Application of passive microseismic surveys is a possible solution both for geologic exploration of hydrocarbon deposits and for a number of technological problems occurring when developing oilfields. The article highlights the features of microseismic methods offered by Gradient CJSC, application experience in Russia and their efficiency for 2005-2014.

**Keywords:** Low-frequency seismic sounding, microseismic background, spectrum, microseismic monitoring, fracture, microseismic activity.

Passive microseismic surveys are well known in engineering geology and seismology; however, in oil and gas industry it is a relatively new geophysical area and their application scope is increasing every year. Currently, application of passive microseismic surveys is a possible solution both for geologic exploration of hydrocarbon deposits and for a number of technological problems occurring when developing oilfields.

**The first area** of microseismic survey application is prospecting and exploration of hydrocarbon deposits.

The method of low-frequency seismic sounding (LFSS) is based on analyzing spectral properties of low-frequency (1-10 Hz) natural seismic background, changing above oil deposits. The effect of change in the low-frequency range of natural microseismic background above oil and gas deposits has been known since the 1990s [1] and it has been observed in various oil and gas regions.

In 2005, the authors of the LFSS method suggested a hypothesis [2] that abnormal spectral maxima are of resonant nature. Any stratified geological medium has its own frequency property, while oil and gas deposit introduces additional contrast in the cross-section that causes changes in the structure (Figure 1) of the spectral maxima. [3] The reason for the change is related to the fact that hydrocarbon deposit is a matter which causes abnormal reflection of low-frequency (1-5 Hz) longitudinal waves.

**Fig. 1. Changes in the spectrum structure of the hydrocarbon deposit based on the model of a geological geophysical cross-section in the form of homogeneous half-space**

Within the scope of the exploration operations on hydrocarbon deposit, the microseismic survey based on the LFSS technique is applicable to
- Prediction of oil and gas prospects in the exploration area;
- Delineation of hydrocarbon deposits;
- Identification of hydrocarbon deposits of a non-structural type.
The microseismic surveys based on LFSS technique include the whole range of operations, starting from field observations and finishing with full-wave numerical simulation, data processing and interpretation (Figure 2).

**Fig. 2. Stages of microseismic surveys based on the LFSS technique**

As the recording systems for the microseismic surveys, the company uses three-component broadband seismometers CME-4111-LT or LE-3DLite and recorders Baikal-ACH88 or SCOUT. The equipment of the seismological class is by far more sensitive than seismic equipment; therefore, it is best suited for microseismic surveys from surface. All calculations associated with office operations are carried out by a supercomputer built on the basis of graphic processors, with a peak performance of 50 tflops.

The company has gained considerable experience in the field of microseismic surveys since 2005: the total surveyed area of over 160 sites makes up more than 1500 km². The microseismic surveys based on the LFSS technique have been used successfully in prospecting in Russia on license areas of Tatneft, Gazprom, LUKOIL, Rosneft and other oil and gas companies.

Let us examine a few examples of operations with application of the LFSS technique.

Figure 3 shows the LFSS surveys in Orenburg region within the north-eastern slope of Zhigulevsky-Orenburgsky arch.

The LFSS surveys covered previously discovered fields, confined to two structures. When performing the operations there was information only on 3 wells NoNo 314, 315 and 317 within the structures containing oil in the sediments of the Lower Carboniferous and 3 wells NoNo 310, 316 and 322 outside the structures lacking oil occurrence in the cross-section.

According to the results of the operations the central part of the eastern structure was described as not very promising, while the western structure, according to the LFSS data, is almost entirely an oil-bearing area.

Borehole assay of wells No 1-5, 8, 16 resulted in a commercial flow of oil from the Lower Carboniferous deposits, while well No 14 in the northern chrest of the eastern structure failed and the deposits of the Lower Carboniferous appeared to be water-bearing.

Subsequently conducted offset VSP in well No 14 showed a decrease of marks to the central part of the eastern structure and its breakdown into two domes.

The next example survey (Figure 4) is confined to the northern part of Samara region of the Russian Federation, within the south-western slope of Southern-Tatar arch.
According to the results of microseismic surveys, the oil-bearing area was revealed only in the southern part of the uplift, lacking oil prospects in the northern part. Drilling well No 253 in the northern part of the uplift identified a sharp decrease in the structural plan in the northern direction and lack of oil-occurrence. Reinterpretation of seismic surveys, which was carried out taking into account the results of drilling well No 253, eliminated northern structural nose of the uplift. Sidetracking of well No 235 in the
north-eastern direction into the oil-bearing area of LFSS penetrated deposits in Bobrikovian sediments (Formation B2) of the Lower Carboniferous.

Application of the LFSS technique is also possible in dealing with unconventional exploration tasks (Figure 5). One of this kind of tasks was identifying irregularities in the thickness of the cross-section, overlying the known gas field in the Caspian depression within the Astrakhan region of the Russian Federation, in order to reduce the risk of complications when drilling wells and prevent accidents.

Due to the developed salt-dome tectonics, LFSS surveys were conducted with the use of 3D-numerical modeling and allowed forecasting possible irregularities above the main producing horizon. Irregularities in this case are decompactification zones, formations with AHFP (abnormally high formation pressure) and natural or man-made hydrocarbon deposits.

The analysis of the results made in collaboration with the customer, including the data on complications in the drilling process in wells that had been already drilled showed good agreement between the irregularities identified by the LFSS data and complication intervals in the wells.

During its existence, taking into account the results of LFSS surveys, the company drilled 121 wells and 105 of them have confirmed the forecast (Table 1). The success rate has been more than 86.7%.

Application of the LFSS technique in combination with traditional seismics will identify and directly delineate hydrocarbon deposits and maintain a high level of deep drilling efficiency.

*The second area of* the microseismic surveys application is solution of technological problems when developing hydrocarbon deposits.

The technological problems include:
- Microseismic monitoring of hydraulic fracturing;
- Microseismic monitoring of active fracturing zones.

The stages of microseismic monitoring surveys are presented in Figure 6.

There are two well-known approaches of microseismic monitoring of hydraulic fracturing [4-9]. They are downhole and surface approaches. Observations of hydraulic fracturing from adjacent wells are well known. The recording is carried out by downhole three-component sensors similar to sensors used for VSP. This method allows locating HF fracture both laterally and vertically.
Table 1. Efficiency of the LFSS technique

<table>
<thead>
<tr>
<th>Year of conducting LFSS</th>
<th>Number of drilled wells</th>
<th>Drilled oil-bearing horizons</th>
<th>Number of effective wells</th>
<th>Prediction success rate, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>38</td>
<td>Tulian-Bobrovskian, Vereiskian-Bashkirian</td>
<td>37</td>
<td>97.4</td>
</tr>
<tr>
<td>2006</td>
<td>15</td>
<td>Devonian, Tournaisian, Bobrovskian, Vereiskian-Bashkirian</td>
<td>11</td>
<td>73.3</td>
</tr>
<tr>
<td>2007</td>
<td>22</td>
<td>Middle Devonian, Famennian, Tournaisian, Bobrikovian, Vereiskian-Bashkirian</td>
<td>17</td>
<td>77.3</td>
</tr>
<tr>
<td>2008</td>
<td>10</td>
<td>Devonian, Famennian, Tournaisian, Bobrovskian, Vereiskian-Bashkirian</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td>2009</td>
<td>3</td>
<td>Bobrikovian</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>2010</td>
<td>12</td>
<td>Tournaisian, Upper Jurassic</td>
<td>11</td>
<td>91.7</td>
</tr>
<tr>
<td>2011</td>
<td>12</td>
<td>Terrig. and Carbon. Devonian, Bobrikovian, Tournaisian</td>
<td>10</td>
<td>83.3</td>
</tr>
<tr>
<td>2012</td>
<td>4</td>
<td>Carbon. Devonian, Bobrikovian, Tournaisian</td>
<td>3</td>
<td>75</td>
</tr>
<tr>
<td>2013</td>
<td>3</td>
<td>Bobrikovian, Tournaisian, Middle Carboniferous</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>2014</td>
<td>2</td>
<td>Carbon. Devonian, Lower and Middle Carboniferous</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>TOTAL</td>
<td>121</td>
<td></td>
<td>105</td>
<td>86.77</td>
</tr>
</tbody>
</table>

Fig. 6. Stages of microseismic monitoring surveys.

Observations in wells are free from surface noise, which allows achieving satisfactory results using relatively simple hardware and methods of processing microseismic signals. However, downhole monitoring has the following disadvantages:
It requires stopping production or injection and lowering equipment used for downhole monitoring. However, the stop of adjacent wells in this case is very often not possible for various reasons, including economic and production ones.

It is not possible without adjacent wells.

The alternative observation method, with the sensors located on the surface does not require using wells which makes this method potentially more versatile than the downhole monitoring, but it requires the use of high precision equipment and intensive surface noise filtering methods.

Gradient CJSC monitors hydraulic fracturing only from the surface. It includes monitoring of standard hydraulic fracturing in vertical wells and multi-stage hydraulic fracturing in horizontal wellbore. The distinctive feature of Gradient CJSC method, in comparison with similar methods used by foreign and Russian companies is the following:

1. Recording is carried out by highly sensitive broadband seismometers used during LFSS operations;
2. The method uses 3D full-wave numerical simulation for receiving three-component responses of the model to impulse action in the formation in the points where sensors are installed;
3. Localization of events is based on the method of maximum likelihood, which uses the full form of model signals and locates the event most accurately keeping a low signal / noise ratio.

When detecting microseismic events of hydraulic fracturing it determines not only its location, but the seismic moment tensor.

Let us examine a few examples of operations on surface microseismic hydraulic fracture monitoring.

Microseismic monitoring of acid hydraulic fracturing in Dankova-Lebedyansky sediments of the Upper Devonian in vertical wellbore of well No 1144 (the Republic of Tatarstan, Russia) showed that the evolved zones of microseismic activity (Figure 7), associated with fracturing process, are characterized by the following directions: north-western direction (azimuth ≈ 307°) which is the main direction; south-western (azimuth ≈ 235°) and northern direction (azimuth ≈ 16°) which branches off from the north-western one. Well tests MPAL and BAK-8 prior to hydraulic fracturing and after hydraulic fracturing in the surveyed well No 1144 and adjacent north-western well No 2583 generally confirm the results of the microseismic monitoring.

![Figure 7. The results of acid hydraulic fracture monitoring in a vertical wellbore](https://example.com/fig7.png)

In 2014, Gradient CJSC assessed the reliability of passive surface microseismic monitoring of hydraulic fracturing by hydrodynamic and indicator tests on three injection wells. The assessment showed good agreement of the results for all three methods, and subsequently the fundamental possibility of conducting surface microseismic hydraulic fracturing monitoring. Figure 8 shows the results of one of the three monitoring procedures.
According to the results of monitoring the microseismic activity is observed in the north-eastern direction. Prior to hydraulic fracturing, there was almost no movement of the indicators in the north-eastern direction. Green and purple arrows show the direction of the indicators before and after hydraulic fracturing respectively. The dotted line shows the directions with very low concentration of the indicators.

After hydraulic fracturing, it was noted that concentration of the second indicator in relation to the first one was generally excessive. It is probably caused by improvement of the well injection capacity by 2.5 times. In addition, for the first time after hydraulic fracturing, significant concentration of the indicator was detected in well No 12296, 11950, 12301, while its concentration was low in well No 12264, which indicates a significant change in reservoir properties in the north-eastern direction. This direction agreed with traceable microseismic activity during hydraulic fracturing. The remaining two wells showed similar results.

Figure 9 presents the results of microseismic monitoring of multi-stage hydraulic fracturing in a horizontal wellbore of a well in Western Siberia, including determination of the azimuth of a fracture forming localized event. Each event is displayed in the form of black segments. The center of a segment is the location of a seismic event along the lateral. The azimuth angle of the segment is the orientation of the subvertical fracture which formed a seismic event. The length of the segment is proportional to the signal/ noise ratio.

When applying axial lines of zones with increased microseismic activity across all stages of hydraulic fracturing on the microseismic activity summary map one can clearly see the concurrence of axial lines from various stages which is probably caused by formation of unified fracturing zones during hydraulic fracturing from ports adjacent to each other.

The majority of the highlighted axial lines are directed to the cross of a horizontal wellbore with an average strike azimuth of 141° which concurs with the azimuth of predominant orientation of fractures that formed the event 142 ±15°, according to the fracture direction rose built on the basis of all events highlighted during 6 stages of hydraulic fracturing.

Arrangement of work on microseismic monitoring of hydraulic fracturing, including detection of real directions of fracturing zone development allows better understanding of the processes occurring in the reservoir during hydraulic fracturing.

Microseismic monitoring of active fracturing zones is a new direction of the company and solves the problem of identifying the active fracturing zones in the cross-section of the formation and determining orientation of fractures forming them.
Fig. 9. Monitoring results of multistage hydraulic fracturing in Western Siberia including determination of fracture azimuths which formed localized events.

Figure 10 presents the results of microseismic monitoring zones of active fractures in the interval of Dankova-Lebedyansky sediments (1404-1476 m) of the Upper Devonian in one of the areas located in the Republic of Tatarstan. Field observations were carried out for 32 days, the recording of microseismic signals was conducted by 46 recording stations distributed in the area by a uniform triangular network with the distance of 500 m between the recording stations.

Fig. 10. Results of microseismic monitoring of active fracturing zones in the Republic of Tatarstan.
As a result of the monitoring, we detected 1326 assured events associated with fracture porosity of Dankova-Lebedyansky sediments of the Upper Devonian. Their parameters were defined.

Based on these results, we built a forecast map of fracture porosity and microseismic activity. Besides, we determined the prevailing fracturing direction of Dankova-Lebedyansky sediments for the exploration area.

Comparison of the data with tectonic diagrams shows that the maximum area of microseismic activity lie conformably with the troughs of the crystalline basement, which are genetically related to deep faults and picked according to geological data.

Preliminary knowledge about active fracturing of the operation area, as well as its direction allow predicting fracturing orientation of sites before arranging hydraulic fracturing, optimizing field development, selecting optimal direction of horizontal wellbores, etc. Ultimately, it allows increasing production of deposits and reducing overhead.

Thus, the passive microseismic surveys have a wide range of applications and appear to be an effective tool in hands of geologists when studying subsoil.

Bibliography: