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Use of induced acoustic emission of reservoirs for the detection and recovery of hydrocarbons

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Abstract. The results of a study of seismoacoustic emission appearing in a saturated porous geological environment with forced acoustic impact on cores and in wells are presented. It is shown that the wave action effectively influences the increase in permeability relative to the initial value and the acoustic emission of a saturated porous medium caused by the wave action serves as a reliable source of information on its reservoir roperties.

The hydrostatic pressure gradient contributes to the acoustic emission mechanism, which creates fluid filtration. In this case, the greater the core permeability, the wider the emission frequency band, the smaller the permeability, the narrower the band of the spectrum, which approaches the form of a discrete set of frequencies. Similar data were obtained in oil reservoirs, where a continuous spectrum is characteristic of porous sandstones of terrigenous reservoirs, and single narrow-band spectra, for fractured carbonate reservoirs.

The principle of excitation of high-intensity waves of elastic energy and registration of waves of emission origin in the reservoir provides reliable information on reservoir productivity in both perforated well and non-perforated well, and can give recommendations on the selection of the perforation interval and also stimulate the inflow of oil from the reservoir.

Keywords: seismoacoustic emission, acoustic impact, saturated porous medium, spectrum of induced acoustic emission, reservoir permeability.

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Core Studies

Elastic energy emission in a productive reservoir bed which shows mixed saturation and a wide range of reservoir properties, has its peculiarities as compared to seismic-acoustic emission of geologic environment caused by its stressed state in case of no saturation. First of all this is associated with presence and properties of internal seismo-acoustic emission sources in these media. A number of theoretical and experimental works have been dedicated to investigations of emission mechanisms in heterogeneous system with different reservoir saturations (Chebotareva, Volodin, 2012; Pikovskii, 2003; Volodin, 2003; Rudenko, 2006; Tertsagi, 1961; Nikolaevskii, Stepanova, 2005; Vilchinskaya, Nikolaevskii, 1984; Kurlenya et al., 1993; Dryagin, 2013).

Seismo-acoustic tomography of an oil pool based on its high emission potential and temporary stability of elastic energy radiation processes provides a reliable source of information for oil and gas prospecting. Special role is played by studies of the environment's response to external mechanical impact and indirect impact occurring in the medium itself under the influence of the so-called seismo-acoustic emission (Dryagin, 2013; Khismatullin, 2007). This very mechanism is the most effective tool for a local impact on saturated medium which may change effective permeability of oil and in this way improve its reservoir properties. In such a case, radiation from induced elastic energy field covers the range from first Hertz to dozens kilo Hertz and depends on the structure and composition of saturated porous medium.

Low-frequency emission signals are formed in dry sands as well (Vilchinskaya, Nikolaevskii, 1984) while the vibrations train spreads from radiation source to the receiver. As the wavefront area expands, the duration and number of low-frequency vibrations within acoustic emission range grow as well. The origin of low-frequency vibrations is associated with a significant relative displacement of particles under the conditions of their contraction, i.e. compaction of soft sands, whereas in case of granite contraction, it is associated with start of fracture development and the sample falling into pieces (Voronina, Epifanov, 1980). In this case stages of granite crushing are accompanied by acoustic emission radiation, starting from 1-12 kHz range, appearance of fractures in 100-800 Hz, and at the end of breakdown, the signal's spectrum concentrated within the 2-50 Hz range with its maximum at 12.5 Hz.

Studies by Nikolaevsky (Nikolaevskii, 1992; Nikolaevskii, 2005) quote models of forming dominant frequencies in formations saturated with water and oil associated with filtering and changes in phase permeabilities under the influence of vibrations of natural or artificial origin. Analyzing what caused a positive effect of a weak seismic impact on increase in the final oil recovery rate, the Author accentuates mechanisms of forming high-frequency elastic vibrations in the formation due to frictions at the contacts between fractures and grains.

Low-frequency vibrations in oil- and water-saturated formation have been observed by many Authors (Belyakov et al., 2004; Alekseev et al., 2004; Kurlenya, Serdyukov, 1999; Barabanov et al., 1987; Poznyakov, 2005; Dangel, 2003; Engelbrecht, 1988), what is more, the frequency range almost coincided and was within the 1.5-50 Hz range in the form of discrete frequencies, for example 18, 20, 24 Hz, etc.; it all depended on properties of the object in the experimental zone. The main peculiarity in this case was that the same frequencies were observed for both oil-saturated formation and water-saturated formation. Of course, everything depended on the water/oil relation in the formation and its filtering properties.

Application of wave action sources with various narrow impacting parameters and attempts to justify the mechanism only by these impacting parameters do not allow to evaluate how the wavefield interacts with porous medium in a single process which covers a wide range of frequencies and interaction between frequencies.

Studies (Venkitaraman, 1995; Roberts, 2000; Roberts, 2005) quote results of a successful application of wavefield energy in ultrasonic range to remove various hard particles from saturated porous medium.

Thus, after ultrasonic treatment of core with 20-250 W/m^2 wavefield at 20-80 kHz frequencies (Venkitariman, 1995), permeability of saturated sandstone and limestone grows by 3-7 times, at the same time efficiency of deep cleaning from hard clay particles, mud and filtrate is no more than 2.5 inch.

Resulting from experiments with core samples (Roberts, 2000) acoustic energy with 300-4500 W/m^2 capacity impacting at 20 kHz frequency allows to efficiently remove paraffin/asphalten deposits in a porous sandstone and to restore its effective permeability up to 12-15 cm depth.

The study (Mitrofanov et al., 1998) reviews the results of laboratory investigations on how acoustic impact (AI) affects phase permeabilities on oil, on water and displacement of oil by water in Terrigenous reservoirs. The experiment was held considering formation conditions and showed that the most sensitive to acoustic impact is the oil's bound phase, which keeps changed properties for longer and predetermines viscosity of colloidal hydrocarbons system in general. The study points out that acoustic impact lasting 10-15 minutes leads to increase in permeability on oil by 17-40%. Effective viscosity of oil in this case diminishes by 8-9%, whereas the share of immovable phase reduces twofolds as compared to the initial one. The Authors link this mechanism to re-distribution of hydrocarbon molecules through weakening of hydrogen connections. Parameters of the acoustic effect field are close to parameters in previous studies: specific capacity of 20000 W/m^2 at 19 kHz frequency.

Wave impact in low frequency domain of 1-500 Hz also shows multiple examples of increasing mobility of multi-phase fluids in productive reservoirs. Example of analysis of low-frequency dynamic effect in the study (Roberts, 2005) shows validity of interest in studies of fluid filtering mechanisms in porous medium using laboratory tests and generation of relevant theoretic models. This work informs on properties of the fluid flow with an abruptly different viscosity in core's porous space under the influence of external low frequency wavefield. At the same time, there is a principal difference in behavior of the fluid flow when the wavefield is imposed, in particular reduction in pressure differential in cores for low-viscosity fluids (decane + water solution) and increased pressure for high-viscosity fluids (oil + water solution). The reason for such diverse behavior of fluids is in different mechanisms of oil and decane wetting with the surface of core's water-wet porous space within a dynamic wave effect field. This study demonstrates for the first time that low-frequency impact in core is as effective in restoring permeability of porous space as is the high-frequency impact. Since low-frequency impact penetrates deeper into the geologic environment, it is more preferable technologically. At the same time, the study highlights a contradiction: on the one hand, low-frequency effect mobilizes oil on a priori mobile water and thus increases the share of oil in the fluid, on the other hand, oil, being more viscous, closes the pores as soon as it begins to move.

The study has established the link between mechanical stress and strain caused by it under the influence of an external dynamic wave impact with changing porous pressure. This pressure does not exceed 2.4 kPa when reaching threshold stress value of dynamic wave effect with 600 kPa amplitude, when changes in fluid flow were noticed. It is also pointed out that effect of changing porous pressure is more important for increasing the porous flow rather than mechanical stress caused by external impacts.

It is necessary to mention that changes in porous pressure may occur as a result of phase transitions of hydrocarbons and their subsequent degassing under the influence of external acoustic field (Stepanova et al., 2003; Stepanova et al., 2005) at various frequencies. At the same time pressure may fluctuate from 50 kPa to 1000 kPa depending on gas factor and parameters of the wave effect.

Stress-strain behavior of the porous medium causes acoustic emission, whereas saturation nature influences accumulation of elastic energy and its release in the form of acoustic emission (Khismatullin, 2007). In order to initiate acoustic emission signals, it is enough to have a minor external disturbance whose amplitude is measurable to natural background of acoustic emission in stress-strained state. This study indicates that cores saturated with oil have maximum accumulated energy and therefore a high energy release speed which has a pulsed nature. Water-saturated cores showed stable decline in energy release, and the dispersion of acoustic emission signal in water was at least 2-3 times less that in oil. This trend was also discovered in an oil pool during investigations on the surface and downhole (Dryagin, 2013; Grafov et al., 1998; Dryagin et al., 2005; Dryagin, 2001).

So, considering a number of studies dedicated to mechanisms of wave effects on saturated porous medium, porous pressure may change within 2-3 orders of magnitude. At the same time, there is an indication on pore pressure threshold which leads to fluid movements, as well as on its non-established mechanism.

An obvious connection between emission activity of saturated porous medium and hydraulic pressure in pores which occurs during wave effect, calls for investigation of its mechanisms and quantitative relations between released elastic energy and parameters of the medium.

Processes of acoustic emission activity in cores in stress-strained state, fluid filtering and wave effect conditions were experimentally tested on a UIK-AE unit.

The tests were carried out with core samples from porous, weakly clayey sandstone from formation BS10(2-3) at Tevlinsky-Russkinsky field in West Siberia (Chebotareva et al., 2016). Dimensions of composite core: diameter – 30 mm, length – 90 mm. The first core sample (sample No. 1) has the following parameters: porosity – $К_{por}$= (20.5-21.4)%, permeability – $К_{per}$= (89.31-89.99)*10^{-3} mm^2, the second sample No.2 – $К_{por}$ = (16.6-16.8)%, $К_{per}$ = (8.02-10.47)*10^{-3} mm^2.

Application of stress on core samples and location of measuring sensors are shown on the chart in Figure 1.

Wave emission processes in cores were studied in the conditions close to formation pressures as much as possible. Compression of the sample to pressures resembling formation pressure included two parts: first one – axial compression (P1) in order to create a stressed state corresponding to rock pressure, second one – hydrostatic contraction of core in order to create formation pressure (P2) of the fluid. Core was previously saturated with residual water in accordance with industry core study standards. During pressure build-up, all fluid pressure parameters and acoustic emission signals were continuously recorded with appropriate sample rate.

Seismo-acoustic tomography of an oil deposit is based on a high emission potential and temporal instability of elastic energy release processes (Khismatullin, 2007; Nikolaevskii, 1992; Nikolaevskii, 2005). The acoustic emission forming in a saturated porous medium is contributed by pressure gradient which provides fluid filtering. In order to study contribution of this effect in forming of acoustic emission, two Terrigenous core samples from Tevlinsky-Russkinsy field with various permeabilities were tested. Tests were also conducted on the UIK-AE unit (Fig. 1), with core samples pre-loaded with axial pressure P1 within 10-21 mPa range and contraction pressure P2 within 33-35 mPa. Filtering was provided by fluid being fed to core entrance by a plunger pump P4, which resulted in core pressure differential ΔP = P4 – P3, established in accordance with its permeability (Fig. 2).

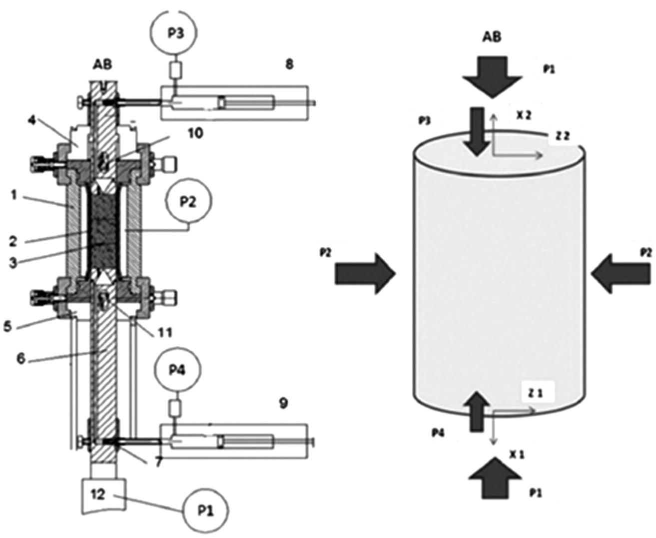


Fig. 1. Core fixing device, force application schematic and location of measuring sensors in UIK-AE unit. P1 – axial compression pressure, P2 – core contraction pressure, P4 – fluid pressure at core entrance, P3 – fluid pressure at core exit, X1 and Z1 – acceleration sensors for longitudinal and shear oscillations at core entrance, X2 and Z2 – sensors at core exit. Core entrance and exit is a conventional notation for feeding the saturating fluid. Main elements of the core holder: 1 – high pressure chamber, 2 – rubber collar, 3 – core, 4 and 5 – folding parts for core fixing and sealing – flanges with O-rings and fixing clamps, 6 – lower footing of a core sample for transfer of axial force and feeding the fluid, 7 – sealed entry choke for fluid input, 8 and 9 – conventional notation of plunger pumps for receiving (8) and feeding (9) the fluid into a core sample, 10 and 11 – measuring sensors of the acoustic emission

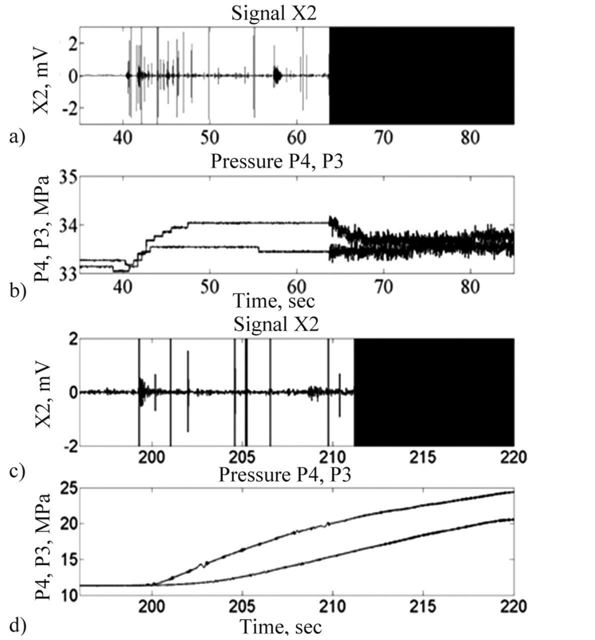


Fig. 2. Fluid movements in core samples, influence of acoustic impact on filtering process

For cores with larger permeabilities K_{per} = (89.31-89.99)*10^{-3} mm^2, pressure grew faster and reached threshold value within 4-5 seconds, whereas for the second sample with low permeability K_{per}= (8.02-10.47)*10^{-3} mm^2, growth of pressure did not complete within 20 seconds of observations, under similar conditions when fluid was delivered to core entrance with the pump (Fig. 2b, d). Throughout the entire time of fluid delivery, acoustic emission signals were recorded using sensor X2 at core exit (Fig. 2a, c). Blackened areas on these curves after the 63^{rd} second (Fig. 2a) and after the 211^{th} second on Fig. 2c correspond to switching-on of the acoustic emitter installed at core exit.

It turned out that during acoustic effect on core, hydrostatic pressure which changes in it along a constant component, also had vibrational nature which was recorded by pressure gages on core entrance and exit (Fig. 1). Pressure variations in this instance depended on core permeability. Trend of their constant components reflected changes in integral filtering properties of all the core which may be evaluated by computation of permeability relative to initial permeability, before acoustic effect according to Darcy's law. But at first it is necessary to examine the vibrational nature of emission and pressure and to compare their energies in order to elaborate a possible model of a physical process in pore space under the influence of external acoustic field.

Such impact field in these tests was represented by emission field of a magneto-striction radiator. The radiator is connected to a wave guide which in its turn is firmly fixed to a core sample. Inside the wave guide is a channel to inject fluid and sensor accelerometer located in the nearest proximity to the core sample.

Filtering in the core sample significantly changes under the influence of external wave impact which in the end leads to changes in absolute permeability of porous medium for any type of fluid which is in its pores. Filtering tests (Fig. 2) attempted to evaluate energy released into fluids in the porous space during acoustic impact, during impact on the core sample. Computation of the energy density of high-frequency pressure vibrations in core was conducted using the $\Delta P = P4 - P3$ difference. Along the amplitude P_m of this difference we established energy density, high-frequency component of fluid fluctuations depending on the frequency. Frequency in this instance was measured by Hilbert-Huang transform (Huang, 1998).

Interaction of waves in elastic field of finite amplitude with behavior of fluid flow in pore space on core samples was examined in such works as (Venkitaraman, 1995; Roberts, 2000; Roberts, 2005), as well as (Khismatullin, 2007; Mitrofanov et al., 1998). Laboratory tests (Roberts, 2005) showed that bound pore pressure fluctuations occurred during wave impact on core. Pore pressure impulse amounted to 1.2-4.8 kPa, which was enough to stimulate pore fluid flow. They specified main mechanisms of influencing the flow based on breakdown of clay particles and changes in wetting of pores by fluid under the influence of low-frequency wave vibrations from external source. Movements of clay particles relative to fluid of matrix may occur when fluid's local pore pressure is generated in pore space and becomes equal to specified value. Primary source of these pressure pulsations was axial stimulation of wave impact from external activator with field parameters with 600 kPa threshold, when changes in fluid flow were observed.

Tests on UIK-AE unit involved magneto-striction acoustic transducer with 19.3 radiating frequency connected to energy supply which provided radiated power not less than 8 W/cm^2 on the end part of the core sample surface. If acoustic impedance of the core sample is known, then it is possible to establish acoustic pressure reached by this radiator in the core sample, and to compare field parameters of actuators' radiation in these units (Roberts, 2005) and in UIK-AE (Table 1).

Pressure signals, in both cases, are received by sensors installed on the body of the core holder's camera. In the UIK-AE unit, these are pressure gages installed in

Source	Unit	Unit
	Peter M. Roberts	UIK-AE
Parameter	Pressure, kPa / Frequency, Hz	Pressure, kPa / Frequency, Hz
Wave impact	(300–1200)/(25–70)	(1800–2300)/19300
Pressure recording	(1,2–4,8)/(25-70)	(200–500)/(4–100)

Table 1

the hydraulic system's channel in the nearest proximity to core's entrance and exit, allowing to record constant and alternating component of pressure from 0 to 100 Hz (Fig. 2).

Variations of the constant pressure component P4 and P3 in sample No. 1 have a faster character than in sample No. 2 (Fig. 3a, c). In accordance with Darcy's law, knowing pressure differential along the core length, it is possible to establish permeability throughout the entire acoustic impact on core relative to initial one, prior to impact (Fig. 3b, d). Therefore, in case of more permeable core samples, permeability increases in the acoustic field within 20 seconds, reaches maximum which exceeds the start value by 2.5. and then reduces returning to its original value, because constant flow in this test was not maintained. For the second sample with low permeability pressure grew a lot slower (Fig. 3c), therefore its relative permeability changes slower and does not reach maximum value during the test. Moreover, permeability changes have a fluctuating nature which signifies discrete filtering of fluid in the core. It is necessary to point at differences in results of wave impact on the fluid flow in core. The study by (Roberts, 2005) shows that low-frequency impact may stimulate the flow, but pore pressure pulsed under the influence of external field on the same frequency. In tests on UIK-AE unit, wave action at a high frequency caused acoustic emission and pressure variations at a low frequency, therefore the medium itself transforms wave impact into the domain typical of its lowest dominant frequency which is its process of filtering synchronization. The same is mentioned by (Roberts, 2005), given that bound fluctuations of pore pressure occurred in the conditions of wave impact actuation in the 25-70 Hz frequency.

Figure 4 shows acoustic emission signal spectrum during fluid filtering before acoustic impact. Spectrum analysis was carried out by Short Time Fourier Transform, in a sliding window with given length. Transform parameters were selected in an optimum way in order to identify details of this process in time, which are typical of this kind of a reservoir. In this case the frequency range of spectrogram was from 50 to 20000 Hz. The spectrogram shows a clear discrete nature of frequency set within acoustic emission signal in core at the stage of pressure differential growth $\Delta P = P4 - P3$.

The Figure shows changes in total acoustic emission energy in core depending on its permeability. So, in low-permeability core samples (8 mD), the greatest contribution in the acoustic impact energy spectrum is made by high-frequency component, approximately 12kHz. At the same time change in energy during fluid filtering in comparison to a background value is only 2.3%. In high-permeability core samples (89 mD), acoustic emission energy is distributed in a wide range, starting from tens of Hz, which indicates presence of filtering in porous and fracture space. In addition, energy dynamics is equal to 101% under similar conditions. At the same time, absolute energy of acoustic emission have an opposite character. For instance, in a very permeable core sample energy is 7-10 times less than in a stiffer sample.

The method of acquisition of such spectrum consists in selection of a limited number of spectral lines which have maximum value in the signal's spectrum from a

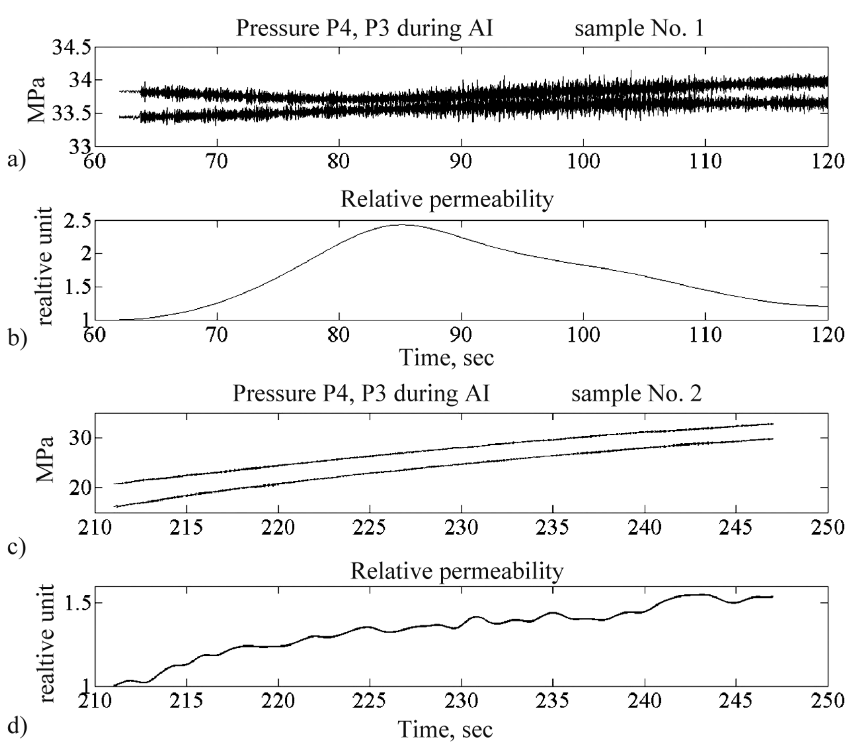


Fig. 3. Changes in relative permeability of core during acoustic impact

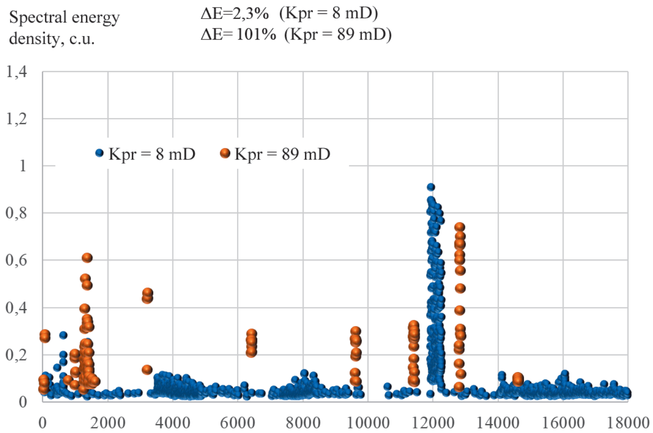


Fig. 4. Discrete range of acoustic emission during fluid filtering (Hz)

sliding window. This signal's spectrum has a discrete nature, and peak frequencies fall into non-linear distribution law over the entire survey range. Such law may for example be represented by non-linearity of the medium with dispersion. In this medium there is interaction of a limited number of waves associated with frequency resonance conditions and wave vectors, i.e. synchronizing conditions (Andronov et al., 1981). In accordance with non-linear system theory, two options are possible in the behavior of non-linear system during interaction of non-linearly connected oscillators, in particular: decay instability and merging of waves. In particular, it is known about interaction of vibrations, for example in a system of three non-linearly connected oscillators, which causes vibrations in the system with combination frequencies. In this case the condition of frequency resonance is followed and it is specified that oscillators may exchange energy when energy of an excited high-frequency oscillator is transferred to two low-frequency oscillators, or an opposite process – merging of low-frequency vibrations. For example, such interaction has a place in a system of three non-linearly connected oscillators described by the following equations:

$$\ddot{x}_i + w_i^2 x_i = \mu \alpha_i x_j x_k ; \quad i = 1, 2, 3; \quad j, k \neq i$$

In case of low μ – it is a weakly non-linear system.

Its behavior is close to a superposition of quasi-harmonic oscillations with slowly changing amplitudes. Due to a non-linear connection, fluctuations of two oscillators from frequencies w_1 and w_2 cause fluctuations with combination frequencies w_1 and w_2. The action of low non-linearity accumulates if the frequency resonance condition is met:

$$w_1 + w_2 = w_3.$$

During deformation of a sandstone, which represents a heterogeneous medium, typical of an oil reservoir, and during application of acoustic field, wave processes form in it. Acoustic emission occurring now is represented by both discrete, impulse component, as well as a continuous noise-like component (Sboev, 1988; Chebotareva et al., 2017; Chebotareva, 2016). Acoustic emission is associated with accelerated movement of dislocations, their exit to a free surface and further formation and development of fractures, as well as other friction processes of local contacts on micro-indented surfaces (Greshnikov, Drobot, 1976; Krylov, 1983; Robsman, 1996). These mechanisms of acoustic emission are suitable for explanation of radiation in kilo-Hertz frequency range, but they do not clarify generation in low-frequency part of the spectrum (tens and hundreds of Hz). In addition, it is necessary to understand mechanism of the connections occurring simultaneously in high-frequency and low-frequency part of the spectrum.

One of such mechanisms is generation of a low-frequency branch of seismic emission, on frequencies enveloping high-frequency vibrations of geo-medium's elements as a result of Lighthill's modulation instability. Such emission component develops within a rock mass in case of a synchronized action of non-linearity and dispersion (Volodin, Chebotareva, 2014). Difference between ranges of carrier wave and modulation wave is established by a scaling factor of the discrete medium, i.e. relation between fragments and their contact zone, and may reach 10^4 and over. High-frequency wave and modulation wave interact through instability mode – self-modulation. Such modes are extremely sensitive to any external impact, including acoustic impact according to this technology. The same discrete frequencies were observed when they analyzed induced acoustic emission in wells.

Investigations of fluid system types in sedimentary oil and gas-bearing basins (Abukova, 1997; Sboev, 1998), indicate that one of them – hydrodynamic type – is associated with a chain of processes: geodynamic compaction, increase in potential energy of elastic strain and appearance of micro-seismic noise. It is also mentioned that against external elastic impact there appear quasi-resonance micro-seismic vibrations with amplitudes exceeding amplitudes of instigating vibrations by 2-3 times. As a result, application to fluidal system of even the smallest wave effects, while maintaining the geologic structure, leads to a part of strain energy being transformed into high-frequency energy, which brings about fluid-dynamic non-linear events.

It was confirmed that elastic energy is transformed from one frequency range into another, which stand apart within the range by one-three units of magnitude, with participation of energy from unlimited source of elastic strain from geo-medium's local zone and informative-energy elastic impact from external wave source.

In such a way direct connection between pore space saturation and acoustic emission was established, and the greatest changes in emission occur in low-frequency area of the spectrum. These changes are likely to be caused by influence from fluid's synchronizing factor in mechanical vibrations of core pore space's structure under the influence of external static load.

The hydrostatic pressure gradient contributes to the acoustic emission mechanism, which creates fluid filtration. In this case, the greater the core permeability, the wider the emission frequency band, the smaller the permeability, the narrower the band of the spectrum, which approaches the form of a discrete set of frequencies. Similar data was obtained in oil reservoirs, where a continuous spectrum is characteristic of porous sandstones of Terrigenous reservoirs, and single narrow-band spectra, for fractured carbonate reservoirs.

Acoustic emission in porous and fracture-porous permeable media increases at fluid saturation and filtering, which is an important informative indication of reservoirs' productivity and filtering properties.

External wave action equally and effectively influences the growth of permeability in a wide range of parameters of the wavefield – from seismic (tens of Hz) to ultrasonic. Thus, wave impact at low and high frequencies leads to similar quantitative growth of relative permeability by tens and hundreds percent relative to initial value.

As the most possible options, mechanisms increasing permeability in the wavefield (for example, increase in wetting of the pores' surface and weakening of hydrogen contacts, which leads to growth of fluid mobility in pores) are a requisite condition of this effect. However variations inside pore pressure carry a more significant information on complex mechanisms of fluid movements in pores and its interaction with the surface, which reflect wave resonance processes of energy flows interaction at various-scale levels.

Finally, increase in permeability at any frequency of external impact, resolution of its changes at fixed impact parameters indicate medium's ability to synchronize filtering processes and to synchronize at multi-scale levels. Accumulation of experimental data and simulation of these processes' models represent a vital task for physics of the oil formation.

Well logging operations

Researching the ways of detailed discovery of residual hydrocarbon resources when developing fields by non-linear geophysical methods based on changes in properties of saturated porous medium under the influence of physical fields, have recently gained new and rather convincing data. The principle of excitation of high-intensity elastic wave energy in a productive formation and recording of emission waves lies at the basis the technology for management of oil and gas extraction at a field.

This principle has been implemented in the following cycle: acoustic impact – acoustic emission logging. Excited waves of elastic energy contribute to initiation of physical-chemical processes in a formation which lead to increase in phase permeability of oil and gas, whereas recorded elastic emission waves carry information on the nature of saturation and filtering capacity of these formations, which makes it possible to conduct controlled impact on the productive deposit.

Technical means allow to implement the entire technology within one running operation using a small 43 mm diameter tool. The software for control, recording, and analysis of oilfield geophysical data provides a possibility to make a decision on optimization of the technology during its application.

We can give many examples of how this technology at present stage of its development is successfully utilized at various fields in our country and abroad. However the main advantage of the technology is in a possibility to adapt it for real-time geophysical conditions of the object's operation. Results of such approach to acoustic impact method can be demonstrated with a case study of LukOIL company's fields in Perm district and in West Siberia. Previously published materials resulted from application of the acoustic impact method in combination with full-scale hydro-dynamic research which showed its high effectiveness (Merson et al., 1999; Mitrofanov et al., 1998).

The study by (Merson et al., 1999) analyzes options of ultrasound in oil extraction and elaborates on why this method is seldom used in oilfield practices. These reasons are mainly in absence of feasibility in selection of development targets and criteria in selection of acoustic field's modes taking into consideration petrophysical properties of reservoir beds and technical state of the "borehole-formation" system in general. These conclusions were made based on detailed hydrodynamic investigations which were planned and executed within the acoustic impact – hydrodynamic survey cycle (Mitrofanov et al., 1998). Unfortunately such studies were not implemented on industrial scale for economic reasons. It was a result of complexity and high labor inputs of performing the hydrodynamic research at a field, as well as due to poor technical state of production parameters control means in those years. At the same time, materials dedicated to studies of reservoir properties acquired in that study provided important formation parameters and showed their changes under the influence of acoustic impact, which became the basis for the technology of real-time process management.

Key formation parameters published by (Mitrofanov et al., 1998) and partially introduced by (Merson et al., 1999) are permeability and hydraulic conductivity of bottomhole and remote zone of the formation, well flow rate, duration of acoustic impact, etc. Fig. 5a, b show changes of permeability in bottomhole zone and remote zone of a formation during acoustic impact for three wells at different fields. Productive formations greatly differ in their filtering properties which is reflected in the results of the impact.

In the article (Mitrofanov et al., 1998) examines the results of acoustic impact tests at Terrigenous Lower Carboniferous productive deposits at three fields of Preduralsky depression: Pikhtovsky (1), Olkhovsky (2) and Unvinsky (3). Within the depression, Tulavian-Bobrikovian deposits differ significantly from similar objects in the platform part. They are characterized by various diagenetic processes and bituminosity, as well as low clay contents (less than 5%). All of that caused non-uniformity of rocks in wettability in combination with high oil saturation and permeability.

One well was treated at each field in order to enhance recovery. All wells were operational, pumping but significantly differed in initial parameters and running mode. Actual changes in the bottomhole zone and remote zone were seen from hydrodynamic studies conducted before and after acoustic impact. The final criterion of acoustic impact efficiency were the data from long-term oilfield research and economic analysis.

According to hydrodynamic survey results, all wells showed a significant improvement in the state of both bottomhole and remote zones in terms of the power capacity of working interlayers, permeability, hydraulic conductivity and production rates (Fig. 5, 6). For example, in well No. 174, four working interlayers showed up instead of three, and their total working thickness grew from 7.8 to 10.6 m. Filtering properties especially improved in the bottomhole zone. The well's productivity factor increased from 2.6 to 5.9 tons/day mPa (by 127 %), hydraulic conductivity – from 6 to 12.8 mkm^{2}cm/mPa·s·(by 111 %), permeability – from 11 to 20 mD (by 82 %). The difference between the bottomhole zone and remote zone of the formation is negated and the well plugging index reduces from 1.34 to 1.03.

A similar trend in changing formation parameters is observed in other two wells. In the well with lowest flow rate (well No. 266, Olkhovsky field) a relative improvement of bottomhole zone occurs to a larger extent. In particular, productivity index increased by 312%.

Peculiarities of changes in key filtering parameters of the formation under the influence of acoustic impact – permeability and hydro-conductivity, depend on the formation's initial permeability level. For example, in a formation with less than 5 mD permeability (well 266) growth of permeability is within 31-38% for bottomhole

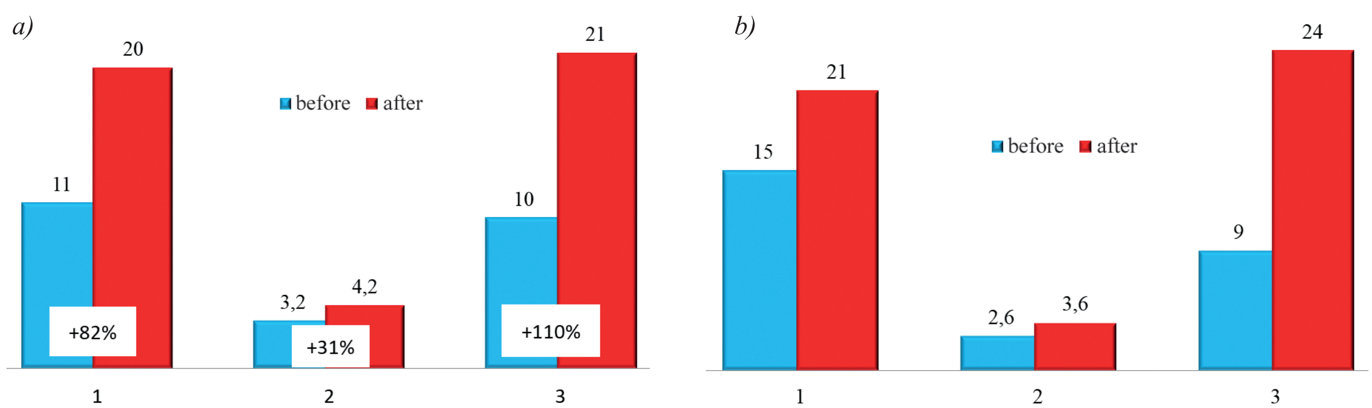


Fig. 5. The change in the permeability of the reservoir during the process of acoustic impact. a) Permeability of the bottomhole zone (mD); b) Permeability of the remote zone (mD). 1 – well No. 174 of the Pikhtovsky field, 2 – well No. 266 of the Olkhovsky field, 3 – well No. 255 of the Unvinsky field

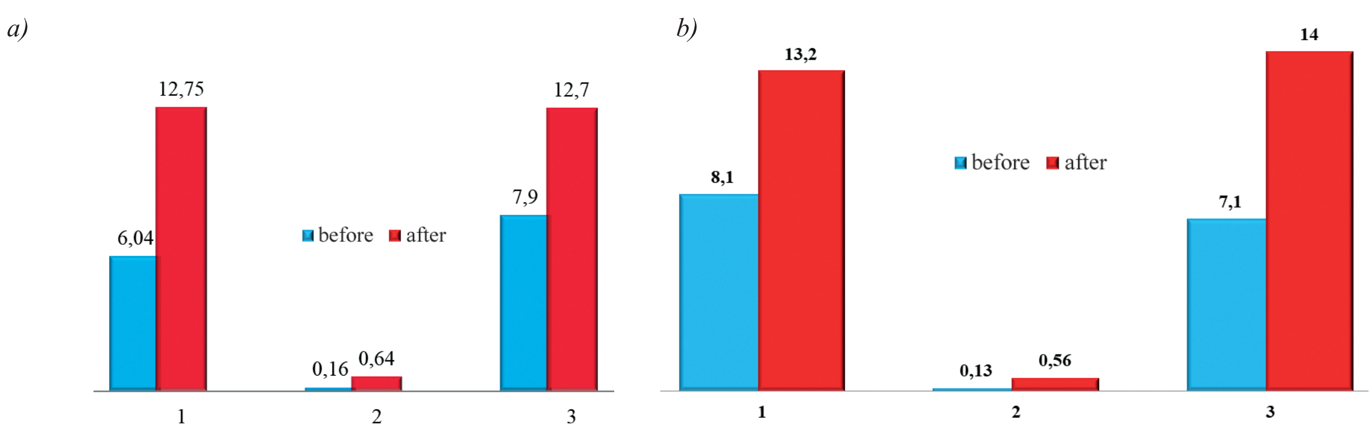


*Fig. 6. a) Hydro-conductivity of a formation's bottomhole zone (mcm^2*m/mPa*s), b) Hydro-conductivity of remote zone (mcm^2*m/mPa*s). Legend on Fig. 5*

area and remote area, whereas hydro-conductivity of such formation grows by 300-330%. This justifies a much stronger effect of acoustic impact on the growth of its filtering properties – formation's working thickness (200%) and productivity factor (312%) (Fig. 7).

But due to potentially low reservoir properties of the formation, flow rate growth (Fig. 8) and cumulative production at this well (Fig. 9) are obviously lower. The duration of the effect (13 months) is however comparable. This leads to a conclusion that acoustic impact method can be and needs to be applied in low-permeability reservoirs.

Well 174 may serve as an example of acoustic impact's final effect. This well passed the entire dynamic cycle of flow rates, including growth, stabilization and decline up to pre-treatment levels. The entire period of well's operation may be divided into five stages, which significantly differ in average daily flow rates. From 1983 to 1986, free flowing wells yielded maximum flow rates – 68.2 tons/day on average. Then, until 1994 an abrupt decline in flow rate occurred up to 4.6 tons/day followed by growth and stabilization at the level of 16.9 tons/day. Post-acoustic period of operation is characterized by a significant growth of flow rate, on average up to 47.6 tons per day, or re-establishment of initial level by 69.8%. Growth of flow rates before acoustic impact (1995) was caused by treatment of the bottomhole area with stabikator solvent or hexane fraction in combination with nitrilotrimethylphosphonic acid.

Throughout the entire period of acoustic effect (16 months), accumulated production reached 23.5 thousand tons, or 30.4% from cumulative production over 12.6 years of operation of the well before the acoustic effect. In accordance with predicted flow rates (7.9 tons per day) it could have reached only 3.9 thousand tons, which, due to acoustic effect, provides guaranteed extra oil in the volume of 19.6 thousand tons (25.3 %). Water cut level during acoustic effect remained unchanged – less than 1 %.

Performance values of acoustic method for enhanced oil recovery have an obvious advantage over results gained after stabikator solvent treatment, as well as hexane fraction in combination with nitrilotrimethylphosphonic acid considering maximum and average flow rates, maximum production rate and time for signs of a positive effect (Fig. 10, 11).

First of all, it is necessary to pay attention to longer duration of the effect as compared to other methods, which in the end caused a significant amount of extra oil extracted. Effect from stabikator is shown per one treatment, time for its development may be taken as equal to 167 days, in this case relative effect of acoustic impact will be 331 days longer (198%).

An essential point is that no workover operations were conducted at any wells after the acoustic impact. Therefore, at well 174 of Pikhtovsky field workover

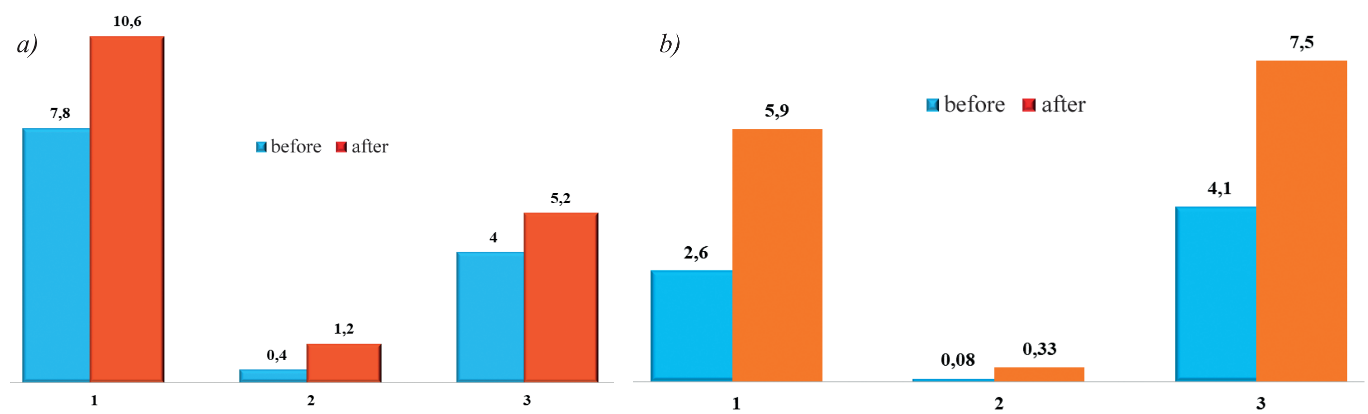


*Fig. 7. a) Formation's working thickness (m), b) Productivity factor (ton/day*MPa). Legend on Fig. 5*

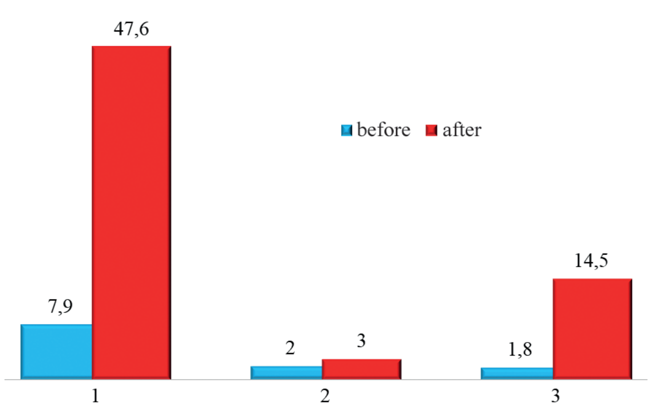


Fig. 8. Changes in average daily flow rate (ton/day). Legend on Fig. 5

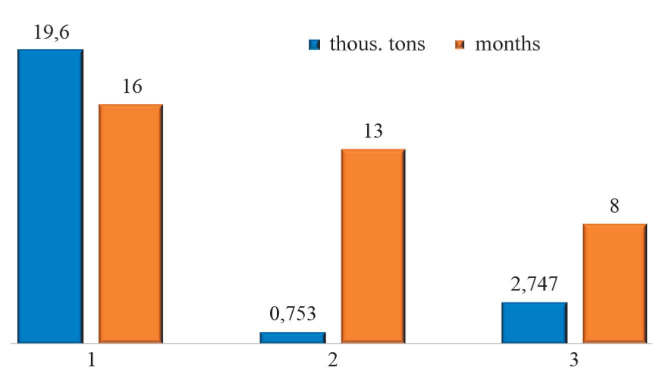


Fig. 9. Accumulated production (thousand tons), duration (months). Legend on Fig. 5

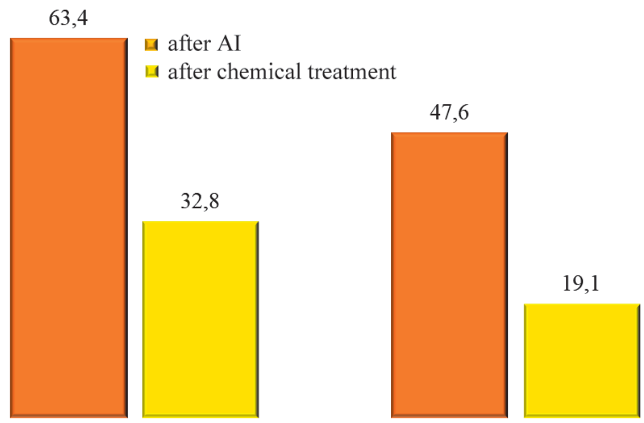


Fig. 10. Maximum flow rate, average flow rate (ton/day)

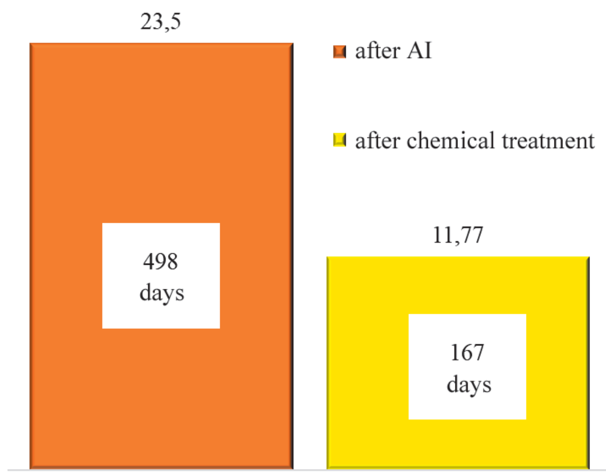


Fig. 11. Extra recovery (thousand tons), duration of the effect (days)

turnaround time amounted to 16.6 months, whereas for well 266 of Olkhovsky field and well 255 of Unvinsky field it will amount to over 13 and 8 months accordingly.

Consequently, at all the three Wells, high-frequency treatments of bottomhole zones in Terrigenous formations applying AAV310 tool equipped with magneto-striction sensors turned out to be successful. Actual and predicted oil recovery data throughout long period after the acoustic effect completely validate conclusions made after hydrodynamic surveys on significant improvement of buttonhole zone and indicate effectiveness of conducted oil recovery enhancement operations.

The hydrodynamic survey method described in this paper is comprehensive in terms of quality and evaluation of efficiency of acoustic impact results, but at the same time it is labor-consuming and expensive for regular use with acoustic impact which is conducted on a small-size tool applying geophysical survey technology. Therefore a control method was developed based on investigations of elastic energy, its parameters and properties depending on the changes in formation's reservoir properties during acoustic effect. Fundamentals of this method lie in the studies of elastic energy's emission in a formation caused by natural processes and induced by various artificial impacts, including acoustic effect (Dryagin, 2001). Elastic energy emission is a process of elastic waves' radiation in a geologic environment in a wide range of frequencies, from tens of Hertz to ultrasound. Such radiation or seismo-acoustic emission undergoes significant changes in a saturated porous medium subject to an impact from a high-intensity elastic vibrations source. Given that, parameters of such impact may also vary within a wide range – from land vibroseis sources to ultrasonic downhole sources. A peculiarity caused by seismo-acoustic emission, is dependency on reservoir properties of a saturated porous medium under the influence of acoustic impact on a productive formation. Results of oilfield tests of the acoustic impact applying AAV400 tool which merged two functions – radiation of a strong magnetic field and receiving weak emission signals in a well within one technological cycle, enabled to gain new and sufficient information on energy processes in reservoirs and their connection with presence and extraction of oil (Dryagin et al., 2005; Dryagin et al., 2014).

Radiation of acoustic field and receiving signals from seismo-acoustic emission are conducted by units installed in one borehole geophysical tool which may move along the borehole during the survey with a given tool operation algorithm. The acoustic emission energy which emanates during impact was established by computation of energy's spectral density over the entire recorded frequency range – from tens of Hertz to 20 kHz. The data was further processed by Intengraf software. Fig. 12 shows an example of comprehensive analysis of acoustic emission signal in a productive formation BC10 at Tevlinsky-Russkinsky field (West Siberia) during acoustic impact.

Fig. 12a shows diagrams acquired while applying acoustic emission logging technology along with acoustic impact in a well. Logging spectrogram is generated in real time during the tool's movement while measuring natural radiation background of seismo-acoustic emission and then during implementation of the cycle: acoustic impact – measurement of acoustic emission for each point with 0.5 m step. The log shows the curves of acoustic emission's energy signals before and after acoustic impact, as well as differences in energy in percentage relative to the background. Fig. 12b shows acoustic emission signal and its time spectrogram which may also be viewed during logging operations. Fig. 12c shows an example of acoustic emission signal spectrum at 2845 m depth before and after acoustic impact. The spectrum was computed using specialized special software in a sliding window with identification of key frequencies. Similar to core samples, discrete frequencies are clearly established as well as their dynamics during acoustic impact.

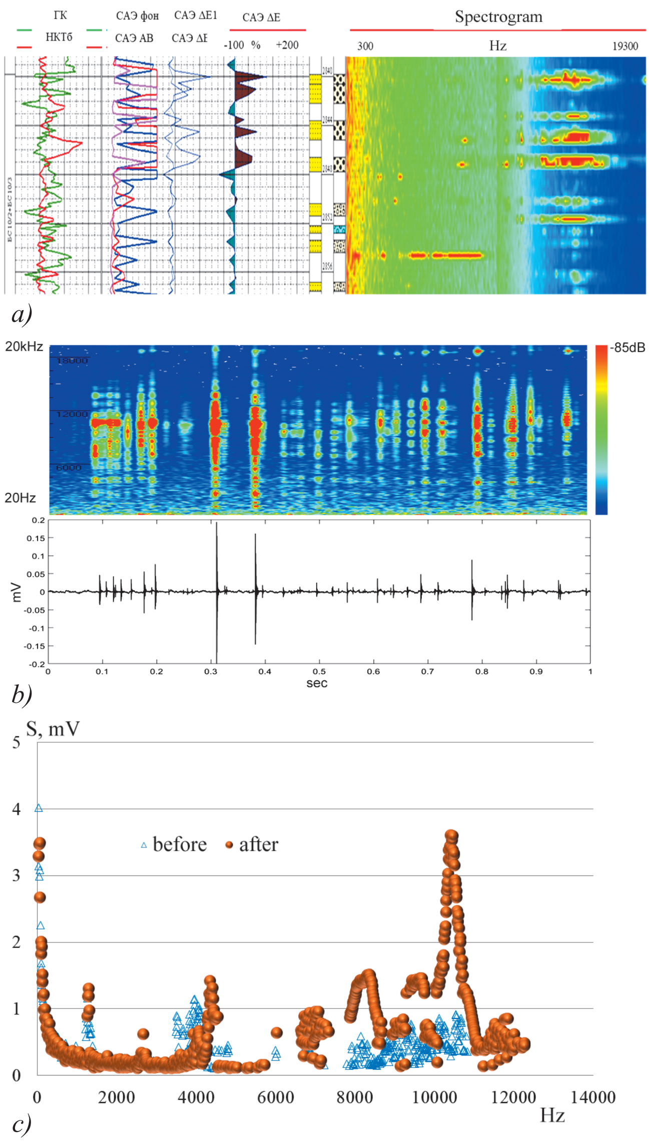


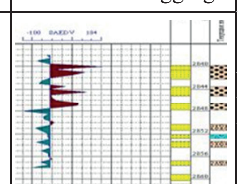
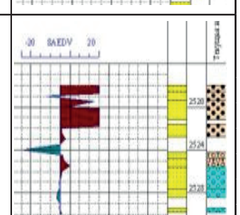
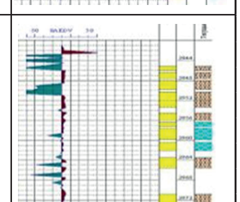
Fig. 12. Analysis of the emission during acoustic impact

Non-uniformity of reservoir properties along the well section is reflected in the curves showing the energy signal of acoustic emission which is measured in percentage relative to a background value, as well as in the form of a logging spectrogram. Since seismo-acoustic emission logging was performed before perforation, the emission induced by the impact only shows potentially oil-saturated intervals in the formation. The lower interval at the bottom of the formation (2846-2847) also shows positive acoustic emission dynamics, but it was not included in the perforation jobs, probably due to fears of its flooding. Probably it should have been included in development activities which could have increased the well's production rate. Nonetheless the well perforated in the mentioned interval yielded flow rate of 48 tons per day, against water cut of 2% (Table 2).

On average, increase in the seismo-acoustic emission signal after acoustic impact is several tens percent in a formation saturated with oil relative to background value. At the same time, individual events of acoustic emission in the form of single impacts of emission sources occur randomly and have typical parameters of signal pulse with finite duration of a certain shape. At the same time, there is presence of dominant frequencies with a certain maximum energy value and pulse-modulated frequency.

According to geological-geophysical data acquired in oilfield tests for oil flow from these formations and comparison with seismo-acoustic emission logging, a connection has been established between emission parameters and the type of its reservoir. Productivity is established through porous and fractured types of reservoirs which are in various ways established due to dominant frequencies and their energy's dynamics

Table 2

Field Formation Well	Interval of study/ perforated	Conclusion about saturation		Results		Diagrams well logging/ seismo-acoustic emission logging
		well logging/ seismo-acoustic emission logging		Flow rate/ K_{water}		
Tevlinsky-Russkinsky BS10/2 -BS10/3 No.XXX5	2838-2858 m 2840-2845 m	Oil	Oil	48 t/s	2%	
Tevlinsky-Russkinsky BS10/2 -BS10/3 No.XXX7	2518-2538 m 2518-2520 m	Oil	Oil	41 t/s	2%	
Druzhnoe YuS1 No.XXX6	2941-2976 m 2945-2952 m + HF	Oil	Water	54 t/s	97%	

after acoustic impact. Porous reservoirs with 2-12 mD permeability have dominant frequencies (6-9 kHz) and 30-40% growth of seismo-acoustic emission energy relative to background values. During inflow tests in two such wells they yielded flow rate of approximately 40 tons per day of oil with water cut not exceeding 2% (Table 2). Similar tests in reservoirs with permeability of 221-444 mD yielded 40 tons per day, with the following acoustic emission parameters: dominant frequency – 10-12 kHz, growth of acoustic emission energy – 180% relative to background values. These reservoirs are characterized by appearance of the second dominant frequencies range in the 2-4 kHz domain with dynamics 2-3 times less than previous frequency. Activity of emission along the formation changes abruptly and non-uniformly, which indicates a vast non-uniformity of the reservoir-bed in terms of its filtering and capacitance properties.

Similar results were gained at well XXX7, which also penetrated formation BC10 at Tevlinsky-Russkinsky field (Table 2). Fig. 13 shows data on emission energy as well as on permeability and electrical conductivity of the formation which was acquired during open hole logging. The setup in this well is close to that in the previous well. Upper part of the formation in the 2518-2522 m interval shows higher resistivity, permeability and emission energy. Below the 2522 m depth emission activity caused by the impact abruptly declines which indicates formation's flooding, this factor is also matched by electrical resistivity. With that, according to final logging data, permeability is abnormally high in the 2525-2528 m interval – approximately 380 mD, however acoustic emission methods and electrical conductivity point at its water saturation. Perforation was conducted in the 2518-2520 m interval, oil inflow amounted to 41 tons per day with 2% water cut.

A water-saturated formation is shown as a case study of well XXX6 at Druzhnoe field in West Siberia. Here we can trace negative dynamics of induced acoustic emission after acoustic impact which is reflected on

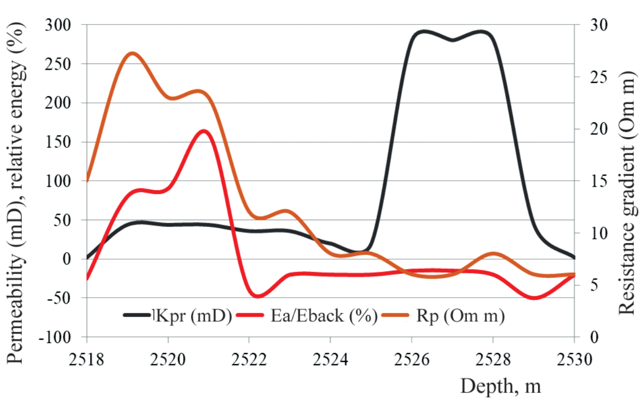


Fig. 13. Well Logging and seismo-acoustic emission energy

logging curves (Table 2). Testing results showed fluid inflow with 54 tons/day rate and 97% water cut. This well underwent hydraulic fracturing which contributed to a larger flow rate, however not taking into account the current saturation of the formation led to almost complete water flooding.

Application of the method in Carbonate reservoirs is shown for Alibekmola field, where oil- and gas-bearing capacity is associated with pre-salt Carboniferous deposits and two productive beds KT-I and KT-II confined to them and split by an inter-carbonate bed of rocks.

In order to study current oil saturation and to enhance oil extraction from productive formations at the field, they applied seismo-acoustic emission logging along with simultaneous impact on the bottomhole zone in the well.

The works applying seismo-acoustic emission technology conducted in well 54 at Alibekmola field, were carried out in the 3158-3378 m interval which matches with an oil pool confined to lower Carbonate bed KT-II with deposits of Upper Visean-Kashirian age, and lithologically consists of mainly limestone with interlayers of greenish-gray mudstone.

The interval investigated in the well refers to a productive formation KT-II-II-4, in which oil saturation was established with Well Logging data, with that effective penetrated thickness is 18.9 m, whereas effective water-saturated thickness is up to 33.4 m. Conventionally water-oil contact for this block was accepted at absolute elevation -3324.8 m. As of the date of seismo-acoustic emission surveys which were conducted twice in 2003 with a 2 months interval, oil recovery parameters over major intervals are given in Table 3.

General characteristics of the well's operation throughout this period were established as non-stable on 7 mm choke with most intensively working intervals being 3262.2-3268 m, 3210.1-3216 m and 3160-3163.1 m. On the 9 mm choke, the well's working mode became established due to operation of lower intervals, with that fluid yield re-distributed over working intervals. For example, the 3280.9-3303.3 m interval became operational with 87 m^3/day flow rate which equaled to 36% of total inflow. The 11 mm choke also saw intensified operation of lower intervals, but in addition there was a sharp growth of flow rate from the 3210.1-3216 m interval: 139.57 m^3/day.

After the acoustic impact, acoustic emission increased in working intervals in proportion to the growth of fluid inflow in them. At the same time, emission signal exists in the intervals before the acoustic impact but then changes its shape and location. The well's performance significantly improved right during the acoustic impact. The impact was applied

Perforated interval, m	Flow rate (m^3/day) -- (% of total) with choke			Dynamics of seismo-acoustic emission after AI, % of background		Operational intervals, m	
	7	9	11	**07.04.2003**	**01.06.2003**	**07.04.2003**	**01.06.2003**
3210-3216	32.8 -- 24.5%	18 -- 7.6%	139.6 -- 38.5%	18	-140	3212,5-3214	3208-3218
3233-3235	0	0	0	-17	-20	3223,5-3234	3232-3235
3262-3268	29.8 -- 22.3%	18.1--	4.4 --	-15	-10	3261-3262	3260-3264
		7.6%	1.2%	-11	-60	3263-3266	3268-3270
					13		3265-3267
3280-3306	1.6 --	87.2 --	82.2 --	11,6	2	3280-3282	3280-3306
	1.2%	36.5%	22.7%	10,8		3284-3286	
					-10		3292-3294
				4,9		3299-3300	
				11,3		3300-3302	
3320-3326	18.2 --	25.3 --	12.8 --	-26	4,3	3320-3322	3320-3322
	13.6%	10.6%	3.5%				

Table 3

consecutively over all perforation intervals starting from the top, and the wellhead pressure grew from 4 mPa to 9 mPa by the time the work was completed in the lower perforation intervals. Similar to testing, increase in the coke size led to capture of water from formations which was indicated by an intensive water kick, leading to extinguishing of associated gas flare. Fig. 14 shows an acoustic emission logging spectrogram at the time of acoustic impact. The acoustic impact itself consisted in radiation by acoustic power field lasting not less than 2 minutes per 1 meter of formation's interval. With that, even the intervals outside of perforation activities were subjected to impact.

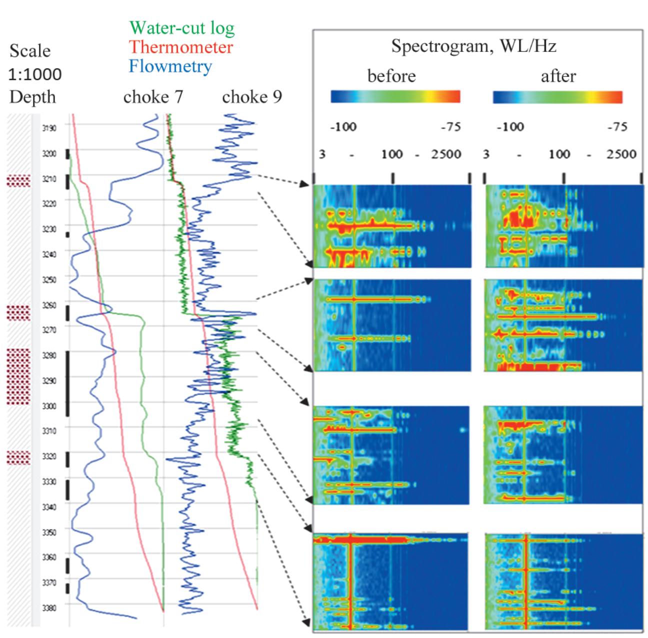


Fig. 14. Alibecmola field, well No. 54

Fig. 15 shows acoustic emission spectra before and after acoustic impact at the points where the tool stopped, at the same time the 3264 m recording point is inside the perforation interval and the 3327 m point is within a non-perforated interval. Since the emission signal outside of the perforation interval has the same large dynamics as in the productive perforation interval, we can say that this interval also has an oil recovery potential.

Non-linear properties of the Carbonate medium found their reflection as discrete frequencies similar to those acquired for Terrigenous reservoirs with core samples and Well Logging data.

Therefore, excitation of high-intensity elastic waves in a productive formation and recording of emission waves provide acquisition of reliable information on current oil saturation of a productive formation in a non-perforated well and may provide recommendations on selection of a perforation interval and stimulate oil flow from the formation.

Conclusions

Elastic energy of a reservoir-bed saturated with oil and gas is a reliable informative parameter of its production capacity.

Induced acoustic emission logging makes it possible to identify reservoirs in Terrigenous and Carbonate sediments, to clarify the geologic structure of deposits.

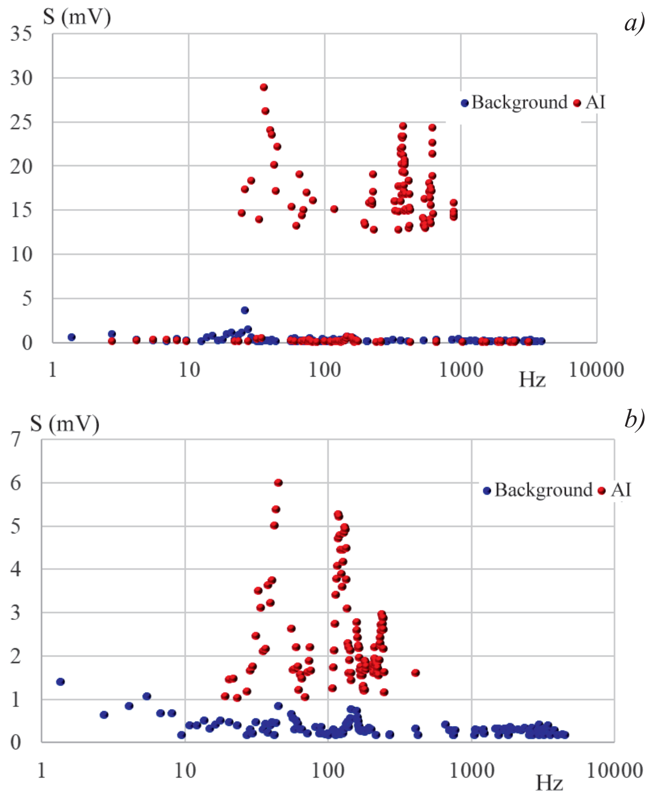


Fig. 15. Acoustic emission spectra during acoustic impact in two points of a surveyed interval. a) acoustic emission spectrum at 3264 m depth, b) acoustic emission spectrum at 3327 m. Background – background record of acoustic emission before acoustic impact, AI – acoustic emission after the impact

The technology enables to reconstruct oil and gas reservoirs, to establish the type of fluid saturation and to provide evaluation of reservoir's capacitance parameters in the conditions of high compartmentalization of the reservoir and non-uniformity in terms of permeability.

The studied technological solutions will be able to provide necessary information to select an optimum development plan and to increase the oil recovery factor.

This technology is realized with a small-size probe 43 mm in diameter and is implemented within one running operation using the MSAE 100 hardware and software package developed by Intensonic.

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