Reconstruction of facies conditions of the sedimentation of bitumen-bearing sandstones according to granulometry data (Volga-Ural oil and gas province, Russian Federation)

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Abstract. For 60 years in the Volga-Ural oil and gas province, the study of Paleozoic sediments was carried out taking into account their industrial oil and gas potential. Therefore, the most studied are deposits of the Devonian and Carboniferous periods. Today, most of the Devonian and Carboniferous oil fields are close to depletion. In recent years, in order to maintain production volumes, oil companies are increasingly focusing on the study of Permian deposits, in which significant resources of natural bitumen and super-viscous oils are concentrated. Their industrial resources are associated with psammite (sandy) deposits of the Sheshmian horizon of the Ufimian stage of lower-Permian period. In this regard, the task of a more detailed study of the conditions for the formation of Sheshmian deposits, which are characterized by a complex geological structure, is becoming ever more acute. Formation conditions affect the spatial distribution and features of geological structures, the definition and refinement of which is important for building high-quality 3D geological models and improving the efficiency of exploration and development of deposits. To determine these characteristics, facies analysis is successfully used, which is carried out on the basis of granulometric and mineralogical studies of sediments to obtain ideas about sedimentation conditions. Lithological-facies studies also make it possible to determine the structural features of the terrigenous rock and its reservoir properties.

1. Introduction

For 60 years, in the Volga-Ural oil and gas province, priority in the study of Paleozoic sediments has been given to sediments that had the greatest potential oil and gas potential. Therefore, the most studied are deposits of the Devonian and Carboniferous periods. Today, most of the Devonian and Carboniferous oil fields are close to depletion. In order to maintain hydrocarbon production, regional oil campaigns are increasingly focusing on the study of Permian deposits, which are concentrated in significant deposits of natural bitumen and super-viscous oils. Their industrial resources suitable for the nearest development are associated with psammite (sandy) deposits of the Sheshmian horizon of the Ufimian stage [1]. Sheshmian deposits occur in the eastern part of the East European platform within the Volga-Ural anteclise. They are located on the western slope of the South Tatar Arch [1, 2]. The horizon is divided into two packs, the lower is clay-sandy and upper is sandy. A clay-sandy pack is represented by clays, siltstones, with rare interbeds of sandstones and carbonates. The upper, sandy pack
is mainly represented by fine-grained sandstone and a small amount of siltstone. The composition of the clastic part is represented by rock fragments, quartz, and a small amount of feldspars. Sands and sandstones of this pack are characterized by varying degrees of cementation and bitumen saturation. Bitumens are concentrated in positive-type structures that extend in a northeastern direction. In connection with the increasing importance of the bitumen deposits of the Sheshmian horizon, the task of a more detailed study of the conditions of accumulation of these deposits is arise. The primary conditions of sedimentation determine the reservoir properties of reservoirs, their structure and localization. For a long time, various geologists put forward theories and arguments about the conditions of sedimentation of these deposits, such as the alluvial, delta, bar, shallow-coastal genesis of these deposits. One of the latest opinions about the origin of the studied horizon was the assumption of the polygenetic formation of the Sheshmian horizon [2]. According to this, all the mineral material of the horizon was transported to the coast of the Paleo Sea by river flows from the slopes of the ancient Urals. Initially, the entire horizon had a homogeneous sandy-clay mineral composition. However, later the upper part of the formed horizon was higher than the surface of the sea and experienced the influence of aeolian activity. This led to the removal of the clay component and the formation of domed bodies elongated in lines parallel to each other. Based on this position, one can explain the division of the initial horizon into two parts (lower and upper), as well as the difference in mineral composition between them, the morphology of sand bodies and their spatial distribution.

Despite a wide range of opinions regarding the conditions of sediment formation, the problem of sedimentation conditions of the Sheshmian deposits has not disappeared so far and requires a more detailed facial analysis. According to the authors, a significant difference of opinion regarding the origin of the studied object is associated with many processes superimposed on the horizon during its long formation. These include the tectonic movements of the territory [3], post-sedimentation processes, the influence of hydrothermal processes in the crystalline basement on the oil content of the sedimentary cover, and even the effect of radioactive elements. In this work, based on granulometry and mineralogical studies, a facial analysis was performed, the results of which were used to determine the conditions for the accumulation of sandstones of the Sheshmian horizon.

2. The methodology

At the first stage, an optical microscopic description of rocks in transparent thin sections was carried out in order to describe the composition, texture and structural features of the samples. As a result, the samples were subdivided into three lithotypes, differing in the degree of their cementation and bitumen saturation. The second stage of the study was to conduct particle size analysis by means of a sieve analysis on a Fritsch Analeset 3 apparatus according to the German standard with the following sizes: 1 mm, 0.8 mm, 0.63 mm, 0.5 mm, 0.315 mm, 0.16 mm, 0.08 mm, 0.063 mm, 0.032 mm, 0.025 mm, with preliminary crushing of cemented samples. Based on the results obtained, tables were constructed with the percentage of each detected dimension of the fraction, and histograms and cumulative curves were constructed from them to obtain primary ideas about the vertical change in the dimension of the fraction and obtain statistical particle size parameters. The obtained statistical parameters were used for a complex of methods for the genetic interpretation of particle size data and for a more accurate prediction of sedimentation conditions. For this, histograms are constructed from statistical data, which serve as the primary stage of the graphic processing of the obtained data. Based on these cumulative table data, cumulative curves were constructed on a semi-logarithmic scale. On the y-axis, the dimension of the fraction was plotted on a logarithmic scale, on the x-axis, the percentage of the fraction. The logarithm of the size of the fraction was carried out according to the Krumbein method [4]. Then, statistical parameters were calculated from the graphs of cumulative curves using the graphical formulas of Folk and Ward. The graphical method for determining statistical parameters, or as it is also called the quantile method, is based on taking certain percentiles from the diagrams manually, and then using them to calculate statistical coefficients. [5]. In addition to them, formulas for calculating the standard
deviation using the Trask method were also used. The standard deviation is determined from the ratio of the first quartile to the third, the first quartile is 25%, the third quartile is 75%, on the cumulative graphs, along the percentage fraction axis, where the percentage is taken 25%, along it along the abscissa, i.e. the axis, where the dimensions of the grain fractions in mm are converted according to the Krumbein scale to the dimension $\Phi$, then the size of the fraction is determined in the same way by 75% [4]. The choice of the logarithmic scale is due to its wide recognition and distribution. For an initial orientation on the genetic affiliation of sediments, we used the generalized data of Fuhtbauer and Muller, where the facies affiliation at the level of the continental, river, and marine facies was determined taking into account the dynamic regimes affecting sorting in them [6]. Then, the genesis of deposits was determined by the ratio of asymmetry to the average deviation according to the K. Bjorlykke chart [7], followed by the use of the K.K. Gostintsev, based on the ratio of asymmetry and excess. To determine the conditions of sedimentation and hydrodynamic conditions, dynamogenetic diagrams of G.F. Rozhkov and R. Passegi [5].

3. Results and Discussions

According to the results of optical microscopy analysis, the studied rocks were divided into three lithotypes: bitumen-saturated sands, bitumen-saturated sandstones, and residually bitumen-saturated sandstones. All three lithotypes are characterized by the same composition represented by quartz, rock fragments, feldspars and belong to the category of quartz graywack [8]. Their differences lie in the fact that sandstones are characterized by varying degrees of carbonate cementation and bitumen saturation.

**The first lithotype** is formed by black bitumen sands. They have a small amount of cementitious substance no more than 5-10%. Carbonate cement is distributed in the rock fragmentarily, in the form of clots on the rock fragments and does not cement the rock in its entire volume. In view of this, sandstones have a large open porosity and, as a consequence, high bitumen saturation.

**The second lithotype** is represented by cemented bitumen-saturated sandstone. These are samples of black and dark brown color, characterized by contour incomplete distribution of carbonate cement, which binds into a relatively dense rock. Due to the low cement content of 10-15%, good grading of clastic material, which provide good, open porosity, the rocks are also very saturated with bitumen.

**The third lithotype** is sandstones residually bitumen-saturated. They are characterized by a relatively high content of carbonate cement of 20%, closed cement, incomplete pore cement, and a high content of silt fraction, which affects the sorting of clastic material, and hence the porosity of the rock. Because of this, this lithotype is characterized by the absence of visible bitumen saturation and gray or gray-green colors.

Granulometric analysis was performed to characterize the clastic component of the studied lithotypes of sandstones. A total of 7 samples were investigated, of which samples 2 and 13 correspond to the first lithotype, 1, 11, 20 - to the second, 29, 44 - to the third. According to the results of particle size analysis, percentages of each fraction of the composing rock and cumulative data on the fractions were obtained. The results of particle size analysis are shown in tables 1 and 2.

Based on the data obtained, the patterns of the distribution of debris fractions along the section of the well that exposed the sandstones of the Sheshmian horizon were analyzed. The results are reflected Fig. 1 and 2.
Table 1. The particle size distribution of sandstones of the P1uss layer of the Ashalchinsky field

| Sample Number | Lithotype | Depth, m | Fraction size, mm | The content of fractions, % |
|---------------|-----------|----------|-------------------|----------------------------|
|               |           |          | >0,15             | 0,315-0,16                 | 0,16-0,08                  | 0,08-0,063                | 0,063-0,032 | 0,032-0,025 | <0,025   |
| 1             | 2         | 63,8     | 9,5               | 67,5                        | 83,47                      | 89,83                     | 97,46        | 99,19        | 100       |
| 2             | 1         | 64,9     | 4,7               | 87                          | 96,24                      | 98,11                     | 100          | 100          | 100       |
| 11            | 2         | 70,6     | 1,57              | 77,02                       | 91,62                      | 94,21                     | 100          | 100          | 100       |
| 13            | 1         | 71,9     | 1,66              | 74,52                       | 90,34                      | 95,14                     | 100          | 100          | 100       |
| 20            | 2         | 78,5     | 2,85              | 83,77                       | 92,99                      | 94,89                     | 100          | 100          | 100       |
| 29            | 3         | 85,1     | 3,82              | 72                          | 15,55                      | 3                         | 5,63         | 100          | 100       |
| 44            | 3         | 93,4     | 2,28              | 67,93                       | 90,26                      | 94,75                     | 100          | 100          | 100       |

Table 2. Cumulative data on the particle size distribution of sandstones in the P1uss layer of the Ashalchinsky field

| Sample number | Lithotype | Depth, m | Fraction size, mm | Content fractions, increasing percentage |
|---------------|-----------|----------|-------------------|------------------------------------------|
|               |           |          | >0,315            | 0,315-0,16                 | 0,16-0,08                  | 0,08-0,063                | 0,063-0,032 | 0,032-0,025 | <0,025   |
| 1             | 2         | 63,8     | 9,5               | 67,5                        | 83,47                      | 89,83                     | 97,46        | 99,19        | 100       |
| 2             | 1         | 64,9     | 6,7               | 87                          | 96,24                      | 98,11                     | 100          | 100          | 100       |
| 11            | 2         | 70,6     | 1,57              | 77,02                       | 91,62                      | 94,21                     | 100          | 100          | 100       |
| 13            | 1         | 71,9     | 1,66              | 74,52                       | 90,34                      | 95,14                     | 100          | 100          | 100       |
| 20            | 2         | 78,5     | 2,85              | 83,77                       | 92,99                      | 94,89                     | 100          | 100          | 100       |
| 29            | 3         | 85,1     | 3,82              | 75,82                       | 91,37                      | 94,37                     | 100          | 100          | 100       |
| 44            | 3         | 93,4     | 2,28              | 67,93                       | 90,26                      | 94,75                     | 100          | 100          | 100       |

Figure 1. Grain size frequency histogram of a samples of oil well
Figure 2. Cumulative percentage frequency curves showing differences between samples of oil well

Then, statistical parameters were calculated from the graphs of cumulative curves using the graphical formulas of Folk and Ward), which are considered the most popular and universally used. In addition to them, formulas for calculating the standard deviation according to the Trask method were also used. The graphical method (Folk and Ward method) for determining statistical parameters, or as it is also called the quantile method, is based on taking manually determined percentiles from the diagrams, and then using them to calculate statistical coefficients.

In the course of the work, the following parameters were calculated: asymmetry (A), measure of excess (E), standard deviation, or sorting coefficient (S₀), median size (Md), maximum size of the coarse-grained fragment material (C).

The asymmetry coefficient (A) was determined by the formula (1):

\[ A = \frac{\varphi_{84} + \varphi_{16} - 2 \times \varphi_{50}}{2 \times (\varphi_{84} - \varphi_{16})} + \frac{\varphi_{95} + \varphi_{5} - 2 \times \varphi_{50}}{2 \times (\varphi_{95} - \varphi_{5})}, \quad (1) \]

where \( \varphi_{5}, \varphi_{16}, \varphi_{50}, \varphi_{84}, \varphi_{95} \) are the values of the particle size on the Krumbeine scale for 5%, 16%, 50% and 95%, respectively, according to the graph of the cumulative curve;

The measure of excess (E) was determined by the formula (2):

\[ E = \frac{\varphi_{95} - \varphi_{5}}{2.44 \times (\varphi_{75} - \varphi_{25})}, \quad (2) \]
The sorting coefficient ($S_0$) was determined in two ways, according to the Folk and Ward formulas, and the Trask method, this was due to the fact that different methods for paleoreconstruction use the sorting coefficient ($S_0$) in different calculation forms.

The sorting coefficient ($S_0$) according to Folk and Ward is calculated by the formula (3):

$$S_0 = \frac{\Phi_{94} - \Phi_{16}}{4} + \frac{\Phi_{95} - \Phi_{5}}{6.6}, (3)$$

The sorting coefficient ($S_0$) according to Trask is calculated by the formula (4):

$$S_0 = \frac{Q_{25}}{Q_{75}}, (4)$$

where $Q_{25}$ and $Q_{75}$ is the particle size in mm for 25% and 75%, respectively, according to the cumulative curve graph;

The median (Md) was determined by 50% along the ordinate axis on the cumulative curve graph and was recorded in two dimensions. In the dimension of the $\Phi$-scale according to Krumbeine and in mm. The maximum size of the coarse-grained part of the detrital material (C) was determined by removing the size of the fraction, expressed in $\Phi$, corresponding to 1% on the percent axis (ordinates).

The importance of determining and analyzing these parameters is due to the fact that each of the parameters contains a certain part of information about sedimentation conditions. Asymmetry (A) provides information on the results of the interaction of the processes of differentiation and integration of various particle size associations at the relative energy level of the sedimentation medium, which is determined mainly by the average median size (Md).

The excess parameter (E) indicates the stability of the dynamic processing and re-sorting of clastic material at this relative energy level.

The sorting coefficient ($S_0$) indicates the degree of uniformity of particle size distribution and is not related to the estimation of dynamic forces, however, it is used by many scientists together with other statistical parameters to determine sedimentation conditions [6].

Coefficient (C) is defined as a 99% quartile, this is the size of the largest grains, which make up 1% of the total mass of debris, characterizes the maximum flow capacity [4]. The calculation results are shown in table 3.

| Sample № | Lithotype | Depth, m | A | E | Md, mm | $S_0$ by Folk and Ward | $S_0$ by Trask | C, mm |
|----------|-----------|----------|----|----|--------|-------------------------|-----------------|------|
| 1        | 2         | 63.8     | 0.469 | 1.3 | 0.202 | 0.93 | 1.99 | 0.493 |
| 2        | 1         | 64.9     | 0.117 | 1   | 0.222 | 0.4 | 1.46 | 0.469 |
| 11       | 2         | 70.6     | 0.371 | 1.6 | 0.207 | 0.6 | 1.53 | 0.376 |
| 13       | 1         | 71.9     | 0.384 | 1.4 | 0.204 | 0.62 | 1.57 | 0.379 |
| 20       | 2         | 78.5     | 0.345 | 1.7 | 0.218 | 0.55 | 1.46 | 0.428 |
| 29       | 3         | 85.1     | 0.376 | 1.5 | 0.209 | 0.63 | 1.57 | 0.442 |
| 44       | 3         | 93.4     | 0.387 | 1.3 | 0.198 | 0.68 | 1.66 | 0.407 |
As a starting point, the starting point in the determination of sedimentation conditions was used generalized information on the particle size parameters of the Fuhtbauer and Muller [6]. In their work, such parameters as asymmetry and sorting coefficient calculated by the Trask method [4] were considered and three basic sedimentation conditions were determined by these parameters: river, aeolian and marine.

According to Fuhtbauer and Muller [6], river environments may include precipitation with sorting greater than 1.2 and asymmetry, as a rule, less than 1 or sometimes more than 1, also for river environments, a decrease in particle sizes upstream is typical. The floodplain is characterized by a sorting of more than 2, the asymmetry is always less than 1. Aeolian environments, in their opinion, have a good sorting, asymmetry is less than 1, a slight variation in grain sizes along the vertical section is characteristic. The median diameter is mainly 0.15–0.35 mm, these parameters are characteristic of sand dunes, loess is characterized by poor sorting, asymmetry is less than 1, the median diameter is less than 0.1 mm. For marine-related beaches, the best sorting is typically 1.1–1.23, with more than one asymmetry. Shallow-water marine deposits are characterized by good sorting, asymmetry less than 1. Deep-sea deposits are characterized by a finely divided fraction, clay can be attributed to them. This method is useful for preliminary detection of sedimentation conditions [6].

As a result, the studied samples were assigned mainly to the aeolian environment, with the exception of samples 1 and 44. The last two samples are characterized by average sorting according to the Trask classification, which corresponds more to river environments, since aeolian species are characterized by good sorting according to the Trask classification. According to the classification of P. Trask, well-sorted precipitation (S₀ = 1.0–1.58), medium-sorted precipitation (S₀ = 1.58–2.12) and poorly sorted precipitation (S₀ > 2.12) are distinguished [4].

Good sorting, which falls in the interval S₀ = 1 - 1.58, speaks in favor of the aeolian environment of samples 2, 11, 13, 20, 29; asymmetry <1 and slight vertical grain size fluctuations [4].

Samples 1 and 44 are more typical for river environments, since their sorting is average, within S₀ = 1.58 - 2.12; asymmetry <1 [4].

To assess the degree of sorting of the sand material and to clarify the facies conditions for the formation of Sheshmian deposits, the diagram of K. Bjorlykke was used [7]. This is one of the relatively simple diagrams; it is based on different relationships of sorting and the nature of the asymmetry of the distribution of fractions of sand-silt rocks.

![Diagram](image)

**Figure 3.** Sorting asymmetry ratio in clastic sediments of various environment for the well by K. Bjorlykke diagram [7]
As can be seen from the diagram (Fig. 3), samples 2, 11, 13, 20, 29 formed in field II, which corresponds to aeolian deposits. Thus, the listed samples can also be attributed to aeolian formations by the ratio of asymmetry to mean deviation. Samples 1 and 44 are in field III and correspond in their parameters to river sedimentation conditions.

Based on the obtained statistical parameters of asymmetry and kurtosis, K.K. Gostintsev and G.F. Rozhkov [5], and samples are marked on them. The diagrams presented below are based on an analysis of the asymmetry – excess ratio, and are based on the principle of mechanical differentiation of sand-aleurite particles of different intensities under various facies conditions [5]. The main difference between these diagrams is that in the first, when obtaining the coefficients, quantitative percentages of the grain content in the fractions are used, in the second, generally accepted weight percentages. As a result of reconstruction on the diagram of K.K. Gostintsev, the samples fell into the field of marine facies and wide sections of river mouths (Fig. 4).

![Genetic diagram of K.K. Gostintsev for the well](image)

**Figure 4.** Genetic diagram of K.K. Gostintsev for the well [9]

On the chart G.F. Rozhkov [5] all sample points that were plotted on the diagram in accordance with their asymmetry and excess and fell into field VIII (Fig. 5), which reflects the exit of wind waves in shallow water, a powerful roll-up surf, the speed of dynamic re-sorting exceeds the speed of arrival clastic material, coastal facies of huge open water areas.
The next step in the analysis of statistical parameters was the construction and analysis of the dynamogenetic diagram of R. Passegi [6]. It is known that this genetic diagram is based on the difference in the ways of transporting debris particles of various sizes, these are: drawing, rolling, saltation, suspended transportation, etc., which prevail in one or another facies setting [5]. According to R. Passseg's diagram, the location of the sample points on the diagram, relative to their parameters, was definitely; precipitation moved in suspension with a certain amount of rolling rainfall. This type of hydrodynamic transportation indicates moderate energy in the sedimentation environment. Such a hydrodynamic regime is characterized by directed flow conditions, lagoons, beaches and river facies.
4. Conclusions

According to the results of the studies, it was found that the sands are mainly of good grading, the hydrodynamic conditions were moderate, most likely at the border of the sea and the continent, since the deposits were influenced both by the coastal waters and by the wind, which affected the grain size of the sands and their sorting. An analysis of the parameters showed that, according to a set of features, sediment formation occurred under conditions of coastal-marine facies and a beach with coastal dunes. The correspondence of some samples to river environments in some methods can be explained by the fact that initially clastic material was transported from the Paleo Urals precisely by river flows. The results can be used to build geological models in the absence of core material. They make it possible to use the interface between two packs of the Sheshmian horizon as a reasonable basement for the bitumen-saturated interval, since the upper sandy pack is of industrial interest. Thus, we can conclude that the main reservoir properties of the upper sand pack were predetermined and are the result of a special and complex combination of transportation and sedimentation processes. In addition, the results of the study
can be used in calculating reserves or for the selection and correction of technological methods for the development of bitumen.

Acknowledgements

This study was funded by the subsidy allocated to Kazan Federal University as part of the state program for increasing its competitiveness among the world’s leading centers of science and education.

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