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ASSESSMENT OF THE CHARACTERISTICS OF THE GEOLOGICAL SECTION OF WELLS BASED ON COMPLEX GEOPHYSICAL AND TECHNOLOGICAL INFORMATION

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Abstract. The effectiveness of well wiring and technological decisions made largely depend on the use of comprehensive geological, geophysical and technological information. In order to study the section more deeply and thereby improve the quality of decisions made on the choice of rock-crushing tools and drilling mud, it is necessary to apply the results of geological and technological information (GTI) in combination with geophysical well surveys (GIS). To this end, in this article, using modern methods based on mathematical statistics and fuzzy set theory, calculations were performed using the example of some wells in the Bahar (Azerbaijan) and Zhetybai (Kazakhstan) fields. This technique provides a more accurate recognition of lithological differences in the rocks of the borehole section. When using comprehensive information, it is possible to follow the intervals of possible complications by comparing changes in rock properties and drilling speed to identify homogeneous intervals in terms of rock properties and drillability in general. The algorithm proposed in the article makes it possible to improve the quality of information about the well section, which in turn will also make it possible to make more correct technological decisions on the choice of rock-crushing tools and drilling mud. As a result of the analysis of complex geophysical and geological-technological information using modern methods based on the principles of mathematical statistics and the theory of fuzzy sets, calculations were performed using the example of some wells.

Keywords: homogeneous intervals, hardness, abrasiveness, geological-technological information, rock properties

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КЕШЕНДІ ГЕОФИЗИКАЛЫҚ ЖӘНЕ ТЕХНОЛОГИЯЛЫҚ АҚПАРАТ НЕГІЗІНДЕ ҰҢҒЫМАЛАРДЫҢ ГЕОЛОГИЯЛЫҚ ҚИМАСЫНЫҢ СИПАТТАМАЛАРЫН БАҒАЛАУ

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Аннотация. Ұңғымаларды өткізудің тиімділігі және қабылданған технологиялық шешімдер көбінесе кешенді геологиялық-геофизикалық және технологиялық ақпаратты пайдалануға байланысты. Кесуді тереңірек зерттеу және осылайша тау жыныстарын бұзатын құрал мен бұрғылау ерітіндісін таңдау бойынша қабылданатын шешімдердің сапасын арттыру үшін Ұңғымаларды геофизикалық зерттеумен (ҰГЗ) кешенде геологиялық-технологиялық ақпараттың (ГТА) нәтижелерін қолдану қажет. Осы мақсатта бұл мақалада математикалық статистика мен анық емес жиынтықтар теориясының ережелеріне негізделген заманауи әдістерді қолдана отырып, Бахар (Әзірбайжан) және Жетібай (Қазақстан) кен орындарының кейбір ұңғымаларының мысалында есептеулер жүргізілді. Белгіленген әдіс ұңғыманы кесу жыныстарының литологиялық айырмашылықтарын дәлірек тануды қамтамасыз етеді. Кешенді ақпаратты пайдалану кезінде тау жыныстарының қасиеттерінің өзгеруін және тау жыныстарының қасиеттері бойынша біртекті интервалдарды және тұтастай алғанда бұрғылауды бөлу үшін ұңғыманың жылдамдығын салыстырмалы талдау арқылы мүмкін болатын асқынулардың интервалдарын бақылауға болады. Мақалада ұсынылған алгоритм ұңғыманың бөлінуі туралы ақпараттың сапасын арттыруға мүмкіндік береді, бұл өз кезегінде тау жыныстарын бұзатын құрал мен бұрғылау ерітіндісін таңдау бойынша дұрыс технологиялық шешімдер қабылдауға мүмкіндік береді. Математикалық статистика мен бұлыңғыр жиынтықтар теориясының ережелеріне негізделген заманауи әдістерді қолдана отырып, кешенді геофизикалық және геологиялық-технологиялық ақпаратты талдау нәтижесінде кейбір ұңғымалардың мысалында есептеулер жүргізілді.

Түйін сөздер: біртекті аралықтар, қаттылық, абразивтілік, геологиялық-технологиялық ақпарат, тау жыныстарының қасиеттері

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ОЦЕНКА ХАРАКТЕРИСТИК ГЕОЛОГИЧЕСКОГО РАЗРЕЗА СКВАЖИН НА ОСНОВЕ КОМПЛЕКСНОЙ ГЕОФИЗИЧЕСКОЙ И ТЕХНОЛОГИЧЕСКОЙ ИНФОРМАЦИИ

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Аннотация. Эффективность проводки скважин и принимаемых технологических решений во многом зависит от использования комплексной геолого-геофизической и технологической информации. Для более глубокого изучения разреза и повышения качества решений по выбору породоразрушающего инструмента и бурового раствора необходимо применять геолого-технологическую информацию (ГТИ) в комплексе с геофизическими исследованиями скважин (ГИС). В данной статье с использованием методов математической статистики и теории нечётких множеств выполнены расчёты на примере скважин месторождений Бахар (Азербайджан) и Жетыбай (Казахстан). Предложенная методика обеспечивает более точное распознавание литологических разностей пород разреза скважины. Комплексный анализ изменений свойств горных пород и скорости проходки позволяет выделять однородные интервалы по буримости и свойствам пород, а также прогнозировать проблемные зоны. Разработанный алгоритм повышает качество информации о разрезе, что способствует принятию обоснованных технологических решений по выбору породоразрушающего инструмента и бурового раствора.

Ключевые слова: однородные интервалы, твёрдость, абразивность, геолого-технологическая информация, свойства горных пород

Introduction. It is well known that the efficiency of well drilling is greatly influenced by the quality of the obtained data. The quality of the integrated geological-technological and geophysical information is primarily determined by the preliminary processing of raw data, its analysis, and the applied methods. The main task during geophysical and geological-technological studies is to ensure operational control over the drilling well. These studies are carried out throughout the construction and preparation phases for well commissioning. Accurate geological section data is critical to making timely adjustments during drilling. A well-organized research approach contributes to achieving high technical and economic indicators and helps meet environmental protection requirements. Such studies are conducted throughout the well construction and commissioning preparation process. Accurate initial data on the geological section is essential for making sound technological decisions, which in turn leads to high technical and economic performance. Insufficient use of modern methods for data processing and information analysis limits the ability to obtain complete and reliable information. This issue impedes the establishment of a reliable base for making technological decisions since drilling data quality does not always meet the level required for project design, directly affecting decision-making processes and complicating them, leading to erroneous conclusions. Experience from well drilling and numerous studies highlight the need for integrated research based on geological-geophysical and geological-technological well data, requiring appropriate data processing methods and information analysis.

This article focuses on analyzing drilling data, evaluating rock drillability, classifying strata, and preparing higher-quality information using modern methods that account for uncertainty in decision-making during various stages of drilling.

Materials and methods of research. In recent years, a significant amount of research has been devoted to understanding the interaction between rock-breaking tools and rock formations, with methods proposed for determining the physicochemical properties and abrasiveness of rocks and their use in assessing drillability. These include experimental studies conducted on core and cuttings material students (Sementsov et al, 1986: 79; Khismetov et al, 2006: 42), as well as research based on geological-geophysical, technological information analysis, and classification methods. (Brown et al, 2000: 119; Cuddy et al, 2002: 219; Efendiyev et al, 2019: 503; Efendiyev et al, 2021: 1828; Dmitrievsky et al, 2020: 31; Mirzadzhanzade et al, 1981: 148). Notable works include theoretical and experimental studies on the mechanism of rock destruction, the effects of various factors on the efficiency of rock breaking and attempts at mathematical descriptions of the corresponding patterns.

As shown by previous studies, the use of integrated geological-geophysical and technological information is essential for making technological decisions. Obtaining and utilizing such data requires the parallel use of modern data processing and analysis methods. It is important to consider the conditions under which drilling occurs, particularly the heterogeneity, fuzziness, and random nature of factors. Reliable decision-making can be supported by methods from control theory and decision-making under uncertainty, which have been widely developed in recent years. Methods for studying geological sections during drilling are also of great importance. Using GTI in combination with geophysical surveys provides a deeper understanding of the strata and improves decision-making quality.

Results and discussion. When analyzing geological-technological drilling data, including measurements, one encounters errors, uncertainty, and unstable correlations between the studied parameters. These challenges are inherent in technical, technological, geological, and geophysical studies due to the difficulties involved in creating and using more accurate drilling measurement tools, as well as characterizing complex geological formations, regime parameters, and more. Comparative analysis of the same parameter measured by different methods becomes complex due to a variety of influencing factors, such as fluctuations in drill bit load, mineralogical composition, lithology, pore fluids, and the penetration of drilling fluid filtrate.

Unlike traditional methods aimed at minimizing errors, error evaluation and analysis reveal that useful information can be hidden within the errors themselves (Sementsov et al, 1986: 79; Khismetov et al, 2006: 42; Mirzadzhanzade et al, 1981: 148). This information can be used to create a reliable tool that complements traditional methods and aids technologists, geologists, and geophysicists in forecasting tasks.

When analyzing drill bit performance, it is useful to divide the strata into homogeneous intervals and examine the patterns of drilling indicators within these intervals. Several classification methods have been proposed for this purpose. One simple method, based on D.A. Rodionov's geological approach, assumes homogeneity across the entire depth of the section and calculates the Rodionov criterion for each interval as per the author's formula:

$$V(r_0^2) = \frac{n_1+n_2-1}{(n_1+n_2)n_1n_2}\sum_{j=1}^{m}\frac{\left(n_2\sum_{t\in A_1}x_{tj}-n_1\sum_{t\in A_2}x_{tj}\right)^2}{\sum_{t\in T}x_{tj}^2-\frac{1}{n_1+n_2}\left(\sum_{t\in T}x_{tj}\right)^2} \quad (1)$$

Where A_1 and A_2 are subsets dividing the space T; n_1 and n_2 are the number of observations in these sets.

According to analysis (Rodionov, 1981), the values of Rodionov's criterion follow Pearson's chi-squared distribution. The program is designed for interval-wise comparison of each calculated value with a table value for a given significance level. Intervals where the calculated criterion exceeds the table value of Pearson's chi-squared distribution represent boundaries between two heterogeneous sections. Using this criterion, the Zhetybay field well section was divided into homogeneous intervals based on hardness, abrasiveness, density, and Poisson's ratio of the rocks. A comparative analysis of drilling indicators within these intervals was conducted. The results of this division are presented in Table 1. Rock hardness and abrasiveness significantly influence drilling performance. Various factors, including grain shape, mineralization, and saturating fluids, affect these properties.

Figures 1. (a,b) show the variation in hardness and abrasiveness with depth, compared with drilling speed for two wells drilled in one of Azerbaijan's fields. Homogeneous intervals, drilled with the same type of bits, are also indicated. The data was processed using a "moving average" method to reduce amplitude and more accurately establish the trend of the parameters being considered. This information can be used in well design planning.

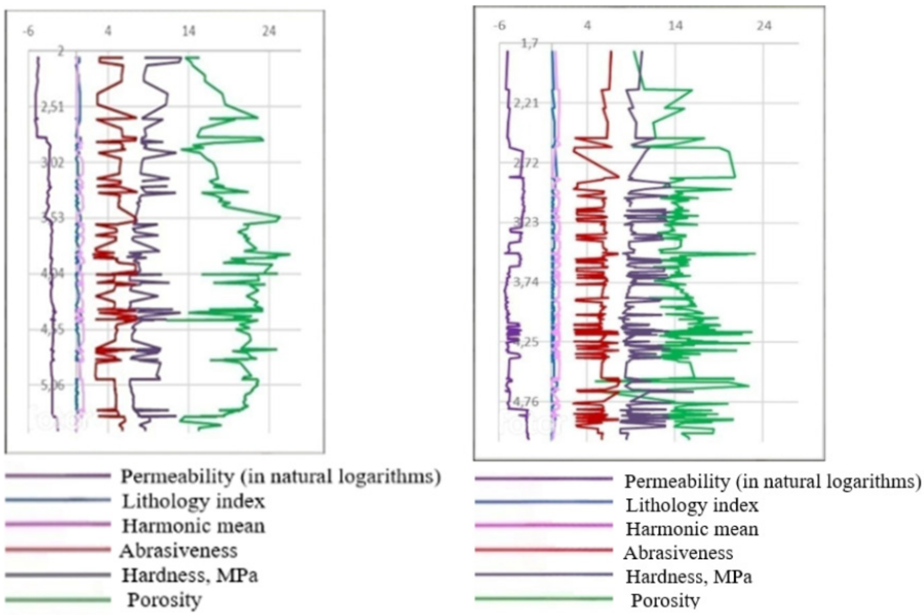

Figure 1. Variation of geological section characteristics with depth compared to rate of penetration for two wells drilled at one of Azerbaijan's fields.

It is known that the selection and refinement of well design is based on parameters necessary to construct a combined chart, which includes gradients of formation pressure, fracture pressure, and drilling fluid density, all expressed in equivalent units. Using the aforementioned method, intervals homogeneous in formation pressure gradients, fracture pressure gradients, and drilling fluid density can be identified to refine well design (Efendiyev et al, 2024: 003). This information is also compared with the results of geophysical surveys, as shown in the referenced study (Efendiyev et al, 2024: 003).

Table 1. Results of dividing the section of one well into homogeneous intervals based on a set of attributes using the Rodionov method

№	Pack number	Interval, km			Density, g/cm^3	Hardness, MPa	The Poisson's ratio	Abrasiveness, cat.
		from	to	□H				
1	1	0.46	0.5	0.04	1.82	10	0.27	6.5
2		0.5	0.55	0.04	1.89	20	0.3	6
3		0.55	0.73	0.19	2.04	30	0.42	4
4		0.73	0.92	0.19	1.86	10	0.27	6.5
5		0.92	1.11	0.19	1.96	20	0.3	6
6		1.11	1.14	0.03	2.12	30	0.42	1.5
7		1.14	1.17	0.03	2.15	20	0.42	1.5

8		1.17	1.21	0.03	1.97	25	0.27	6.5
9		1.21	1.23	0.03	2.07	30	0.3	6
10		1.23	1.26	0.03	1.98	31	0.27	6.5
11		1.26	1.29	0.03	2.18	32	0.3	3
12	2	1.29	1.29	0.01	2.09	32	0.3	6
13		1.29	1.3	0.01	2.49	33	0.25	3
14		1.3	1.3	0.01	2	33	0.27	6.5
15		1.3	1.35	0.04	2.18	34	0.42	3
16		1.35	1.38	0.04	2	35	0.27	6.5
17		1.38	1.42	0.04	2.49	35	0.25	3
18		1.42	1.46	0.04	2.49	150	0.25	4
19	3	1.46	1.49	0.04	2.49	155	0.36	2.5
20		1.49	1.57	0.08	2.21	160	0.42	4
21		1.57	1.66	0.08	2.49	40	0.25	4
22		1.66	1.74	0.08	2.23	42	0.42	4
23		1.74	1.75	0.01	2.5	45	0.36	4
24		1.75	1.77	0.01	2.26	30	0.42	4
25		1.77	1.78	0.01	2.1	45	0.27	6
26		1.78	1.85	0.07	2.21	60	0.3	6
27		1.85	1.91	0.07	2.11	35	0.27	6
28	4	1.91	1.98	0.07	2.29	37	0.42	3
29		1.98	2.08	0.1	2.25	40	0.3	6
30		2.08	2.18	0.1	2.1	44	0.27	6
31		2.18	2.28	0.1	2.28	49	0.42	1.5
32		2.28	2.31	0.04	2.11	54	0.3	6
33		2.31	2.35	0.04	2.23	45	0.27	6
34		2.35	2.39	0.04	2.39	50	0.42	1.5

The fuzzy logic proposed in the work (Zadeh, 1965: 338), which has been developed in recent years by various researchers, particularly in works (Fang et al, 1997: 185; Freund et al 1980; Aliev et al, 2014; Turksen et al, 2013: 21), has played a significant role in solving geological and technological problems in the theory and practice of oilfield development.

The analysis has established that the variance around the mean value is one of the main factors that create fuzziness. As a result, in works (Freund et al 1980; Efendiyev et al, 2024: 003), the authors attempted to justify why this parameter characterizes fuzziness and necessitates the application of fuzzy logic. This circumstance must be considered due to the various types of uncertainties present in modeling and decision-making. The presence of uncertainty, associated with both random and fuzzy variables, significantly complicates the successful resolution of technological process modeling tasks. According to interpretation, random variables can take different values with varying probabilities. In contrast, fuzzy variables describe the approximation in determining the values of these variables. Furthermore, fuzzy variables may be preferable in cases where there is insufficient information (statistical data) and, consequently, the need for more reliable and accurate estimates. For instance, such estimates of mechanical properties of rocks can be made based on their physical properties, evaluated using geophysical well logging data and probabilistic-statistical methods, as well as fuzzy set theory.

The study of these dependencies has allowed the development of a well-grounded calculation scheme for evaluating the characteristics of a geological section (Efendiyev et al, 2024: 003).

In order to outline a unified approach that includes both probabilistic and fuzzy modeling as special cases, the concept of *fuzzy-random* quantities is discussed in the literature (Cuddy et al, 2002: 219; Zadeh, 1965. In this case, a fuzzy-random quantity is a random variable whose values are not ordinary real numbers, but fuzzy numbers.

This paper considers the possibility of applying these principles in the case of predicting the lithology of rocks in one of the drilled wells at the Zhetibai field based on a set of features (hardness, abrasiveness, Poisson’s ratio, density of the rock), obtained from geological-geophysical and technological studies conducted during drilling, as well as the joint use of geophysical and geological-technological research results to calculate the gradients of formation pressure, fracture pressure, and drilling fluid density. The distribution analysis showed that each of the listed parameters follows a normal distribution. In this case, the probability density function for any observation (denoted as x) measured in the dataset, with an arithmetic mean μ\muμ and a standard deviation σ\sigmaσ, is expressed by the formula given in Table 2. As shown in the subsequent expressions, the variables used are the values of hardness, abrasiveness, Poisson's ratio, density of the rock, and their respective arithmetic means and standard deviations.

If a rock type exhibits a distribution of hardness values (or/and abrasiveness, Poisson's ratio, rock density), with a mean μ\muμ and a standard deviation σ\sigmaσ, the fuzzy probability of each of these characteristics for a given rock can be calculated using the first formula given in Table 2. The mean value and standard deviation are obtained from the data of geological-technological and geophysical research during drilling, as well as core samples for each lithotype of the rock according to (Efendiyev et al, 2024: 003). Without repeating the sequence of further analysis and calculations, which are detailed in publications (Brown et al, 2000: 119; Cuddy et al, 2002: 219; Efendiyev et al, 2019: 503; Efendiyev et al, 2019: 503), we note that the subsequent calculations were performed using the expressions presented in the aforementioned table, and the results in graphical form are shown in Figure 1. A brief description follows.

Let us assume that we have a set of characteristics describing the rock type—these are the values of hardness, abrasiveness, Poisson's ratio, and rock density. Based on these values, it is necessary to classify the identified rock into one of the lithological types. As an example, data from several wells of the Zhetibai field are used. Table 2 presents the necessary mathematical expressions for calculations, allowing us to assess the relationship between fuzzy probability for each rock type and the fuzzy probability of the mean or most probable value. This is achieved by denormalizing the first equation, yielding the following results. In works (Brown et al, 2000: 119; Cuddy et al, 2002: 219), formulas are provided for the calculations necessary for geomechanical predictions of geological section characteristics, which are utilized in works (Efendiyev et al, 2019: 503; Efendiyev et al, 2021: 1828; Efendiyev et al, 2024: 003).Based on these works, we have developed and implemented a calculation scheme for the predictive assessment of geological section characteristics of wells in the Zhetibai field. Since these works provide detailed explanations and there is no need to repeat them in this article, the expressions used for calculations are summarized in Table 2.

Table 2. Computational Formulas for Estimating Rock Properties and Dividing the Geological Section into Homogeneous Intervals

Parameter	Mathematical Expression	Input Variables
Density of normal distribution	$P(x)=\frac{e^{-(x-\mu)^2/2\sigma^2}}{\sigma\sqrt{2\pi}}$	
Fuzzy probability of the measured mean value μ	$P(\mu)=\frac{e^{-(\mu-\mu)^2/2\sigma^2}}{\sigma\sqrt{2\pi}}=\frac{1}{\sigma\sqrt{2\pi}}$	***μ*** *– mean (arithmetic average)* ***σ*** *– standard deviation*
Relative fuzzy probability R(xf) that x belongs to type f in comparison with the fuzzy probability of measuring the mean value μf	$R(x_f)=e^{-(x-\mu_f)^2/2\sigma_f^2}$	
Fuzzy probability that rock x belongs to type *f*	$F(x_f)=\sqrt{n_f}\,e^{-(x-\mu_f)^2/2\sigma_f^2}$	n_f *– frequency of occurrence of each rock type in the well section.*
Cumulative fuzzy probability	$C_f=\frac{4}{\frac{1}{F(P_{sh})}+\frac{1}{F(A)}+\frac{1}{F(\nu)}+\frac{1}{F(\rho)}}$	P_{sh} *– Rock hardness;* ***A*** *– Abrasiveness;* ***ν*** *– Poisson's ratio;* ***ρ*** *– Rock density.*

Thus, to refine the lithological differentiation of the rock, it is necessary to:

- Calculate the arithmetic meaning **μ** and the standard deviation **σ**;
- Determine the probability density **P(x)**;
- Compute the relative fuzzy probability **R(x)**;
- Calculate the fuzzy probability **F(x)** by multiplying **R(x)** by the relative frequency;

- Find the inverse values and the harmonic meaning **Cf**.

This process is repeated for each lithotype **f**. The lithotype associated with the highest cumulative fuzzy probability is considered the most likely for the given set of characteristics. The corresponding fuzzy probability **Cf(max)** increases the reliability of the lithological forecast.

An example of the stratigraphy of the examined well, drilled at the Zhetybai field, is presented.

The calculations were performed according to the outlined scheme, and the results are shown in Figures 2, 3, and 4.

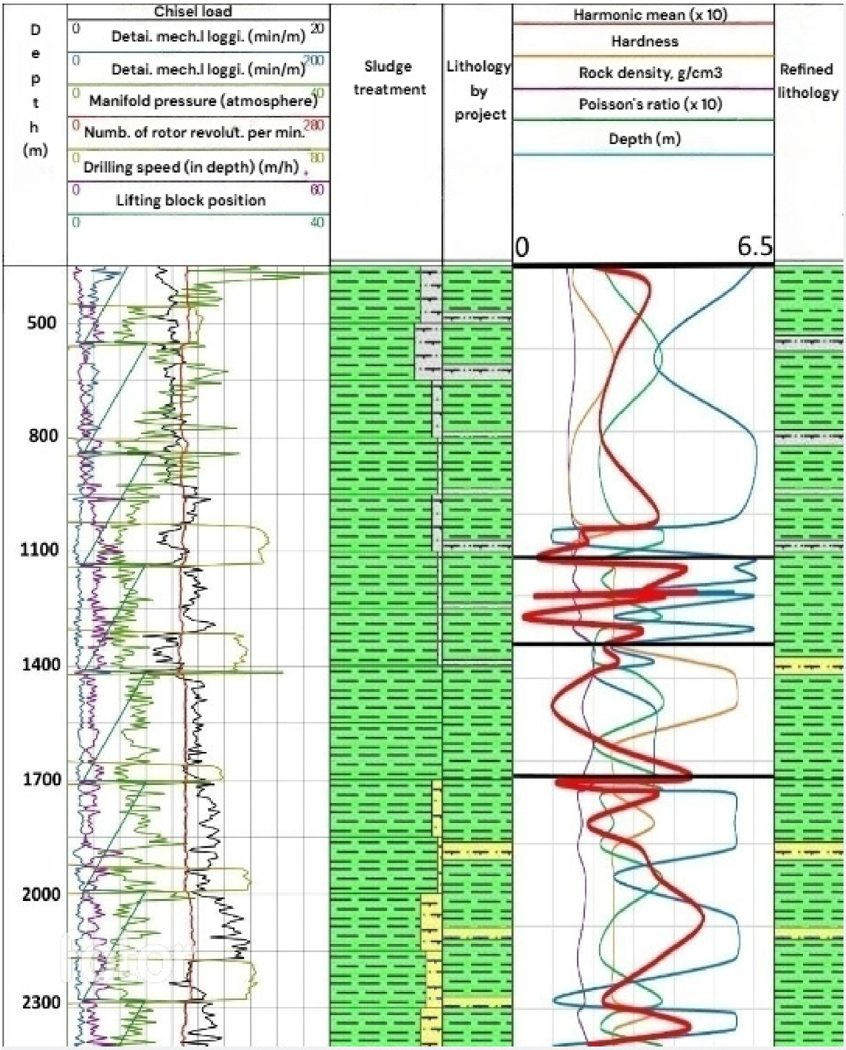

Figure 2. Results of the calculation and the refined lithological column of the well (conditionally X1) at the Zhetybai field

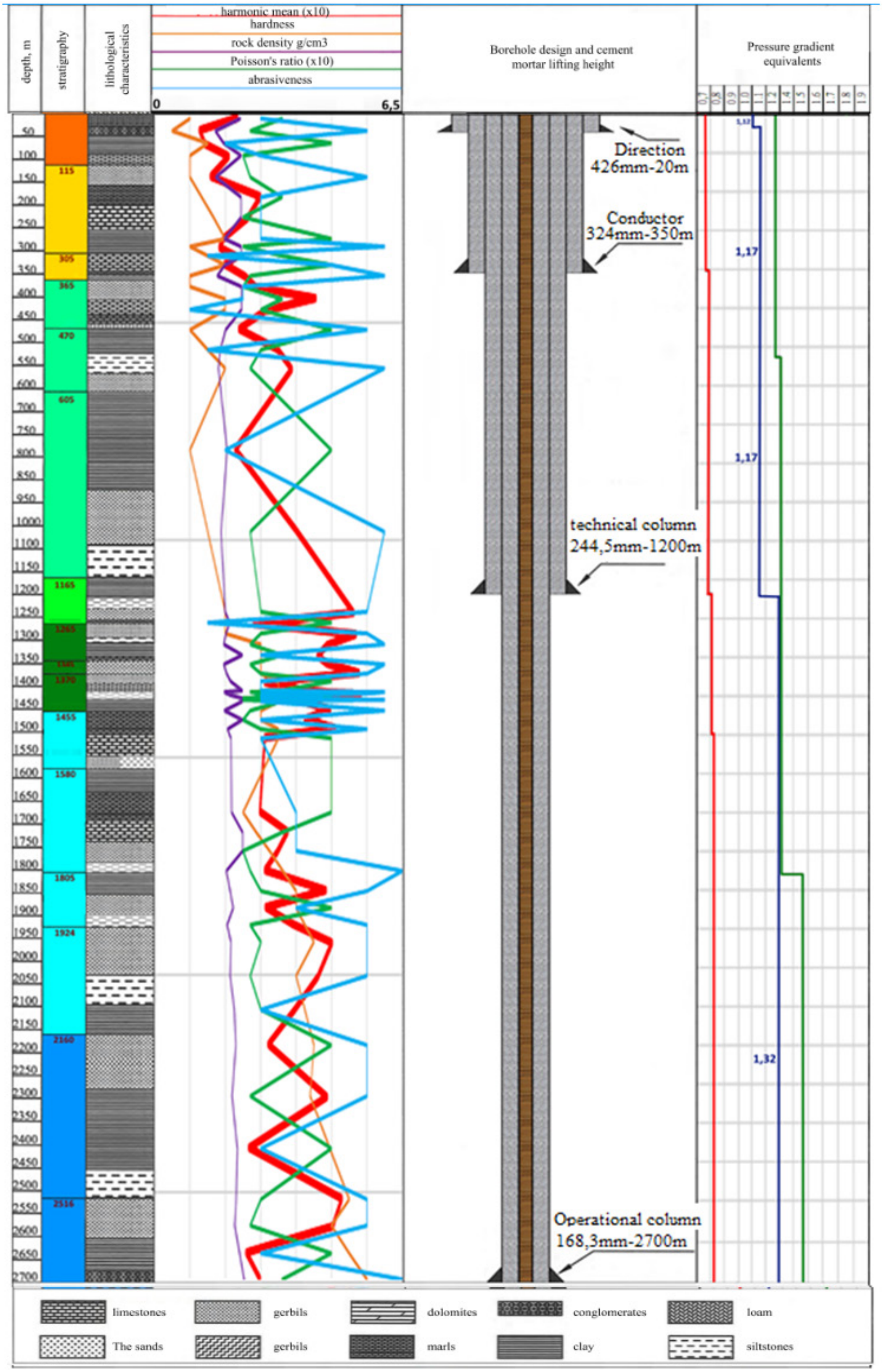

Figure 3. Results of the calculation and the refined lithological column of the well (conditionally X2) at the Zhetybai field

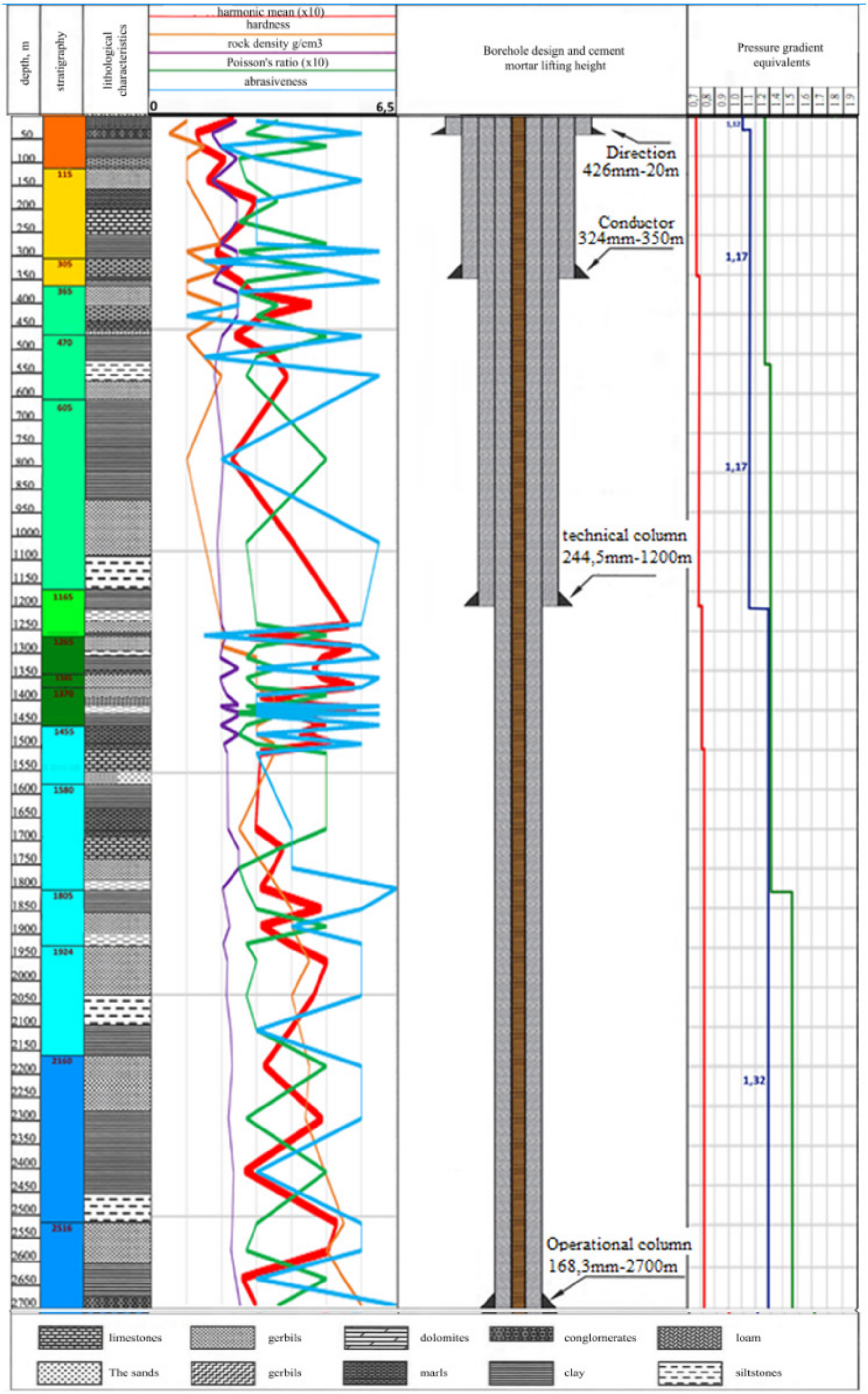

Figure 4. Results of the calculation and the refined lithological column of the well (conditionally X3) at the Zhetybai field

The figures display two lithological columns: the one provided in the well design and the refined one based on the calculation scheme described. The comparison shows a good agreement between the lithological columns. The methodology discussed in this article was implemented through the analysis of a large volume of data collected from well-logging (GIS) and well-test (GTI) results. This approach differs from traditional methods in that fuzzy logic combines fuzzy probabilities harmonically by comparing multiple feature evaluations, which is particularly effective when dealing with heterogeneous data. Furthermore, when comparing lithologies that are equally likely and have similar probabilities, harmonic averaging provides more reliable results.

1. In the case discussed, the lithological forecast using the probabilistic-statistical method and fuzzy logic is based on the assertion that a specific lithology type may cause any reading from the raw data, such as a logging diagram, though some readings are more probable than others. This is determined through calculations. For example, it is most likely that clean sandstones will be highly porous, permeable, abrasive, and have a higher sigma-logging value. However, there is a finite probability that geophysical surveys could have recorded values that differ from the typical values for the considered rock type. Comprehensive geological-geophysical and technological research results are necessary. In this case, using the method based on the combined probabilistic-statistical and fuzzy approach will ensure high-quality forecasting information (Turksen et al, 2013: 21; Shvedov, 2013).

2. The development and wide implementation of modern technical means and technologies for providing information during the well-drilling process, as well as the use of contemporary mathematical methods, allow for higher-quality data, which is crucial for future decision-making. Real-time data obtained during drilling plays a significant role, especially in poorly studied regions with complex geological, mining, and environmental conditions. As illustrated in Figure 1, by comparing changes in rock properties and drilling speed, it is possible to identify homogeneous intervals based on rock properties and drilling efficiency, track potential complications, and so on (Turksen et al, 2013: 21; Shvedov, 2013).

Conclusion

The probabilistic-fuzzy approach proposed in this article improves the quality of information about the well section, which will, in turn, allow for more accurate technological decisions regarding the selection of rock-breaking tools and drilling fluids. As a result of the analysis of integrated geophysical and geological-technological information using modern methods based on the principles of mathematical statistics and fuzzy set theory, calculations were performed using data from several wells at the Bahar (Azerbaijan) and Zhetybai (Kazakhstan) fields. The proposed methodology ensures more precise identification of lithological differences in the well section.

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