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IMPORTANCE OF ACCOUNTING MACRO HETEROGENEITY OF PRODUCTIVE STRATA TO IMPROVE EFFICIENCY OF WATER ALTERNATING GAS INJECTION PROCESS

The paper focuses on improvement of reliability of geological information used in the water alternating gas injection projects for productive strata in the course of scavenger oilfield development. Spotlight is on the study of macro heterogeneities revealed by interpretation of drilling and seismic survey data.

One of the critical objectives of this research is updating of interwell correlation according to the analysis of seismic wavefield recorded in the interval of productive strata occurrence. The paper describes a case-study of the revised concept on the structure of BV10 stratum in the Nizhnevartovsk oil and gas area of the West Siberian oil and gas province. As a result, instead of the current concept on the parallel bedding of the test sedimentation, the progradation structure of the latter is assumed, which eliminates the use of would-be lithological screens in delineation of oil reservoirs. The disregard of the progradation structure in oilfield development would have an adverse influence on the oil recovery efficiency.

The integrated interpretation of drilling and seismic survey data reveals screening fractures which make an impact on oil displacement efficiency. It is necessary to take such fractures into account in water alternating gas injection. Inclusion of sufficient vertical discriminability of well information and lateral discriminability of seismic survey data in the analysis allows predicting the change in petrophysical parameters in interwell space. The authors exemplify interpolation of well data with regard to wavefield properties. The information on macro heterogeneities of reservoir properties helps improve the water alternating gas injection performance and, accordingly, enhance the sweep efficiency. The paper presents also the physical framework for the adjustment of fluid flow in reservoirs using the seismic survey data.

Keywords: *Reservoir, productive strata, oil, water alternating gas injection, reservoir properties, effective thickness, seismic survey, correlation*
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Introduction

The current challenge in the oil sector is the oil recovery enhancement. The situation gets worse with the general complication of the structure of hydrocarbon reservoirs [1, 2]. Percentage of difficult-to-recovery oil grows gradually as well. Minimum half of total oil is unrecoverable from conventional reservoirs using the common methods [3]. For this reason, such oil is assumed to belong to the difficult-to-recover reserves. In this respect, it is undoubtedly required to develop and improve enhanced oil recovery technologies [4, 5]. One of the possible ways in this regard is the actualization of the reservoir pressure maintenance technology. What is meant is promotion of the water alternating gas injection process [6, 7]. This technology includes the reservoir pressure maintenance and has a positive effect on the coefficient of oil displacement from productive series [8]. This technology seems to be promising in difficult-to-recover oil stimulation [9, 10]. Efficiency of the treatment depends in many ways on correct identification of geological heterogeneities in a target reservoir.

Research objective

The research objective is enhancement of the water alternating gas injection efficiency based on the analyses of methods to acquire information on macro heterogeneities of an object under mining.

We understand macro heterogeneity as the variability of lithology and petrography of a stratum or a reservoir. When studying an object to be subjected to the water alternating gas injection, the spotlight is on lithology, stratigraphy and tectonics of the object. Moreover, modification and updating of technologies applied to oil recovery from reservoirs engaged in long-term production also requires taking into account induced heterogeneities. It is highly important to know about variability of poroperm properties of reservoirs in interwell space [11]. Macro heterogeneities affect the reservoir permeability and the sweep efficiency and, consequently, the displacement front structure [12]. The scope of special interest embraces the zones of occurrence of very poorly permeable rocks; Darcy's law is fulfilled not to the full extent [13]. This governs relative retardation of oil displacement in certain areas, which predetermines breaking of the displacement front in other zones [14]. For the reliability assessment of macro heterogeneities in reservoir properties to be improved, it is necessary to use the field geophysics methods. Owing to complexing of well data [15], having good vertical discriminability, with the methods of seismic survey and electric exploration, which allow determining general areal variability of reservoir properties, the geological modeling reliability becomes much more reliable, which has a beneficial effect on the water alternating gas injection performance in oil reservoirs.

Updating of crosswell correlation by seismic survey data

Alongside with the structural planning of reflection horizons, the seismic survey data are usable in updating of detail correlation of pay-out beds based on the analysis of well logging data. An illustration of such work may be a case-study of the Achimov Formation [11] and BV_{10} group strata of some oil reservoirs in the Nizhnevartovsk area of the West Siberian oil and gas province. This sedimentation took place during starved sagging of the deposition bottom, which governed the progradational structure of the strata under discussion [16]. Initial lack of attention to that fact essentially complicated oil recovery. The intended detail correlation procedure assumed that the pay-out layers occur in parallel to the upper-lying clayey cover. Such approach seems to be well-taken as the bottom layer of the cover features a high stability. However, the oil saturation studies showed that structure factor ungoverns the reservoir morphology [17]. In particular, in geological modeling, the authors had to assume the presence of

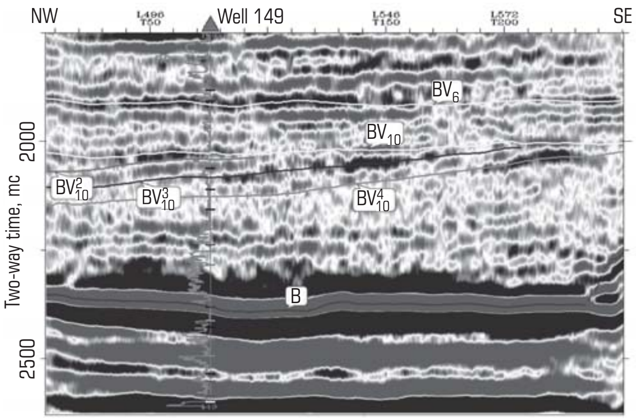

Fig. 1. Illustration of reflection of progradational structure of BV_{10} thickness in wavefield of traverse seismic profile of the Nizhnevartovsk arch field

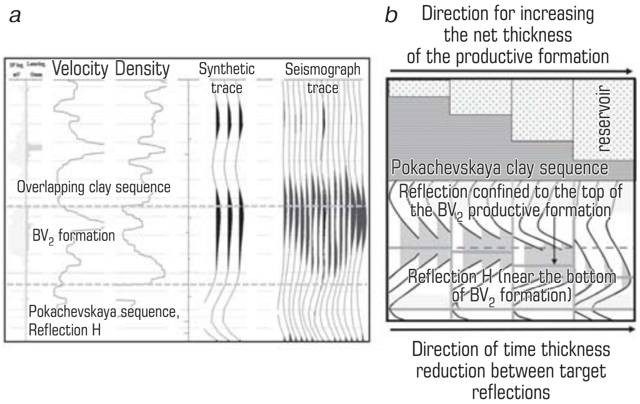

Fig. 2. Illustration of stratigraphic tying of seismic reflections and modeling of change in time spans depending on physical properties of BV_2 formation overlying the Pokachi clay sequence:
a–example of tying seismic reflection of BV_2 reservoir of the field; *b*–seismogeological modeling

lithological screens inside a reservoir, though such screens never existed (**Fig. 1**).

The concept on the structure of a pay horizon totally changed after 3D seismic survey [18]. The acquired information proved the necessity of profound adjustment of the detail correlation. The wavefield fitting BV_{10} pay thickness contains no parallel reflections. Moreover, at the roof of the test group of strata, an erosion-type inconsistency is recorded. Northwestward there is an increase in the time spans between the reflections of BV_{10}, formed at the roof of the test group strata, and $BV_{10}{}^4$, formed at the bottom of this thickness. It appears that in this case, we record a system of wedgeouts rather than a sub-parallel bedding system. Furthermore, the new detail correlation results and the well logging data interpretation point at successive clayification of the test deposition in the course of its paleo-downwarping. Apparently, the depth of the paleo-basin grew in the northwest direction during sedimentation. The accumulation of this group strata finished the compensation of the general sagging of ground surface at the late Neocomian stage. Based on complexing of the well data and seismic survey results, a geological model was constructed without would-be lithological screens. The model shows that there is a uniform hydrodynamic connection between the pay horizons in the test deposition. The fluid injection limit is regulated by wedging-out of reservoir layers. In case of using a proportional bedding system or assuming the roof-parallel stratification, the structure-and-stratigraphy framework would include different-age deposits, which contradicts the original structure of the test group of strata and, accordingly, the water alternating gas injection would fail to produce the wanted effect on the strata.

Detection of tectonic-type macro heterogeneities

When predicting the water alternating gas injection effect on productive series, a certain interest lies in heterogeneities of tectonic type [18]. In particular, hydrocarbon reservoirs adjoining the Vasyugan productive series of the Upper Jurassic age feature a stepped structure of water–oil contacts which, moreover, are affected by fractures. In our case, a screening fracture was detected between blocks for which a 20 m-difference was found in the water–oil contact from the prospecting and production drilling logs. Thus, inobservance of such screens can result in violation of the planned oil displacement front and, consequently, can affect introduction of the advanced reservoir stimulation techniques. For another thing, anisotropy of permeation in productive series comes under the influence of conductive fractures which are paralleled by open joint systems, as a rule. Finally, fluids flow in the vicinity of such fractures, which should be taken into account in water alternating gas injection in reservoirs. It is worthy of mentioning that the conductive and screening fractures are reliably distinguished from the evidence of simultaneous hydrodynamic tests in wells. The seismic survey data only indirectly inform on properties of fractures.

Prediction of petrophysical heterogeneities in interwell space with regard to wavefield properties

In the framework of the analysis of macro heterogeneities in petrophysics of pay series, the dynamic analysis of wavefield was carried out during interpretation of seismic survey data. One of the results is the forecast mapping of petrophysical parameters based on interpolation of relevant interwell space data with regard to wavefield properties [18, 19]. The outcome is the increased reliability of geological models, appraisals of oil and gas reserves and, consequently, quality of reservoir simulation [20].

In interpolation of petrophysical parameters in interwell space with regard to wavefield properties, it seems to be expedient to follow the well-reputed procedure [18]:

- Analysis of acoustic and density characteristics of both a pay-out bed and enclosing rock mass to be the basis for 1D geology-and-seismicity modeling. The stratigraphic tie of a target seismic reflection is carried out in this framework (**Fig. 2a**). At this stage, it is necessary to determine an optimal window for the attribute analysis.
- Identification of basic laws and relations to calculate synthetic acoustic and density curves to serve the basis for 2D wavefield modeling for the specific and anticipated geological situations (see Fig. 2a).
- Extraction of seismic attributes from the synthetic wavefield and their further analysis to reveal the most informative attributes to predict petrophysical parameters in interwell space.
- Analysis of the revealed seismic attributes in a special geostatistical package and mapping of prediction parameters.

By way of example, we discuss the studies of BV_2 stratum in some reservoirs in the west of the Nizhnevartovsk arch, West Siberian oil and gas province [18], adjoining the middle of the Lower Cretaceous-age Vanden Formation. Within this area, the test stratum is mostly composed of sandstone and siltstone with some mudstone layers. The reservoir rocks are mostly grey-brown, grey and, seldom, dark grey sandstone and siltstone. The formation components are quartz (25–35%), feldspar (40–45%), re-deposited debris (20–25%) and mica (1–3%).

The cement is mainly clay and clay–carbonate. The rocks have a fine- and a very fine-grained structure. Sandstone has mostly thin-layered, wave-layered and stratified structure (with a signature presence of carbonaceous–plant detritus), and, seldom, a massive texture, sometimes, with biogenic mudding. There are fragments of bivalve shells, gastropods and unidentified detritus. Subvertical and diagonal paleo-cracks are healed with secondary calcite.

Sedimentation of BV_2 stratum occurred in mostly shallow sea. At the early stage of the target stratum sedimentation, there were streams which contributed to local washout of the clay underlayer and to subsequent sandstone and siltstone deposition within these washout zones [18]. At the later stages of the productive sedimentation, general transgression started, which governed the increased content of clayey fractions in sandstone and siltstone beds in the top of the section. As a result, the spontaneous potential log curve of the most wells in the roof contain the bell-like elements typical of sandstone and siltstone sedimentations of the early stage of transgression.

These sedimentations are underlaid with the Pokachi clay sequence characterized with the abnormally low impedance for this part of the section. This is favorable for studying the properties of the target stratum. The reservoir of BV_2 stratum features a higher average interval velocity as against the clayey sediments: 3630 m/s and 3460 m/s, respectively. On the other hand, the reservoir density is lower than the clay sediment density: 2.26 g/cm^3 and 2.33 g/cm^3, respectively. The clay layers immediately atop BV_2 stratum feature an average interval velocity of 3430 m/s and an average density of 2.33 g/cm^3. The stratum BV_2 is underlaid with the low-velocity (3300 m/s upon average) and low-density (1.91 g/cm^3) series of the Pokachi Formation. The clay sediments above the pay stratum feature an average interval velocity of 3380 m/s and a density of 2.31 g/cm^3. Thus, the positive and negative reflections form at the roof and at the bottom of the test productive stratum (see Fig. 2a).

The analysis of acoustic and density characteristic shows that the reservoir features the average velocity of 3630 m/s and density of 2.26 g/cm^3. The clayey sediments have the average velocity of 3460 m/s and density of 2.33 g/cm^3. All in all, 9 synthetic models of wavefield were constructed, with the effective thickness ranged from 8 to 24 m. Then, in the target intervals of the synthetic wavefields, the attributes were extracted to study their connection with the effective thickness. The most stable connection was found between the effective thickness and two attributes—the percentage of window with half energy and the time span between the reflections formed at the roof and floor of BV_2 stratum.

The physical sense of the second attribute is of specific interest [18]. In this case, the time span between the reflections formed at the roof and floor of BV_2 stratum should be considered as a seismic attribute. An increase in this parameter is conditioned by the partial washout of the Pokachi Formation, for the first turn, and by the sandstone and siltstone sedimentation there later on (**Fig. 2b**). The circumstance governed displacement of the positive reflection toward the negative reflection nearby the low-velocity clay layers.

Mapping of the effective thickness of BV_2 stratum used the empirical connection between the effective thickness with the time span size calculated between the reflections at the roof and floor of BV_2 and the attribute "percentage of window with half energy" calculated in the window of 15 ms (between 5 ms above the roof and 10 ms below the roof of BV_2) in the real-life wavefield [18]. The connection is approximated using the formula:

$$h_{ef} = 35.9 - 0.922\Delta T - 0.153HTIME,$$

where h_{ef} is the effective thickness, m; HTIME is the percentage of window with half time, %; DT is the time span, ms.

The comparison of the integrated analysis results on the drilling and seismic survey data, with the adjustment of boundaries of facial zones, with the information acquired in the course of actual hydrocarbon production shows a stable connection between the fluid permeation and productive sedimentation features [11]. In the interwell space, the zones with and without reservoir properties are identified. The latter points at incipience of lithological screens. In the mapped paleo washout wedge, the bottom is surrounded by the Pokachi clayed sediments. During the reservoir stimulation with fluid injection, it should be taken into account that the fluid permeation will depend on the position of this paleo channel. This governs the permeation anisotropy. In this manner, inclusion of the macro heterogeneities detected by seismic surveying in the analysis enables more accurate prediction of the reservoir stimulation performance and, thereby, the enhanced efficiency of oilfield development.

There is one more benefit from using the 3D seismics data obtained during actual oil recovery. It is possible to obtain supplemental information evolution of macro heterogeneities conditioned by specifics of hydrocarbon production. For the first turn, this relates to studying variations in reservoir pressure. For instance, in the zones of operation of the injection wells, the opposite seismic anomalies arise. They are mostly governed by the decreased toughness in the zones of the decreased reservoir pressure [2, 21]. The best information on macro heterogeneities available in reservoirs is obtained from repeated performance of 3D seismics. In this case, it is possible to monitor the dynamics of the induced change in the structure of oilfields.

Conclusions

The integrated analysis of drilling and seismic survey data reveals major macro heterogeneities to be taken into account in the project of water alternating gas injection in scavenger oil fields. The critical task is to update the interwell correlation, which is of special concern in wedgeout-structure reservoirs overlaid with a scoured surface. In this case, it becomes difficult to provide lateral permeation of fluid because of the cutoff spread of reservoir layers, which also affects the sweep efficiency.

Seismic surveys can detect local screens conditioned by fractures and substituted hydrocarbon zones. Alongside with the above-said, this approach enables predicting the nature of areal change in the petrophysical parameters. The most comprehensive attention should be drawn to the analysis of the time spans between the reflections formed nearby the target pay stratum. Such petrophysical map can serve both as the seismicity and geology attribute. Inclusion of the revealed macro heterogeneities in the analysis makes it possible to predict the fluid behavior in a reservoir, which improves the reservoir stimulation efficiency.

The proposed approach to the quantitative and qualitative estimation of macro heterogeneities has been effectively implemented in geological modeling and in the water alternating gas injection designs for some Upper Jurassic and Lower Cretaceous oil reservoirs in the Surgut and Nizhnevartovsk oil and gas areas in West Siberia.

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FORMATION CONDITIONS OF SEDIMENTARY BASINS IN THE BLACK SEA–CASPIAN REGION

The article discusses formation conditions of sedimentary basins in the Black Sea–Caspian region. The system of basin-like structures includes three mega basins–Precaspian, Mysian and Aegean, and two large basin systems–Scythian–Turan and Black Sea–South Caspian. In the Paleogene–Neogene, shaping of sedimentary basins was connected with the formation of a foredeep ahead of the front of the Greater Caucasus folding. The longitudinal strike of the belt of the basin-like structures in the north of the region under consideration obeys the general strike of the zone of interaction between the Greater Caucasus folding orogeny and the Scythian Platform, which points at the dominating, at least, in the center, submeridional vectors of the regional stresses responsible for the formation of the piedmont mega basin. Farther from the mountains and toward the platform, the basin-like structures in the study region degrade, and sedimentation in the platform area, where sedimentation is geologically possible, occurs not like a basin but like a mantle.

Keywords: *formation conditions, sedimentary basins, Black Sea–Caspian region, basin morphometry series, basin analysis, sedimentary mantle, structural map*
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Introduction

The basin-like structures in the Black Sea–Caspian region include three mega basins—Precaspian, Mysian and Aegean, and two large basin-like structures—Scythian–Turan and Black Sea–South Caspian [1–7]. The Paleogene–Neogene age of the sedimentary basins is connected with the formation of a foredeep ahead of the front of the Greater Caucasus folding. The pattern of the Cenozoic basin-like structures characterizes the contemporary age of this region. The east–west strike of the belt of the basin-like structures in the north of the study regions obeys the general strike of the zone of interaction between the orogenic folded structure of the Greater Caucasus and the Scythian Platform, which