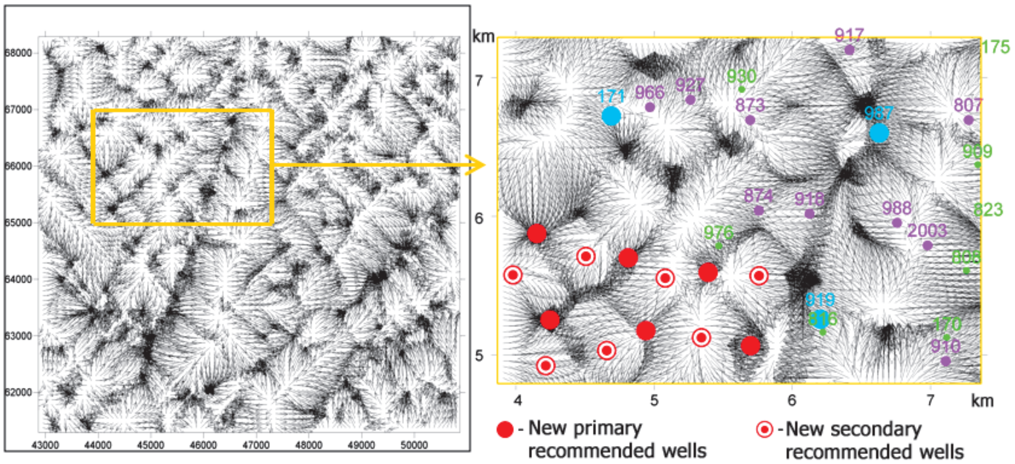

Fig. 5. An example of a reservoir mini-block structure created by diagonal and radial fracturing systems, and its enlarged fragment with recommended well locations (on the right) according to the fracturing field vector-gradient obtained by MSE waves and SLEC technology. Reservoir depth of about 4 km, Rostashinskoye field, Orenburg region

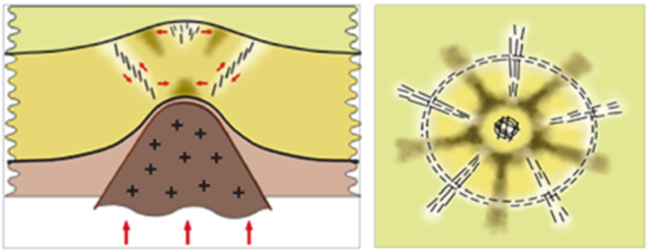

Fig. 6. Tectonophysical model of fracturing and compaction zones distribution on an anticline structure in vertical section (left) and horizontal section (right)

vectors. And given that the main vector of compression in the geological environment corresponds to lithostatic pressure, the vast majority of fractures in the geological environment are subvertical. In addition, taking into account that the lithostatic pressure increases with depth, then the intensity of open fracturing increases accordingly with depth. Moreover, positive and negative anomalies corresponding to intervals of more brittle (carbonates) and more ductile (salt, clay) rocks can be identified in the sedimentary layer against the overall growth of fracturing with depth.

The aforementioned dilation effect (compaction and decompaction zones paragenesis) is also an important regularity in the distribution of fracturing in the geomedia, which should be taken into account when interpreting the results of processed seismic materials obtained during multi-stage hydraulic fracture monitoring (MHF).

According to the results of numerous studies, it was noted that in the geological environment the distribution of fractures in their size and number (with given size) corresponds to an inverse linear relationship on a logarithmic scale, i.e. Guttenberg-Richter law (Richter, 1963). This indicates on the absence in the geological environment of single fractures (ruptures) having large dimensions of hundreds of meters without smaller fractures accompanying them. There are fracturing zones in geoenvironment, in which there are both a multitude of small and large fractures with maximum sizes, which were formed at the coalescence and connection of small, medium and large fractures. Therefore, as the main model of MSE seismic hydraulic fracture monitoring interpretation should be considered not a single symmetrically diverging (from the wellbore) fracture, as is customary for fracture modeling in an isotropic medium, but a fracture zone consisting of open fractures of various sizes, including main mega-fractures. This model allows estimation of size, configuration, azimuth, etc. of both the zone itself, and major fractures in it.

Fractures change over time

The time factor influences the process of fracturing and transformation of fractured zones in the geological environment. These changes can be associated with both geological and current time intervals.

In geological time, open fractures are usually became resistive in case of aqueous solutions flow through the cavities of the fractures, which generates post-sedimentation processes, secondary minerals deposition, etc. In this situation, the cavities are filled with resistive material closing the fractures. As a rule, a set of closed fractures form the zone of compaction in the geological environment including reservoir. This zone becomes a screen for the flow of fluid, although it was previously the main fluid flow line. At the same time, in the subsequent geological time in this zone there is no open fracturing with the same strike as the closed one. In that case it is possible the formation of open fractures with orthogonal direction of the strike. It is also interesting to note the fact that at present extended zones of geological environment disruption (faults, fractures, etc.) formed during the past geological time are usually represented in their middle part by closed fracturing, and at the ends are open, which indicates possible development of the fault.

Open fracturing undergoes constant changes in contrast to closed fracturing. This is due to the unstable state of open fractures, their periodic opening and collapsing, constant accumulation and emission of elastic energy. Open fractures (or open fracturing zones) are constantly changing their shape, structure and location. Dynamics of these changes over time is determined by the gradient of space-time (4D) change in the stress state of the geological environment. A good example presented in Fig. 6, is the increase in the activity of the fracturing process (according to MSE data) in the time interval of the maximum Earth's gravity gradient caused by solid-state Lunar-solar tide. In the period of the high tide, when the moon is at its zenith, the medium is compacted due to partial collapse of open fractures, and at low tide (the moon is in a nadir); the geo-medium is softened due to the increase in open fracturing. This effect is illustrated in Fig. 7, which shows the graphs of the change in time of the MSE intensity (top) and the Earth's gravity gradient (bottom) over the study area. There is a good synchronicity of changes in these parameters, which indicates the real existence of compaction and decompaction phases of the geological environment during solid-state Lunar-solar tide effects. It should be noted that the full period of the lunar-solar compaction-decompression of the geological environment is the lunar day and is a kind of "Earth's breath" (Kuznetsov et al., 2006b, Kuznetsov, Lyasch et al., 2016).

According to our experience in seismic hydraulic fracture monitoring, the phenomenon of lunar-solar geomedia compaction-decompaction has an impact on the process of technogenic fracturing. An open fracturing zone with the maximum possible area dimensions is

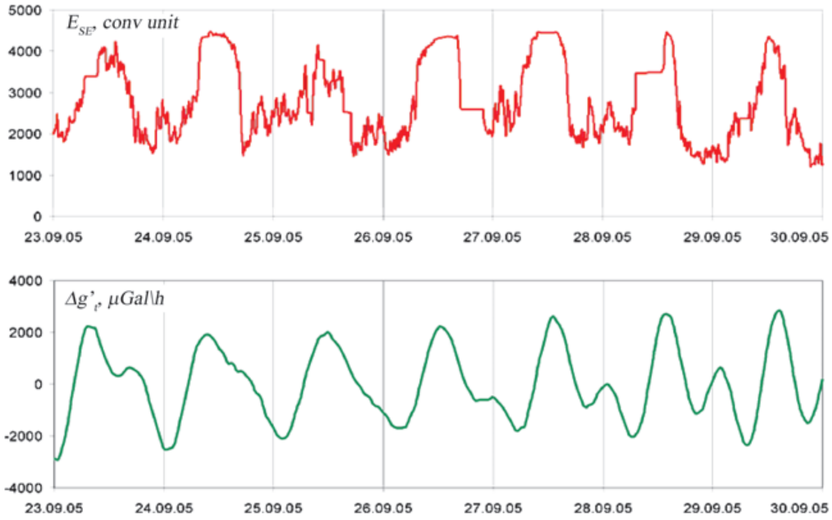

Fig. 7. Comparison of the averaged (moving average) MSE waves energy (top) and the temporal Earth's gravity gradient within the oil field (bottom)

formed in the time decompaction phase, while the area dimensions are minimal in case of compaction phase. In the latter case, some problem situations arose with the injection of proppant into the reservoir during the geomedia compaction, which should also be taken into account when choosing the timing of hydraulic fracturing.

The lunisolar phases of geomedia compaction and decompaction act as a peculiar geodynamic pump mechanism, the subvertical fracturing zones, which permeate the entire sedimentary cover and often evolving from the basement. Taking into account that the size of these zones can be on average 1 km in diameter and 5 km in height, considering fracture porosity of 0.1% and daily changes in the intensity of the fracturing for the geological environment (according to the results of our research) of 15%, then the total volume of intake and squeezing fluid will be about 0.5 ml m^3 per day. When the pump is operating, this volume of fluid moves mainly from bottom to top along the zone and entering the reservoirs. If we consider that the pump is quite "leaky" (fractured), then not all of the calculated fluid volume is pumped into the reservoirs. But still, 0.1% of this volume is enough to carry out the effect of a mini-fracturing operation every day, i.e. generate flushed lines for fluid (water and oil) movement. Moreover, taking into account the differences in density, philicity and phobicity of the fluid and rocks, the flushed highways (the main channels of water and oil movement) will be different, and in case of its crossing, there will be observed a blockage of one of the fluids (most likely oil) movement.

As an example, Fig. 8 shows the diagrams of the main flows of water and oil identified in the field of MSE gradients average energy and dispersion respectively compared with the oil production forecast for the entire oilfield area at the current monitoring period. The diagram clearly shows the blocking of oil flow coming from the geodynamic pump by the flow of water in the eastern part of the field. Due to the blocking of the oil flow, there is a low oil saturation of the northeastern zone and a low oil flow rates of the producing wells located here. In order to unblock the oil flow, it is necessary either to temporarily stop injection wells, or to set injection to cyclic flooding mode. The radial zone in the northern part of the area should be considered as an example of successful matching of fluid flows. The production wells located here have a maximum production rate.

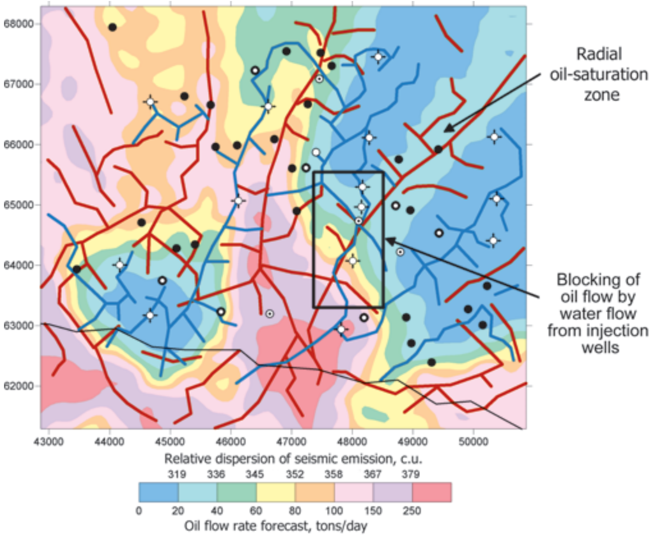

Fig. 8. Diagrams of the main flows of water and oil identified in the field of MSE gradients average energy and dispersion respectively compared with the oil flow rate forecast for the entire oilfield area at the current monitoring period. Rostashinskoe oilfield, Orenburg region

Fig. 9 shows the correlation between the values of the current flow rate and the variance of the MSE process on the basis of which an oil production rate was predicted for the entire field area (Fig. 8) as well as identified the primary production wells, in which well

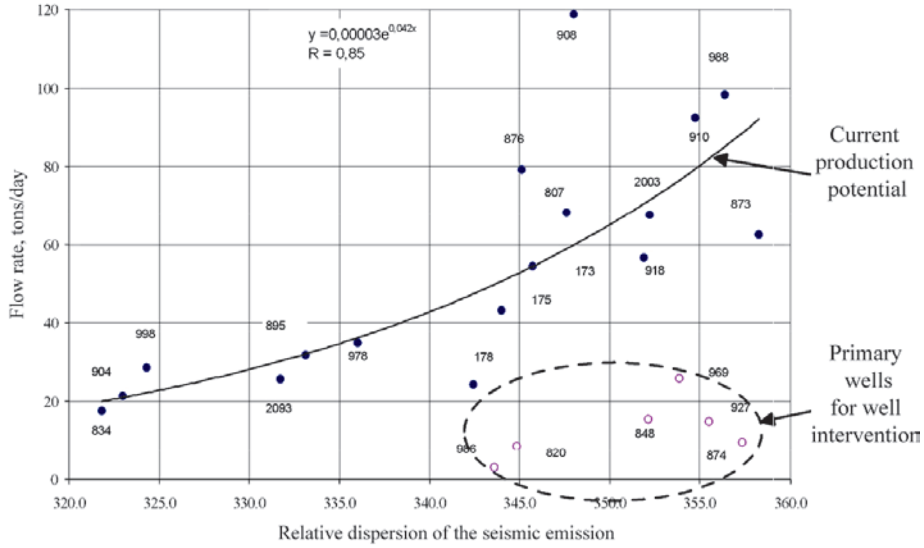

Fig. 9. Correlation between the values of the current flow rate and the dispersion of the MSE process

stimulation operations would allow a multiple increase in production rates.

Identification of scattered and MSE waves by 3D seismic data processing

Further improvement of the SLBO and SLEC technologies allowed the processing of initial CDP-3D seismic materials based on the algorithms of the lateral and normal location surveys. The first direction of processing was previously used to identify scattered waves and construct a fracturing cube based on CPD-3D initial data. The results of the second direction are presented for the first time after numerous experimental studies on different exploration areas. Fig. 10 shows CDP-3D seismic survey standard acquisition system at one of the areas in Texas, USA. Open fracturing cubes for diffuse waves and oil content for MSE waves were obtained according to the results of the materials reprocessing. Fig. 11 shows the slices of the open fracturing intensity and oil content along the Sligo horizon. Fig. 12 shows the vertical graphs of fracturing and oil saturation along the Cooke-3 wellbore. The graph shows (down to the bottomhole depth of 14 thousand feet) the oil-containing intervals of the section, which were identified during the well drilling, indicates the reliability of the results obtained. According to the results of oil content distribution in the Sligo formation, there is an oil-saturated part of reservoir limited in the north by a sublatitudinal normal fault, which act as an impermeable screen. This normal fault is not indicated on the structural map; however, it can be clearly seen on seismic time slices. In addition, within the oil-saturated area (Fig. 11, below), there is a good correspondence between the minimum oil saturation and the local synclinal areas bounded by the 13150-ft hypogype located in the central-eastern and north-central parts of the area. It should be noted that this interrelation (of structural factor and oil-saturation) was identified from independent information, the reflected and emission waves.

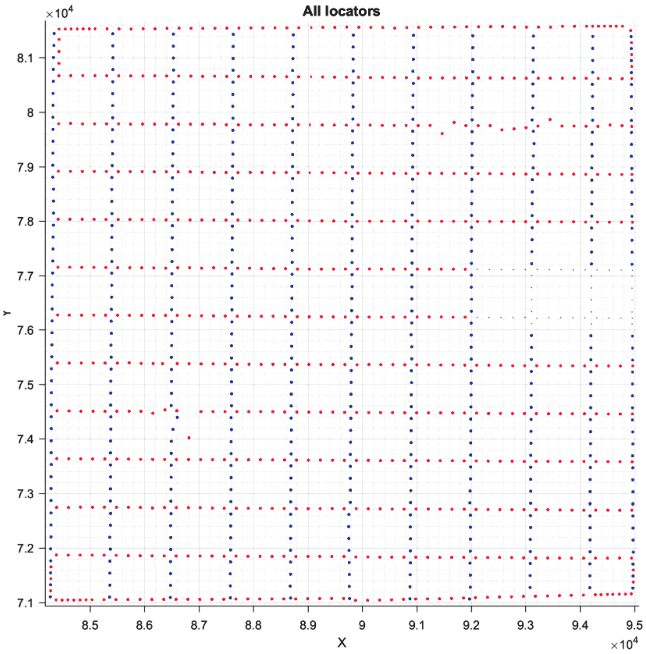

Fig. 10. CDP-3D seismic survey standard acquisition system (receiver points are shown in blue, shotpoints are shown in red)

Conclusion

Since the 70s of the last century, scientists and specialists of the “Scientific School of Oil and Gas Seismic Acoustics of Prof. Kuznetsov O.L.” have been carried out theoretical and experimental seismoacoustic studies of fractures and fluid saturation distribution in the geological environment. Since that time were created some special methods and technologies, which, as they were applied, were constantly improved to increase the efficiency of their use and the reliability of the geological environment characteristics studying results. It was found that the most reliable results of fracturing identification by seismic studies can be obtained by

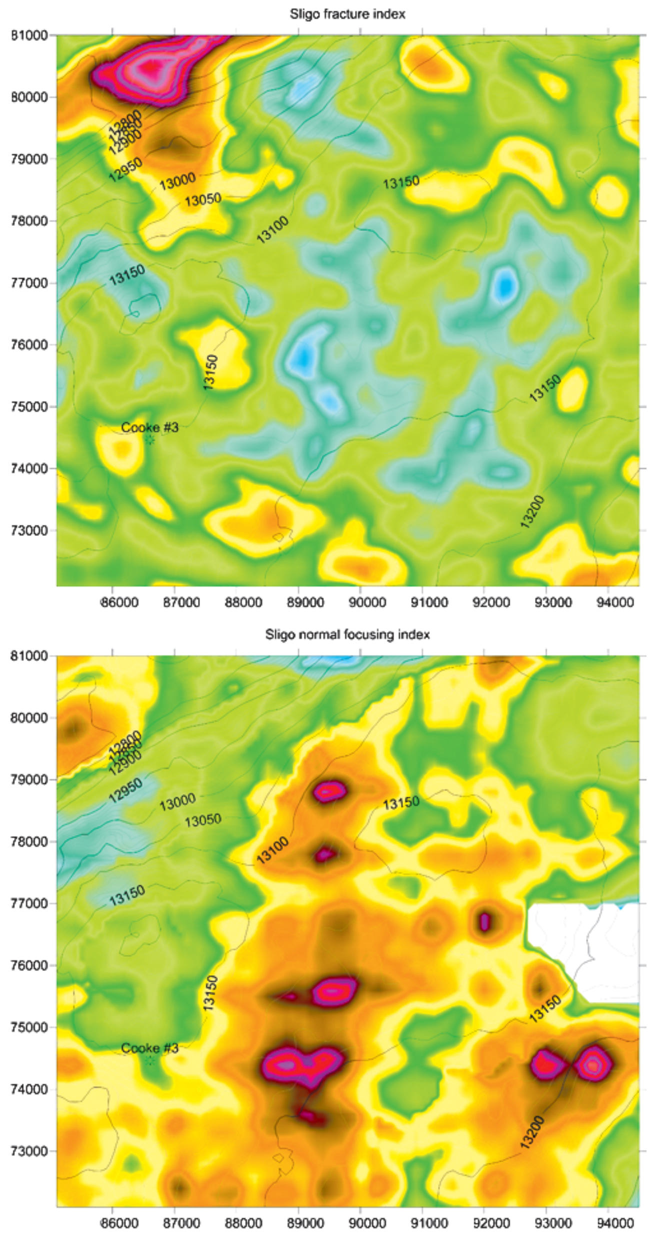

Fig. 11. Open fracture intensity (top) and oil-bearing capacity (bottom) slices along the Sligo structural horizon

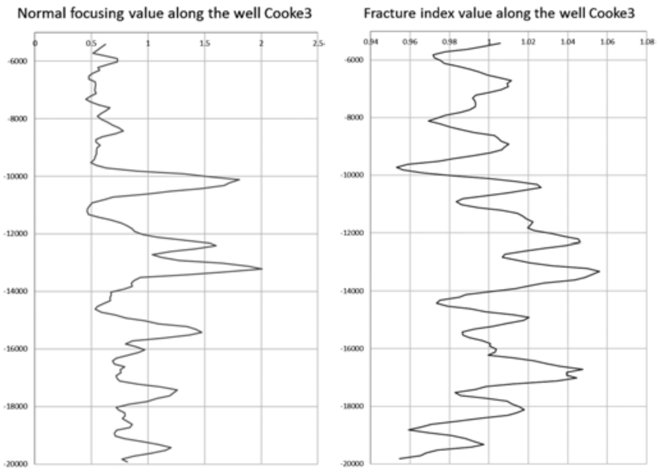

Fig. 12. Vertical graphs showing fractures (left) and oil saturation (right) along the Cooke-3 wellbore

diffuse reflection waves, while the type of fluid saturation can be identified by microseismic emission waves (Kuznetsov et al., 2006a; Chirkin et al., 2014).

The creation of technologies for seismoacoustic 3D and 4D fracturing distribution studies made it possible to identify a number of regularities and peculiarities associated with the presence in the geological environment of:

- Stress-strain state (tectonophysical models);
- Sub-vertical zones of open fracturing (“geodynamic pumps”);
- Mini block (“platy”) structures of the sedimentary sequence;
- Lunisolar phases of compaction and decompaction (“breathing”) of the Earth’s crust;
- Compaction and decompaction zones paragenesis (dilation effect), etc.

All these features of fracturing distribution in the geomedia are taken into account when interpreting the results of fracturing studies in order to solve important applied problems of choosing the well location aimed to obtain the maximum possible inflow of hydrocarbons, predicting hazardous drilling intervals and control of fracturing changes under technogenic impact on the formation, etc.

It was also identified the effect of fracturing on acoustic and microseismic elastic energy emission and patterns of change in the emission process amplitude-time parameters depending on the type of rocks fluid saturation (gas, water, oil) as well as physical impact on them of natural and/or technogenic nature. Based on the revealed regularity, the SLEC technology was created, the ANCHAR technology was improved and the regularities of the “direct prospecting” effects in other seismic technologies were established: “bright spot”, approach of Vedernikov G.V. et al. Currently, based on the SLEC technology, it is possible to implement both special processing of initial 3D data to obtain information on the oil-saturation of the geological environment, and continuous real-time monitoring of changes in heterogeneity and unevenness of fluid-saturation during oilfield development. Such a possibility of the SLEC technology allows solving a wide range of important applied problems in the prospecting, exploration and development of oil and gas fields, while the integration of SLEC with CDP and SLBO technologies significantly increases the reliability of solving these problems.

This paper presents examples of solving only some (of a large variety) of applied problems, many of which were not previously determined for seismic exploration due to its great limitations, since in traditional seismic technology, CDP-3D, uses only reflected waves for solving geological problems, on the basis of which it is possible to obtain reliable information only about the structure of the geological environment. Therefore, the complex use of seismic waves of a different class (reflected, scattered and emission) observing, identifying and positioning on the basis of complex technological solutions, makes it possible to efficiently optimize oil and gas fields development.

Created and successfully using (in Russia and abroad) seismoacoustic SLBO, SLEC, ANCHAR and GDP technologies awarded the Russian Government Prize in the field of science and technology in 2008, which indicates recognition (at the governmental level) of their effectiveness in oilfield exploration and development and also the expediency of their widespread introduction into the practice of geological exploration and oil and gas production.

References

Akselrod S.M. (2013). Real-Time Geophysic Control of Hydrofracturing: Possibilities, Implementation and Limitations (Based on Analysis of Foreign Sources). *Karotazhnik*, 8, pp. 84-116. (In Russ.)

Arutyunov S.L., Kuznetsov O.L., Karnaukhov S.M., Ermakov B.D., Sirotinskii Yu.V. (1997). ANCHAR – new principles of exploration geophysics. *Mezhdunarodnaya Geofizicheskaya Konferentsiya i Vystavka EAGO* [EAGO International Geophysical Conference and Exhibition], Moscow. (In Russ.)

Chirkin I.A., Rizanov E.G., Koligaev S.O. (2014). Monitoring of microseismic emission is a new direction in seismic prospecting. *Pribory i sistemy razvedochnoi geofiziki* [Instruments and systems of exploration geophysics], 3, pp. 6-15. (In Russ.)

Dorofeeva T.V. (1986). Tectonic fracturing of rocks and conditions for formation of fractured oil and gas reservoirs. Moscow: Nedra, 223 p. (In Russ.)

Gzovskii M.V. (1975). Fundamentals of tectonophysics. Moscow: Nauka, 536 p. (In Russ.)

Kuznetsov O.L., Lyasch Yu.F., Chirkin I.A., Rizanov E.G., LeRoy S.D. and Koligaev S.O. (2016). Long-term monitoring of microseismic emissions: Earth tides, fracture distribution, and fluid content. *Interpretation,* 4(2), pp. T191-T204. http://dx.doi.org/10.1190/INT-2015-0047.1

Kuznetsov O., Chirkin I., Firsov V. (2006a). Seismic monitoring as a tool for increasing the efficiency of oil field development. *Tekhnologii TEK*, 6, pp. 12-19. (In Russ.)

Kuznetsov O.L., Chirkin I.A., Chakhmakhchev V.G., Rogotskii G.V. et al. (1981). The phenomenon of the paragenesis of subvertical zone-ring-shaped geophysical, geochemical and biochemical fields in the sedimentary cover of the Earth's crust. *Ezh. BSE*. (In Russ.)

Kuznetsov O.L., Chirkin I.A., Kur'yanov Yu.A. et al. (2004). Experimental research. Moscow: Gosudarstvennyi nauchnyi tsentr Rossiiskoi Federatsii – VNIIgeosistem, 362 p., Seismoakustika poristykh i treshchinovatykh geologicheskikh sred [Seismoacoustics of porous and fractured geological media], vol. 2. (In Russ.)

Kuznetsov O.L., Chirkin I.A., Kur'yanov Yu.A. i dr. (2007b). New technologies and solution of applied problems. Moscow: OOO "Tsentr informatsionnykh tekhnologii v prirodopol'zovanii", 434 p., Seismoakustika poristykh i treshchinovatykh geologicheskikh sred [Seismoacoustics of porous and fractured geological media], vol. 3. (In Russ.)

Kuznetsov O.L., Chirkin I.A., Zhukov A.S., Volkov A.V. (2006b). The influence of lunar-solar tides on the change of oil and gas erservoirs open fracturing and the applied significance of this effect. *Geoinformatika = Geoinformatics*, 10. (In Russ.)

Kuznetsov O.L., Dyblenko V.P., Chirkin I.A. i dr. (2007a). Features of mechanical stresses energy accumulation and abnormal seismoacoustic radiation in oil-bearing rocks. *Geofizika = Geophysics*, 6, pp. 8-15. (In Russ.)

Kuznetsov O.L., Simkin E.M., Chilingar Dzh (2001). Physical basis of vibration and acoustic effects on oil and gas reservoirs. Moscow: Mir, 261 p. (In Russ.)

Rikhter Ch.F. (1963). Elementary seismology. Moscow: Izdatel'stvo inostrannoi literatury, 670 p. (In Russ.)

Vedernikov G.V., Maksimov L.A., Chernyshova T.I. (2011). Forecast of hydrocarbon deposits by microseismic characteristics. *XI ezhegodnaya mezhdunarodnaya konferentsiya "Gal'perinskie chteniya – 2011"* [XI annual international conference "Halperin Readings – 2011"]. Moscow: TsGE. (In Russ.)

Zhukov A.P., Shneerson M.B. (2000). Adaptive and nonlinear methods of vibration seismic exploration. Moscow: OOO "Nedra-Biznestsentr", 100 p. (In Russ.)

Zhukov A.P., Tishchenko I.V., Kalimulin R.M., Gorbunov V.S., Tishchenko A.I. (2011). Adaptive vibroseism exploration in conditions of heterogeneous structure of the upper part of the geological section. *Tekhnologii seismorazvedki* [Seismic exploration technologies], 2, pp. 5-13. (In Russ.)

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