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Prospects for the Spectral Noise Logging Application in the Analysis of Stimulated Reservoir Volume in Horizontal Wells with Multistage Fracturing

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Abstract

The most effective technique of low-permeability reservoir development is multistage hydraulic fracturing (hydrofrac) in horizontal wells. One of the specific features in operating such wells is that in the vast majority of cases flow rates from the created fractures are insignificant and remain below the sensitivity threshold of most tools that are part of the conventional production logging suite. In addition, development of unconventional reservoirs, such as Bazhenov formation, requires application of special hydraulic fracturing techniques. Therefore, estimation of the contribution from each frac stage into the total production and diagnostics of active fracs are essential and challenging tasks. To solve these tasks, the production logging suite that was run in a horizontal well to Bazhenov formation included Spectral Noise Logging tool which can not only locate the flow zones but is also suitable for identification of the flow zone type. This paper discusses the approaches to Spectral Nose Logging data analysis focused on the problem mentioned above and provides several case studies dealing with application of the production logging suite supplemented with SNL in a horizontal well drilled in Palyanovo area of Kranoleninsk field where multistage fracs had been carried out in the Bazhenov Deposits.

Introduction

To ensure effective development of the low-permeable Bazhenov formation, a dense network of small fractures needs to be created in a large volume acting as a drainage area in the stimulated reservoir volume (SRV). This can be achieved by applying advanced hydrofrac techniques that use high-rate injection of low-viscosity frac fluid. To assess the frac effectiveness it is essential to determine if only a single planar fracture is flowing or a network of small fractures.

The background for development of a network of small fractures or large single planar fractures is determined by the geological conditions, such as rock brittleness and anisotropy. Both these properties vary vertically and laterally and this is why the diagnostics of the stimulated reservoir volume are very important for planning future well drilling and frac design optimisation.

There are no techniques currently available in the industry that could reliably provide a full picture of flows through the entire volume of created fractures because all production logging techniques, despite their high resolution, have considerable limitation in regard to scanning radius which, at best, reaches only as far as the first few metres from the wellbore. Special acoustic techniques of locating hydraulic fractures in the reservoir, such as microseismic monitoring, have sufficient reservoir scanning radius but they do not provide enough resolution. The success in solving this problem appears to be in combining all available fracture diagnostic techniques.

To assess the flows from the fractured zones and identify the type of flowing fractures, Spectral Noise Logging (SNL) was run in addition to the conventional production logging techniques. Both theory and practice show that flows in the reservoir stimulated with hydrofracs can be estimated with sufficient accuracy, but this requires the use of high-sensitivity equipment. The integrated approach to SNL tool calibration and data processing makes it possible to utilize acoustic data from different wells in absolute units of acoustic pressure, which offers new opportunities in SNL data analysis for identification of flow zones and the type of flowing reservoir zone.

Description of applied techniques

Brief descriptions of the applied techniques that helped to identify the type of flow in the reservoir stimulated by hydraulic fracturing are given below.

Spectral Noise Logging

Spectral Noise Logging is widely used to solve the majority of downhole logging objectives, such as well integrity assessment, identification of flow zones and behind-casing channelling [1-3]. AT the momenta an increasingly greater focus has been placed on the unconventional reservoirs development and, therefore, hydrofrac diagnostics according to SNL data is a specific task that requires additional theoretical studies and laboratory tests, as well as an upgrade of the logging suite.

Conventional downhole logging suite

The conventional downhole production logging suite, including temperature, multiphase sensors, HEX, CCL, GR and spinner, is a main part of any production logging survey. The surveyed wells have a horizontal section with several (from 6 to 7) frac stages and relatively low (less than 1 m^3/day/m) specific flow rate. In that view, the quantitative analysis of flow profile over frac stages is a complicated task. Spinner as the direct method in this case has substantial limitations due to low specific inflows and the sensitivity threshold of this type of sensor. In order to enhance the informative value of fractured reservoir diagnostics, the following upgrades have been made in the conventional production logging suite:

High-Precision Temperature Logging (HPT). In this work, the main emphasis in quantitative analysis is placed on temperature logging; it was essential that a high-precision sensor and relevant logging procedures were in place to derive high-definition temperature profiles. TermoSim™ was used for quantitative analysis of temperature logging data.

Active Collar Location Sensor. As regular passive CCL sensors used for correlation of logging data and defining actual perforation zones of each frac stage proved to be ineffectual due to the specifics of tool conveyance and well completion, the preference was given to active collar locators, the physical principle of which is similar to electromagnetic defectoscopy (EmPulse) [4].

Noiseless GR Logging. In this work, a specially developed GR sensor [5] was used for reliable SNL data correlation to depth, which, unlike regular GR sensors, does not affect the SNL tool data. The precise SNL data correlation to depth across a nonconventional reservoir is especially important in assessing the flow regime in artificially created fractures.

Heat Exchange Sensor (HEX). The conventional memory logging tools containing the anemometers is normally characterised by high power consumption, which affects logging data quality and shortens the tool operation time. Due to this, logging engineers often have to reduce the number of logs. An upgraded HEX sensor was used in this work. It has a heater that operates in pulse mode [6] with an option of power control, which makes it possible to select the optimal sensor overheat and record as many logs as necessary. Additionally, a special tool housing design was selected for a more accurate estimation of longitudinal flow velocity component in reference to the well axis. However, due to multiphase flow in the surveyed wells, the flow velocity profile by HEX data was used for reference only.

Field overview and reservoir parameters within the survey zone

The pilot Bazhenov formation development project was launched in Palyanovo area in 2013. As part of the project, in 2013-2015 five vertical wells were drilled, cored and logged with an extended logging suite. Then two more subhorizontal wells were drilled in order to improve the competence in drilling horizontal wells with multistage fracs. The acquired information was used as the foundation for planning the first two horizontal wells in Palyanovo area, which were drilled and put on stream in 2015-2016. These wells, in terms of technologies applied, are highly competitive with the ones drilled in the USA for shale oil, and the obtained results showed that the Bazhenov formation had a high potential within the boundaries of Palyanovo are as a target to be developed by drilling horizontal wells with multistage fracs [7].

April 26, 2017, Alexander Novak, the Minister of Energy of the Russian Federation, pursuant to Decree No. 1217-r by the Government of the Russian Federation dated July 03, 2014, assigned a national status to PJSC Gazprom Neft's project aimed at promoting the creation of domestic technologies and high-tech equipment for the Bazhenov formation development. Palyanovo area was given the status of the national project's testing ground.

In 2017, a project of sidetracking four suspended wells was launched in the field under study. Its results confirmed that the project was technically viable and the Bazhenov formation could be commercially attractive as a recompletion target.

In 2018, Palyanovo testing ground entered a new phase of large-scale development of the Bazhenov formation potential. Two extensive horizontal wells with horizontal section length minimum 1000 m and minimum 10 frac stages were spudded simultaneously from two pads. The experience accumulated over 5 years was instrumental in transforming the project from purely geological one, when the Bazhenov formation development objectives were associated with the zones of high natural productivity, to a more technologically advanced project, where the Bazhenov formation was regarded mainly as a target to be stimulated using the modern techniques of hydraulic fracturing in horizontal wells. This objective cannot be attained without selecting the optimal frac design. In this regard, development of methods to assess the effectiveness of stimulation in horizontal wells with multistage fracs appears to be an important and relevant trend.

Lithological and stratigraphic properties of the Bazhenov Deposits

The Bazhenov formation is one of the most widely studied targets with more than 50 years' history of exploration, but its oil and gas potential remains uncertain to this day. The estimations of reserves-in-place differ by more than two orders of magnitude (from 600 million to 175 billion tonnes). Up to date, there is no reliable technology in the national petroleum industry for commercial development of the Bazhenov formation.

Accumulation of the Bazhenov formation deposits within the boundaries of Krasnoleninsk dome was taking place in a large epicontinental sea basin at depths below the wave effect zone and predominantly under anaerobic conditions. Sedimentation was extremely slow and did not compensate for downwarping of the sea basin in which biogenic sedimentation dominated over terrigenic. These circumstances determined the high lateral continuity of the formation in general. The cyclites boundaries of the Bazhenov formation horizon are distinct; they were formed in the conditions when background terrigenic/biogenic sedimentation was changing to purely biogenic. The biogenic strata correspond to the periods of cold and oxygen-saturated arctic water penetration into the Bazhenov formation sedimentation basin, which led to outbreaks of zooplankton bioproductivity, the relics of which formed interlayers of high continuity over a large area.

An important result of the core studies was the identification in the Bazhenov formation of five layers (units) differing in composition, reservoir porosity and permeability, as well as mechanical properties of the rock. A brief description of the units is given below. The numbering sequence is from bottom to top.

Member I is formed by horizontal sequences of dark-grey argillitic, low carboniferous silicites (with silicon minerals content of more than 60%, $C_{org} < 3\%$) and light-grey low carboniferous silicites (with silicon minerals content of more than 80%). Mutual merging between the lithotypes is gradual.

The predominant texture is pelitomorphic or organogenous-pelitomorphic, with relics of former bioproducers, such as radiolarian chert (up to 50%) in the form of small light-coloured spheres of 0.05 – 0.15 mm diameter encountered in the background.

Member II consists mainly of dark-brown carboniferous silicites ($3 < C_{org} < 6\%$) with phosphate concretions. The silicious component share is growing upsection and in the top part of the Member a thin layer of light-grey carboniferous silicites with biogranular structure (50% of well-preserved radiolarian relics) is located, which in lateral direction are sometimes replaced by low carboniferous gark-grey silicites with relic radilolarian structure.

Member III consists of dark-brown argillaceous and siliceous rocks (the total content of argillaceous and siliceous minerals is more than 80%), and argillaceous, highly carboniferous silicites ($C_{org} > 6\%$) of pelitomorphic texture, massive or with thin horizontal strata. Spherical sulphide concretions are present; the interlayer surfaces have imprints of ammonite shells and phosphatised relics of marine fauna. In the top half of the member, thin (up to 1.5 cm) carbonate streaks formed by conchial detritus are encountered. They form a thin laminated texture.

Member IV consists of dark-brown argillaceous-siliceous-carbonaceous (with each component's content less than 60% and aggregate content of any two components less than 80%), highly carboniferous and pelitomorphic massive rocks. The main matrix rock is packed with oval, globular and compressed carbonate, siliceous-carbonate, and low carboniferous concretions with sphero-micritic or sphero-patterned textures. The upper part of the member contains carbonate-phosphatic carbonaceous rocks with granular structure (coprolitic phosphates) which form lenticular interlayers and spherical nodules.

Member V, the last in the Bazhenov formation, consists of argillaceous-pyritic-silicious carboniferous and highly carboniferous pelitomorpic rocks of metalescent dark-brown colour. The rock has distinct horizontal minute folding. The rock has typically high (up to 30%) content of microaggregates of pyrites evenly dispersed in the matrix. The interlayer surfaces have imprints of marine fauna relics.

Member II and IV have the highest development potential in the sequence [8]. The reservoir in Member II is associated mainly with the silicites of primary organogenic structure (radiolarites) and are characterized by porous (partially fractured-porous) type of the voids, which, in turn, results in a large holding capacity (average porosity factor is 8.5%) and low permeability (permeability factor is 0.04 mD). The presence of mobile oil in reservoirs of Member IV is associated with compressed carbonaceous, and silicious-carbonaceous low carboniferous concretions and coprolitic phosphates in the upper section. This reservoir has a lower holding capacity in comparison with the previous one (permeability factor is 0.2 mD) and is characterised by fractured-microcavernous-porous type of the voids.

Acoustic laboratory tests

The problem of aero- and hydrodynamic sound generation is the topic of numerous studies, both theoretical and experimental. The general conclusion of these studies is that sound can only be generated in a turbulent fluid or gas flow [9]. The experimental studies of sound generation in permeable cores (including fractured ones) have shown that acoustic signal spectra tend to be shifting to the high-frequency band as the typical size of core channels through which fluid or gas flows gets smaller [10]. As it happens, the spectrum shape and typical spectrum peak frequency practically do not depend on the type of flow (gas or liquid) through the core. This fact can be explained in terms of Kolmogorov's theory of turbulent flow [11], which defines the generated acoustic signal spectrum peak location as $\omega_{max}\sim v/l^2$, where v is kinematic viscosity of the fluid and l is typical turbulence scale. At pressures of several hundred *psi* and higher, the kinematic viscosity values of water and gas are close and, consequently, similar fluid flow parameters should lead to generation of acoustic signals at more or less the same frequencies.

It is very important to note that the physics of sound generation by fluid flows through a porous medium and through fractures are essentially different. Fluid flow through a fractured core is similar to turbulent flow through a rectangular pipe. The hydraulic diameter of such pipe is defined by the following expression:

$$D_h = \frac{2Lb}{L+b}, \tag{1}$$

where L is fracture length and b is fracture opening. The Reynolds's number for flow in a rectangular pipe is:

$$Re = \frac{V \cdot D_h}{v} = \frac{QD_h}{vLb} = \frac{2Q}{v(L+b)}, \tag{2}$$

where v is kinematic viscosity of fluid, V - flow velocity, and Q – volumetric flow rate. Then the critical flow rate will be:

$$Q_{cr} = \frac{1}{2} v(L+b) Re_{cr} \tag{3}$$

The critical Reynolds's number value for a rectangular pipe with rough walls will be $Re_{cr} = 400$. After the fluid flow has reached the critical value, the flow pattern will change from laminar to turbulent. To study the acoustic emission processes, a special lab stand placed in an anechoic chamber was used (Fig. 1).

Figure 1—Anechoic chamber for studying acoustic emission processes located in TGT technology centre in Kazan, Russia.

The acoustic anechoic chamber can imitate unrestricted space during acoustic equipment calibration and testing. The internal surfaces of the anechoic chamber are lined with cuneiform panels which absorb acoustic waves and prevent multiple reflections of acoustic waves from the chamber walls. This chamber is located in the TGT Service Technology Centre in Kazan, Russia.

The acoustic stand CAS 2.1 has been especially developed for lab test to study spectral characteristic of acoustic signals generated by fluid flows through natural and artificial core samples. CAS 2.1 can use a spectral noise logging tool of any modification or reference hydrophones as the detector. The main advantage of the stand is that it has a wide range of test sample sizes varying from 25 to 50 mm and that it is suitable for the tools with either 38 mm or 42 mm OD. The stand is equipped with an automated noiseless injection system and high-precision pressure gauges and flowmeters.

Five artificial core samples made of a mixture of sand and cement at the ratio 1:4, with rectangular apertures cut out in four samples to imitate fractures openings of $b \sim 0.5$, 1.5, 2.5 and 3 mm (Fig. 2) were prepared for the lab test.

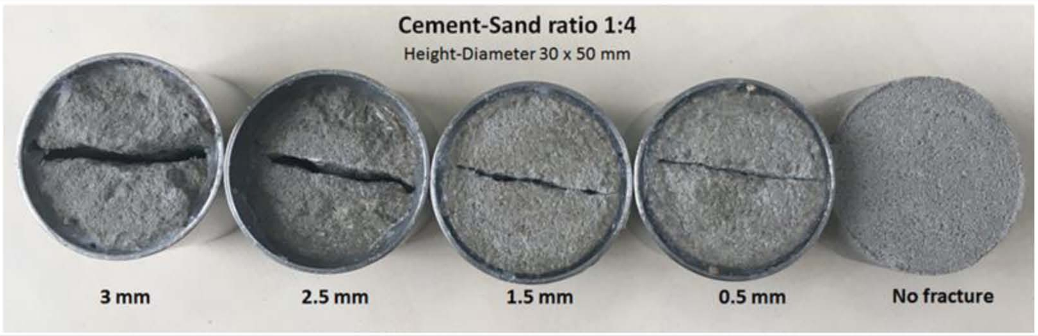

Figure 2—Artificial cores with fractures

Fig. 3a shows the spectra of acoustic signals generated by water flows through artificial cores (See Fig. 2) with fracture openings of 0.5 mm and 3.0 mm. The water flow rate through these fractures was 3.4 l/min and 3.5 l/min, respectively. Fig. 2b shows the measured spectra of acoustic signals generated by water flows through artificial cores with fracture openings of 0.5, 1.5 and 3 mm. The water flow rate during the test was 3.1 l/min, 1.8 l/min and 2.6 l/min, respectively. In all cases the flow rate values were higher than the critical value calculated by the expression (3) and, consequently, the conditions were adequate for capturing meaningful acoustic signals. It can be seen that with an increase of fracture opening in an artificial core sample the high-frequency components in the generated acoustic signal spectra disappear, and the spectrum itself tends to shift towards the low-frequency range, which is consistent with the theoretical concepts of sound generation by turbulent flows through a permeable medium. Therefore, the spectra indicate that the acoustic signal generated by fluid flow through a fracture is a single-tone signal decreasing towards high frequencies, with the characteristics dependent on many parameters, primarily, flow rate and degree of fracture opening. It can also be seen in Fig. 3a, b that if the flow takes place through fractures with smaller openings, the amplitude of the generated acoustic signal may be higher than the amplitude of acoustic signal generated by the flow through larger fractures, even at relatively lower flow rates. This observed phenomenon is in agreement with Lighthill's theory [9] which establishes a relation between the generated noise power and the square of typical diameter of channels through which fluid flows take place in porous media, and 8th power of flow velocity.

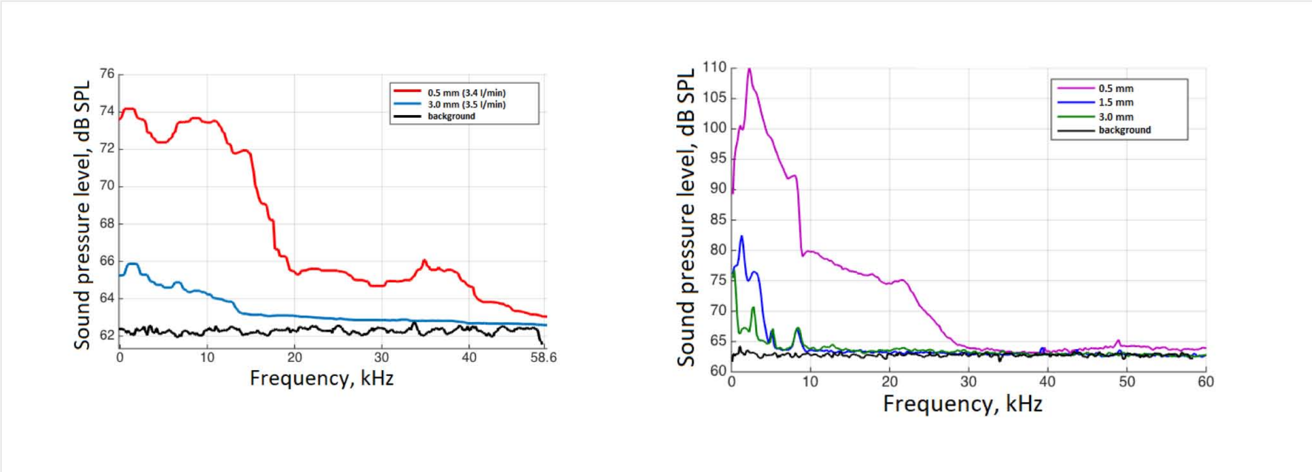

Figure 3—a) Spectra of acoustic signals generated by water flow in artificial cores through fractures with 0.5 mm and 3 mm openings; b) Spectra of acoustic signals generated by turbulent water flow in artificial cores through fractures with 0.5, 1.5 and 3 mm openings. Black line represents background noise level.

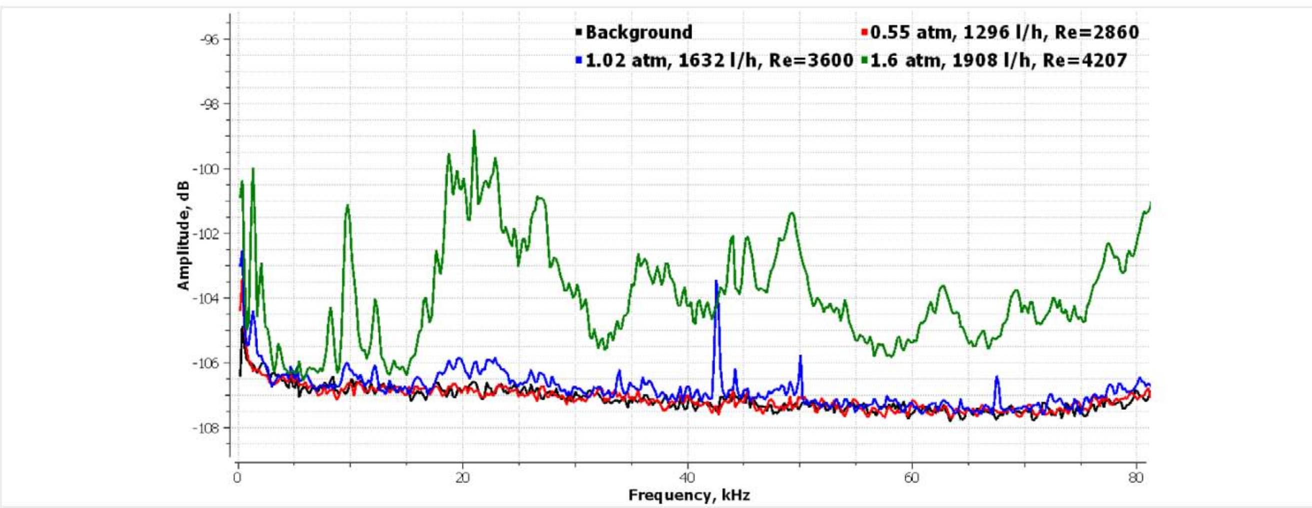

Figure 4—Spectra of acoustic signals generated by fluid flow in artificial core without fractures (cemented sand with the permeability of 1.65 D)

Fig. 5 shows the spectra of acoustic signals generated by fluid flows in artificial core samples without fractures (permeability is 1.65 D). After the critical flow rate has been reached, the generated acoustic signal spectrum becomes broadband. This signal differs from the spectra shown in Fig. 3 because it has no typical frequency-specific trend and is featured by multiple positive frequency amplitude peaks.

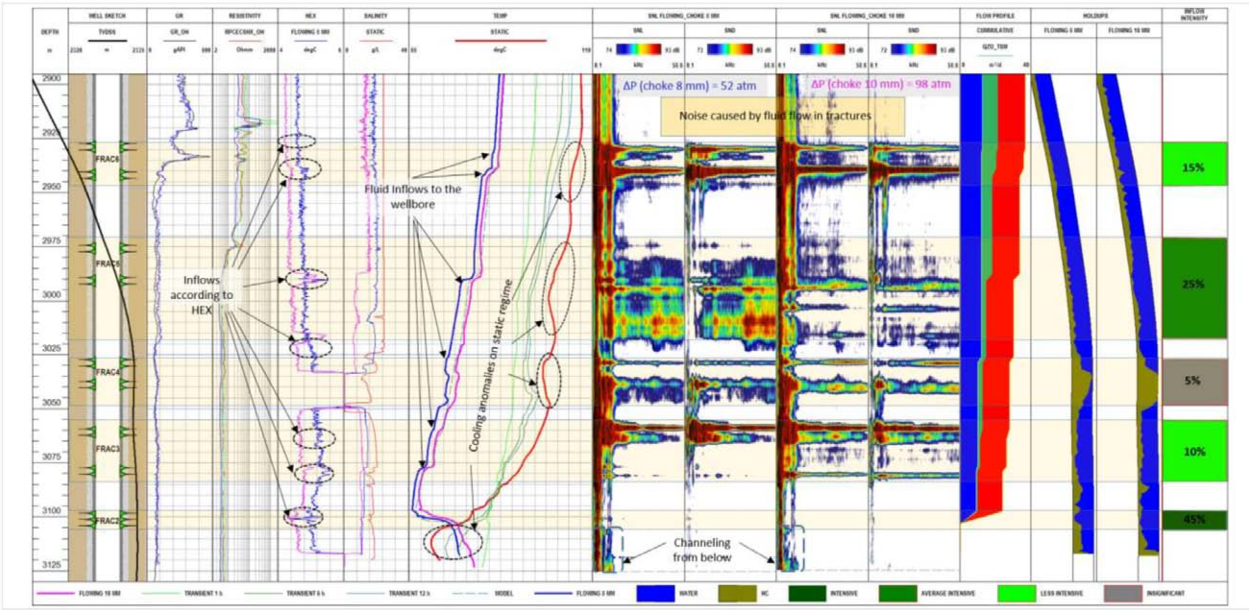

Figure 5—Downhole logging results – Well D1

Case studies

Production Logging Survey results in wells D1, D2 and D3

The case studies of production logging surveys in horizontal wells drilled to Bazhenov formation at Palyanovo area of Krasnoleninsk field are given below. The integrated production logging data were recorded in several well operation regimes.

Wells D1, D2, and D3 with horizontal wellbore sections were completed with cemented liners and then multistage hydrofrac were carried out using the hybrid technique. Logging was performed in static, several flowing, and also during transient conditions. The toolstring was run on coil tubing. High repeatability is observed on Flowing SNL and HPT data (Fig. 5, 6 and 7).

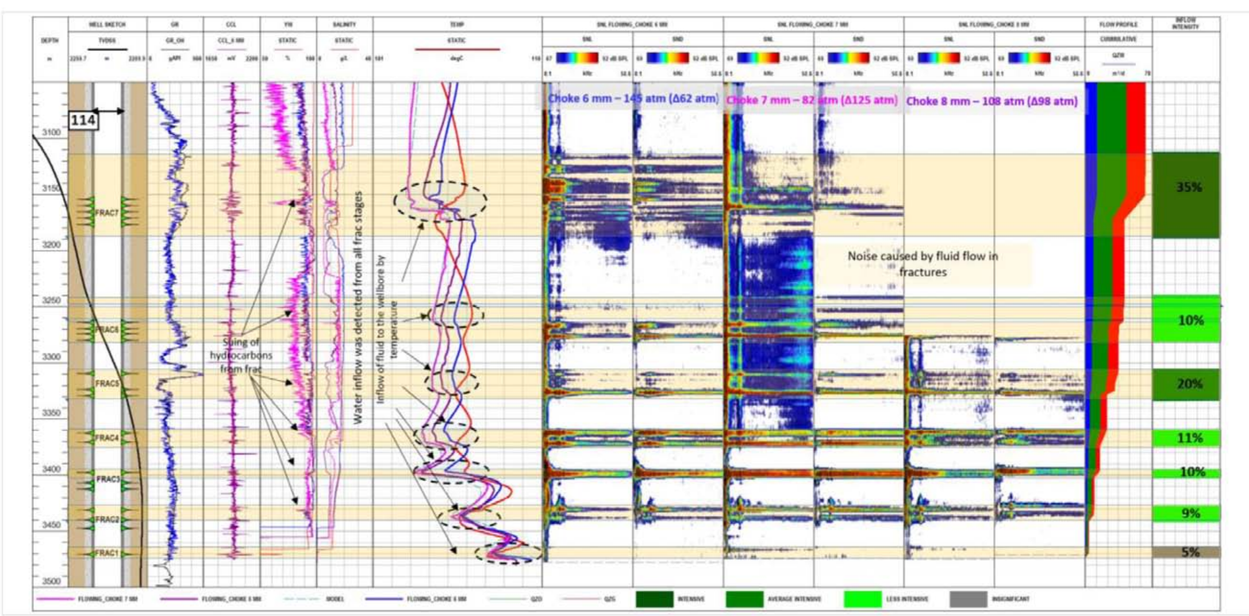

Figure 6—Downhole logging results – Well D2

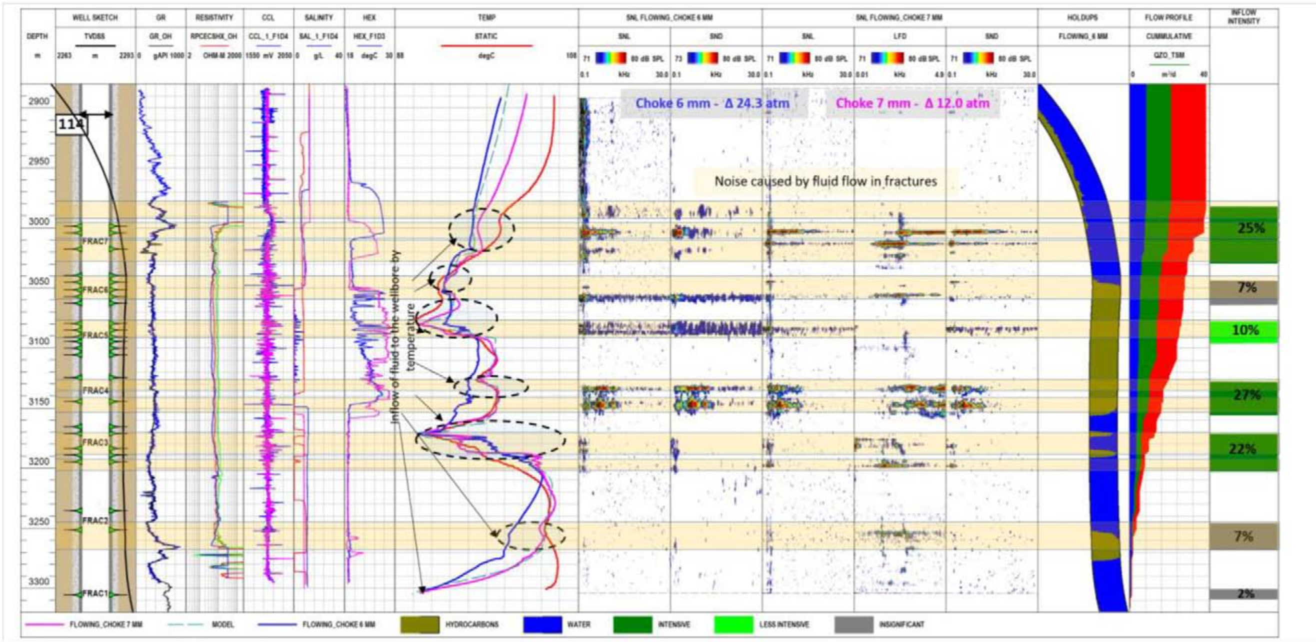

Figure 7—Downhole logging results – Well D3

The specific feature of the HPT data consists in the fact that during the hydraulic fracturing operations a large volume of frac fluid with temperature different from the surrounding rock temperature was injected into the well resulting thermal contrast that helps to enhance the informative value of the HPT data.

The active flowing intervals with artificially induced fractures were identified by the anomalies on the SNL data (SNL panel). Part of acoustic signal is affected by wellbore flow generating low (less than 2 kHz) and medium (2-7 kHz) frequency range signals, thus, a denoising procedure was applied to the SNL raw data. As a result of this procedure, the signals generated by wellbore flows and nonstationary signals that give no information on reservoir fracture flows were excluded from the spectrum (SND panel) [8]. According to the SNL data, the active flowing zones in some cases correlate very well with temperature disturbances created during hydraulic fracturing, which gives additional confidence in identifying the effective reservoir thickness stimulated by hydrofracs. It should be noted, however, that due to the difference in hydrodynamic characteristics of created fractures in different frac stages, the static temperature profile at some cases is distorted due to wellbore cross-flow.

As the results of the production logging survey, an inflow profile based on temperature modelling was derived and active flowing reservoir zones were identified. It can be concluded that the recorded HPT logs can reliably describe the frac stages performance at relatively low (less than 1 m3/day/m) specific flow rates that are typical for horizontal wells targeting Bazhenov formation. Regretfully, this information alone is insufficient to make a conclusion regarding the effectiveness of the fracture stimulation itself. To identify the type of the effective thickness, it would be necessary to be able to determine the inflow type in the stimulated zone of the reservoir. The SNL data analysis may assist in solving this problem.

SNL data analysis to determine the fracture flow type

A comparison of SNL data from wells D1, D2 and D3 shows a qualitative similarity between the amplitude-frequency distribution of measured signals that represent the broadband acoustic anomalies with a high-amplitude component in the low-frequency range (Fig. 8), and the signals generated by fluid flow through an artificial core sample fracture. Specific signals of this type can be encountered practically in each fracture stage and, therefore, such acoustic anomalies can be with a high confidence associated with planar fracture flows.

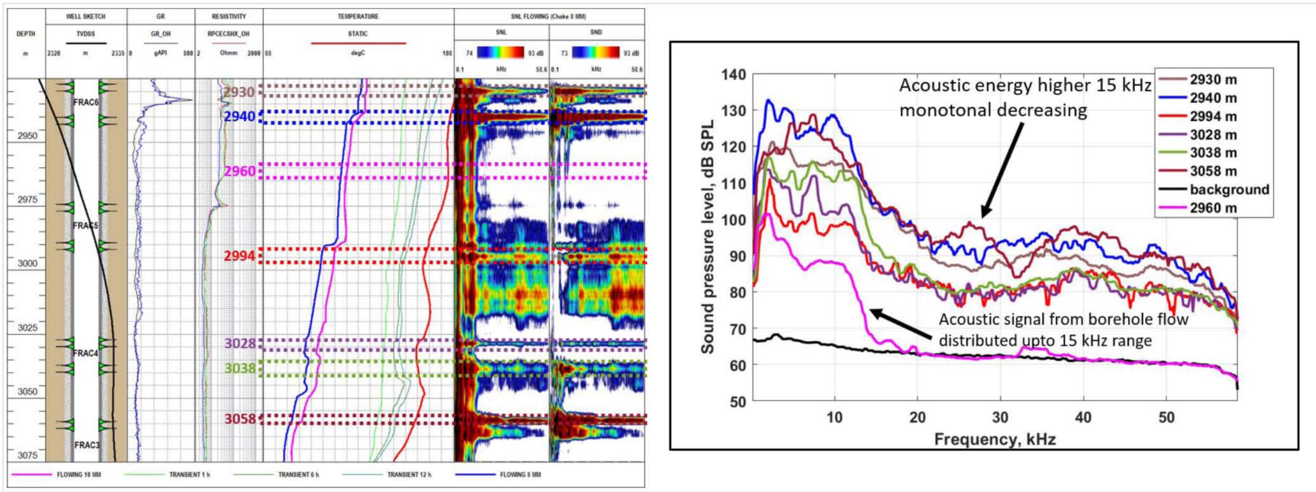

Figure 8—Spectral distribution in Well D1

Another type of signals encountered on the SNL logs is represented by frequency-specific signals of the amplitude that most often is relatively lower. The aggregate of such signals characterises the effective thickness of the created hydraulic fractures along the wellbore. According to the logging results, there is a certain correlation between the intensity of multistage frac flows and the total effective thickness along the wellbore. As can be seen from the above, such analysis offers the opportunity to perform QC assessment of the SRV and, consequently, determine if the applied hydrofrac technique was successful.

In this respect, the examples shown in Fig. 5 and 6 more illustrative, where the zones with a specific flow pattern determined according to the SNL results contribute the most into the total inflow. In these zones the signal is more distributed and can be associated with the flow from a volume formed by a network of small fractures. This indicates that the stimulation effectiveness in these zones is higher. In both cases an alternative frac design was tried out as an experiment in an attempt to improve the SRV characteristics. The result of the integrated production logging suite was decisive – the experiment was successful, and the alternative design improved the stimulation effectiveness.

Conclusion

In the context of development of hard-to-recover and unconventional reserves using multistage fracs, the priority is to improve the available integrated production logging suite intended for identification of flow zones in low-rate wells and determination of the reservoir flow zone type (single fracture or a network of small fractures in the stimulated reservoir volume). One of the advanced techniques to solve this problem is the method of combining the conventional production logging suite with Spectral Noise Logging. This paper introduces the results of lab tests studying fluid flows through fractures in artificial core samples and provides the results of downhole logging in three horizontal wells with multistage fracs in Bazhenov formation. Production logging survey results show that the described approach is viable and can be used for assessment of the effectiveness of reservoir stimulation by hydraulic fracturing in low permeable Bazhenov formation.

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List of Acronyms

GR	Gamma Ray
CCL	Casing Collar Locator
PLT	Production Logging Tool
HEX	Heat Exchange Sensor
SNL	Spectral Noise Logging
SNL-HD	High-Definition Spectral Noise Logging
SND	Spectral Noise Drift

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