Submarine fan reservoir architecture and heterogeneity influence on hard-to-recover reserves. Achimov Fm.

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Abstract. Due to the fact that simulation model calculation is the basic method used for estimating the efficiency of a development strategy, it is necessary to design geological and simulation models within which reservoir properties and heterogeneity are defined. In addition, the estimation of the influence of various kinds of geological uncertainties on reservoir properties will allow defining a more effective development strategy.

The Achimov formation of the Vingapur oil field was considered in the current study. The northern part of the field is now quite attractive for the development of this formation. The goal of this paper was the complex investigation of petrophysical properties to make a prognosis for the field and assess the effect of geologic uncertainties on production. The first step implied studying the western part of the field where core data are available, the next stage was developing an algorithm to make a prognosis for properties and the geologic and reservoir simulation models were eventually constructed to study the effect of geologic uncertainties in the northern part. As the result of the sedimentary analysis, a model of deposition was defined within which structural elements were also determined. On the basis of wireline and core data analysis, the petrophysical model of the reservoir was build where the method of Rock Types identification using specific cut-off values for wireline logs was applied for the evaluations. In addition to this, the Hydraulic Flow unit approach was employed, which allowed estimating the less extensively explored areas of the field where core had not been retrieved from. Also, this paper provides the results of the seismic attribute analysis and calculations in order to characterize uncertainty in cumulative oil production under the influence of petrophysical and geological heterogeneity.

1. Introduction
Nowadays, the dropping number of high-quality reservoirs raises the issue of developing low permeability reservoirs that were previously considered non-promising. In Western Siberia, as a rule, these types of reservoirs were deposited in a deep-marine environment and represented by turbidite flow or gravity flow deposits. Apart from low permeability, they are also characterized by a complex geologic structure, high petrophysical heterogeneity and compartmentalization. Therefore, the study and evaluation of geologic and petrophysical heterogeneity in connection with a depositional environment, the influence of the uncertainty degree on a subsurface flow are of immediate interest. This study will provide a scenario of model refinement with geological information being useful for reservoir development and making management decisions.

The Achimov formation of the Vingapur field is extensively explored from the viewpoint of sedimentology and petrophysical heterogeneity, thus the accepted modeling approach and sedimentary environment interpretation does not reflect the reservoir complexity. The novelty of this work is in the
improvement of the depositional model, the methods of reservoir prognosis, estimation of the effect of geological uncertainties on field development.

The objectives of this work are as follows:
1. Integrated study of petrophysical properties;
2. Estimation of reservoir properties;
3. Effect of geological uncertainties on production assessment

2. General information
The Vingapur field is located in Purovsky region of the Yamalo-Nenets Autonomous District and partially in Niznevartovsky region of the Khanty-Mansi Autonomous District, and is geographically located in the northern part of the West Siberian Plate [1].

The Lower Cretaceous deposits are represented by the Megionskaya group conformably underlain by Bazhenov formation argillites. The top of the Megionskaya group is represented by the BV8 formation with the biggest share of production amounts. The bottom of the group consists of predominantly shales being 10-30 m thick. The Achimov formation is above it and is highly variable laterally and vertically. Lithologically, the formation consists of fine-grained sandstones interbedded with siltstone and shale within argillites, there are also thin layers of sandstone and siltstone being 1-40 mm thick. Horizons BV8, BV7 are located above the Achimov formation. The age of the Megionskaya group is Berriasian-Valanginian (K1b-v) [13].

3. Field geologic structure
This section summarizes the data and results of the previous studies related to the geologic architecture and genesis of the Achimov formation that are relevant to this particular study. The first concept of the Achimov formation was proposed by Gurari in 1959. According to it, it is composed by laterally and vertically extensive lenticular beds consisting of sandstone and siltstone [6]. The fact that nowadays the genesis and architecture of the Achimov formation is an open question is quite important. Thus, it was assumed that sedimentation occurred here as the result of common transgression [1]. Some authors relate the Achimov formation to submerged shoals [10], where the architecture was associated with a sea bed relief and submarine currents. The clinoform Neocomian architecture was introduced by Naumov, according to which the deposits of the same age plunge in the basin-ward direction with facies variability [6]. The shelf zone represents the place of erosion and sedimentation depending on sea level variations and amount of deposits. Filling-in the fondoform part was related to the prevalence of the sedimentation velocity over the rate of sea bed sinking. According to the Naumov theory, turbidity currents and slumps were the prevailing mechanisms of sediment transport. The seismostratigraphic complexes include the undaform (shallow marine environment), the clinoform (shelf slope) and the fondoform (slope base), according to Peiton terminology [12]. The individual parts of seismic cyclite are related genetically, whereas seismic cyclite itself has a sigmoid shape. Thus, based on the regional 3D seismic surveys, it can be inferred that the area of the Vingapur Neocomian deposits has a three-stage structure with steep angles of the upper transgression complexes, typical presence of the fondoform part of a significant thickness deeply advanced in the western direction, that is a part of a lower, more regressive cycle of sedimentation [4].

Depending on the flow density, the coherency of sediments, the shale content and position relatively to the shelf slope type of process may change from a slide, slump to debris flow and turbidity current [15]. The type of this process determines the dimension and geometry of the sand bodies, while from the reservoir point of view its petrophysical properties are closely linked with the energy of the current, position in the depositional environment [15]. The fact that similar structures can be related to different types of processes brings an additional uncertainty in interpretation.

The facies distribution within the reservoir, interaction between them lies within the stratigraphic and structural framework where reservoir connectivity has a significant influence on the subsurface flow. The first step is recognizing the reservoir boundaries of various orders related to sequence boundaries, which is commonly implemented using 3D seismic surveys. [8]. Next, with the sufficient
3D seismic quality and resolution, it is possible to reveal facies distribution within the defined structural framework according to the difference in the acoustic properties on the boundaries between facies units [11].

Petrophysical heterogeneity in turbidity reservoirs is reflected in variable permeability within several orders of magnitude for the given values of porosity, therefore it is quite important to determine major factors controlling reservoir quality in order to appropriately predict it in the model. In this study, the authors [3, 7] suggest an approach to rock type discrimination based on differences in the pore throat size, lithology, particularly in the shale volume content. In work [2], the authors used the Multi-Resolution Graph-Based Clustering method with Facimage where data points could be clustered in multi-dimensional space for log facies prediction. The log identification was based on certain cut-off values defined on the basis of the cross plot of grain density versus the absolute value of the separation between the resistivity in the washed zone and the true formation resistivity characterizing the effectiveness of mud filtrate propagation in the reservoir. It was established that the deposition processes, as well as the diagenetic alteration, have an impact on porosity and permeability distribution within the reservoir. The authors also studied the statistical moments of grain size distribution versus permeability and porosity and it was concluded that permeability is a function of the skewness and standard deviation rather than grain size [5].

As a rule, facies distribution within the reservoir plays a significant role in a subsurface fluid flow. Uncertainties in this parameter connected with the lack of knowledge about distribution, connectivity and poroperm properties may cause variations in displacement efficiency, production and economic values. The example of such an uncertainty study in a turbidite reservoir is represented in work [9].

Net oil, sweep efficiency and cumulative recovery factor were chosen as the measures of uncertainty.

4. Workflow
The first part of the present study is focused on the western part of the Vingapur field description due to the fact that this area is characterized by such core data that make it possible to validate formation evaluation results. On the basis of sedimentary logs, the model of the depositional environment was constructed. After that, an attribute analysis was carried out in order to define the distribution and shape of the sand bodies on a large scale. It must be said that it was decided to perform the re-interpretation of the depositional environment due to the fact that it stated the common features of the Achimov formation that were defined in other fields. Thus, it was suggested in general that this formation represented turbidity current deposits, slump, mass flow deposits with elements of sand waves. Therefore it was decided to define the particular type of deep marine deposits in order to infer significant architectural elements from it.

Further, a petrophysical analysis was made after the sedimentary environment description. It was meant to estimate the degree of formation heterogeneity using statistical techniques. On the basis of the poroperm data and wireline response, Rock Types were defined with the use of specific cut-off values on the basis of the Hydraulic Flow Unit approach. After Rock Typing, the correlation on the basis of wireline logs was carried out in order to investigate the inter-well correlation of the formation itself and the Rock Types within it. Eventually, as the result of the first part of the study, the petrophysical and geological heterogeneity of the Achimov formation was described, controlling factors were defined and the relation with the processes of deposition was established. The authors also defined an approach making it possible to predict poroperm values based on Rock Types in areas that are not characterized by core data, but are close enough to make one suggest a similar sedimentary environment.

An attribute analysis was also performed in the northern part for two purposes: first – to validate the assumption about depositional environment similarity and second – to plot porosity and Net-to-Gross maps. It was subsequently used to define the trends of these properties. Further, on the basis of the acquired data, several geological and simulation models were constructed. The simulation results
of these various models were analyzed in order to define the degree of heterogeneity distribution within the formation in terms of production and well performance.

5. Results. Sedimentary Environment

It should be noted that the successions in the wells under study have a similar character and interpretation as turbidites. It should be noted that there is a possible alternative interpretation of sedimentary processes in the area under consideration. This uncertainty in interpretation is illustrated in figure 1. Despite the similarity of structures in these two interpretations, there is a significant difference in the processes of deposition. A turbidity current implies a turbulent flow, while a debris flow suggest a laminar flow, where mudclasts typical of turbidite in the debris flow interpretation are oriented parallel to the mass flow suggesting a linear flow. Also, (C) the Bouma division may represent the evidence of the bottom current reworking of sediments [14]. The conceptual model of deposition is represented in figure 2. On the basis of core description, attribute analysis and seismic interpretation, it may be concluded that the sandstones and siltstones of the Achimov formation were deposited in the basement of the shelf slope. Despite the uncertainties in interpretation, the turbidity model of deposition where sediments were deposited in a channelized lobe system (figure 2) was selected for further studying.

![Bouma Divisions](image)

**Figure 1.** Interpretation [14]
6. Attribute analysis in the western part of the field

In order to identify depositional features, the large-scale interpretation and attribute analysis of seismic data were carried out. The seismic resolution is sufficient for analyzing the Achimov formation with the average thickness of about 100 m, but it is insufficient to clearly resolve individual beds with the thickness of less than 10 m suggesting the presence of the tuning effect, as it can be seen from the time cross-sections.

From the average energy attribute calculated between the surfaces of the ACH top (the top of the Achimov formation) and B (the top of the Bazhenov formation) in a 20 ms window, the amalgamated system of individual fans represented by the ACH2 and ACH3 horizons deposited in a depression on the shelf slope can be inferred. The evidence of the shelf edge progradation can be seen in the east. Surface attributes, Variance and Envelope, were calculated in search window 15 ms below the ACH2 top in order to minimize the edge effect related to the pinching out of the formation. On this attribute maps, one can definitely see the evidence of the channel (figure 3) of sediment transport on a shelf slope that further turns into a submarine fan system.

The time section in the normal direction and in the direction being parallel to the sediment flow reveals the architecture of these deposits. The Achimov formation is pinching out in the western direction, and has a lenticular shape in the normal cross-section that coincided with the suggested depositional environment. It is a typical Neocomian clinoform structure that has a sigmoid shape and is prograding basin-wards. During the detailed examination of the time cross-sections of the impedance cube in direction being normal to the shelf edge, one can see anomalies that are related to the downcutting of the submarine fan system and the evolution of the geometry from proximal to distal parts (figure 4). The following sections of this work are focused on the petrophysical heterogeneity description of the Achimov formation in order to define the model of deposition.
When analyzing dependences for the Achimov formation, one should note that this formation is characterized by the high degree of permeability heterogeneity, thus, for example, with the porosity value being equal to 0.17, the value of permeability may vary within several orders of magnitude. Therefore, it is necessary to employ methods focused on defining certain dependences within the data point cloud.

With due account for the methods revised previously, it was decided to define specific lithotypes corresponding to particular lithology and including specific petrophysical information and related to some defined elements of the depositional environment. The integration of HFU and rock types allows classifying and defining rock types not only on the basis of lithology, but also from the viewpoint of
the depositional environment and providing information about petrophysical properties related to pore geometry.

The first step in rock type discrimination was the definition of the boundary conditions of specific cut-off values on the basis of wireline log curves. Using the values of neutron and gamma ray tools, the authors distinguished between tight sandstones and siltstones being essentially non-reservoir rocks. Further, they identified thin interbedded shales and siltstones using the cross plot shown in figure 5a. After the discrimination of non-reservoir rock types, the cross section still comprises intervals consisting of sandstone and siltstone. To discriminate these lithology types, the authors used the cross plot of Gamma Ray versus apparent bulk density defined on the basis of a density tool response (figure 5b). The application of this type of curves is governed by the fact that these two methods are mutually independent, which in turn provides a more reliable subdivision of rocks. Speaking about the application of the other wireline logs, it should be noted that the sound wave velocity depends on density that as the result leads to the overlapping of data points complicating subdivision.

During the next step, Hydraulic Flow Units (HFU) were defined within the sandstone and siltstone intervals. In this case HFU are directly related to the defined lithology.

Next, on the basis of Gamma ray and Later log tools having quite a high definition from log suite were acquired for the Flow Zone Indicator predictor.

On the porosity versus permeability cross plot, Rock Type 1 is well-defined, while Rock Types 2 and 3 are overlapping with Rock Type 4 that is a transitional variety between sandstone and siltstone. This function was approximated by the third-order polynomial equation using a multiple regression approach in Statistics software.

\[ FZI_{log} = -22.52 - 1.23 \times BK + 0.17 \times BK^2 - 0.0067 \times BK^3 + 11.83 \times GR - 1.79 \times GR^2 + 0.089 \times GR^3; \]

Eventually were established the following cut-off values:

- Rock Type 1 if (DENSITY < 2.4 and GR < 6.5) and (FZI_log > 0.78 and FZI_log < 2.17);
- Rock Type 2 if (DENSITY < 2.4 and GR < 6.5) and (FZI_log > 0.46 and FZI_log < 0.78);
- Rock Type 3 if (DENSITY < 2.4 and GR < 6.5) and (FZI_log > 0.1 and FZI_log < 0.46);
- Rock Type 4 if (DENSITY > 2.4 and GR > 6.5) and (FZI_log > 0.43 and FZI_log < 2);
- Rock Type 5 if (DENSITY > 2.4 and GR > 6.5) and (FZI_log > 0.1 and FZI_log < 0.43);
- Rock Type 6 if GR > 7.3 uR/hr;
- Rock Type 7 if NKTD > 3.73uE;

The average properties and description of the defined rock types are represented in figure 6.

![Figure 5. GR vs. Neutron tool response cross-plot (a) and GR vs. density tool response cross plot (b)](image-url)
8. Permeability heterogeneity

For the purpose of permeability heterogeneity assessment, well 492PO located in the proximal part of the submarine fan system and well 612R located in the distal zone were chosen. According to the values of Coefficients of variation and Lorenz, the formation in the area of well 612R is more heterogeneous, which can be explained by the depositional environment. Besides, well 612R is located farther from the bottom of the shelf slope, therefore, the distance from the sedimentary source is

![Figure 6. Rock type characteristics](image)
longer, corresponding to the middle-distal part of the channelized lobe complex. This difference in the position controls the degree of properties degradation in the formation.

9. Statistical analysis of grain size distribution
The next step after the sedimentary environment analysis and Rock Types identification was the analysis of statistical moments of grain size distributions in order to define parameters controlling the porosity and permeability of the formation.

It can be seen from the permeability vs. median grain size relation that there is a trend towards permeability increment with the grain size. Besides, the correlation for Rock Type 1 is quite high while that for other Rock Types is not so robust. Permeability increases with improvement in sorting as well and, according to the standard deviation values, varies from moderate to poorly sorted. One can see from the plot that the deposits in the distal part of the submarine fan system and reworked by bottom currents and their sorting is better.

The skewness in distribution shows that the prevalence of fines is typical of all Rock Types, although there is a trend towards permeability increment when distribution is skewed to coarse grains, the relations are not robust and characterized by significant scattering. It should be noted that the major factor apart from statistical moments is the lithological composition of rocks that is directly related to the depositional environment, the energy of a sediment flow that, in turn, resemble the defined Rock Types.

10. Prognosis for the reservoir properties of the northern part
The second part of the study implied the translation of methods of properties estimation from the western part to the northern one using a defined algorithm for Rock Types identification, and petrophysical relations for Rock Types on the grounds of the fact that according to regional 3D seismic surveys, using seismic facies identified the presence of a submarine fan system in both zones being parts of the same depositional system. In addition the formation has a fixed stratigraphy position and located within the same field.

The application of seismic attributes and time sections allowed evaluating the sand body geometry and depositional environment elements. Prediction was carried out using nine basic wells where the average values of porosity and NTG were calculated in the interval of the ACH2 horizon. The typical structure of the Neocomian anticlines can be seen on the time cross-sections.

Porosity prediction was based on the calculated attributes employing multiple regression where the coefficient of correlation was $R^2=0.92$. With a similar multiple regression tool, a function for the NTG prognosis with the coefficient of correlation, $R^2=0.79$, was received.

The calculated porosity and NTG maps are represented in figure 7. The porosity map analysis shows that higher porosity values belong to the central zone, while the average porosity values decrease as they approach the proximal zone. The NTG values in the proximal eastern part are higher due to the proximity to the sedimentary source and significant erosion resulting from higher flow energy.
11. Effect of geological uncertainty on subsurface flow estimation

Rock types within the model were distributed using the Sequential Indicator Simulation algorithm of pixel modeling. Type 1 model represents a simple structure consisting of a reservoir and non-reservoir unit being the present approach to Achimov formation modeling at V-Field. The model belonging to the second type includes Rock Types, where Rock Type 6 and 7 are non-reservoir and correspond to tight rocks and thin bedded shales and siltstone. In the model of the third type, shales and tight rocks were assigned as discrete bodies with the correlation range being equal to 100 m representing the case when carbonatization zones are locally developed whereas shales have a small length. The model belonging to the fourth type comprises shales and tight rocks with a correlation range being equal to 2,500 m. These bodies are laterally extensive, and it is also a probable scenario. The fifth model is based on the model with extensive non-reservoir rocks with changed transmissibility between Rock Types being equal to 0.1 that represents the absence of erosion between the reservoir units and can have thin layers of shale between them being a barrier to flow. The conceptual schemes of the models are presented in figure 8. Figure 9a provides the comparison of the simulation results for type 1 and type 2 models. Cumulative production in case of a simple model is higher in 70,000 m³, which is connected with the absence of reservoir heterogeneity related to the reservoir architecture, while the prognosis based on the model comprising the full set of submarine fan depositional elements represented by Rock Types gives more pessimistic results.

The next figure 9b compares the third and the fourth models. The plot of cumulative production shows that production is higher in 40,000m³ for the model with continuous shales and tight rocks. As a result, the presence of the significant amount of small-scale heterogeneities prevents a subsurface fluid flow that, in turn, leads to heterogeneity incensement and related to a production decrease.

The presence of laterally extensive units leads to reservoir homogenization, which results in a production increment, but due to the early breakthrough, production rates subsequently demonstrate the same trend. Figure 9d presents calculation results for the model where the coefficient of permeability anisotropy varies from 0.1 to 1 representing extreme cases. Cumulative production for the case with high Kv/Kh is less in 20,000 m³, which is connected with a vertical permeability restraint. Initially, the difference in the rates is not so significant, even if water breakthrough occurs. Simultaneously, the rate of water cut for the case when Kv/Kh=1 is higher, which leads to higher production rates. Figure 9c presents the results of calculation for the fifth and the second models. Cumulative production for the case where there are erosional boundaries between the Rock Types is higher in 45,000m³. The occurrence of such contacts may be related to the erosion of Rock Types by the Rock Type 1 that is associated with the channel axis. Thus, increasing transmissibility between the units, which, in turn, leads to higher production, occurs as the result of erosion.
The influence of transmissibility between the Rock Types on water flooding effectiveness was further analyzed. Figure 10 shows the slice of a geologic model that represents the distribution of Rock Types and oil saturation for the cases with various unit transmissibility levels. In the first case, the propagation of the displacement front within the units is more frequent than between the units. As one can see from figure 10, the displacement in Rock Type 1 corresponding to the channel axis is more effective. It is less effective in Rock Type 2, as it has poorer reservoir qualities. The worst results are for the region of Rock Type 3. It must be said that due to the transmissibility reduction between the units, the spatial organization of the units becomes more significant. In addition, erosion leads to an evenly distributed displacement front and more symmetrical saturation distribution within the element of development (figure 10).

![Figure 8. Types of models used for simulation](image)

![Figure 9. Simulation results](image)
12. Conclusions
The present study allows making the following conclusions:

1. The Achimov formation of the Vingapur field is a complex system of amalgamated channelized lobes where parts of this system are represented by specific Rock Types associated with structural elements: axial part represented by massive fine grained sandstone (Rock Type 1), off-axis part composed of cross-beded very fine-grained sandstone (Rock Type 2), farther from the lobe, the axis is represented by very fine-grained sandstone interbedded with shales (Rock Type 3). The distal deposits of the lobe also include massive siltstone in the axial zone and siltstone interbedded with shales in the off-axis zone.

2. The authors applied the method of Rock Types Identification using certain cut-off criteria for the Wireline log curves and Hydraulic flow unit approach. An algorithm for properties and Rock Types prognosis within the field based on Wireline logs were only proposed on this basis.

3. According to the calculation results, permeability heterogeneity increases from the proximal to distal zones of the submarine fan system. There is a trend towards the increase in NTG from the proximal to the distal part and also higher porosity values are associated with the central zones on the basis of the attribute analysis.

4. The main factor controlling permeability is variations in lithology related to depositional environment elements.

5. The main influence on production is exerted by the complexity of reservoir representation in the model, additional details lead to a more pessimistic prognosis.

6. Reservoir heterogeneity grows in case of discrete shales and tight rocks, which prevents a subsurface fluid flow, while the reservoir is more homogeneous in the laterally extensive case, which leads to a production increase. The type of contacts between the units is also quite significant, the barriers between the units impede the inter-unit flow leading to displacement front propagation preferentially within the units.

Figure 10. Slices of simulation model representing oil saturation distribution in case: (a) without erosion, (b) with erosion
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