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ГОРНЫЕ НАУКИ И ТЕХНОЛОГИИ

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ЭЛЕКТРОННЫЙ НАУЧНО-ПРАКТИЧЕСКИЙ ЖУРНАЛ

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Деятельность научно-практического журнала «Горные науки и технологии» (Mining Science and Technology (Russia)) направлена на развитие международного научного и профессионального сотрудничества в области горного дела.

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В журнале публикуются оригинальные статьи, описывающие результаты исследований, опыт реализации проектов в горнопромышленном комплексе, обзорные публикации.

Журнал стремится развивать такие междисциплинарные направления, как технологическая и экологическая безопасность, организация и управление проектами в горной промышленности, развитие территорий, правовые аспекты использования природных ресурсов и другие, которые способствуют прогрессу в горном деле и реализуются исследователями и практиками.

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MINERAL RESOURCES EXPLOITATION

Research paper

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Justification of the optimal width of a front bank

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Abstract
Reducing the cost of finished products by using the most economically advantageous processes and techniques for the extraction and beneficiation of minerals is one of the most pressing tasks in mining industry. The width of front bank has a significant impact on the cost of placer deposits mining. Existing methods for calculating the most advantageous width of front bank are based on ensuring dredge maximum productivity that is justified in placer bulk mining. With increasing depth of a placer deposit occurrence and thickness of overburden, traditional methods for calculating the optimal width of a front bank do not ensure minimizing production costs. The aim of the research is to determine the most advantageous width of a front bank, taking into account a peat (overburden) thickness and acceptable stripping flow sheet. The idea behind this work is that the optimal width of a front bank should be determined not only based on the maximum productivity of a dredge, but also on the condition of ensuring the lowest cost of extraction of valuable components (taking into account the productivity of all mining equipment and the stripping costs). The study analyzes the impact of placer parameters (peat thickness and productive layer thickness, front bank width) on the cost of sand extraction and processing, and identifies the dependencies of mining parameters on technical and economic performance. The study examined more than 100 process flow sheets for the integrated operation of stripping and mining equipment and provided an economic assessment of their effectiveness. Recommended values for correction factors for determining the optimum front bank width are given. The study findings serve as methodological material for substantiating the parameters of a placer mining system.

Keywords:
placer deposits, dredging, front bank width, stripping, dredge productivity, mining costs

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РАЗРАБОТКА МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Научная статья

Обоснование оптимальной ширины дражного забоя

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Аннотация
Снижение себестоимости готовой продукции за счет применения наиболее экономически выгодных процессов и технологий добычи и обогащения полезных ископаемых – одна из актуальных задач в горнодобывающей отрасли промышленности. Значительное влияние на себестоимость добычи полезного ископаемого россыпей оказывает ширина дражного забоя. Существующие методы расчета наивыгоднейшей ширины забоя драги основаны на обеспечении ее максимальной производительности, что оправдано при валовой разработке россыпей. С увеличением глубины залегания россыпи и мощности вскрышных пород традиционные методы расчета оптимальной ширины дражного забоя не обеспечивают минимальной себестоимости добычных работ. Целью исследований является обоснование наивыгоднейшей ширины забоя драги с учетом мощности торфов и приемлемых технологических схем вскрышных работ. Идея работы заключается в том, что оптимальная ширина забоя должна устанавливаться не только исходя из максимальной производительности драги, но и из условия обеспечения наименьшей себестоимости добычи ценных компонентов (с учетом производительности всего горного оборудования и себестоимости вскрышных работ). В исследовании проводится анализ влияния пара-

метров россыпи (мощности торфов и продуктивного пласта, ширины забоя) на себестоимость добычи и переработки песков, а также выявление зависимостей влияния параметров горных работ на технико-экономические показатели. В рамках исследования было рассмотрено более 100 технологических схем комплексной работы вскрышного и добычного оборудования и дана экономическая оценка их эффективности. Приведены рекомендуемые значения поправочных коэффициентов к определению оптимальной ширины забоя драги. Результаты исследования служат методическим материалом для обоснования параметров дражной системы разработки россыпей.

Ключевые слова
россыпи, драгирование, ширина забоя, вскрышные работы, производительность драги, себестоимость добычных работ

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Talgamer B.L., Meshkov I.A., Murzin N.V., Roslavtseva Yu.G. Justification of the optimal width of a front bank. *Mining Science and Technology* (*Russia*). 2025;10(2):99–108. https://doi.org/10.17073/2500-0632-2024-11-332

Introduction

The dredging method of placer deposit development, thanks to continuous flow process technology, minimizes the costs of extracting valuable components from placer deposits [1]. This is the only way to successfully develop deep waterlogged and large man-made placer deposits with low content of useful components [2, 3], which account for the largest share of the undistributed placer reserves [4]. Further improvement of the competitiveness of this method largely depends on the feasibility of increasing dredging productivity, including by extending mining season, reducing process downtime, improving the quality of reserve preparation for extraction, and optimizing dredging process parameters [1, 5]. When developing rather wide placers, productivity can be increased by optimizing a front bank width.

The optimal and most advantageous width of a front bank (a dredge "face") is determined taking into account maximum daily productivity of a dredge [6]. Under relatively favorable conditions for dredging and applying bulk mining of reserves, which prevailed in the second half of the 20th century, this method of calculation provides the highest technical and economic performance indicators for dredging. At the same time, due to the permanently complicating conditions of placer exploitation with increasing scope of capital mining operations, the determination of an optimal front bank width based on ensuring a dredge maximum productivity will not be entirely accurate, since the efficiency of a dredge depends not only on its productivity, but also on the scope and costs of capital mining operations, the amount of losses and dilution of a mineral, the recovery of valuable components, and the economic indicators of a deposit's development.

Increasing a front bank width leads to higher costs for stripping, as well as for removing ice scum (in autumn) and ice (in spring) and, as a rule, for recultivation. As a front bank width decreases, sand losses (including inter-step and inter-run losses) or dilution increase, the concentration of suspended solids in the process water increases that in some cases can lead to a decrease in the recovery of valuable components and, as studies show, to a significant negative impact on water bodies [7–9], and a dredge turning becomes more difficult.

Thus, the optimal front bank width should be determined based on the condition of ensuring the lowest cost of extraction of valuable components, but not only taking into account reaching a dredge maximum productivity. At the same time, the greatest impact on the economic performance indicators of dredging development is exerted by stripping, the volume of which has been steadily growing in recent years [10].

Despite the fact that dredging mining has a significant impact on various components of the environment [11, 12], especially on water bodies [13, 14], it remains one of the most economically efficient methods [15] and is currently actively used in the development of placer deposits both in Russia [10, 16] and abroad [17, 18] that indicates relevancy of the task of determining an optimal front bank width.

Theoretical treatment

When designing mining operations for excavation and loading equipment, the optimal cut width is substantiated, which in most cases is determined by the operating parameters of mining machines. When using excavators, a cut width is mainly determined based on the digging reach and dumping radius, and sometimes the type of transport facilities used is taken into account. When dredging placers, a rational front bank width (dredge cut width) is determined using a more complex relationship that takes into account not only the operating parameters of a dredge, but also its operating conditions and the placer characteristics.

Several methods are known for calculating the optimal width of the front bank (or optimal maneuvering angle) of a dredge[1] [6, 19]. All of them take into

[1] Kudryashev V. A. Some issues of the theory and technology of deep placer deposits development using dredging method. [Abstr. Dr. Sci. (Eng.) Diss.] Moscow: MSTU Publ.; 1975. 42 p. (In Russ.)

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account the characteristics of a placer deposit and a dredge parameters and provide for its maximum daily productivity. The values obtained from calculations using these methods differ slightly, but overall indicate that the optimal front bank width is closer to its minimum possible value and significantly less than the maximum width. 380-liter dredge performance dependencies on the front bank width, as applied to the conditions of development of one of the Sakha (Yakutia) placers, are shown in Fig. 1.

The average thickness of the productive layer of the placer deposit under consideration is 10 m, the thickness of peat is 2–6 m (4 m on average), and the average width of the placer deposit is 560 m.

Fig. 1 shows that the 380-liter dredge maximum productivity corresponds to the front bank width of 65 to 105 m.

To further investigate the effect of stripping on the optimal front bank width, we use the most well-known and widely used design technique developed by V.G. Leshkov [6], in which the daily productivity of a dredge is determined using the following expression:

$$Q_{day} = \frac{3600 v_l\, HaTR \sin\beta_1}{0.0175 K_l R_{avg}\beta_1 + 30 v_l (t_1 + K_l t_2)}, \qquad (1)$$

where v_l is speed of lateral dredge movement along a front bank, m/s; H is a placer deposit thickness, extracted by the buckets, m; a is a value of moving (step) of a dredge per a front bank, m; T is dredge operating time per day, h; R_{avg} is average dredge digging radius when mining a placer deposit of H thick, m; β_1 is half the maneuvering angle of a dredge, degrees; $K_l = H/h$ is number of rock layers extracted by the buckets during layer-by-layer mining of one front bank; t_1 is time required for one step, min; t_2 is downtime of a dredge in front bank node points when advancing to a lower rock layer extraction, min; 0.0175 is digital coefficient for converting degrees to radians.

The works of V.G. Leshkov [6] describe a method for calculating the optimal front bank width, which takes into account the thickness of a sand to be dredged and the design parameters of the mining equipment. The most advantageous width of a single front bank is established based on the conditions of maximum dredge productivity in terms of rock mass and is determined by the most advantageous maneuvering angle. The calculation formula is as follows:

$$\beta_{ma} = 47.8\sqrt{1000\frac{v_l h}{HR_{avg}}\left(t_1 + \frac{H}{h}t_2\right)}. \qquad (2)$$

The most advantageous width of a single front bank, m, is calculated using the following equation:

$$B_{ma} = 2R_{avg}\sin\frac{\beta_{ma}}{2}. \qquad (3)$$

The method proposed by V.G. Leshkov for calculating the most advantageous front bank width takes into account the main parameters of equipment operation and the nature of a productive layer, but does not assume the presence and scope of overburden. Therefore, it is necessary to predict how the most advantageous (optimal) front bank width will change, when taking into account the work involved in extracting and transporting peat.

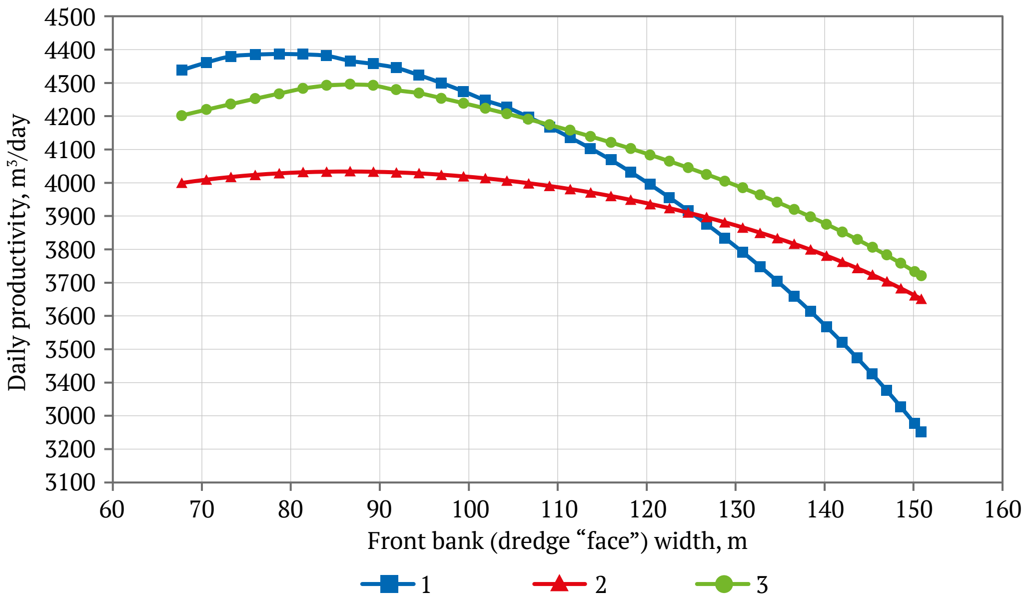

Fig. 1. Daily productivity of a 380-liter dredge as a function of front bank width:
1 – according to the technique of V.A. Kudryashev; *2* – according to the technique of V.G. Leshkov;
3 – according to the technique of S.M. Shorokhov

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Research tasks and objectives

The main objective of the research was to determine an optimal front bank width depending on the thickness of a mineral deposit and overburden. To achieve this goal, it is necessary to establish the influence of peat thickness on the costs of mineral extraction, determine the front bank parameters, which ensure minimum costs for a placer deposit development, and improve the method for calculating the most advantageous width of a front bank (a dredge run) for the development of wide placer deposits.

Research techniques

Graphical and technical-economic calculation methods were used to solve the tasks set.

The influence of stripping on the optimal front bank width was assessed based on the calculation of the costs of mineral extraction depending on the parameters of the front bank, peat thickness, and the method used for the peat extraction and stockpiling.

For peat thickness of up to 6 m, the calculations were performed for bulldozer stripping method, and for the thickness more than 6 m, the calculations provided for direct dumping method with the use of draglines. According to approved stripping flow sheets, peat dumps are placed on one side of a placer deposit or into worked-out space left from the previous dredging run. Transport technique for stripping with the use of a combination of excavators and dump trucks was not considered, as its high cost (2–3 times higher than direct dumping and bulldozer methods) means that it is practically never used in dredging mining.

To determine the costs of stripping and mining operations under different mining parameters of a placer deposit and flow sheets used, the dependencies of mining equipment productivity and the volume of earthwork on a front bank width were found. The productivity of bulldozers was determined based on the transportation distance and the height of the dumps, while the volume of excavation work was calculated taking into account changes in the rehandling coefficient. The costs of stripping and mining operations were determined based on the cost per machine-hour of the equipment used, its productivity, and the scope of stripping.

Findings

The influence of stripping technique on an optimal front bank width was assessed based on the calculation of the costs of stripping (in Rubles per cubic meter of sand extracted) and the costs of dredging. Minimum costs for stripping and mining operations are achieved with maximum productivity of the equipment used.

Based on a dredge's productivity, the costs of extracting and processing of one cubic meter of sand were calculated. Fig. 2 shows curves of cost of sand extraction as a function of a front bank width at three productive layer thicknesses of 10, 20, and 28 m.

As can be seen from Fig. 2, the minimum costs were achieved at a front bank width of 70–100 m.

In order to assess the influence of stripping on the total costs of extracting one cubic meter of sand, the productivity of bulldozers was calculated when using front bank width values of 50–155 m and varying sand thickness (from 6 to 28 m). The thickness of sand also affects the front bank width, as the width increases at the top. For peat thickness of 2–6 m, the relationship between the productivity and costs of stripping using bulldozers (with a power of 350–400 kW) and the front bank width was established.

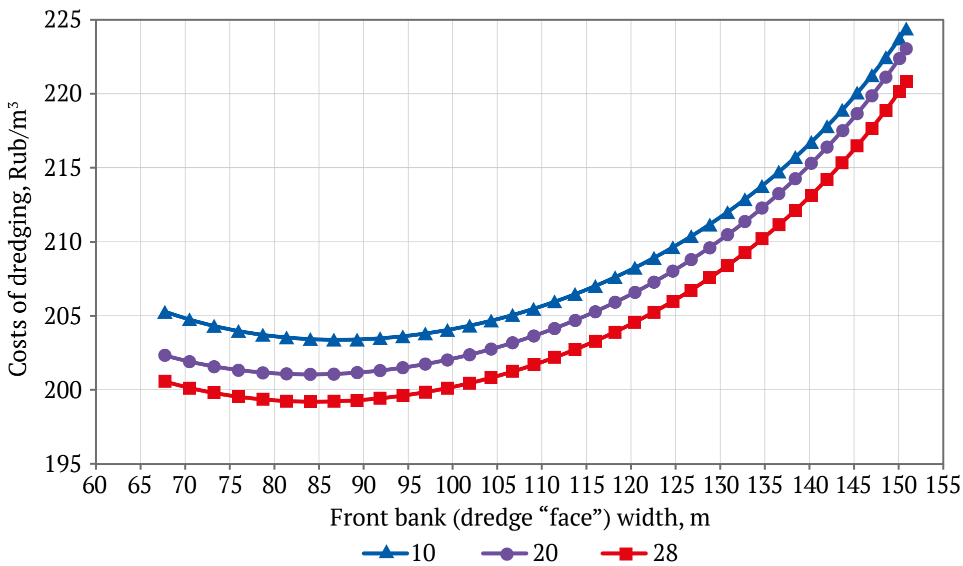

Fig. 2. Curves of cost of dredging as a function of a front bank width for a 380-liter dredge at three productive layer thicknesses of 10, 20, and 28 m

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The bulldozer's productivity for each case was determined based on the distance of peat transportation. As the front bank width increases, the distance of transportation and the parameters of the bulldozer dump (height, required capacity) increase, while the productivity of the stripping equipment decreases and, as a result, the costs of sand extraction increase.

The cost of extraction and processing of one cubic meter of sand (taking into account the costs of stripping by bulldozers) as a function of front bank width are shown in Figs. 3–5. Table 1 shows the results of calculating the costs of extraction at different values of peat and sand thicknesses and front bank width.

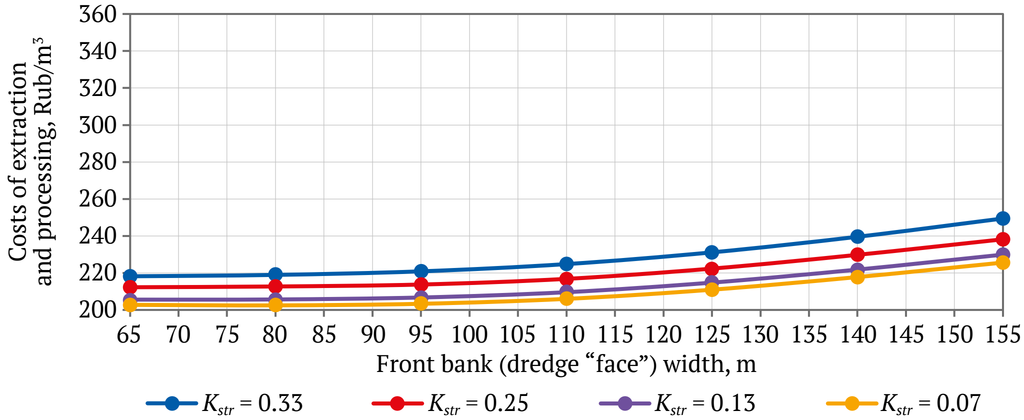

Fig. 3. Cost of extraction and processing of a mineral as a function of front bank width at a peat thickness of 2 m and a stripping ratio K_{str} = 0.07–0.33

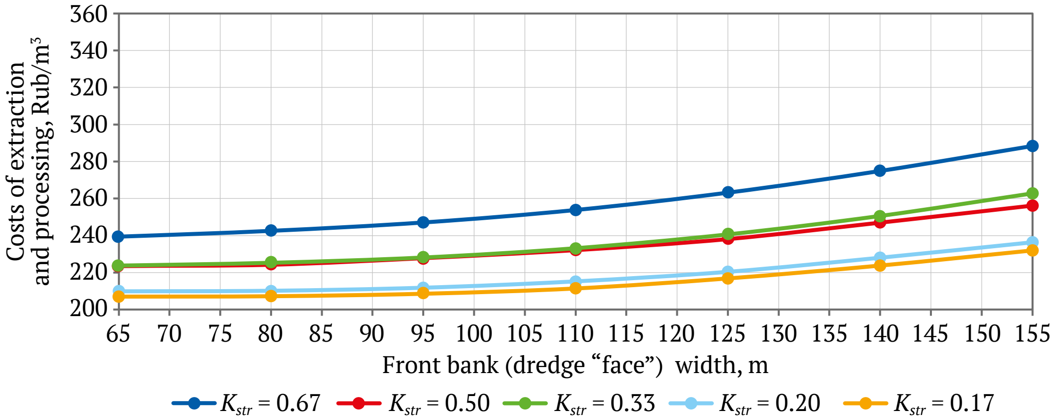

Fig. 4. Cost of extraction and processing of a mineral as a function of front bank width at a peat thickness of 4 m and a stripping ratio K_{str} = 0.17–0.67

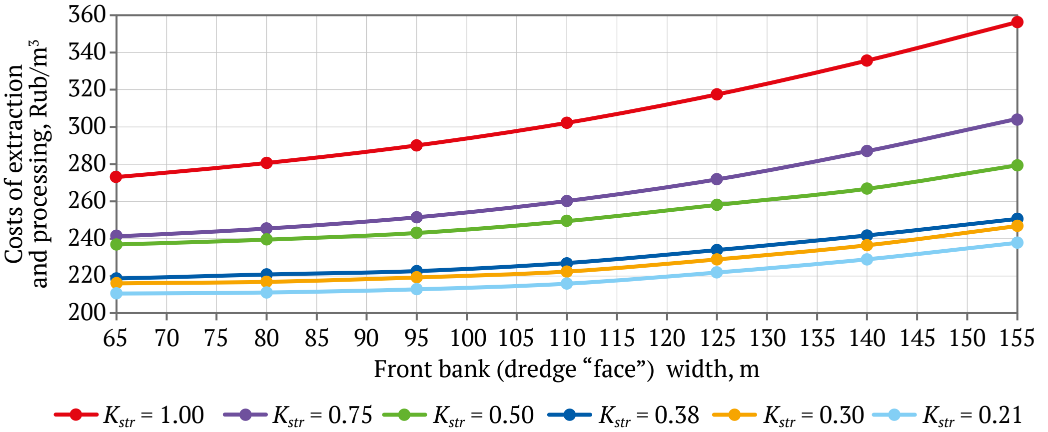

Fig. 5. Cost of extraction and processing of a mineral as a function of front bank width at a peat thickness of 6 m and a stripping ratio K_{str} = 0.21–1.00

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Figs. 3–5 show that when a front bank width exceeds 95 m, the costs of mineral extraction and processing sharply increase. This confirms that when designing dredging operations and determining an optimal front bank width, the parameters of stripping must be taken into account.

Table 2 shows the data for calculating an optimal front bank width using formula (2) and the indicators identified taking into account the conduct of stripping operations. The correction factor was calculated, which is proposed to be used in formula (2) when calculating the optimal front bank width for a 380 l dredge under similar placer parameters.

As the thickness of peat increases, the cost of extracting minerals rises, while an optimal front bank width gradually decreases. As can be seen from Table 2, the difference between the calculated values of the optimal front bank width without and with bulldozer stripping ranges from 0 to 35.6%. The graphical representation of the correction factor variation depending on certain parameters of a placer deposit (peat thickness and stripping ratio) is shown in Fig. 6.

When dredging developing placers with peat thicknesses exceeding 5–6 m, the feasibility of using bulldozers for stripping decreases; instead, a direct dumping technique is applied.

When studying the influence of a front bank width on the cost of dredging with the use of direct dumping technique, 140 flow sheets for stripping using an ESh 20/90 dragline were analyzed, in which the thicknesses of the overburden (5–20 m), sand (6–28 m), and the front bank width (50–140 m) varied. For each flow sheet, the rehandling coefficients were calculated using a dummy unit-load method and are presented in Table 3.

The data in Table 3 show that at the highest values of the front bank width, the rehandling coefficient for the stripping dragline is maximal; therefore, the costs of stripping in such conditions will be higher.

The cost of stripping and dredging has been calculated for each option. Table 4 shows the results of calculating the extraction costs when using direct dumping technique for stripping.

By analogy with the analysis of the bulldozer method of stripping (peat removal) (see above), the indicators calculated without taking into account stripping and with its taking into account when using direct dumping technique were compared (Table 5).

Table 1

Costs of extraction and processing of sand using a dredge, including stripping by bulldozers, Rub/m³

Thickness, m		Costs of extraction and processing of a mineral at different values of front bank (dredge “face”) width, m							
peat	sand								
T_p	T_s	50	65	80	95	110	125	140	155
2	6	217.8	218.2	218.9	220.5	227.1	231.1	239.6	249.5
	8	211.9	212.3	212.7	213.4	219.1	222.4	229.8	238.2
	12	212.1	211.9	211.9	212.7	218.5	221.6	229.1	238.0
	16	205.8	205.6	205.7	206.3	212.0	214.8	221.9	230.0
	20	205.2	204.9	204.7	205.4	211.1	213.6	220.5	228.9
	24	203.1	202.7	202.4	202.9	208.4	210.9	217.8	225.6
	28	202.7	202.3	202.1	202.5	207.8	210.3	217.1	225.0
4	6	236.8	239.4	242.6	246.8	256.1	263.2	274.9	288.4
	8	222.1	223.5	224.2	227.5	234.4	238.1	247.0	256.2
	12	222.7	223.8	225.3	227.9	235.5	240.7	250.6	262.8
	16	211.5	211.5	211.9	213.3	219.7	223.3	230.4	239.7
	20	209.6	209.9	210.2	211.4	217.7	220.4	228.0	236.4
	24	206.9	207.0	207.2	208.2	213.8	216.8	223.8	231.9
	28	206.2	206.0	206.1	206.9	212.5	215.4	222.3	230.9
6	6	266.5	273.1	280.7	289.8	304.5	317.4	335.6	356.3
	8	235.1	237.0	239.5	242.8	251.8	258.2	266.8	279.4
	12	237.7	241.2	245.4	251.2	262.5	271.8	287.0	304.4
	16	217.8	218.6	220.7	222.1	229.3	233.8	241.7	250.6
	20	214.7	216.0	216.8	218.7	224.7	228.8	236.4	246.8
	24	211.9	212.4	213.1	213.9	220.5	223.4	231.5	240.6
	28	210.3	210.6	211.1	212.4	218.2	221.8	228.9	237.7

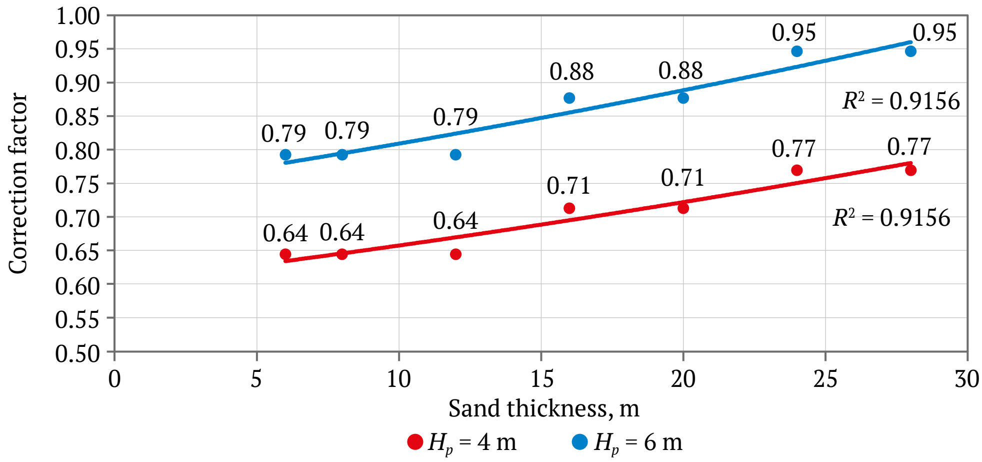

Fig. 6. Dependence of the correction factor on placer deposit parameters when using bulldozers in stripping work and peat thicknesses of 4 and 6 m

Table 2

Optimal front bank width taking into account stripping W_{str} and not taking into account stripping W with the use of bulldozers

T_p	T_s	K_{str}	W	W_{str}	Difference, %	Recommended correction factor
2	6	0.33	100.9	100.0	0.9	1.00
	8	0.25				
	12	0.17				
	16	0.13	91.2	95.0	–	1.00
	20	0.10				
	24	0.08	84.5	95.0	–	1.00
	28	0.07				
4	6	0.67	100.9	80.0	20.7	0.79
	8	0.50				
	12	0.33				
	16	0.25	91.2	80.0	12.3	0.88
	20	0.20				
	24	0.17	84.5	80.0	5.3	0.95
	28	0.14				
6	6	1.00	100.9	65.0	35.6	0.64
	8	0.75				
	12	0.50				
	16	0.38	91.2	65.0	28.7	0.71
	20	0.30				
	24	0.25	84.5	65.0	23.1	0.77
	28	0.21				

Notes: T_p is peat thickness, m; T_s is sand thickness, m; K_{str} is stripping ratio, m³/m³; W_{str} is optimal front bank width taking into account stripping, m; W is optimal front bank width without taking into account stripping, m.

Table 3

Rehandling coefficients, m³/m³, for different flow sheets of stripping with the use of a ESh 20/90 dragline

Overburden thickness, m	Sand thickness, m	Rehandling coefficient for different front bank (dredge "face") width, m				
		50	65	90	120	140
5	6	0	0	0	0	0
	8	0	0	0	0	0.08
	12	0	0	0	0	0.14
	16	0	0	0	0.05	0.24
	20	0	0	0	0.13	0.29
	24	0	0	0	0.29	0.37
	28	0	0	0	0.33	0.4
10	6	0	0	0	0	0.17
	8	0	0	0	0	0.23
	12	0	0	0	0.08	0.27
	16	0	0	0	0.23	0.37
	20	0	0	0	0.32	0.43
	24	0	0.08	0.17	0.41	0.49
	28	0	0.1	0.25	0.44	0.51
15	6	0	0	0	0.05	0.2
	8	0	0	0.05	0.1	0.25
	12	0	0	0.06	0.14	0.31
	16	0	0	0.12	0.25	0.46
	20	0	0.04	0.2	0.36	0.58
	24	0.04	0.09	0.37	0.48	0.76
	28	0.08	0.11	0.4	0.6	0.85
20	6	0	0	0.13	0.19	0.36
	8	0	0	0.19	0.26	0.43
	12	0	0.09	0.3	0.31	0.47
	16	0.08	0.13	0.32	0.48	0.57
	20	0.11	0.19	0.43	0.51	0.69
	24	0.15	0.21	0.54	0.56	1.08
	28	0.17	0.23	0.58	0.69	1.51

Table 4

Costs of extraction and processing of sand using direct dumping technique in stripping work, Rub/m³

Peat thickness, m	Sand thickness, m	Front bank (dredge "face") width, m				
		50	65	90	120	140
5	6	221.9	221.0	220.1	229.1	237.6
	8	217.8	216.8	216.0	223.9	233.2
	12	213.6	212.6	211.8	218.7	228.1
	16	208.6	207.8	207.5	214.6	224.4
	20	207.3	206.6	206.3	213.4	222.8
	24	204.7	204.0	204.6	210.8	219.7
	28	204.1	203.4	203.9	210.0	218.8
10	6	238.6	237.6	236.8	249.9	263.2
	8	230.3	229.3	228.5	239.5	252.9
	12	221.9	221.0	224.3	230.2	241.4
	16	214.8	217.2	216.9	224.6	234.9
	20	212.3	214.1	213.8	221.8	231.5
	24	210.7	211.1	211.5	217.9	227.1
	28	209.3	209.6	209.9	216.2	225.2
15	6	255.3	254.3	266.0	272.9	287.7
	8	242.8	241.8	251.9	258.3	271.6
	12	235.8	235.6	238.8	242.5	254.6
	16	225.7	225.0	226.6	234.0	246.1
	20	221.1	220.8	222.6	229.9	241.4
	24	216.6	216.4	219.0	225.3	236.9
	28	214.7	214.2	216.5	223.4	234.3
20	6	271.9	287.6	294.2	302.3	320.5
	8	255.3	266.8	274.1	281.8	297.5
	12	246.9	248.5	253.6	258.7	271.7
	16	235.3	235.6	239.3	248.0	258.7
	20	229.2	229.8	233.6	240.2	252.0
	24	223.5	223.6	227.9	233.3	249.3
	28	220.0	220.4	224.3	230.8	249.4

Table 5

Optimal front bank (dredge "face") width taking into account stripping W_{str} and not taking into account stripping W when using direct dumping technique

T_p	T_s	K_{str}	W	W_{str}	Difference, %	Correction factor
5	6	0.83	100.9	100.0	0.9	0.99
	8	0.63				
	12	0.42				
	16	0.31	91.2	90.0	1.3	0.99
	20	0.25				
	24	0.21	84.5	85.0	0.0	1.01
	28	0.18				
10	6	1.67	100.9	90.0	10.8	0.89
	8	1.25				
	12	0.83				
	16	0.63	91.2	90.0	1.3	0.99
	20	0.50				
	24	0.42	84.5	85.0	−0.6	1.01
	28	0.36				
15	6	2.50	100.9	65.0	35.6	0.64
	8	1.88				
	12	1.25				
	16	0.94	91.2	65.0	28.7	0.71
	20	0.75				
	24	0.63	84.5	65.0	23.1	0.77
	28	0.54				
20	6	3.33	100.9	50.0	50.5	0.50
	8	2.50				
	12	1.67				
	16	1.25	91.2	50.0	45.2	0.55
	20	1.00				
	24	0.83	84.5	50.0	40.8	0.59
	28	0.71				

Notes: T_p is peat thickness, m; T_s is sand thickness, m; K_{str} is stripping ratio, m³/m³; W_{str} is optimal front bank width taking into account stripping, m; W is optimal front bank width without taking into account stripping, m.

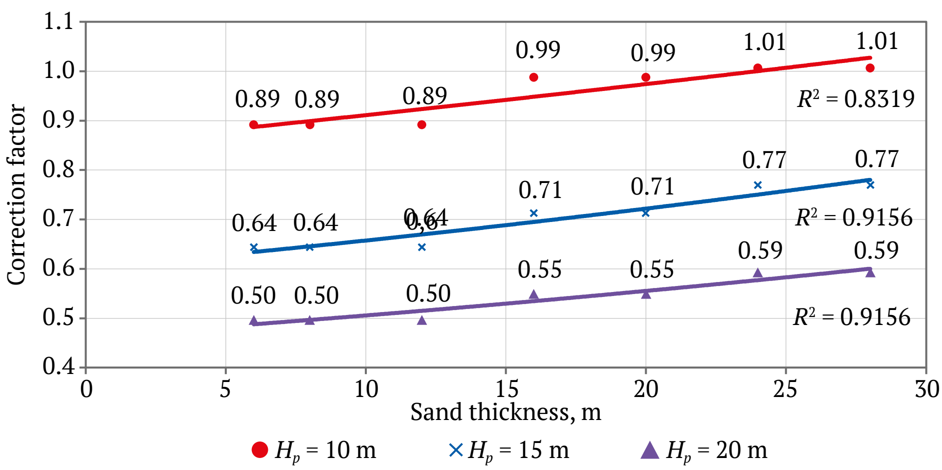

Fig. 7. Dependence of the correction factor on placer deposit parameters when using direct dumping in stripping work and peat thicknesses of 10, 15, 20 m

As can be seen from Table 5, the difference between the two calculation options results varies from 1.3 to 50.5%. With high peat thickness, consideration of stripping when calculating the optimal front bank width has a more significant effect.

Graphical dependencies of the correction factor on the parameters of a placer deposit when using direct dumping in stripping work are shown in Fig. 7.

Thus, when calculating an optimal front bank width, it is proposed to take into account a correction factor, the values of which are given in Table 2 (for bulldozer stripping) and Table 5 (for direct dumping stripping). The formula will assume the form of:

$$B_{ma} = K_{corr}\left[2R\sin\frac{\beta_{ma}}{2}\right], \quad (4)$$

where K_{corr} is a correction factor that takes into account the parameters of a placer deposit and the equipment used in stripping.

Conclusions

1. The presence of overburden on dredging sites has a significant impact on the most advantageous front bank width, which, depending on the thickness of peat, is reduced by 1.05–1.5 times (by 5–50%) relative to the recommended values.

2. It is most important to take into account stripping when determining the optimal front bank width for a 380-liter dredge at peat thickness exceeding 2 m (when using bulldozers) and peat thickness exceeding 5 m (when using direct dumping with ESh 10/70, ESh 20/90 draglines).

3. With an increase in peat thickness and the stripping ratio, the optimal front bank width is significantly reduced and should be taken as equal to the minimum possible value for the bulldozer method of stripping (peat overburden removal) at a peat thickness of more than 6 m, and for direct dumping technique, more than 15 m.

4. It is recommended to calculate the optimal front bank width using the formula developed by V.G. Leshkov with the use of the proposed correction factor. When using less powerful equipment for stripping, such as bulldozers with a power of 200–250 kW or ESh 6/45 dragline excavators, the proposed correction factors will be significantly reduced.

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Role of strike-slips and graben-rifts in controlling oil and gas reservoirs in deep horizons of the Russko-Chaselsky Ridge (West Siberian Province)

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Abstract
The study of the geological setting features of the West Siberian Oil-and-Gas Province (OGP) is relevant for establishing the relationship between the spatial distribution of local strike-slip dislocations (Russko-Chaselsky Ridge) and the structure of the regional Pai-Khoi-Altai shearing zone. The work aims to identify the regularities of hydrocarbon accumulations location associated with fault systems of this zone. The paper presents the results of studies aimed at assessing the nature of the Earth crust disturbance within the regional Pai-Khoi–Altai shearing zone and the prerequisites for the occurrence of hydrocarbon accumulations within it. A complex set of regional and detailed geophysical data, including 2D and 3D seismic surveys and digital models of gravity and magnetic fields, was used as a factual basis. Based on these materials, cross-sections and maps were drawn showing the structural features of the sedimentary cover and consolidated basement, and an analysis of the nature of the Earth crust disturbance within the shearing zone was performed. It was revealed that the disjunctive dislocations of the regional Pai-Khoi–Altai shearing zone have a characteristic morphology described by a right-lateral strike-slip (dextral) fault strain ellipsoid. Within the Russko-Chaselsky Ridge, patterns were identified in the manifestation of strike-slips and graben-rifts systems caused by the tectonic activity of the regional Pai-Khoi–Altai shear. The shearing zone, en echelon faulting, and associated Riedel shears constitute a single, hierarchically subordinate system of the upper Earth crust disturbance. It is characterized by the development of en echelon system of disturbance zones in the platform cover and the upper part of the consolidated basement, interpreted as Riedel shears of prevailing submeridional strike. Based on the interpretation of seismic cross-sections along the Riedel shears, "flower structures" extending from the Lower Cretaceous to the top of the Paleozoic were distinguished. Structures of this type, located within the West Siberian Oil-and-Gas Province and represented by dislocation systems, may act as drainage in further substantiation of the mechanisms of migration and accumulation of hydrocarbons.

Keywords
shear structures (strike-slips), graben-rift, Western Siberia, oil and gas reservoirs, gravity anomalies, magnetic anomalies, seismic surveying, potential fields, Riedel shears

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ГЕОЛОГИЯ МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Научная статья

Роль сдвиговых дислокаций и грабен-рифтов в контроле нефтегазоносности глубинных горизонтов Русско-Часельского вала (Западно-Сибирская провинция)

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Аннотация

Изучение особенностей геологического строения Западно-Сибирской нефтегазоносной провинции (НГП) актуально для установления взаимосвязи между пространственным распределением локальных сдвиговых дислокаций Русско-Часельского вала и структурой региональной Пай-Хой–Алтайской сдвиговой зоны. Цель работы – выявление закономерностей локализации УВ-скоплений, ассоциированных с разрывными нарушениями этой зоны. В статье представлены результаты исследований, направленных на оценку характера деструкции земной коры в пределах региональной Пай-Хой–Алтайской сдвиговой зоны и предпосылок локализации месторождений углеводородов в ее пределах. В качестве фактологической основы задействован комплекс региональных и детальных геофизических данных, включающий 2D и 3D сейсморазведку, цифровые модели гравитационного и магнитного полей. На основе этих материалов были построены разрезы и карты, отображающие особенности строения осадочного чехла и консолидированного фундамента, выполнен анализ характера деструкции земной коры в пределах сдвиговой зоны. Выявлено, что разрывные дислокации региональной Пай-Хой–Алтайской сдвиговой зоны имеют характерную морфологию, описываемую эллипсоидом деформаций правостороннего сдвига. В пределах Русско-Часельского вала определены закономерности проявления системы сдвиговых дислокаций и грабен-рифтовых структур, обусловленных тектонической системой регионального Пай-Хой–Алтайского сдвига. Сдвиговая зона, оперяющие разломы и связанные с ними сколы Риделя составляют единую иерархически подчиненную систему деструкции верхней коры. Для нее характерно развитие эшелонированной системы зон деструкции платформенного чехла и верхней части консолидированного фундамента, интерпретируемой как трещины Риделя с преобладанием субмеридионального простирания. По результатам интерпретации сейсмических разрезов вдоль трещин Риделя выделяются «структуры цветка», простирающиеся от нижнего мела до кровли палеозойских отложений. Структуры этого типа, локализованные в пределах Западно-Сибирской нефтегазовой провинции и представленные системами дислокаций, могут выступать дренажом при дальнейшем обосновании механизмов миграции и аккумуляции месторождений углеводородов.

Ключевые слова

сдвиговые структуры, грабен-рифт, Западная Сибирь, нефтегазоносность, гравитационные аномалии, магнитные аномалии, сейсморазведка, потенциальные поля, трещины Риделя

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Introduction

We examined the geological setting features of the West Siberian Oil-and-Gas Province (OGP) in order to establish the relationship between the spatial distribution of local strike-slip dislocations (within the Russko-Chaselsky Ridge) and the dislocation system of the regional shearing zone in connection with the study of the regularities governing the location of hydrocarbon accumulations associated with a complex system of disjunctive dislocations that are part of the regional Pai-Khoi-Altai shearing zone [1, 2].

Within the West Siberian OGP, the bulk of the identified hydrocarbon accumulations [3–5] are confined to Cretaceous sediments. The Bazhenovsky horizon is considered to be the oil source strata; the Lower Cretaceous terrigenous rocks act as the reservoir; the Podachimovsky horizon mudstone is the impermeable layer [6–8]. The mechanism of hydrocarbon migration can be largely explained by the development of a system of disjunctive dislocations. Many researchers studied the nature of shear dislocations in consolidated basements and the lower parts of the sedimentary cover of the West Siberian geosyncline [9, 10]. For instance, A.E. Kontorovich distinguished between major shear dislocations of different directions (first order) penetrating into the Lower Cretaceous horizons and secondary shears (second order) mapped in the Cenozoic sequence [3, 11, 12].

A.I. Timurziev, based on an in-depth study of the 2D and 3D seismic survey data, concluded that regional shearing zones are widely manifested in the northwestern part of the West Siberian geosyncline [2, 9]. The author notes that the results of the 2D seismic surveys do not always accurately reflect horizontal shear structures (strike-slips), unlike the results of the detailed 3D seismic surveys [11, 13]. An important feature of the shears, in his view, is the almost complete absence of vertical displacements at the level of the uppermost consolidated basement.

Detailed studies within the Ety-Purovsky accumulation have shown that regional shears are framed by a system of en echelon tension stress and shearing dislocations. Within the shearing zones, based on the 3D seismic data, the author has identified a system of northwestward strike-slips and en echelon northeastward strike-slips on the sides and in the spaces separating the major strike-slips [9–13].

In our research, we considered the features of the deep structure of the regional Pai-Khoi–Altai shearing zone, which, judging by a complex of geological and geophysical data, extends from the Altai-Sayan folded area to the Pai-Khoi. The zone includes the main fault (geosuture) and a system of en echelon extension faults and strike-slips (shears) [14, 15] (Fig. 1). This system of tectonic dislocations developed against the backdrop of a consolidated basement formed by formations of different age, from the Yenisei (Baikalides), Kazakhstan and Altai-Sayan (Caledonides), Ural and Central-Western Siberian (Hercinides) folded areas [14].

Research techniques and factual material

The area of our detailed research (Fig. 1, *a*), including the outline of the Russko-Chaselsky Ridge, is characterized by a high level of geological and geophysical knowledge [16]. As a factual basis for the research, we used the results of seismic surveys, deep drilling data, and potential geophysical fields data borrowed from the Gravimag database at a scale of 1 : 200,000 [16, 17].

The study area at local level was selected depending on the seismic cross-section outlines. To simulate shear dislocations and investigate the structure of the basement and sedimentary cover within the study area, we performed a series of procedures: calculation of potential field transformants [18], including factorization into regional and local components, calculation of gradients, etc. [19, 20]. To estimate the amplitudes of tectonic deformations, seismic cross-sections were filtered using surface-consistent procedures, adaptive noise suppression, 5D regularization, and Kirchhoff depth migration (using OVT panels), as well as post-processing[1] [21]. In addition, the results of solving inverse problems of gravity and magnetic surveys, etc. were used (Fig. 2) [21]. The methodological approach involved applying a multi-level data processing scheme at regional and local levels to identify characteristic patterns of subordination of geological structures.

A.I. Timurziev found similar horizontal shear structures (strike-slips) are manifested in the sedimentary cover by linear en echelon systems of downthrow faults and thrust faults; the en echelon faults are grouped into a linear zone of NW strike (310–320°) with a width ranging from 1.0–1.5 km in the lower part of the sedimentary cover to 5.0–6.5 km in the Upper Cretaceous top. Along the strike, the suture zone comprises grabens and depressions of shear extension [9, 22].

A qualitative interpretation of the transformants [18, 23] allowed to identifying elongated positive anomalies of the gravitational and magnetic fields of submeridional strike in the central part of the

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detailed study area, which, in our opinion, are manifestations of rift structures [23–25]. On the structural-tectonic diagrams compiled based on these data (see Fig. 2), first-order shear dislocations (strike-slips) have a predominantly northwestern strike, while second-order rift structures are oriented northeastward and located in the space between the major shear dislocations [23, 26, 27].

The manifestations of these dislocations at a detailed level in seismic cross-sections of the Bazhenovsky reflective horizon interval (Fig. 3) are expressed in graben-rift structures, traced in the form of "Riedel shears" oriented at an angle of 30° to the main shear axis [28, 29].

According to most researchers, the main shear dislocations are deeply seated [30, 31]. The extension structures are most likely seated near the surface [32]. In this regard, we studied geological and geophysical cross-sections based on reference seismic profiles [11, 15]. In the interval between 1,000 and 2,000 ms, a system of disjunctive dislocations with a characteristic "flower structure" morphology can be traced (Fig. 4) [14]. Above this interval, only anticline folds are manifested that indirectly confirms the assumption of an attenuation of tectonic deformations in the Upper Jurassic sediments [31, 33].

The Figure demonstrates the strike-slips joining en echelon the plane of major shear in a fan-like manner [1, 34]. The appearance of the "flower structures" indicates the strike-slips (shears) of northeastern strike [35, 36] that allows assuming trans-tensional nature of the strike-slips [13, 34]. The roots of these faults can be traced below the uppermost basement (below 6 km) [37, 38].

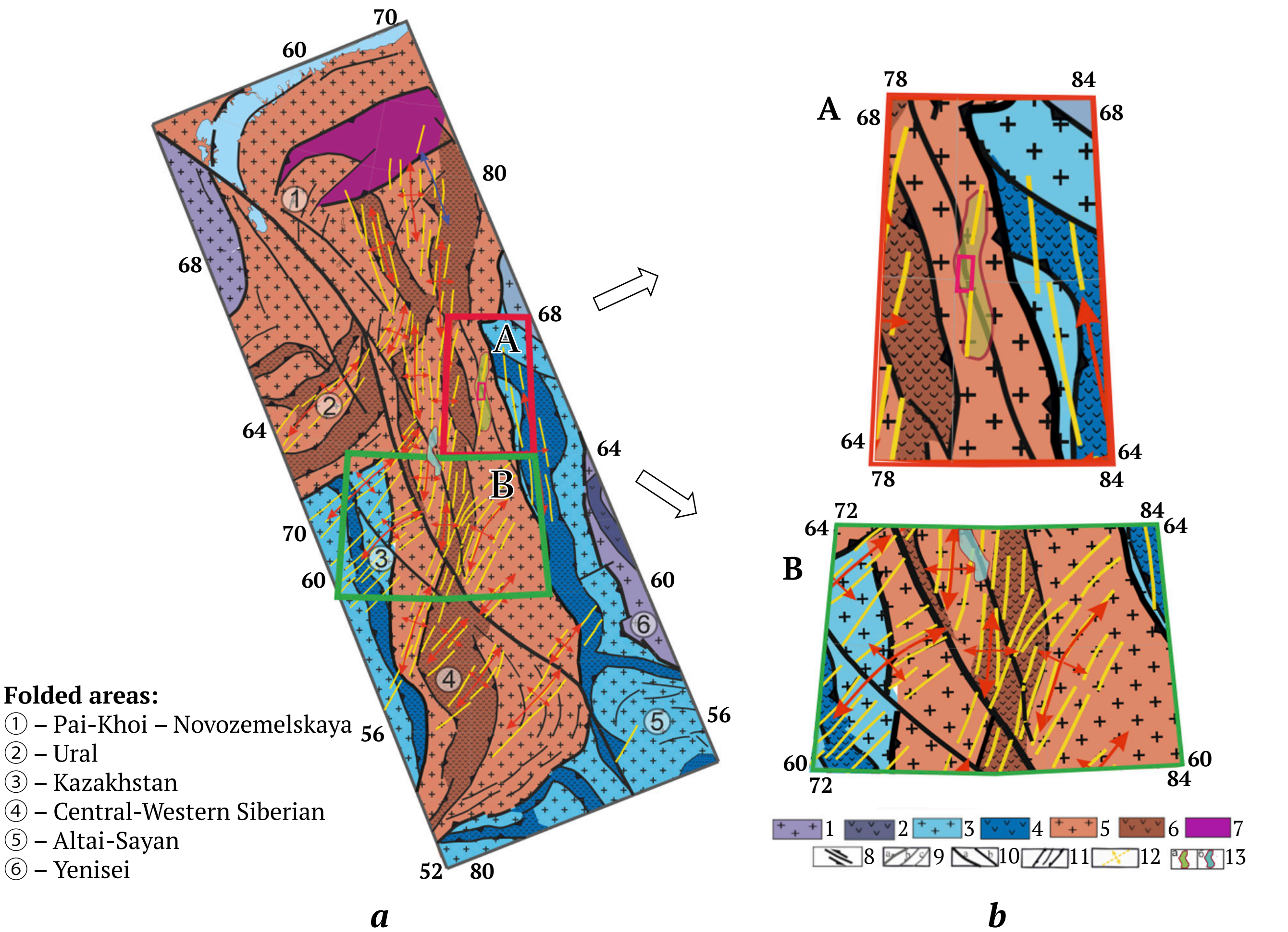


Fig. 1. Fragment of a map of the deep geological setting of the consolidated basement of the West Siberian OGP with the location of the study area (*A*), the territory of the Russko-Chaselsky Ridge, and with the outline of the neighboring area (*B*), within which the Ety-Purovsky Ridge is located [15]:
1–7 – structural and material subdivisions of the consolidated crust: *1–2* – Epibaykal folded areas (*1* – blocks, *2* – interblock zones), *3–4* – Epicaledonian folded areas (*3* – blocks, *4* – interblock zones), *5–6* – epihercinian folded areas (*5* – blocks, *6* – interblock zones), *7* – ancient platforms; *8–11* – disjunctive dislocations: *8* – the Pai-Khoi – Novozemelsky shear displacement direction, *9* – en echelon disjunctive dislocations, *10* – boundaries of interblock suture zones, *11* – rift boundaries, *12* – lineaments and rift development direction, *13* – Ridge outlines (*a* – Russko-Chaselsky, *b* – Eti-Purovsky)

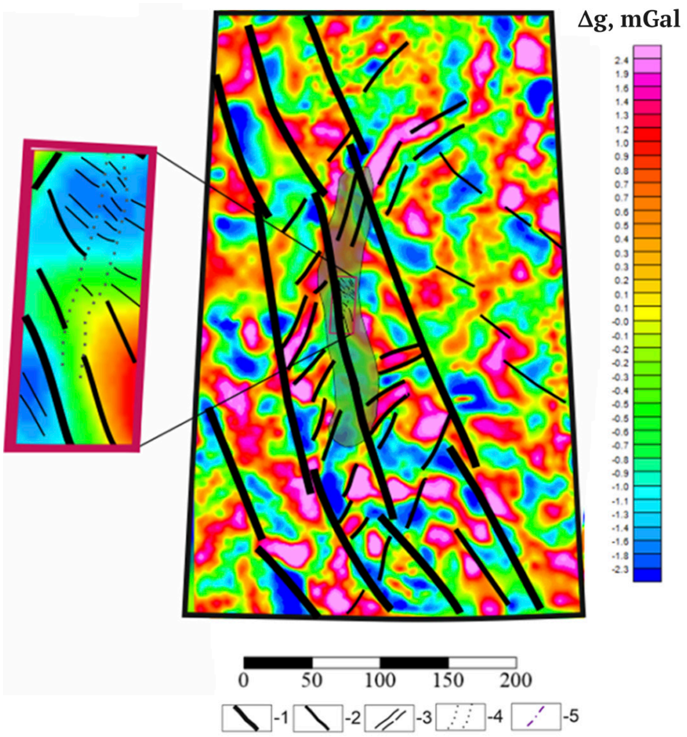
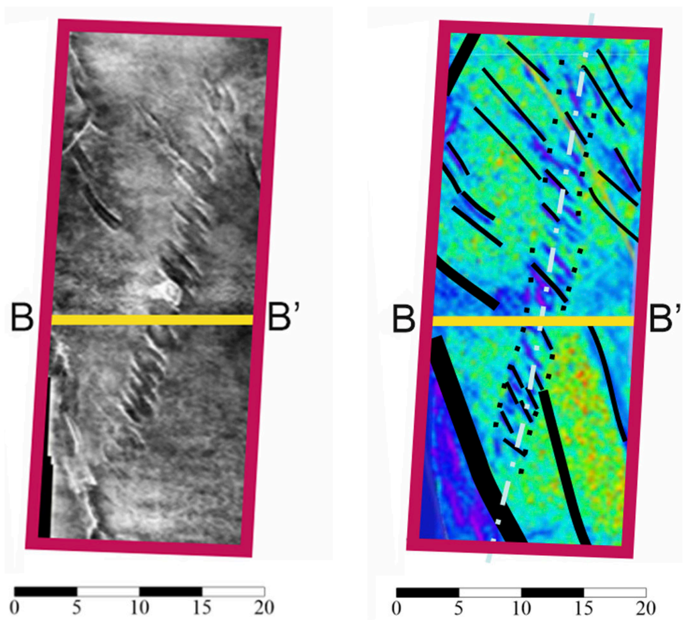


Fig. 2. Results of interpretation based on potential fields (according to the map of the local component of the gravitational field) [compiled by the authors]: *1* – boundaries of rift structures (I rank); *2* – strike-slip; *3* – rift structures (II rank); *4* – presumed boundaries of Riedel shear development zone; *5* – axial direction of Riedel shear development



a ***b***

Fig. 3. Interpretation within the detailed study area with the position of seismic profile B–B' (highlighted in yellow), performed on the basis of a horizontal cross-section of the total 3D cube in the interval of the Bazhenovsky reflective horizon (characteristic dimensions of kilometers) – *a*, and the amplitude distribution diagram along the seismic cross-section – *b* [compiled by the authors]

The results obtained confirm that the manifestation of rifts and strike-slips in the form of Riedel shears creates favorable conditions for the migration and accumulation of hydrocarbons in traps [39]. For example, Riedel shears can serve as channels for hydrocarbon migration and also change the mechanical properties of rocks that in turn affects their ability to retain oil and gas and characterize the novelty of the authors' research [2, 40].

The practical application of the results obtained lies in the use of structural factors (Riedel shears, "flower structure") in solving predictive problems using both geophysical and geological-structural criteria for determining oil and gas potential.

Conclusion (findings)

Thus, it can be concluded that the disjunctive dislocations of the regional Pai-Khoi–Altai shearing zone have a characteristic morphology described by a right-lateral strike-slip (dextral) fault strain ellipsoid.

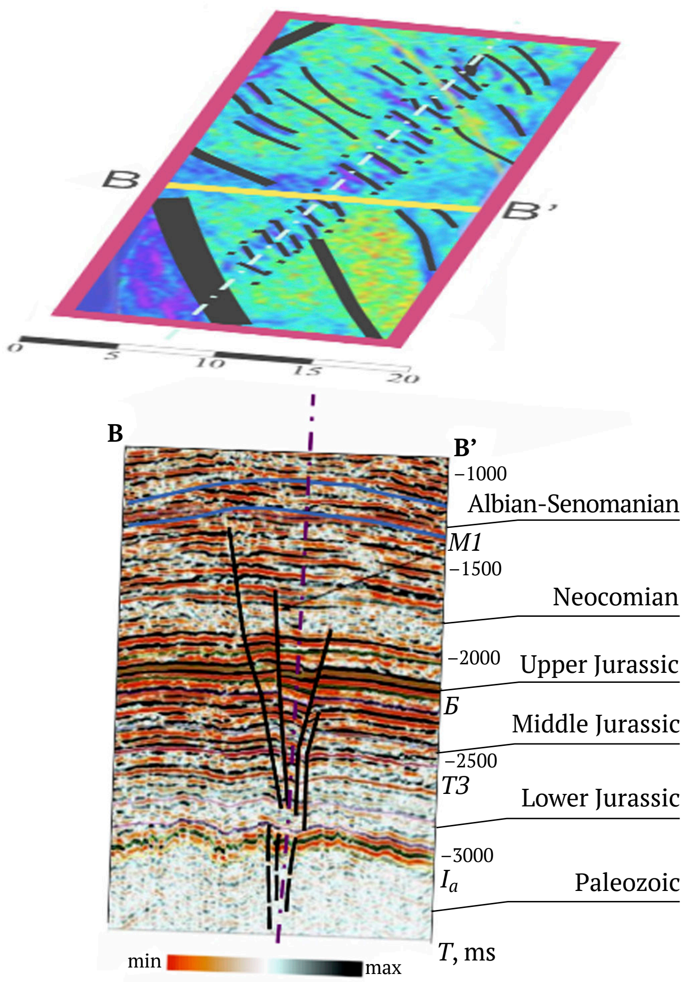


Fig. 4. The manifestation of the "flower structure" and Riedel shears based on seismic data interpretation (see legend to Fig. 2) [compiled by the authors]

The shearing zone, en echelon faulting, and associated Riedel shears constitute a single, hierarchically subordinate system of the upper Earth crust disturbance and are promising for further study of hydrocarbon migration and accumulation mechanisms [5].

Within the Russko-Chaselsky Ridge, patterns were revealed in the manifestation of strike-slips and graben-rifts systems caused by the tectonic activity of the regional Pai-Khoi–Altai shear; This zone is characterized by the development of en echelon system of disturbance zones in the platform cover and the upper part of the consolidated basement, interpreted as Riedel shears of prevailing submeridional strike.

The main shearing zone within the study area is 6 km long and 0.8 km wide. In the cross-section, an interconnection between disjunctive dislocations can be traced, in the distribution of which a “flower structure” can be identified, extending from the Lower Cretaceous to the uppermost Paleozoic and demonstrating a fan-shaped orientation of faults (within the studied area).

Structures of this type, located within the West Siberian Oil-and-Gas Province and represented by dislocation systems, may be considered as drainage in further substantiation of the mechanisms of migration and accumulation of hydrocarbons.

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Mineral resource base of Russia's cobalt: current state and development prospects

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Abstract
The *relevance* of this study stems from the need to obtain a comprehensive picture of the state of the cobalt mineral resource base of the Russian Federation. *Objective:* to examine the current state of Russia's cobalt mineral resource base, the spatial distribution of cobalt deposits by ore formation types and within ore provinces, and the prospects for national cobalt production. *Methods:* statistical, graphical, and logical analysis. *Results:* a consolidated schematic map of Russia is presented, featuring 25 cobalt-bearing provinces and a sample of 150 of the most significant cobalt deposits across various ore formations, along with prospective sites and areas. Key characteristics are provided for the main ore formations hosting cobalt deposits in Russia, as well as for cobalt-bearing provinces and deposits outside these provinces. In Russia, cobalt is extracted as a by-product from sulfide copper-nickel ores (9.2 Kt in 2022). As of January 1, 2023, Russia's balance reserves of cobalt totaled 1,562.3 Kt. The largest volumes of cobalt reserves are associated with the copper-nickel formation (62.5%) and the silicate-cobalt-nickel formation (19.9%), with the remaining 17.6% distributed among all other ore formations. By province, the Norilsk province accounts for 47.0% of Russia's cobalt reserves, the Ural province – 24.7%, the Kola and Shoria-Khakass provinces – 7.4% each, the Easten Sayan province – 6.1%, and all other provinces – 7.7%. The Russian Federation has been allocated exploration areas on the international seabed in the Pacific Ocean, where geological surveys are underway in the cobalt-rich ferromanganese crust formation of the Magellan Mountains (resources of 110 Kt Co, with 0.50–0.61% Co) and in the ferromanganese nodule formation of the Clarion-Clipperton ore field (resources of 985 Kt Co, with 0.22–0.29% Co). Despite a substantial base of prepared cobalt reserves, Russia lacks a systematic accounting of forecast cobalt resources, complicating the planning of geological exploration for cobalt. A systematic review of existing geological and geochemical data on known occurrences and points of cobalt mineralization is proposed, with the aim of assessing forecast resources using a unified methodology and producing a consolidated forecast resource balance for cobalt in Russia. For deposits of the silicate-cobalt-nickel formation, where previous assessments were based on maximizing nickel reserves, a reassessment is proposed with 3D special modeling of cobalt distribution as the primary ore component. Such deposits can then be managed specifically for cobalt production. Advancements in underground and heap leaching technologies, as well as bioleaching of cobalt-bearing ores, will enable the development of cobalt deposits with low-grade ores and small reserves, as well as the reprocessing of technogenic materials derived from beneficiation and metallurgical processes. The most promising targets for cobalt extraction using in-situ leaching, heap leaching, and bioleaching technologies are the deposits of the silicate-cobalt-nickel formation.

Keywords
strategic raw materials, cobalt, ore formations, ore provinces, balance reserves, resources, primary and by-product components, review

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ГЕОЛОГИЯ МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Обзорная статья

Минерально-сырьевая база кобальта России: состояние, возможности развития

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Аннотация
Актуальность работы обусловлена необходимостью получения максимально полной картины состояния минерально-сырьевой базы кобальта Российской Федерации. *Цель*: изучение состояния минерально-сырьевой базы кобальта России, пространственного размещения месторождений кобальта

по типам рудных формаций и в пределах рудных провинций, перспектив национальной добычи кобальта. *Методы*: статистический, графический, логический. *Результаты*: Представлена сводная карта-схема России, включающая 25 кобальторудных провинций и выборку из 150 наиболее значимых месторождений кобальта различных рудных формаций, перспективных объектов и площадей. Даны характеристики основных рудных формаций, месторождения кобальта которых имеются в России, а также кобальторудных провинций и месторождений вне провинций. В России добыча кобальта производится в качестве попутного продукта из сульфидных медно-никелевых руд (в 2022 г. – 9,2 тыс. т). В России по состоянию на 01.01.2023 г. учтено 1562,3 тыс. т балансовых запасов кобальта. Наибольшие объемы запасов кобальта приходятся на медно-никелевую (62,5 %) и силикатно-кобальто-никелевую (19,9 %) формации и 17,6 % на все остальные рудные формации. По провинциям на Норильскую приходится 47,0 % от российских запасов кобальта, на Уральскую – 24,7 %, на Кольскую – 7,4 %, Шорско-Хакасскую – 7,4 %, Восточно-Саянскую – 6,1 %, на остальные – 7,7 %. За Российской Федерацией закреплены разведочные районы международного морского дна в Тихом океане, где ведутся геологические исследования формации кобальтоносных марганцевых корок на Магеллановых горах (ресурсы 110 тыс. т Co, 0,50–0,61 % Co) и формации железомарганцевых конкреций рудного поля Кларион-Клиппертон (ресурсы 985 тыс. т Co, 0,22–0,29 % Co). На территории Российской Федерации несмотря на значительную базу подготовленных запасов кобальта отсутствует системный учет его прогнозных ресурсов, что осложняет планирование геологоразведочных работ на кобальт. Предлагается произвести системную ревизию имеющихся геологических и геохимических материалов по известным проявлениям и точкам кобальтовой минерализации с оценкой прогнозных ресурсов по единой методике и собственно составить баланс прогнозных ресурсов кобальта по России. На месторождениях силикатно-кобальт-никелевой формации, где ранее их оценка производилась исходя из задачи максимизации запасов никеля, предлагается произвести переоценку с геометризацией распределения кобальта в качестве главного компонента руд. Такие объекты становятся управляемыми при планировании добычи именно кобальта. Развитие технологий подземного и кучного выщелачивания, а также биовыщелачивания кобальтсодержащих руд позволит вовлекать в эксплуатацию кобальторудные объекты с низким качеством руд и небольшими запасами, а также техногенные образования продуктов обогащения и металлургического передела. Наиболее интересными для геотехнологических способов добычи кобальта являются месторождения силикатно-кобальт-никелевой формации.

Ключевые слова
стратегическое сырье, кобальт, рудные формации, рудные провинции, балансовые запасы, ресурсы, главные и попутные компоненты, обзор

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Introduction

Cobalt is used in a wide range of applications: in the cathodes and anodes of electric batteries and accumulators (as cobalt oxide), in oxidation catalysts (cobalt acetates, carboxylates, and carbonyls), in blue pigments and dyes (cobalt phosphates and aluminates), in heat-resistant alloys (e.g., Vitallium, cermets), hard alloys (e.g., Stellite, Pobedit), and magnetic alloys (e.g., Alnico), as well as in strengthening powder coatings and alloy compositions. Global cobalt consumption reached 187 Kt in 2022 [1] and continues to rise due to growing demand for rechargeable batteries (Fig. 1). The leading cobalt-producing countries are the Democratic Republic of the Congo (76% of global production), Indonesia (9.7%), Russia (3.0%), Australia (2.0%), and the Philippines (1.9%). The cobalt market is considered high-risk due to the fact that primary cobalt deposits are extremely rare, and the cobalt available on the market is typically a by-product of the mining of copper, copper-nickel sulfide, and silicate-nickel deposits. As a result, the supply of cobalt is highly inelastic, which has led to price crises and sharp spikes in cobalt prices, such as in 1978 (due to the war in Zaire, now the Democratic Republic of the Congo) and in 2017 (due to a surge in demand for energy storage systems) [2, 3].

In Russia, cobalt is classified as a strategic mineral resource, although its production volumes are not critical, as they significantly exceed domestic demand. Nevertheless, the issue of limited controllability over cobalt supply volumes does exist in Russia, as cobalt is extracted as a by-product from ores of the copper-nickel sulfide formation [4]. Despite Russia's considerable accounted balance reserves of cobalt, planning to increase production in the context of the growing lithium-ion battery industry [5] will be challenging for new development projects targeting complex copper-nickel, silicate-nickel, iron ore, and sulfide (pyrite) deposits, where cobalt is of secondary importance. It is also worth noting the lack of a consolidated balance of forecast cobalt resources across the Russian Federation, as well as the inconsistent methodologies used by different authors to estimate cobalt reserves and resources at individual deposits.

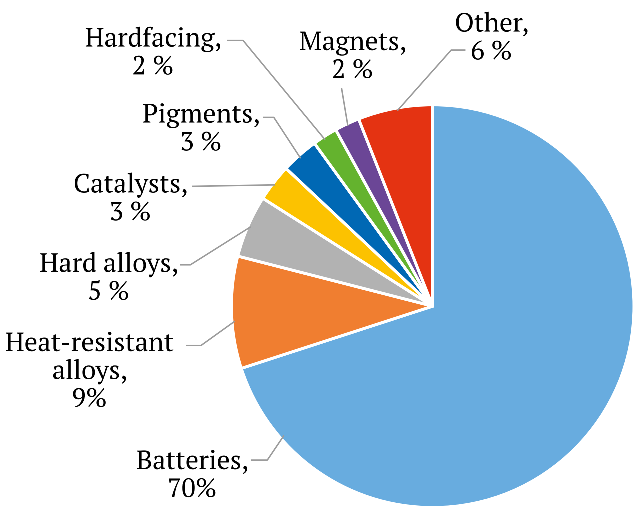

Fig. 1. Distribution of global cobalt consumption in 2022 [1]

Given global trends of rising cobalt consumption – and the potential for a sharp increase in domestic demand – it is necessary to assess the capabilities of Russia's cobalt mineral resource base, which is the aim of the present review.

Research methodology

To assess the state of Russia's mineral resource base of cobalt, data were compiled on reserves and forecast resources of cobalt and cobalt-bearing deposits as of January 1, 2023. Sources included state reports of the Ministry of Natural Resources and Environment of the Russian Federation[1], informational reports on the status and prospects of mineral resource use[2], state cadastral passports of deposits and mineral occurrences in Russia[3] and published open-access literature on cobalt deposits and resources. All figures on cobalt reserves, resources, and production are given in metric tons of contained cobalt (100% Co). A general schematic map of Russia was compiled, showing cobalt-ore provinces and a selection of the most significant cobalt deposits from various ore formations, along with promising targets and areas for geological exploration. The study also examined the potential for cobalt mining development using innovative extraction and processing technologies for cobalt-bearing ores [6]. An analysis was carried out on the status of balance reserves by ore formation and by cobalt-ore province.

State of the cobalt mineral resource base in Russia

Russia ranks 6th globally in cobalt reserves, following the Democratic Republic of the Congo, Australia, Indonesia, Cuba, and the Philippines. It holds 3rd place in primary cobalt extraction, after the Democratic Republic of the Congo and Indonesia, and 6th place in refined cobalt production, after China, the United States, Finland, Canada, Japan, and Norway [4, 7]. Russia's cobalt mineral resource base is primarily composed of deposits belonging to two key geological-industrial types: the copper-nickel sulfide type and the silicate-cobalt-nickel type. At present, cobalt is extracted exclusively as a by-product from copper-nickel sulfide ores. Mining at silicate-cobalt-nickel deposits has been suspended since 2012, and at arsenide-cobalt deposits since 1991. Balance reserves of cobalt are also recorded at currently developed copper-pyrite and skarn-type iron ore deposits, but cobalt is not extracted from these due to technological and economic limitations.

Based on the compiled data, the following materials were developed:

– a general map of Russia's cobalt-ore provinces, major deposits, and cobalt occurrences (Fig. 2);

– charts presenting cobalt reserves by ore formation (as of 2021) (Fig. 3) and by province (Fig. 8);

– charts showing cobalt reserves by province within individual ore formations (Fig. 4).

The following sections provide an overview of the cobalt-bearing ore formations identified within the Russian Federation, as well as the corresponding cobalt-ore provinces.

Cobalt ore formations

Cobalt-bearing ore formations are classified into two groups: (1) primary cobalt formations, where cobalt is the principal (most valuable) mineral component, and (2) cobalt-associated formations, where cobalt occurs as a by-product. The first group includes the endogenic arsenide-cobalt formation and the biogenic formation of cobalt-rich crusts on oceanic seamounts. The second group comprises cobalt-associated endogenic formations such as the copper-nickel sulfide, low-sulfide platinum-group element (PGE), copper-pyrite, skarn iron-ore, va-

[1] State report on the status and use of the mineral resources of the Russian Federation in 2021. Ministry of Natural Resources and Environment of the Russian Federation; 2022. 626 p. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[2] Information on the status and prospects of use of the mineral resource base in the regions of the Russian Federation (as of 01.01.2022). St. Petersburg: VSEGEI, State Assignment No. 049-00018-22-01 of January 14, 2022; 2022. URL: http://atlaspacket.vsegei.ru/?v=msb2021#91474d2e700eb6c90

[3] Passports of cobalt deposits. Russian Federal Geological Fund. The unified fund of geological information about the subsurface. The register of primary and interpreted data; 2023. 2023. URL: https://efgi.ru/

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Fig. 2. Cobalt-ore provinces, deposits, and occurrences by geological and technological type:

1 – cobalt-ore provinces; *2–13* – geological and technological types of cobalt deposits (*a* – reserves + resources over 10,000 t Co; *b* – 1,000–10,000 t Co): *2* – copper-nickel cobalt-bearing, *3* – low-sulfide platinum group element (PGE) cobalt-bearing, *4* – silicate cobalt-nickel, *5* – pyrite-type cobalt-bearing, *6* – skarn-type iron ore cobalt-bearing, *7* – titanomagnetite-type cobalt-bearing, *8–12* – arsenide-cobalt (*8* – cobalt-nickel, *9* – bismuth-cobalt, *10* – primary arsenide-cobalt, *11* – gold-silver, *12* – tin-tungsten), *13* – uranium-type cobalt-bearing, *14* – manganese-ore cobalt-bearing; *15* – cobalt-iron-manganese crusts and nodules; *16* – technogenic cobalt-ore provinces: I – North Caucasian, II – Ergeninsky, III – Voronezh, IV – Baltic, V – Karelian, VI – Kola, VII – Ural, VIII – Norilsk, IX – Salair, X – Shoria-Khakass, XI – Altai–Western Sayan, XII – Eastern Sayan, XIII – North Baikal, XIV – Dzhugdzhur, XV – Yana–Adycha, XVI – Seymchan, XVII – Koryak, XVIII – Kamchatka. Cobalt deposits and occurrences: *1–24* – cobalt–copper–nickel (*1* – Elan, *2* – Pedrorechenskoe, *3* – Semchozerskoe, *4* – Voloshovskoe, *5* – Zhdanovskoe, *6* – Tundrovoe, *7* – Sopchuayvench, *8* – Poaz, *9* – Nyud-Moroshkovoe, *10* – Nittis-Kumuzhya-Travyanaya, *11* – Oktyabrskoe-Cu-Ni, *12* – Talnakhskoe, *13* – Norilsk-1, *14* – Maslovskoe, *15* – Chernogorskoe, *16* – Vologochanskoe, *17* – Kingash, *18* – Verkhnekingash, *19* – Tokty-Oy, *20* – Chaya, *21* – Kun-Manie, *22* – Ariadnoe, *23* – Dukukskoe, *24* – Shanuch); *25–32* – low-sulfide platinum group element (PGE) cobalt-bearing (*25* – Shalozerskoe, *26* – Viksha, *27* – Kievey, *28* – Monchetundrovskoe, *29* – Pyatirechenskoe, *30* – Mainitskaya, *31* – Valaginsko-Karaginskaya, *32* – Snezhnoye); *33–48* – silicate cobalt-nickel (*33* – Buruktal, *34* – Novokievskoe, *35* – Sakharinskoe, *36* – Elizavetinskoe, *37* – Serovskoe, *38* – Yareney, *39* – Belininskoe, *40* – Aleksandrovskoe); *41–49* – pyrite-type cobalt-bearing (*41* – Khudesskoe, *42* – Kizil-Dere, *43* – Gaiskoe, *44* – Dergamysh, *45* – Ivanovskoe, *46* – Saumskoe, *47* – Pyshminsko-Klyuchevskoye, *48* – Savinskoe, *49* – Degdenreken); *50–59* – skarn-type iron ore cobalt-bearing (*50* – Techenskoe, *51* – Peschanskoe, *52* – Chesnokovskoe, *53* – Tashtagolskoe, *54* – Anzasskoe, *55* – Abakanskoe, *56* – Volkovsky Fe, *57* – Izygskoye, *58* – Oktyabrskoe-Fe, *59* – Taezhnoe); *60–62* – titanomagnetite-type cobalt-bearing (*60* – Magazin-Musyur, *61* – Volkovsky Fe-V-Cu, *62* – Chineyskoe); *63–77* – arsenide-cobalt: *63–67* – cobalt-nickel (*63* – Bazasskoe, *64* – Butrakhtinskoe, *65* – Atbashi, *66* – Kuruozek, *67* – Khovu-Aksy), *68–73* – bismuth-cobalt (*68* – Yantau, *69* – Karakul, *70* – Perevalnoe, *71* – Uronaysky, *72* – Belogorskoe, *73* – Verkhne-Seimchanskoe, Vetrovoe), *74* – Haradzhul (primary arsenide-cobalt), *75–76* – cobalt-bearing gold-silver (*75* – Orekhozero, *76* – Podgornoe), *77* – Alys-Khaya (cobalt-bearing tin-tungsten); *78–80* – uranium-type cobalt-bearing (*78* – Bogorodskoe, *79* – Shargadykskoe, *80* – Kummolovskoe); *81–86* – manganese-ore cobalt-bearing (*81* – Tetrauk, Zianchurinskoe, *82* – Matyuzhikha, *83* – Selezenskoe, *84* – Mazulskoe, Bityatskoe, Butkeevskoe-2, Tsepelyaevskoe, *85* – Kamenskoe, Rudnoe, Zapadny, *86* – Yuzhno-Khinganskoe, Bidzhanskoe); *87* – Pavlovskoe occurrence of continental cobalt–ferromanganese crusts; *88–89* – technogenic deposits (*88* – dumps of the Allarechensky copper-nickel deposit, *89* – dumps of the Allarechensky copper-nickel deposit) nadium-titanomagnetite, uranium-phosphate, and manganese-ore formations, as well as the exogenic silicate–cobalt–nickel formation. In the course of mining operations across these various formations – particularly under selective mining conditions and in waste management systems – technogenic cobalt-bearing deposits are also formed, giving rise to the technogenic formation.

At present, only complex copper–nickel formation deposits are being actively developed for cobalt. Previously, deposits of the silicate cobalt–nickel formation were exploited in the Ural, and arsenide–cobalt formation deposits in the Altai–Western Sayan and Seimchan provinces.

The currently developed cobalt-bearing copper–nickel and silicate cobalt–nickel formation deposits account for a combined 82.5% of Russia's total economic cobalt reserves, whereas deposits of the primary cobalt (arsenide–cobalt) formation that were exploited in the past contribute only 3.0% (see Fig. 3). Consequently, due to the limited volume of proven cobalt reserves, it is extremely challenging to systematically plan for an increase in domestic cobalt supply.

An analysis of the spatial distribution of deposits with varying compositions across most endogenic cobalt-bearing formations indicates their spatial association with basic–ultrabasic rock complexes, with the exception of deposits and occurrences in the Seimchan and Yano–Odychan provinces. However, even in these regions, the presence of such complexes at depth is considered possible, due to the presence of siderophile elements (Co, Ni, Cr) in the ore bodies [8]. In virtually all cobalt and cobalt-bearing formations, cobalt is accompanied by nickel, often in considerably high concentrations (see Fig. 4).

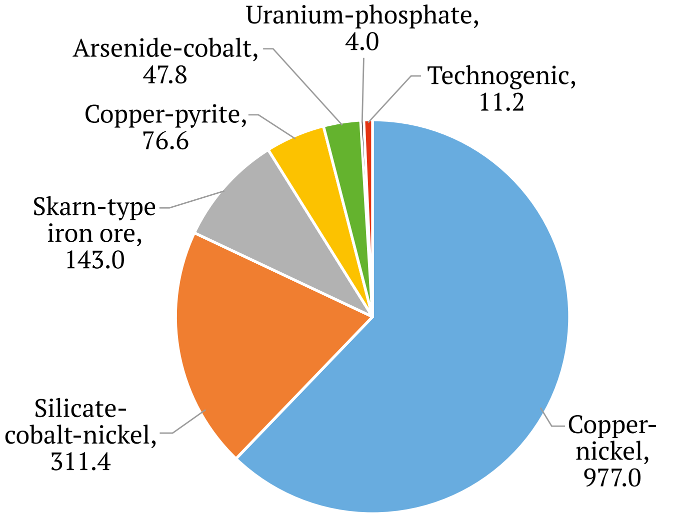

Fig. 3. Distribution of cobalt balance reserves in the Russian Federation by cobalt ore formation (as of 2021)

In ophiolitic complexes, cobalt is concentrated in pentlandite (up to 3% Co), pyrrhotite (up to 0.9% Co), and pyrite (up to 1.8 % Co), while the majority of rock-bound cobalt occurs as a minor admixture in olivine (0.008 % Co), pyroxenes, and amphiboles (up to 0.004 % Co) [9, 10]. During hydrothermal alteration of basic and ultrabasic rocks–particularly in the course of endogenic serpentinization of olivine–cobalt readily enters solution and contributes to the formation of new ore parageneses. These include cobalt-bearing pyrite in the copper–pyrite formation [11]; arsenide and sulfoarsenide mineralization in the arsenide–cobalt formation [9, 10]; and cobalt-pyrite and cobaltite mineralization in the skarn-type iron ore formation [12] and vanadium–titanomagnetite formation.

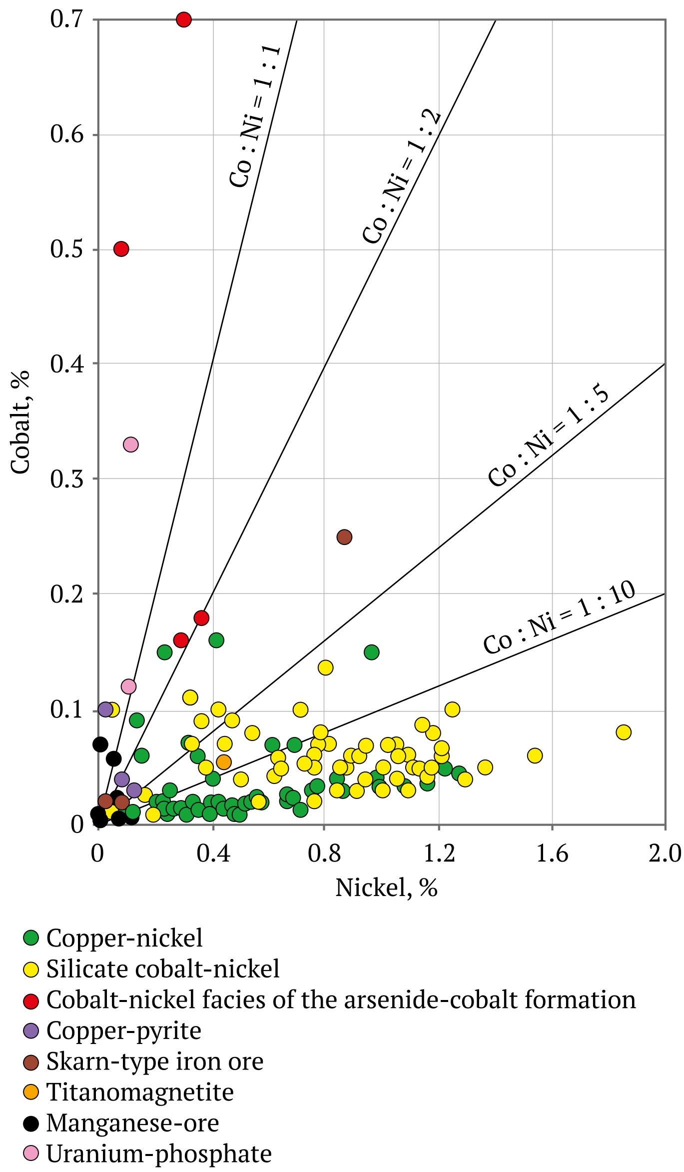

Fig. 4. Scatter plot of average cobalt and nickel grades in deposits by ore formation

Under supergene conditions, weathering of ophiolitic rocks leads to serpentinization of silicates and oxidation of sulfides, resulting in the mobilization of both cobalt and nickel. This process forms ore bodies of the silicate–cobalt–nickel formation, with cobalt accumulating in nontronite and garnierite, as well as being adsorbed on goethite, asbolane, and other manganese oxides and hydroxides [13, 14]. With further infiltration, cobalt precipitates at chemical barriers formed by diagenetic sulfides in the uranium–phosphate formation [35] and in manganese-ore formation bodies [9].

According to Co : Ni ratios (Table 1), the highest values are observed in the manganese-ore, copper–pyrite, uranium–phosphate, and arsenide–cobalt formations. In these, the primary cobalt concentrators are, respectively: manganese oxides, pyrite, organic matter, and cobalt arsenides and sulfoarsenides. The lowest Co : Ni ratios are found in copper–nickel formation deposits, where pentlandite serves as the main cobalt-bearing mineral, and in the silicate–cobalt–nickel formation, where nontronite and garnierite are the main cobalt and nickel carriers.

Table 1

Cobalt-to-nickel ratios by cobalt ore formation

Formation	Co : Ni ratio
Copper-nickel	0.088* / 0.02–0.67
Silicate cobalt-nickel	0.089 / 0.01–0.34
Iron ore	0.51 / 0.25–1.0
Titanomagnetite	0.315 / 0.13–0.5
Arsenide-cobalt	2.08 / 0.5–6.25
Copper-pyrite	2.1 / 1.2–3.0
Uranium-phosphate	1.92 / 0.25–5.0
Manganese-ore	6.92 / 0.35–11.65

* – the numerator shows the average value, the denominator shows the range of values.

The copper-nickel formation is currently the primary source of cobalt in Russia and is represented by a number of producing and explored deposits. Sulfide copper-nickel deposits are spatially and genetically associated with mafic and ultramafic igneous massifs located along platform margins (Norilsk-type), within cratons (Pechenga-type), and in the central parts of fold belts [15]. The main commercial products of these deposits are copper and nickel, while cobalt, platinum-group elements, selenium, and tellurium are extracted as by-products [16].

According to officially recorded reserves, the copper–nickel formation accounts for 62.5% of Russia's balance cobalt reserves (977 kt of Co)[4] (see Fig. 2), with average cobalt grades in the deposits reaching up to 0.19%. In total, 73 copper–nickel deposits and occurrences with reported cobalt reserves or resources are known in Russia, including 50 containing over 1 kt and 25 with more than 10 kt of cobalt. Mining of copper–nickel ores and extraction of cobalt from them is carried out at deposits in the Norilsk and Kola provinces (operated by PJSC MMC Norilsk Nickel), as well as in the Kamchatka province (JSC SPC Geotekhnologiya). Copper–nickel deposits containing cobalt are currently being prepared for development in the Eastern Sayan, Dzhugdzhur, and Voronezh provinces (see Fig. 5, *a*). In 2022, 12,651 t of cobalt was produced in Russia from cobalt–copper–nickel formation ores, the majority of which was exported[5].

The main cobalt-bearing mineral in copper-nickel ore deposits is pentlandite, which contains between 0.1 and 3.0 % cobalt, in which cobalt isomorphically replaces nickel and iron. In the ores of some sulfide copper–nickel deposits, cobalt-bearing pyrite is also present, with cobalt grade up to 1.8 %.

Adjacent to the copper-nickel formation is the **low-sulfide platinum-group element (PGE) formation**, in which dispersed sulfide mineralization contains only minor copper–nickel components, and the primary economic value lies in PGE mineralization [17–19]. These deposits and occurrences also contain associated cobalt, with average grades reaching up to 0.07%. PGE deposits and occurrences are known in the Kola, Karelian, Ural, and Chukotka–Koryak provinces.

[4] State report on the status and use of the mineral resources of the Russian Federation in 2021. Ministry of Natural Resources and Environment of the Russian Federation; 2022. 626 p. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[5] Ibid.

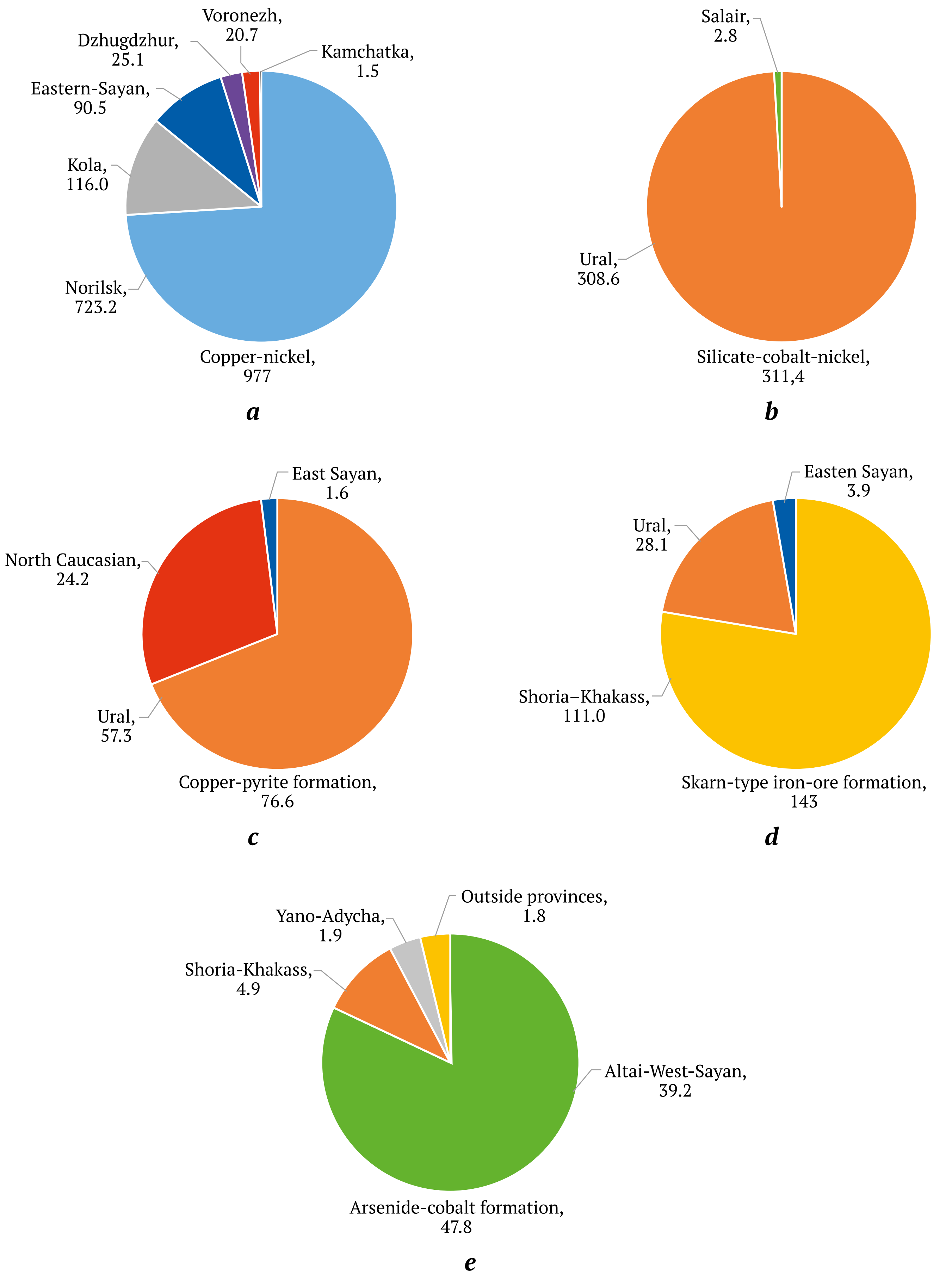

Fig. 5. Distribution of cobalt balance reserves by individual cobalt ore formations across Russian provinces as of 2021, kt: *a* – copper–nickel; *b*– silicate–cobalt–nickel; *c* – copper–pyrite; *d* – skarn-type iron ore; *e* – arsenide-cobalt

The silicate-cobalt-nickel formation represents the products of supergene weathering of serpentinized ultramafic and mafic rocks, including both residual and infiltration types [13]. Serpentinite massifs with cobalt-bearing nickel-rich weathering crusts are known within the Ural and Salair provinces.

At deposits of the silicate cobalt–nickel formation, the distribution pattern shows generally lower Co : Ni ratios compared to deposits of the copper–nickel formation (see Fig. 4), indicating relative cobalt enrichment in weathering crusts in comparison to nickel. However, within the Co : Ni ratio distribution across silicate cobalt–nickel formation deposits, no significant differences are observed between the deposits of the Ural and Salair provinces (Fig. 6).

Nickel tends to accumulate in the middle part of the weathering profile within the nontronite zone, primarily as nickel-bearing hydrosilicates (garnierite, revdinskite, nepouite, etc.), whereas cobalt is typically concentrated in the lower part of the profile, in the ocher zone, together with manganese, occurring as cobalt-containing manganese oxides and hydroxides (asbolane, cobaltian manganite, cobalt-rich psilomelane). As a result, the spatial distribution patterns (geometry) of nickel and cobalt halos may not coincide, forming localized enrichment zones of either nickel or cobalt. Given that geological exploration is primarily focused on nickel, cobalt resources may be underestimated when its mineralization occurs outside the assessment contour of the primary ore component.

The highest cobalt concentrations are observed when it is sorbed onto asbolane (according to the literature, up to 32% Co [9]); at the Kaincha occurrence in the Salair province, values of up to 10% Co have been reported. In the Ural province, the Elizavetinskaya group of deposits {No. 36} is classified as asbolane-bearing. At sites where asbolane is identified as the principal cobalt concentrator (see Fig. 7, Table 2), the highest average cobalt contents are recorded. Cobalt-bearing goethite and hydrogoethite are sometimes found accumulating alongside asbolane [14]. Nontronite and garnierite occur predominantly in the central nontronite zone of the weathering crust, where nickel accumulates, typically at lower cobalt concentrations. However, in some cases, linear weathering zones host unusual garnierite veins with high contents of both nickel and cobalt. These may have been enriched through late-stage hydrothermal alteration of the weathering crust material [20, 21].

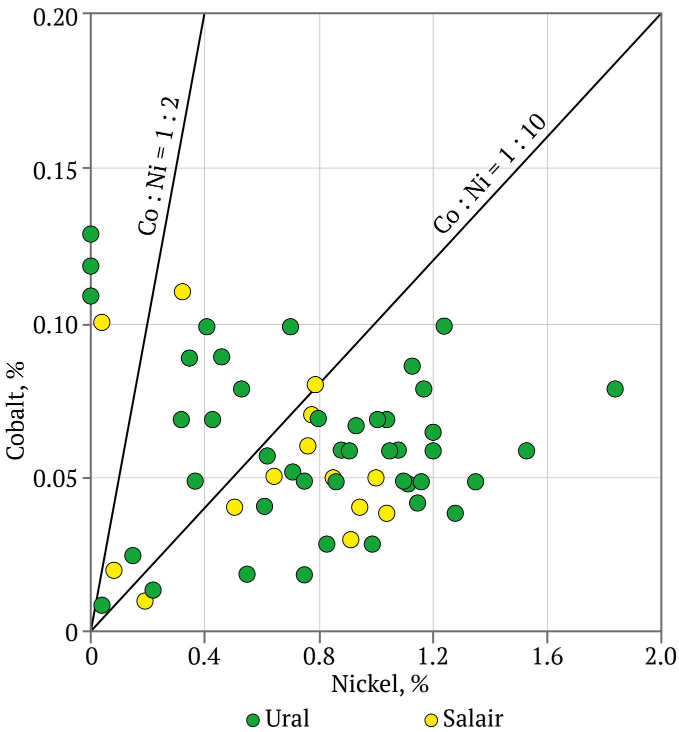

Fig. 6. Average cobalt and nickel grades in deposits of the silicate–cobalt–nickel formation by province

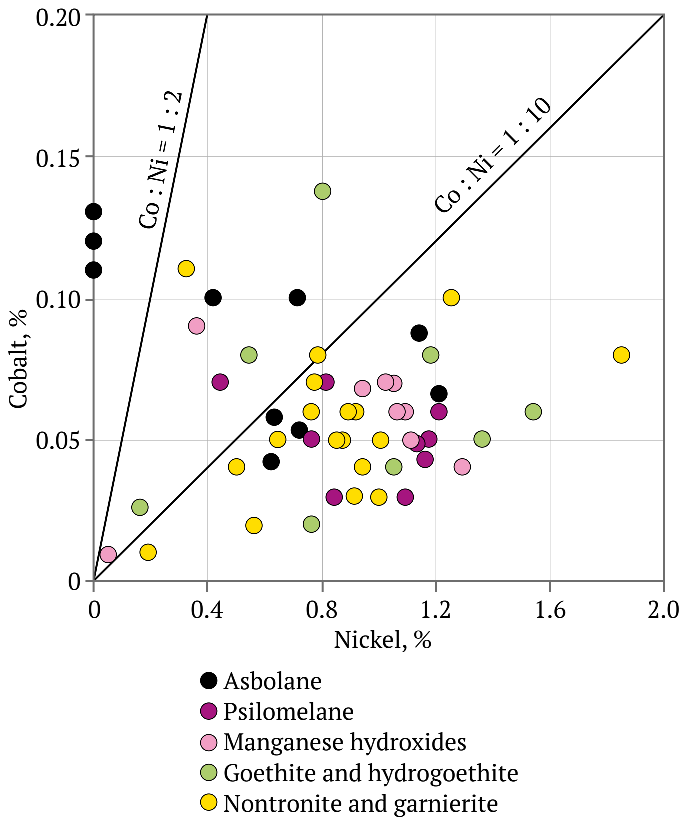

Fig. 7. Average cobalt and nickel grades in deposits of the silicate–cobalt–nickel formation by cobalt-bearing minerals

Table 2

Cobalt-nickel ratios by cobalt-bearing minerals in deposits and occurrences of the silicate–cobalt–nickel formation

Main cobalt-bearing mineral	Co : Ni ratio
Asbolane	0.105* / 0.05–0.24
Goethite	0.088 / 0.03–0.17
Manganese Hydroxides	0.096 / 0.03–0.25
Garnierite	0.053 / 0.04–0.07
Nontronite	0.079 / 0.01–0.34
Psilomelane	0.062 / 0.03–0.16

* – the numerator shows the average value, the denominator shows the range of values.

According to officially recorded reserves, the silicate–cobalt–nickel formation accounts for 19.9% of Russia's cobalt balance reserves (311.4 Kt of Co)[6] (see Fig. 3), with average cobalt grades in deposits reaching up to 0.11%. In total, 59 deposits and occurrences of silicate–cobalt–nickel ores with recorded cobalt reserves or resources are known in Russia, including 33 with more than 1 Kt and 6 with over 10 Kt of cobalt. Silicate–cobalt–nickel ore extraction was previously carried out at deposits in the Ural province by Southern Urals Nickel Plant PJSC (Kombinat Yuzhuralnikel) (until 2013). The occurrences of silicate–cobalt–nickel ores identified through geological exploration in the Salair province have not yet been prepared for development (see Fig. 5, *b*).

[6] State report on the status and use of the mineral resources of the Russian Federation in 2021. Ministry of Natural Resources and Environment of the Russian Federation; 2022. 626 p URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/; Information on the status and prospects for the use of the mineral resource base of the regions of the Russian Federation (as of January 1, 2022). St. Petersburg: VSEGEI, State Assignment No. 049-00018-22-01 dated January 14, 2022. 2022. URL: http://atlaspacket.vsegei.ru/?v=msb2021#91474d2e700eb6c90

The copper–pyrite formation represents a mixed group of deposits of volcanogenic hydrothermal–sedimentary and hydrothermal–metasomatic origin, occurring as bed- and lens-shaped accumulations of consolidated sulfide ores, with pyrite and copper sulfides playing the leading role [22, 23]. The formation of cobalt-bearing copper–pyrite deposits is primarily driven by the release of cobalt from the olivine mineral matrix during hydrothermal serpentinization of ultramafic rocks, followed by its precipitation onto sulfides [11]. Most copper–pyrite deposits are located in the Ural province, where they are mined primarily for copper and zinc; some are also found in the North Caucasus province. Many copper–pyrite deposits in both the Ural and North Caucasus provinces are characterized by cobalt as a by-product mineralization [24, 25] (see Fig. 5, *c*).

Two types of cobalt-bearing pyrite–copper deposits are distinguished: the so-called Cyprus-type sulfur-copper–pyrite deposits and Ural-type copper–zinc pyrite deposits [26]. The Cyprus type is characterized by cobalt occurring in the mineral form of cobaltite, and to a lesser extent as an impurity in pyrite and chalcopyrite. These deposits are generally small, occasionally medium in size. Most of the Cyprus-type sulfur–copper–pyrite deposits (some of which were mined for cobalt) have now been depleted. In contrast, cobalt in Ural-type deposits is predominantly found in cobalt-bearing pyrite, and less frequently in cobalt-bearing pyrrhotite. Copper–zinc pyrite deposits of the Ural type are notable for their significant reserves of zinc and copper, and some also contain cobalt as a by-product, which is primarily associated with the pyrite ores rather than the copper–zinc ores. The cobalt grade in copper concentrates from Ural deposits reaches 0.005%, and in zinc concentrates, 0.003%. As a result, at the currently operating Ural-type copper–zinc pyrite deposits, cobalt is not extracted during copper and zinc production and instead accumulates in pyrite-rich tailings from the beneficiation process.

The cobalt-bearing copper–pyrite formation accounts for 4.9% of Russia's officially recorded cobalt balance reserves (76.5 Kt of Co)[7] (see Fig. 3), with

[7] State report on the status and use of the mineral resources of the Russian Federation in 2021. Ministry of Natural Resources and Environment of the Russian Federation; 2022. 626 p. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

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average cobalt grades in deposits reaching up to 0.07%. In total, 28 deposits and occurrences of cobalt-bearing copper–pyrite ores with recorded cobalt reserves or resources are known in Russia, including 9 with more than 1 Kt and 2 with over 10 Kt of cobalt. Cobalt is not extracted from the mined copper and zinc ores due to the lack of economic viability of extracting cobalt-bearing pyrite concentrates.

The cobalt-bearing skarn-type iron ore formation is represented by contact-metasomatic deposits occurring at the interface between intrusive rocks ranging from mafic to felsic composition and limestone sedimentary rocks. Iron-rich skarn formations serve as the substrate for superimposed sulfide mineralization containing cobalt minerals [12, 27]. The sulfide mineralization consists of pyrite and copper minerals (chalcopyrite, bornite). Cobalt occurs in cobalt-bearing pyrite, occasionally as cobaltite, and sometimes in tetrahedrite-group minerals (fahlores).

A total of 21 cobalt-bearing skarn-type iron ore deposits and occurrences are known in the Russian Federation, where cobalt reserves or resources have been identified. Among them, 14 objects contain more than 1 kt, and 6 objects contain more than 10 kt of cobalt, with average cobalt grades in individual deposits reaching up to 0.18%. These deposits are located in the Ural and Shoria-Khakass provinces (see Fig. 5, *d*), as well as outside the delineated provinces – including the Oktyabrskoe-Fe deposit in Irkutsk Region {No. 58} (reserves of 6 kt Co, 0.028% Co), the Tayozhnoye boron–iron ore deposit in the Republic of Sakha (Yakutia) {No. 59}, which contains blocks enriched in cobalt mineralization (11.6 kt Co, 0.11% Co) [28], and the Chesnokovskoe occurrence in Altai Territory {No. 52} (1 kt Co, 0.02% Co) [29]. Cobalt is not extracted from mined high-grade iron ores due to the absence of a sulfide phase separation process during beneficiation. However, there have been successful attempts to extract cobalt-bearing pyrite concentrate from the magnetic separation tailings of iron ores from the Shoria-Khakass province at the Abagur beneficiation plant [30].

Cobalt-bearing skarn-type iron ore formations account for 9.0% of Russia's total economic cobalt reserves (141 kt of Co)[8], (see Fig. 3).

[8] State report on the status and use of the mineral resources of the Russian Federation in 2021. Ministry of Natural Resources and Environment of the Russian Federation; 2022. 626 p. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

The vanadium-bearing titanomagnetite formation is paragenetically related to the cobalt-bearing skarn-type iron ore formation. In this formation, postmagmatic sulfide mineralization containing copper and cobalt minerals is superimposed on magmatic titanomagnetite ores [31, 32]. Cobalt is present in titanomagnetite ores as part of cobalt-bearing pyrite [28] and, to a lesser extent, as cobaltite. For three deposits of this formation with identified cobalt mineralization, off-balance cobalt reserves and resources have been estimated, with average Co grades at individual sites reaching up to 0.04%.

The arsenide–cobalt formation represents a group of deposits and occurrences with diverse parageneses of arsenides, sulfoarsenides, and sulfides, all characterized by the predominant role of cobalt and cobalt-bearing minerals [9, 10]. A distinct arsenide–cobalt facies can be identified, as well as cobalt–nickel, bismuth–cobalt, gold–silver, and tin–tungsten facies of hydrothermal cobalt-bearing formations. The occurrences of the arsenide–cobalt formation are most extensively developed in the Altai–Sayan fold system, particularly concentrated in the Altai–Western Sayan province, as well as in the Seymchan and Yano–Adychan provinces (see Fig. 5, *d*), with one known occurrence in the Karelian province. Some bismuth–cobalt facies sites lie outside the delineated cobalt ore provinces – for example, the Uronaysky deposit in Zabaykalsky Krai {No. 71}, with cobalt reserves of 1.2 kt at 0.06% Co [33], and the Belogorskoe occurrence in Primorsky Krai {No. 72}, where overprinting mineralization is hosted by the skarn polymetallic ores of the Partizanskoye deposit [34]. The cobalt ore bodies of the arsenide–cobalt formation are predominantly vein-shaped and are spatially associated with fault zones. They also show a spatial association with alkaline-basaltic and granitoid magmatism, as well as proximity to pre-ore ophiolitic formations, which may have served as a source of cobalt mobilization during hydrothermal activity. The mineral form of cobalt in the arsenide–cobalt facies is represented by cobaltite, smaltite, and cobalt-bearing pyrite; in the cobalt–nickel facies – by cobaltite, smaltite, glaucodot, and tennantite; in the bismuth–cobalt facies – by cobaltite, glaucodot, and fahlore ores; in the gold–silver facies – by cobaltite and glaucodot; and in the tin–tungsten facies – by cobaltite and tetrahedrite-group minerals.

Cobalt production from the arsenide–cobalt formation was previously conducted at the Khovu-Aksy cobalt–nickel deposit (1956–1991) and at a group of cobalt-bearing gold deposits in the Seymchan area (Verkhne-Seymchanskoye, Vetrovoe).

In the Russian Federation, 43 deposits and occurrences of the arsenide–cobalt formation have been identified that contain recorded cobalt reserves or resources. Among them, 14 sites hold over 1 kt of cobalt, and 3 sites exceed 10 kt. The average cobalt grade in individual deposits reaches up to 2.26 %. This formation accounts for 3.0% of Russia's total cobalt reserves (47.8 kt Co)[9] (see Fig. 3).

Cobalt-bearing organophosphate uranium ore formation. Russia's cobalt reserve balance includes 35.4 kt (2.3%) associated with complex phosphate–rare-earth–uranium ores in the *Ergyninsky province*, located in the Republic of Kalmykia [35]. These ores represent accumulations of fish bone remains embedded within marine clays of the Oligocene Maikop Horizon. The genesis of these metalliferous formations is interpreted as sedimentary, involving the sorption of uranium onto organic matter and the capture of other metals by diagenetic sulfides. In addition to uranium and cobalt, the Ergeninsky deposits contain reserves of other associated elements, including molybdenum, phosphorus, and rare-earth elements. Similar geological conditions are observed in the *Baltic province* (within the Baltic oil shale basin), where Ordovician Dictyonema shales (black oil shales) and obolites (phosphatic sandstones) host diagenetic uranium mineralization. These deposits contain documented reserves of associated vanadium, nickel, molybdenum, and rhenium [36]. Cobalt has also been identified, with a Co:Ni ratio of approximately 1:3, although its resources have not been assessed [36, 37]. Elevated concentrations of metals (U, Mo, Re, V, Ni, Co, Zn, Se) are also recorded in the oil shales of the Volga shale basin, including the Orlovskoye, Kashpir–Khvalynskoye, Perelyubskoye, and Kotsebin deposits [38]. The formation of these metalliferous bodies is attributed to the fossilization of organic matter during sedimentation, accompanied by the formation of diagenetic pyrite and the sorption of metals from seawater [39].

The direct development of cobalt-bearing organo-phosphate uranium ores is feasible primarily from the standpoint of uranium extraction. However, the proposed heap and in-situ leaching technologies offer the potential for the extraction of associated valuable components, including molybdenum, rhenium, nickel, cobalt, and others [40]. In a broader sense, considering the cobalt-bearing potential of uranium ore formations also brings attention to the metalliferous nature (including cobalt content) of the more widespread black shale formation [41].

Manganese minerals (asbolane, psilomelane, pyrolusite, etc.) serve as natural adsorbents of cobalt from infiltration solutions in both supergene and hypogene processes. In typical marine sedimentary–diagenetic and diagenetic manganese deposits, cobalt is consistently present (ranging from thousandths of a percent to 0.01%) [9]. This highlights the need to define a separate **cobalt-bearing manganese ore formation**, comprising ore objects formed in sedimentary basins proximal to substantial cobalt source areas – such as denudation zones of serpentinized ultrabasic massifs and their associated weathering crusts.

According to the inventory data of manganese deposits in the Russian Federation, 14 documented sites contain elevated concentrations of cobalt in manganese ores (up to 1%). The Mazulskoe deposit in Krasnoyarsk Krai, now depleted, was initially explored in the 1930s specifically as a cobalt–manganese deposit. Some occurrences of cobalt-bearing manganese ores are located within known cobalt ore provinces (Ural [42], Salair [43], Shoria–Khakass [4], and Easten Sayan[45]), consistent with their genesis through sorption of infiltrated cobalt released from serpentinites of ophiolitic complexes in these regions. However, occurrences of cobalt-bearing manganese ores are also found outside the established cobalt ore provinces – for example, the Mazulskoe deposit {No. 84} in Krasnoyarsk Krai (average grade of 0.023% Co) [46], and the Yuzhno-Khinganskoe and Bidzhanskoe deposits {No. 86} in the Jewish Autonomous Region (0.05% Co) [47]. These geological features suggest the possible existence of large-scale sources of mobile cobalt in the supergene environment and the potential for discovering new cobalt ore provinces.

The cobalt content of manganese ore formations has not been systematically studied, and cobalt resources in manganese deposits across Russia have not been assessed, despite the known tendency of manganese minerals to sorb infiltrating cobalt. Sampling of manganese ores for cobalt during geological exploration was sporadic and limited to isolated spot samples. Due to the generally low concentrations detected, cobalt did not attract significant interest. Consequently, there is no data on the distribution of cobalt within the ore bodies of manganese deposits or on potential enrichment zones.

[9] State report on the status and use of the mineral resources of the Russian Federation in 2021. Ministry of Natural Resources and Environment of the Russian Federation; 2022. 626 p. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

The technogenic formation results from human impact on the subsurface, giving rise to new deposits of secondary mineral raw materials, including waste dumps of overburden and substandard ore, tailings and intermediate product storage from beneficiation processes, slag and calcine dumps from metallurgical processing, and mineralized mine waters [48]. In Russia's cobalt reserves, the technogenic formation accounts for 0.8% of the balance (12.2 kt Co)[10]. Three technogenic deposits with registered cobalt reserves are known within the Russian Federation: the tailings storage facility of the Norilsk concentrator {No. 89} (reserves of 11.1 kt, 0.09% Co), the cooling pond Lake Barernoye of the nickel plant (0.023% Co) in Norilsk, and the waste dumps of substandard ores from the Allarechensky deposit {No. 88} in Murmansk Oblast (0.015% Co) [49]. For waste products derived from copper–nickel ores, a higher Co : Ni ratio is observed compared to the original ores, indicating relative cobalt enrichment.

Cobalt resources totaling 1.8 kt with an average grade of 0.112% have been estimated in only three of the five sluiced tailings cells formed from the beneficiation of arsenic–cobalt–nickel ores at the Tuvacobalt plant. As part of an environmental initiative aimed at neutralizing arsenic in long-term storage waste, the extraction of cobalt and nickel from these tailings is considered feasible [50].

At the beneficiation plant of the Gai Mining and Processing Plant (Gai GOK), which processes pyrite-bearing copper–zinc ores, pyrite concentrates from tailings containing up to 0.05% cobalt are stored separately. Similar storage facilities exist at other concentrators that process Ural copper–pyrite ores, as well as at former sulfuric acid production plants that accumulated pyrite cinders in dumps [51]. The cobalt resources of these technogenic stockpiles have not been evaluated.

Overall, the resource potential of technogenic deposits remains underestimated due to the limited scope of specialized geological exploration conducted at waste facilities of mining enterprises developing copper–nickel and copper–pyrite deposits.

Cobalt-rich ferromanganese crust formation. By decision of the International Seabed Authority (ISA), the Russian Federation has been granted rights to the Russian Exploration Area for cobalt-rich ferromanganese crusts (REA-CRC), located in the western segment of the Magellan Seamounts in the Pacific Ocean. Within this area, the State Scientific Center Yuzhmorgeologiya is conducting assessments of cobalt, nickel, and manganese resources in accordance with the ISA's *Regulations on Prospecting and Exploration for Cobalt-Rich Ferromanganese Crusts in the Area* [52]. Cobalt-rich ferromanganese crusts are accumulations of iron and manganese hydroxides formed on exposed rock surfaces of underwater uplifts (guyots) at depths ranging from 800 to 3,000 meters. The crusts can reach thicknesses of up to 25 cm, with productivity rates of 60–80 kg/m^2. The cobalt content in these crusts ranges from 0.5 to 0.7%, with estimated average grades of 0.50–0.61% across the evaluated blocks; nickel content is 0.4–0.5%, and manganese content is 19–23% [53]. The genesis of these crusts is interpreted as both hydrogenetic and biogeochemical, involving sorption of cobalt, nickel, and manganese from seawater by bacterial mats [54]. The estimated cobalt resources in the crusts on the Alba, Kotzebue, Govorov, and Vulkanolog guyots within the Russian Exploration Area amount to 110,000 t of cobalt [53, 55]. Overall, deposits of the cobalt-rich ferromanganese crust formation are considered highly promising targets for cobalt extraction, although progress in developing the required deep-sea mining technologies remains slow [56]. Closely related to this formation is the *ferromanganese nodule formation* of oceanic abyssal plains. However, due to their greater depths and the classification of cobalt as a secondary (by-product) component (Co content of 0.22–0.29%), they are of lesser interest compared to CRC deposits [53], despite the estimated cobalt resources in the Clarion–Clipperton Zone (CCZ) ferromanganese nodules within the Russian contract area reaching 985,000 t.

The confirmed presence of significant cobalt-rich ferromanganese crust deposits in the World Ocean indicates the possibility of analogous formations within onshore geological structures in the Russian Federation. To explore this potential, it is essential to identify geological complexes with conditions resembling those of present-day marine environments where cobalt precipitates from seawater. This includes developing exploration criteria, such as revising existing geological data, conducting prospecting activities, and evaluating CRC-type resources. The importance of this task is underscored by the presence of continental analogues – for example, the occurrences in the Pavlovskaya area (site No. 87) in Primorsky Krai [57].

[10] State report on the status and use of the mineral resources of the Russian Federation in 2021. Ministry of Natural Resources and Environment of the Russian Federation; 2022. 626 p. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

Cobalt ore provinces

Due to the predominance of deposits belonging to the copper–nickel formation and, to some extent, the copper–pyrite formation, cobalt ore provinces partially or entirely overlap with the contours of copper ore provinces – namely, the North Caucasus, Voronezh, Karelian, Kola, Ural, Easten Sayan, Norilsk, North Baikal, Dzhugdzhur, Koryak, and Kamchatka provinces [16]. Provinces have been identified that are dominated by deposits of the silicate–cobalt–nickel formation (Salair province), skarn-type iron ore formation (Shoria–Khakass province), arsenide–cobalt formation (Altai–Western Sayan, Yana–Adycha, and Seymchan provinces), and uranium–phosphate formation (Ergeninsky and Baltic provinces).

Numerous deposits of the *copper–pyrite formation* are known in the **North Caucasus province**. Some of them have registered associated cobalt reserves – for example, the Kizil-Dere reserve deposit {No. 42} with 17.7 kt Co at an average grade of 0.03% Co [24], and the Khudes deposit {No. 41}, which is being prepared for mining (combined reserves and resources amount to 21.2 kt Co, 0.02% Co). In total, the North Caucasus province accounts for 24.2 kt of economically viable (balance) cobalt reserves, representing 1.5% of the national total (see Fig. 8), or 31.6% of the reserves attributed to the copper–pyrite formation (see Fig. 5, *b*). Numerous copper–pyrite occurrences have also been identified in the region, some of which contain cobalt mineralization (cobalt-bearing pyrite, cobaltite) [58, 59].

In **the Ergyninsky (Kalmykia) province**, there are deposits and occurrences of the *cobalt-bearing organophosphate uranium ore formation* [35, 40], including the Bogorodskoe deposit {No. 78} (combined reserves and resources: 20.8 kt Co, 0.04% Co) and the Shargadyk deposit {No. 79} (12.6 kt Co, 0.01% Co). These ore bodies consist of accumulations of uranium-bearing fossilized fish bones and scales cemented by clay material containing pyrite and melnikovite. Cobalt is concentrated in diagenetic pyrite and melnikovite. Open-pit mining has been proposed for the uranium deposits of the Ergeninsky district, followed by heap leaching of valuable components using sulfuric acid and nitric acid schemes [40]. The cobalt balance reserves of the Ergeninsky province (4 kt) account for 0.26% of Russia's total cobalt reserves.

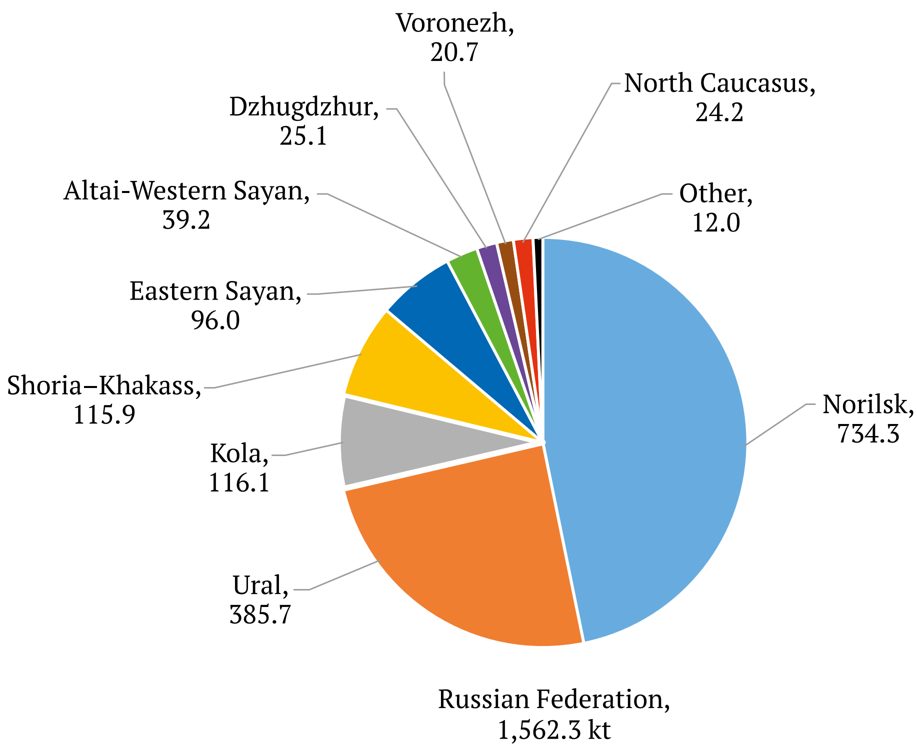

Fig. 8. Volumes of recorded cobalt reserves in the Russian Federation by province as of 2021

Sources: State report on the status and use of the mineral resources of the Russian Federation in 2021. Ministry of Natural Resources and Environment of the Russian Federation; 2022. 626 p. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/; Information on the status and prospects for the use of the mineral resource base of the regions of the Russian Federation (as of January 1, 2022). St. Petersburg: VSEGEI, State Assignment No. 049-00018-22-01 dated January 14, 2022. 2022. URL: http://atlaspacket.vsegei.ru/?v=msb2021#91474d2e700eb6c90

In the **Voronezh province**, deposits and occurrences of the *cobalt-bearing copper–nickel ore formation* are known [60, 61], including the Elan deposit {№ 1} with recorded associated cobalt reserves of 15.3 kt at an average grade of 0.036% Co, and the Elkinskoye deposit (5 kt Co, 0.03% Co). Cobalt is concentrated in pentlandite, cobaltite, and gersdorffite. The cobalt reserves of the Voronezh province (20.7 kt) represent 2.12% of Russia's copper–nickel ore formation reserves.

In the **Baltic province**, there are deposits and occurrences of the *cobalt-bearing organophosphate uranium ore formation* [35, 36], which were mined in the 1950s for uranium extraction [62]. Known uranium deposits in the area with recorded associated reserves of nickel, vanadium, molybdenum, and rhenium include Kummolovskoe, Kotlovskoe, Kaibolovskoe, Krasnoselskoe, and Ranolovskoe. Although cobalt resources in these uranium-bearing sediments have not been assessed, estimates based on nickel-to-cobalt ratios suggest a cumulative cobalt potential of up to 4 kt with an average grade of 0.013% Co across the known deposits [36, 37]. Cobalt recovery (together with other associated valuable components) may be feasible using proposed heap and in-situ leaching technologies applied to the uranium-bearing Dictyonema shales of the Baltic region [40]. No cobalt balance reserves have been recorded for the Baltic province.

The Karelian province is located in the southeastern part of the Fennoscandian Shield. Based on geological exploration, 16 deposits and occurrences with associated cobalt have been identified in this area, including 13 belonging to the copper–nickel formation, 2 to the low-sulfide platinum-group element (PGE) formation, and one to the gold–silver facies of the arsenide–cobalt formation. The most promising are the *copper–nickel* deposits of Semchozerskoe {No. 3} (resources: 80 kt Co, average grade 0.02 % Co), Pedrorechenskoye {No. 2} (50 kt Co, 0.06% Co) [63], and Voloshovskoe {No. 4} (14 kt Co, 0.02% Co), all characterized by copper–nickel ores with associated cobalt mineralization [64]. The *low-sulfide PGE formation* includes the Viksha occurrence (Vikshozero, Kenti, and Shargi areas) {No. 21} (4.5 kt Co, 0.01% Co) [65] and the Shalozerskoe (Kukruchey) site {No. 20} (0.15 kt Co, 0.17% Co) [63]. An occurrence of the *gold–silver facies of the arsenide–cobalt formation* with cobaltite and glaucodot has also been identified – Orekhozero {No. 75} (2.5 kt Co, 0.07% Co) [66]. The Karelian province accounts for 10 kt of cobalt balance reserves, or 0.64% of the national total.

The Kola province is located in the northern part of the Fennoscandian Shield, where the rift-related Pechenga–Imandra–Varzuga greenstone belt hosts numerous Paleoproterozoic layered intrusions. These intrusions include deposits and occurrences of sulfide copper–nickel and low-sulfide PGE formations with associated cobalt–copper–nickel mineralization [67, 68], as well as occurrences of cobalt-bearing vanadium-rich titanomagnetite ores of magmatic origin [31]. The Kola province holds 116.1 kt of cobalt balance reserves, which accounts for 7.4% of Russia's total (see Fig. 8).

Within the Kola province, 30 deposits and occurrences of the *copper–nickel formation* have been identified, with recorded reserves and resources of associated cobalt. These include the actively developed Zhdanovskoe deposit {No. 3} (combined reserves and resources: 68 kt Co, average grade 0.024% Co), Sopchuivench {No. 5} (23.7 kt Co, 0.01% Co), Nyud-Moroshkovoe {No. 7} (21.3 kt Co, 0.02% Co), Poaz {No. 6} (21.2 kt Co, 0.01% Co), Nittis–Kumuzhya–Travyanaya {No. 8} (16.9 kt Co, 0.19% Co), and Tundrovoe {№ 4} (16.7 kt Co, 0.023% Co). In addition, there are 9 other cobalt–copper–nickel sites with total cobalt reserves and resources exceeding 1 kt. In total, the copper–nickel deposits of the Kola province account for 116 kt of balance cobalt reserves, or 11.9% of the cobalt reserves hosted in copper–nickel ores in Russia (see Fig. 5, *a*). Associated cobalt mineralization is also known at the platinum-group element (PGE) deposit of Kievey {No. 22} and the PGE occurrences of Monchetundrovskoe {No. 23}, Chuarvy Vostochnoye, and Severny Kamenik. Cobalt resources at these PGE sites are generally small, typically under 1 kt.

In the East Kievey Belt of the Baltic titanomagnetite province, geological exploration has confirmed the presence of cobalt at the *vanadium-bearing titanomagnetite magmatic formation* of the Magazin–Musyur deposit {No. 60} (resources: 51.5 kt Co, 0.02% Co), located within the Early Proterozoic Magazin–Musyur gabbro-anorthosite intrusion.

The Ural province is located within the Ural Fold System. This region hosts deposits and occurrences of silicate cobalt–nickel ores, as well as copper–pyrite, skarn-type iron ore, and PGE–copper–nickel formations, all featuring associated cobalt mineralization [26, 67, 70, 71]. The Ural province accounts for 385.7 kt of Russia's balance cobalt reserves (24.7%), yet mining of silicate cobalt–nickel ores has been discontinued since 2013, and cobalt is not recovered during the development of cobalt-bearing copper–pyrite and iron ore deposits.

Supergene deposits of the *oxide–silicate cobalt–nickel formation* in the Ural province are represented by residual and infiltration products of Mesozoic exogenous weathering of serpentinized ultramafic and mafic rocks in the Orsk–Khalil (Southern Urals), Ufaley, and Rezh (Middle Urals) cobalt–nickel ore districts [21, 23]. Based on formation characteristics, the primary substrate for the development of these supergene deposits consists of cobalt- and nickel-bearing ultrabasic rocks. Of their total outcrop area within the Ural province, 89.7% is occupied by rocks of the dunite–harzburgite formation, 8.7% by the dunite–clinopyroxenite formation, and 1.6% by the pyroxenite–peridotite and alkaline olivine basalt formations [13].

The Ural province hosts 45 deposits and occurrences of silicate cobalt–nickel ores, including the Buruktal deposit {No. 33} (reserves: 136.7 kt Co at an average grade of 0.058% Co) [72], Serovskoe {No. 37} (133.8 kt Co, 0.026% Co), Sakharinskoe {No. 35} (reserves + resources: 11.7 kt Co, 0.06%), Novokievskoe {No. 34} (reserves: 15.5 kt Co, 0.08% Co), Elizavetinskoe {No. 36} (14.1 kt Co, 0.07% Co), as well as 20 cobalt–copper–nickel sites with total cobalt reserves and resources in the range of 1–10 kt. Cobalt is concentrated in asbolane, psilomelane, cobalt–nickel oxyhydroxides, nontronite, and hydrogoethite. Among the promising sites is the Yareney area {No. 38} in the Polar Urals (resources: 125 kt Co, 0.11% Co), spatially associated with a manganese-rich siallite–ferruginous weathering crust developed on Devonian sandstone–shale formations. The ore mineralization here is represented by fine-crystalline, granular, or botryoidal aggregates of cobalt–nickel asbolane.

The accounted cobalt reserves in silicate cobalt–nickel deposits of the Ural province amount to 308.6 kt, representing 99.1% of Russia's total reserves in this formation (see Fig. 5, *b*). Until 2013, silicate cobalt–nickel ores were extracted from deposits in the Ural province by Southern Urals Nickel Plant PJSC and processed primarily into ferronickel at the Orsk, Ufalei, and Rezh nickel plants. Many small and medium-sized cobalt–nickel deposits have been either fully or partially depleted. Since cobalt is considered a harmful impurity in ferronickel production, mining operations prioritized selective extraction of high-grade nickel ores, leaving behind pillars of boulder asbolane ores that were low in nickel but rich in cobalt.

In the *copper–pyrite formation* of the Ural province, cobalt is found in so-called Cyprus-type and Urals-type sulfur-rich copper–pyrite deposits. These are associated with submarine sedimentary–volcanogenic basaltic formations formed during the early stages of the eugeosynclinal development of the Southern and Central Urals [69]. A total of 21 cobalt-bearing copper–pyrite deposits and occurrences have been identified in the province, with cobalt reserves or resources reported at each. Among them, nine contain over 1 kt of cobalt, and one – Gai deposit {No. 43} –contains more than 10 kt (resources: 17 kt Co at an average grade of 0.02% Co) [73].

The balance reserves of cobalt in the Ural province amount to 50.8 kt of Co, or 66.3% of Russia's cobalt reserves hosted in copper–pyrite formations (see Fig. 5, *c*). Cobalt-bearing Cyprus-type sulfur–copper–pyrite deposits are generally small in terms of reserves and largely depleted, such as the Dergamysh {No. 44} [74], Ivanovskoe [25], and Ishkinino [75] deposits in the Southern Urals, and the Pyshminsko-Klyuchevskoye {No. 45} deposit [76] in the Middle Urals. In Cyprus-type deposits, cobalt occurs predominantly in the form of cobaltite, which sometimes forms monomineralic concentrations in massive sulfide bodies. Average cobalt contents in these deposits range from 0.05% (Dergamysh) to 0.12% (Southern Yuluk). Cobalt was recovered from pyrite ores during the development of some Cyprus-type deposits (Dergamysh– 1.3 kt; Nikitovskoye – 0.1 kt). Ural-type cobalt-bearing copper–zinc–pyrite deposits are characterized by significant reserves of zinc and copper, with associated cobalt recorded at a number of sites, including: Saumskoe {№ 46} (reserves: 37 kt Co, 0.058% Co), Gaysky (reserves + resources: 17 kt Co, 0.02% Co), Ivanovskoe, Osenneye (reserves: 4.4 kt Co, 0.062% Co), Shemurskoye (reserves: 4.3 kt Co, 0.06% Co), Novo-Shemurskoye (reserves: 4.3 kt Co, 0.07% Co), Sibayskoye (reserves: 2.4 kt Co, 0.026% Co), among others. In these deposits, cobalt is primarily concentrated in cobalt-bearing pyrite, and less commonly in cobalt-bearing pyrrhotite. However, copper–zinc ores are generally low in cobalt compared to true cobalt-bearing pyrite ores. As a result, cobalt does not accumulate in the final metals or industrial products during ore processing. Consequently, cobalt-bearing pyrite ores either remain unmined (as they are of no interest for copper and zinc extraction) or end up in processing tailings.

The *cobalt-bearing skarn-type iron ore formation* in the Ural province is represented by Silurian–Devonian contact-metasomatic bodies overprinted by later copper and cobalt sulfide mineralization [12]. In total, 8 deposits and occurrences of the cobalt-bearing skarn-type iron ore formation have been identified in the Ural province, all of which have assessed cobalt reserves or resources, with 6 sites exceeding 1 kt Co. Five of these deposits are located in the Middle Urals: Techenskoe {No. 50} (resources: 13.6 kt Co, at an average grade of 0.028% Co), Severo-Goroblagodatkoye (reserves: 8.7 kt Co, 0.01% Co), Peschanskoe {No. 51} (reserves: 6.9 kt Co, 0.02% Co), Lebyazhinskoye (reserves: 6 kt Co, 0.02% Co), and Vysokogorsk (reserves 3.4 kt Co, 0.03% Co) [12]; and one deposit is in the Polar Urals: Novogodnee (resources: 2.7 kt Co, 0.015%) [77]. Cobalt is primarily concentrated in cobalt-bearing pyrite, as well as in cobaltite (at the Peschanskoe, Lebyazhinskoye, and Vysokogorsk deposits) and pyrrhotite (at Novogodnee). The Ural province accounts for 28.1 kt of cobalt in reserves, representing 19.9% of Russia's total reserves in the cobalt-bearing skarn-type iron ore formation (see Fig. 5, *d*).

The Ural province also hosts an operating deposit of *vanadium-bearing titanomagnetite formation with associated cobalt mineralization* – the Volkovsky copper–titanomagnetite deposit {№ 61} (resources: 5 kt Co, 0.004% Co) [32]. It is composed of Silurian–Devonian contact-metasomatic bodies with later overprinting of copper and cobalt sulfide mineralization. Cobalt is not recovered from the copper concentrates at the Volkovsky deposit due to economic considerations.

The Salair province is located on the northwestern flank of the Altai–Sayan orogenic system. Prospecting and geological exploration have identified deposits and occurrences of silicate cobalt–nickel, as well as manganese and copper–nickel formations with associated cobalt mineralization [13]. Within the Salair province, 17 deposits and occurrences with cobalt mineralization have been discovered, including 15 belonging to the silicate cobalt–nickel formation, one to the copper–nickel formation, and one to the cobalt-bearing manganese ore formation. Seven deposits have a total cobalt reserve and resource exceeding 1 kt, with average grades of up to 0.11% Co.

The supergene deposits of the *oxide–silicate cobalt–nickel formation* in the Salair province are represented by linear and areal weathering crusts of Mesozoic exogenous origin, developed over serpentinized Cambrian ultramafic intrusions of the Salair ophiolite belt [9]. Fifteen deposits and occurrences have been identified here, including 7 with total cobalt reserves and resources exceeding 1 kt: Belininskoe {No. 39} (reserves: 2.8 kt Co, 0.04% Co), Alexandrovskoye {No. 40} (reserves: 1.1 kt Co, 0.11% Co), Uksunayskoye (resources: 6 kt Co, 0.04% Co), Stary Tyagun (resources: 6 kt Co, 0.05% Co), Tyagunskoe (resources: 5 kt Co, 0.06% Co), Kolpachek (resources: 4 kt Co, 0.01% Co), and Yaminskoye (resources: 1 kt Co, 0.07% Co). At most of these sites, cobalt occurs in nickel-bearing nontronite, although noteworthy concentrations are found in goethite and psilomelane (e.g., the Alexandrovskoye deposit), as well as in cobalt-bearing asbolane at the Novofirsovskoye (up to 1.31% Co) and Kaincha (up to 10% Co) occurrences. Previously, these supergene silicate cobalt–nickel deposits in the Salair province were not considered promising due to their small size, but with advances in underground leaching technologies for nickel and cobalt, sulfuric acid leaching of cobalt–nickel ores were investigated at the Belininskoe deposit [78].

Among other cobalt-bearing sites in the Salair province are the Sedova Zaimka occurrence of the *copper–nickel formation* (0.016% Co, 0.3% Cu, and 0.48% Ni), featuring superimposed cobaltite–gersdorffite mineralization [79], and the Matyuzhikha occurrence of the *manganese ore formation* (up to 1% Co) in a residual Silurian weathering crust [43].

The Shoria–Khakass province is situated in the southern part of the Kuznetsk Alatau orogenic structure, within the Mrassko–Batenevo anticlinal structural–formational zone. This zone is characterized by a thick sequence of Riphean–Cambrian–Ordovician deposits rich in volcanic rocks of the basalt–andesite–trachyte–liparite group and was shaped by Late Early Paleozoic dioritic and plagiogranitic magmatism of the Salair or Early Caledonian tectonic cycle [80]. The region hosts deposits and occurrences of the skarn-type iron ore formation, as well as of the arsenic–cobalt and manganese ore formations. The total cobalt reserves in the Shoria–Khakass province amount to 115.9 kt, representing 7.4% of Russia's total cobalt reserves (see Fig. 8).

The deposits of the *skarn-type iron ore formation* are Cambrian contact-metasomatic formations with superimposed cobalt mineralization. Within the Shoria–Khakass province, 7 deposits and occurrences of cobalt-bearing skarn-type iron ores are known, of which 5 contain over 1 kt of cobalt, and 4 exceed 10 kt. These include the Tashtagol deposit {No. 53} (reserves: 65.4 kt Co, 0.02% Co), Volkovsky {No. 56} (resources: 42 kt Co, 0.02% Co), Anzasskoe {No. 54} (reserves: 29.9 kt Co, 0.02% Co), and Abakanskoe {No. 55} (reserves: 26.9 kt Co, 0.18% Co). Cobalt is primarily hosted in cobalt-bearing pyrite, and in some cases as the cobaltite mineral phase, the latter forming locally enriched zones within the iron ore at the Abakanskoe deposit. Cobalt-bearing fahlore ores are also present at the Tashtagol deposit, while cobalt-bearing magnetite occurs at Volkovsky. As the Shoria–Khakass deposits are developed primarily for high-grade iron ore without beneficiation, cobalt is not recovered. Cobalt reserves in the skarn-type iron ore deposits of the Shoria–Khakass province amount to 111 kt, or 77.6% of Russia's total reserves in this formation (see Fig. 5, *d*).

In the Shoria-Khakass province, geological exploration has identified occurrences of the hydrothermal *arsenic–cobalt formation*, including the Bazasskoe occurrence {No. 63} (resources of 7 kt Co at an average grade of 0.25% Co, with tennantite and annabergite mineralization), the Butrakhtinskoe deposit {No. 64} (1.2 kt Co, 0.16% Co, with tennantite and cobaltite mineralization), and the Kharadzhulskoye deposit {No. 74} (3.7 kt Co, 0.08% Co, with cobaltite and cobalt-bearing pyrite mineralization). Cobalt reserves of the arsenic–cobalt formation in the Shoria-Khakass province amount to 4.9 kt, or 10.2% of Russia's total cobalt reserves of this formation (see Fig. 5, *d*).

At the Selezenskoe deposit {№ 78}, a *manganese-ore formation* located near the Tashtagol iron ore deposit, cobalt has been recorded at concentrations of up to 0.016% [81].

The Altai–Western Sayan province is the region with the highest concentration of hydrothermal cobalt mineralization in Russia. Targeted exploration for deposits of the *arsenic–cobalt formation* has been carried out in this area [82]. Nearly all facies of the arsenic–cobalt formation are found in this region:

– true arsenic–cobalt occurrences: Yustydskoye [83], Olen-Dzhularskoye [82], Zagadka (Karagemskoye) [84], Toshtuozekskoye (0.15% Co), Svetly (1.45% Co) [82], Ulandryk [85], Tsentralny Akchat (0.15% Co), Shemush-Dag (0.19% Co), Bai-Taiga, Sagsayskoye, Kok-Uzek [82], Talailyk, Shemushdag, Aksumon, Akoyuk, Oyukhemskoye [10];

– nickel–cobalt occurrences: Khovu-Aksy deposit {No. 67} (19.8 kt Co, 2.26% Co) [86]; occurrences Atbashi {No. 65} (9.4 kt Co, 0.22% Co), Kuruozek {No. 66} (7.3 kt Co, 0.18% Co) [82], Vladimirovskoye (0.5% Co) [87], Kokkaya (0.7% Co), Askhatin-Gol, Khuren-Taiga, Kyzyl-Oyuk [82], Akol, Uzunkhem, Uzyuk, Sarytash [10];

– bismuth–cobalt occurrences: Karakul deposit {No. 69} (25.7 kt Co, 0.33% Co) [88]; occurrences Yantau {№ 68} (1.6 kt Co, 0.03% Co), Perevalnoe {No. 70} (6.1 kt Co, 0.08% Co), Uzunoyskoye, Mogenburenskoye, Kaat-Taiga [82], Chergak [89], Butrakhtinskoe, Dzhulukul [82], Kyzylshin [10].

Arsenic–cobalt deposits occur as zones or veins with sulfide–arsenide and sulfoarsenide mineralization, including cobaltite, glaucodot, Co–Ni–arsenopyrite, cobalt-bearing pyrite and pyrrhotite, as well as other cobalt sulfides, arsenides, and sulfoarsenides [86, 88]. The cobalt ores also contain minerals of nickel, copper, gold, bismuth, tungsten, and uranium.

Cobalt mineralization in this province occurred in three distinct metallogenic epochs, corresponding to periods of extensive ultramafic and mafic magmatism [90, 91]:

– Devonian–Early Carboniferous ($D–C_1$): Yustydskoye, Sagsayskoye, Khovu-Aksy, Vladimirovskoye, Butrakhtinskoe;

– Permian–Triassic ($P_2–T$): Chergakskoye, Askhatin-Gol, Khuren-Taiga, Uzunoyskoye, Mogenburenskoye;

– Late Jurassic–Early Cretaceous ($J_3–K_1$): Kok-Uzek, Kyzyl-Oyuk, Khuren-Taiga, Kaat-Taiga, Sergeyevskoye, Dzhulukul.

It is evident that the mineral facies of cobalt deposits form parageneses based on the surrounding rock substrate (as the source of ore material and metasomatic energy) and are not bound to a specific age, being observed across all three epochs.

A total of 27 deposits and occurrences of the arsenic–cobalt formation is known in the Altai–Western Sayan province, of which 7 contain cobalt reserves or resources exceeding 1 kt, and 3 exceed 10 kt. Individual deposits feature average cobalt grades of up to 2.26%. The province accounts for 82% of Russia's balance cobalt reserves of the arsenic–cobalt formation (39.2 kt Co)[11]; see Fig. 5, *d*), or 2.5% of the country's total cobalt reserves. The Altai–Western Sayan province remains the most promising area for the discovery of new arsenic–cobalt formation deposits.

The Eastern Sayan province is located at the junction of the northeastern part of the Altai–Sayan orogenic zone and the southwestern margin of the Siberian Platform. The region hosts deposits and occurrences of copper–nickel (3 sites), pyrite (1 site), skarn-type iron ore (1 site), and manganese (3 sites) formations. The Eastern Sayan province accounts for 96 kt of cobalt reserves, representing 6.1% of Russia's cobalt reserve base (see Fig. 8).

The *copper–nickel formation* deposits are associated with serpentinized ultrabasic rocks of the gabbro–peridotite–dunite magmatic formation and contain disseminated cobalt–PGE–copper–nickel mineralization. The Kingash {No. 17} (reserves: 46.0 kt Co, 0.02% Co) [92] and Verkhnekingash {№ 18} (reserves: 44.1 kt Co, 0.0017% Co) [93] deposits are being prepared for mining

[11] State report on the status and use of the mineral resources of the Russian Federation in 2021. Ministry of Natural Resources and Environment of the Russian Federation; 2022. 626 p. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

operations targeting Ni, Cu, Pt, Pd, and Co. Geological exploration is underway at the Tokty-Oy site {No. 19}, which hosts cobalt–copper–nickel mineralization (resources: 30 kt Co, 0.02% Co). The Eastern Sayan province holds 9.1% of Russia's cobalt reserves associated with the copper–nickel formation (90.5kt) (see Fig. 5, *a*).

A notable geological site assigned to the *pyrite formation* is the Savin cobalt deposit {No. 48} (reserves:1.9 kt Co, 0.0017% Co), where cobalt-bearing pyrite mineralization is superimposed on the main magnesite body of the Savin deposit [94].

In the Irbinskaya group of Cambrian *skarn-type iron ore deposits*, cobalt-bearing pyrite mineralization has been identified at the Izygskoye deposit {No. 57} (reserves: 3.9 kt Co, 0.011% Co).

In the Prisayan Depression, elevated cobalt concentrations have been recorded in manganese-bearing horizons of the Upper Riphean Tagul Formation (Izansko–Bolsheerminskaya manganese-bearing zone). These include the Kamenskoe manganese deposit {No. 85} (0.01% Co) and the Rudnoye (0.014% Co) and Zapadny site (0.01% Co) occurrences [95]. Cobalt mineralization has also been reported at the Nikolaevskoye deposit within the same manganese-bearing zone (0.02–0.15% Co) [45].

The Norilsk province is located in the northwestern part of the Siberian Platform at its junction with the Yenisei–Khatanga Trough. The region hosts world-class *copper–nickel formation* deposits notable for both the scale and quality of their reserves. Cobalt is recovered as a by-product of ore processing. The currently operating deposits include Oktyabrskoe-Cu-Ni {No. 11} (reserves :376.6 kt Co, 0.034% Co), Talnakhskoe {No. 12} (reserves: 230.5 kt Co, 0.026% Co), and Norilsk-1 {No. 13} (reserves: 80.3 kt Co, 0.016% Co). The Maslovskoe {No. 14} (reserves: 26.3 kt Co, 0.013% Co) and Chernogorskoe {No. 15} (reserves: 20.9 kt Co, 0.026% Co) deposits are being prepared for development [96]. Cobalt is also accounted for in the resources of other deposits in the province, including Vologochanskoe {No. 12} (resources: 31.8 kt Co, 0.019% Co), the Southern Norilsk branch (resources: 23.5 kt Co, 0.01% Co), Norilsk-2 (resources: 3.9 kt Co, 0.03% Co), Gorozubovskoye (resources: 6.2 kt Co, 0.15% Co), and an exploration area in the Chibichete River basin (resources: 2.6 kt Co, 0.01% Co). The Norilsk province accounts for 734.3 kt of cobalt reserves, representing 47% of Russia's cobalt reserve base (see Fig. 8), and 723.2 kt of cobalt reserves in the copper–nickel formation, or 74% of Russia's reserves in this formation (see Fig. 5, *a*).

The North Baikal province is located in the southeastern part of the fold belt bordering the Siberian Platform, where *platinum–copper–nickel mineralization* has been identified within dunite–troctolite–gabbro intrusions [97]. Since the 1980s, authorial assessments have been carried out to evaluate the significance of copper–nickel formation deposits and occurrences in this province, including the Chaikskoye deposit {No. 20} (resources: 27 kt Co, 0.02% Co) [98], the Yoko-Dovyren massif (resources: 9.5 kt Co, up to 0.14% Co), the Avkit massif (up to 0.032% Co), and the Marinka massif (up to 0.089% Co) [99].

The Dzhugdzhur Province is located on the eastern flank of the Dzhugdzhur–Stanovoy mobile belt, which experienced Proterozoic and Mesozoic tectonic reactivation. This region hosts deposits and occurrences of the copper–nickel formation with associated cobalt mineralization [99]. The most developed deposit is Kun-Man'ye {No. 21} (reserves: 25.1 kt Co, 0.015% Co) [100], and copper–nickel mineralization has also been identified in the Nyandoma prospective area in the eastern part of the province [101]. The Dzhugdzhur Province accounts for 2.6% of Russia's balance reserves of cobalt in copper–nickel formations (25.1 kt). The province also contains 25.1 kt of cobalt balance reserves overall (1.5% of the national total) (see Fig. 8) or 2.5% of Russia's cobalt reserves in copper–nickel formations (see Fig. 5, *a*).

The Yana–Adycha province is situated within the Kular–Nera belt of the Verkhoyansk–Kolyma fold system, which formed in the Jurassic–Cretaceous period as a result of the intrusion of collisional granitoids of the Kolyma Series into Triassic terrigenous sediments, producing gold–quartz, gold–antimony, and tin–tungsten mineral systems [102]. The tin–tungsten ore systems of the region are characterized by the presence of Early Cretaceous arsenopyrite–pyrite and stibnite mineralization [102].

The Alys-Khaya tin–tungsten deposit {No. 77} (reserves:1.4 kt Co, 0.08% Co) is classified as a tin–tungsten facies of the *arsenic–cobalt formation* [102]. Cobalt mineralization is represented by cobaltite and cobalt-bearing arsenopyrite and fahlore ores. Other occurrences of this facies include the Ilin-Tas deposit (reserves of 0.4 kt Co, 0.015% Co), and the Burgachan and Ergelyakhskoye occurrences.

Ophiolite complexes are absent in the Yana–Adycha province, and it is assumed that the source of siderophile elements (Co, Ni, Cr) in the ore bodies may be deep-seated, yet unidentified sources [8].

The Seymchan province is located within the Sugoy Trough of the Verkhoyansk–Kolyma fold system, composed of Paleozoic terrigenous–carbonate

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sediments intruded by Cretaceous alkaline granites, which are associated with gold ore deposits of the gold–rare-metal formation [103]. The granitoids are characterized by elevated concentrations of Ni, Cu, As, Pb, Sr, Ag, Nb, and Y, while the gold ore bodies exhibit high contents of volatile elements (As, Bi, Se, Te) [103, 104]. The Seymchan province hosts cobalt deposits of the arsenic–cobalt and pyrite formations.

The Verkhne-Seymchan deposit of the bismuth–cobalt facies of the *arsenic–cobalt formation* {No. 73} (reserves: 0.7 kt Co, 0.11% Co) was mined in the 1950s, yielding 0.8 kt of Co (including from the adjacent Vetrovoe deposit). Cobalt is present in the form of cobaltite, gersdorffite, and glaucodot. The Verkhne-Seymchan ore cluster also includes other deposits and occurrences of the bismuth–cobalt facies such as Vetvistoye, Volochok, Vetrovoe [104], Levo-Seymkanskoye, Obkhod [105], Solnechnoye, Vysoky, Khetagchan, and Khalali [103].

The Podgornoe occurrence {No. 76}, with combined reserves and resources of 1.2 kt Co at 2.6% Co, belongs to the gold–silver facies of the arsenic–cobalt formation. The cobalt mineralization occurs in the form of cobalt-bearing arsenopyrite. The Natalka gold deposit, which also contains cobalt-bearing arsenopyrite mineralization, can likewise be attributed to this facies [106].

The Porozhistoye tin occurrence, with cobalt-bearing arsenopyrite mineralization, belongs to the tin–tungsten facies of the arsenic–cobalt formation.

At the Degdenreken (Piritovy) copper deposit of the *copper–pyrite formation* {No. 49} (resources: 80 kt at 0.01% Co), cobaltite mineralization has been identified.

As in the Yano–Adychan province, ophiolite complexes – traditionally regarded as cobalt sources for cobalt ore formations – are absent in the Seymchan province.

The Koryak province is located in the northern part of the Koryak–Kamchatka Mesozoic–Cenozoic volcanic belt, where occurrences of *low-sulfide PGE–copper–nickel formation* have been identified within Alpine-type mafic–ultramafic complexes [18, 19]. The identified targets within the Mainitskaya {No. 30} and Valaginskaya–Karaginskaya {No. 31} [19] prospective areas, as well as the Ust-Beloe, Chirina, Krasnaya Gora, and Snezhnoye {No. 32} occurrences of the low-sulfide PGE formation, are associated with copper–nickel mineralization and contain cobalt as an accessory component [28]. The geology of the Koryak province remains poorly explored, and the discovery of new deposits of the PGE–copper–nickel formation, including those with cobalt content, is considered highly likely.

The Kamchatka province is situated in the southern part of the Koryak–Kamchatka Mesozoic–Cenozoic volcanic belt, where *copper–nickel formation* deposits associated with hornblende peridotites and gabbroids have been identified within the Late Cretaceous–Paleocene Kvinum–Kuvalarog metallogenic zone. These include the currently operating Shanuch deposit {No. 24} (reserves: 1.9 kt, 0.145% Co) [107], whose copper–nickel ores are exported. This metallogenic zone also hosts deposits of cobalt-bearing copper–nickel formation: the Dukukskoe {No. 23} (resources: 15 kt, 0.03% Co), Kvinum I (resources: 5 kt, 0.11% Co), Kvinum II (resources: 2 kt, 0.05% Co), and Kuvalarog (0.01% Co).

In total, the Kamchatka province accounts for 1.9 kt of cobalt reserves (0.1% of Russia's total), or 0.2% of the country's copper–nickel formation reserves (see Fig. 5, *a*).

Discussion of challenges in Russia's cobalt resource base

Difficulties in planning and managing cobalt production volumes. The majority of cobalt reserves in the Russian Federation are concentrated in ore formations where cobalt occurs as an associated component and is recovered as a by-product. At such deposits, production planning and management are focused on maximizing the recovery of the main ore components, while the extraction of by-products like cobalt is treated as a secondary objective. Consequently, for complex deposits with associated cobalt, it is virtually impossible to regulate production volumes based on market demand for cobalt products.

Several *development projects for new copper–nickel formation* deposits include provisions for by-product cobalt recovery, with the following projected annual outputs (kt/year): Chernogorskoe (0.73), Norilsk I, southern section (0.7), Maslovskoye (0.7), Kingash and Verkhnekingash (4.0), Kun-Manie (1.8), and Elan and Elkinskoye (0.9)[12]. These projects will be launched at different times, and some of the additional copper–nickel ore volumes will be processed at PJSC MMC Norilsk Nickel's existing metallurgical facilities without

[12] State report on the status and use of the mineral resources of the Russian Federation in 2021. Ministry of Natural Resources and Environment of the Russian Federation; 2022. 626 p. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

increasing total throughput. As a result, the actual increase in cobalt output will be significantly lower. The Buruktal *silicate cobalt–nickel deposit* is also expected to yield by-product cobalt, with projected output of up to 0.13 kt/year[13]. Overall, cobalt production from copper–nickel formation deposits remains tied to copper and nickel output levels. As such, production volumes can only be estimated based on expected metal recovery, not on market demand.

In contrast, meaningful cobalt production planning is only feasible at *deposits where cobalt is the primary ore component*. These include deposits of arsenide–cobalt formations and cobalt-rich manganese crust formations. For the arsenide–cobalt formation, it is important to note that the total reserves of explored and mothballed deposits are relatively modest – 47.8 kt of Co – and the potential for new discoveries is limited due to the absence of a systematic national resource forecasting program. Nevertheless, development of the Karakul deposit (Altai Republic) and the restart of mining operations at the Khovu-Aksy deposit (Tyva Republic), including reprocessing of tailings and dumps from the Tuvacobalt plant, remain feasible options. As for cobalt-rich manganese crust deposits in the Magellan Mountains of the Pacific Ocean, they are still at the early geological exploration stage. Their prompt development is currently unrealistic. Moreover, mining and processing technologies for this deposit type are still under development, and the implementation of such projects is further hindered by environmental factors (extreme weather conditions) [108, 109] and geopolitical risks [110].

In summary, an uncontrolled increase in cobalt production from copper–nickel and silicate cobalt–nickel formation deposits are estimated at up to 8 kt/year, while a controlled increase from arsenide–cobalt formation deposits could reach up to 4 kt/year.

Weakness in the forecast resource base. As previously noted, there is no systematic accounting of forecast cobalt resources across Russia. Even for the copper–nickel formation, estimates of forecast resources along flanks and at depth have been made only for a few major deposits.

[13] State report on the status and use of the mineral resources of the Russian Federation in 2021. Ministry of Natural Resources and Environment of the Russian Federation; 2022. 626 p. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

Targeted exploration for cobalt mineralization was conducted in the 1960s–1970s, but only within the Altai–Sayan fold region. Even there, forecast resource assessments were carried out inconsistently by individual researchers and did not cover all known occurrences. Nevertheless, these efforts led to the discovery of numerous deposits and occurrences of the arsenide–cobalt formation, as well as resource and reserve estimates for associated cobalt at deposits of the skarn-tupe iron ore formation. A wide range of mineral parageneses (facies) has been identified for arsenide–cobalt mineralization [9, 10], indicating cobalt's involvement in the formation of many hydrothermal ore systems – such as those of gold, silver, copper, nickel, bismuth, antimony, tin, and tungsten – as well as in non-metallic systems, including fluorite-bearing [111] and magnesite-bearing [94] deposits with associated cobalt. A *nationwide, systematic review of geological data on known cobalt mineralization* – accompanied by forecast resource assessments based on a unified methodology – is needed.

Cobalt geochemical anomalies have often been recorded during systematic lithogeochemical sampling conducted as part of regional geological mapping and specialized geochemical surveys of various scales. However, in most cases, these anomalies were interpreted as lithological in origin, linked to the distribution of basic and ultrabasic rocks. Only when there were clear signs of copper–nickel, cobalt–nickel, or arsenide–cobalt mineralization were these anomalies reclassified as ore-related and considered worthy of further evaluation [112]. As a result, many potentially cobalt-rich but less obvious occurrences – such as ferromanganese crusts and nodules, fluorite- and magnesite-associated deposits, and other cobalt-bearing formations—were excluded from exploration efforts. As part of the proposed re-evaluation of existing geological materials and forecast resources, these previously overlooked "lithological" cobalt anomalies should also be revisited.

At silicate cobalt–nickel formation deposits, exploration has traditionally focused on maximizing nickel reserves. While cobalt is closely associated with nickel, it tends to concentrate in the lower rather than middle parts of the weathering crust profile [13]. Some cobalt-enriched ore zones may lie outside the current resource estimation boundaries, particularly in unmined pillars at many previously exploited silicate cobalt–nickel deposits in the Ural province. For similar reasons, no resource estimates have been made for asbolane-type occurrences in the Salair province, which are rich in cobalt but have low nickel content. A desk-based re-evaluation of previously explored silicate cobalt–nickel deposits is warranted, with 3D modeling of the spatial distribution of cobalt as a primary ore component. A reassessment of nickel- and iron-rich weathering crusts is also necessary to identify cases where cobalt may play the dominant ore-forming role. Similar analysis is needed for deposits of the cobalt-rich ferromanganese ore formation (e.g., Mazulskoe, South Khingan group, and others).

Regarding the *cobalt-rich ferromanganese crust formation*, dedicated investigations are required to assess the potential for onshore occurrences within the Russian Federation. This would involve reviewing existing geological data, identifying diagnostic features, developing exploration criteria, and conducting prospecting and evaluation for cobalt-rich ferromanganese crust deposits.

Advancement of cobalt extraction technologies. At present, cobalt in Russia is extracted solely by PJSC MMC Norilsk Nickel from copper–nickel ores. It is recovered during hydrometallurgical refining as a hydroxide precipitate in the process of nickel anolyte purification, followed by the production of electrolytic (cathode) cobalt [6]. At the arsenide–cobalt deposit of Hovu-Aksy, the Tuvacobalt plant previously processed ores using an ammonia–carbonate hydrometallurgical method in autoclaves to obtain a bulk concentrate [113]. Silicate cobalt–nickel ores from Ural deposits were mainly processed at the Orsk, Ufaley, and Rezh nickel plants through electric smelting to produce ferronickel. Cobalt, concentrated in the smelting slag, was then recovered via sulfuric acid leaching in autoclaves.

The advancement of beneficiation and processing technologies for cobalt-bearing ores is making it possible to bring into production deposits that were previously uneconomical or technologically unviable. *In-situ* (*borehole*) *and heap leaching methods* – specialized forms of hydrometallurgy – significantly enhance project profitability by reducing both capital and operational expenditures [114]. These approaches are well-established in uranium in-situ leaching and gold heap leaching. Heap leaching trials for nickel and cobalt have been carried out on silicate ores from the Serov deposit (Ural province) [115] and the Belininskoe deposit (Salair province) [78], achieving cobalt extraction rates of up to 88%. Pilot tests of in-situ leaching at the Rogozhinskoye deposit (Ural province) have confirmed the technical feasibility of this method for cobalt and nickel recovery [116]. A bioleaching process is being developed for the cobalt–copper–nickel ores of the Shanuch deposit (Kamchatka province). This method involves the direct oxidation of sulfides and arsenides within the ore body using acidophilic chemolithotrophic microorganisms [117], allowing for subsequent sulfuric acid leaching of cobalt, copper, and nickel from the oxidized ore via in-situ or heap leaching. Heap bioleaching trials have also been conducted on low-grade copper–nickel ores and technogenic materials from deposits in the Kola province [119], with nickel and cobalt recovery rates reaching up to 60%. Heap and in-situ leaching methods are also under consideration for cobalt-bearing uranium–phosphate deposits in Kalmykia [40]. The integration of sulfide oxidation biotechnology with in-situ and heap leaching techniques enables the development of low-grade and small-scale cobalt resources, as well as the reprocessing of waste materials from earlier beneficiation and metallurgical operations. Deposits of the silicate cobalt–nickel formation are among the most promising targets for such hydrometallurgical extraction approaches.

Conclusions

Russia's balance cobalt reserves are considerable (1,562.3 kt), sufficient for decades of production. Current cobalt output (9.2 kt/year) exceeds domestic consumption. At the same time since 97% of Russia's balance reserves and 100% of its cobalt production are concentrated in ore formations where cobalt occurs solely as a by-product, the country faces limited ability to control cobalt supply volumes. With the expected growth in cobalt demand driven by the lithium-ion battery industry, planning for increased cobalt production will be complicated. New development projects targeting complex copper–nickel and silicate–nickel deposits are primarily geared toward nickel and copper output; cobalt production is a secondary, dependent variable. Average cobalt grades in such complex ores are low: up to 0.17% in copper–nickel formations, 0.11% in silicate cobalt–nickel formations, 0.07% in copper–pyrite formations, and 0.18% in iron ore formations. At these concentrations, cobalt cannot be economically extracted on its own. Primary cobalt deposits in the Russian Federation belong to the arsenide–cobalt formation, where cobalt grades reach up to 2.42%. However, the prepared reserves of this formation account for just 3.0% of the national cobalt balance. New projects involving deposits with by-product cobalt could collectively add up to 8 kt/year of cobalt production, while deposits of the arsenide–cobalt formation offer the potential for a controlled increase of up to 4 kt/year.

Russia holds exploration rights in international seabed areas of the Pacific Ocean, where geological investigations are underway at cobalt-rich ferromanganese crust formations in the Magellan Seamounts (resources: 110 kt Co) and ferromanganese nodules in the Clarion–Clipperton Fracture Zone (resources: 985 kt Co). These deposits are promising for cobalt extraction, but their development is constrained by slow progress in deep-sea mining technologies, the need for new processing methods for unconventional ores, and environmental and geopolitical risks.

Despite having a solid base of prepared cobalt reserves, Russia lacks a systematic inventory of forecast cobalt resources, hindering exploration planning.

A nationwide reassessment of existing geological data on known cobalt mineralization is proposed, including a unified forecast resource assessment methodology and the compilation of a national cobalt resource forecast balance. This assessment should extend beyond established cobalt-bearing formations and include occurrences of cobalt mineralization in other ore and non-metallic formations. The results of geochemical surveys should also be reviewed, as cobalt anomalies were often dismissed as lithological in origin and excluded from further exploration.

At silicate cobalt–nickel deposits, where previous assessments focused on maximizing nickel reserves, a reassessment is proposed to model cobalt distribution as a primary ore component. Nickel- and iron-bearing weathering crust occurrences should also be re-evaluated for the potential leading role of cobalt in ore formation. These types of deposits offer greater control in cobalt production planning.

Advancements in in-situ and heap leaching technologies, including bioleaching of cobalt-bearing ores, will enable the development of low-grade and small-scale cobalt deposits, as well as the reprocessing of waste from past beneficiation and metallurgical operations. Silicate cobalt–nickel formation deposits are among the most promising candidates for these hydrometallurgical approaches.

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Analysis of the mechanism of cyclic geomechanical treatment to increase well productivity in carbonate reservoirs

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Abstract

Methods for creating microfracture zones (loosening of reservoir rock) in well vicinity by significant reducing pore pressure and techniques for increasing well productivity based on these methods have been actively developed by Russian Academy of Sciences institutes over the past decades. A prerequisite for the application of such methods is the creation of a depression of sufficient magnitude and duration in wells to form man-made microfractures. The paper discusses cyclic geomechanical treatment (CGT), one of the methods for increasing the productivity of oil wells in carbonate reservoirs based on the creation of a deep depression in a well. Effective planning and application of such methods requires understanding the mechanism of microfracturing in the vicinity of a well when a critical pore pressure reduction value is reached. The aim of this study is to substantiate the geomechanical mechanism of microfracturing formation consistent with the results of laboratory studies of core samples and the application of CGT and related methods in wells. The objectives of the study included analyzing the characteristics of laboratory experiments and their results, identifying possible mechanisms and criteria for the formation of microfracturing, and conducting coupled hydrogeomechanical modeling with an assessment of the characteristic dimensions of the affected area. It has been shown that the results of the laboratory experiments and experimental application of the CGT method are inconsistent with the shear failure mechanism, but can be explained by the compaction failure mechanism. Coupled numerical hydrogeomechanical modeling of the pilot CGT application in a well was performed with an assessment of the compaction failure criteria parameters based on core data. The estimated radius of the stimulation zone was approximately 7 m, with the estimated increase in the productivity index to be consistent with actual data.

Keywords

well, productivity, permeability, reservoir, microfracturing, cyclic geomechanical treatment, fracturing (failure), geomechanical criterion, hysteresis, modeling, experiment

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СВОЙСТВА ГОРНЫХ ПОРОД. ГЕОМЕХАНИКА И ГЕОФИЗИКА

Научная статья

Анализ механизма циклического геомеханического воздействия для увеличения продуктивности скважин в карбонатных коллекторах

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Аннотация

Методы создания околоскважинной области микротрещиноватости (разуплотнения породы коллектора) за счет глубокого снижения порового давления и основанные на них способы повышения продуктивности скважин активно развиваются в рамках научной деятельности институтов РАН в последние десятилетия. Обязательным условием применения таких методов является создание достаточной по величине и продолжительности депрессии на скважинах для формирования техногенной микротрещиноватости. В статье рассматривается циклическое геомеханическое воздействие (ЦГВ) – один из методов увеличения продуктивности нефтяных скважин в карбонатных коллекторах, основанных на создании глубокой депрессии на скважине. Эффективное планирование и применение таких методов связано с пониманием механизма возникновения микротрещиноватости в околоскважинной зоне при достижении критической величины снижения порового давления. Целью работы является обоснование геомеханического механизма формирования микротрещиноватости, согласующегося с результатами лабораторных исследований керна и применения ЦГВ и близких ему методов на скважинах. Задачи исследования включали анализ особенностей постановки лабораторных экспериментов и их результатов, определение возможных механизмов и критериев формирования микротрещиноватости, а также проведение сопряженного гидрогеомеханического моделирования с оценкой характерных размеров области воздействия. Показано, что результаты лабораторных экспериментов и опытного применения метода ЦГВ не согласуются с механизмом сдвигового разрушения, но могут быть объяснены механизмом разрушения сжатия. Выполнено сопряженное численное гидрогеомеханическое моделирование опытного применения ЦГВ на скважине с оценкой параметров критерия разрушения сжатия по керновым данным. Расчетный радиус зоны воздействия составил около 7 м, при этом оцененный прирост коэффициента продуктивности хорошо согласуется с фактическими данными.

Ключевые слова
скважина, продуктивность, проницаемость, коллектор, микротрещиноватость, циклическое геомеханическое воздействие, разрушение, геомеханический критерий, гистерезис, моделирование, эксперимент

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Introduction

Methods for creating microfracturing zones (loosening of reservoir rock) in a well vicinity by significant reducing pore pressure, and techniques for increasing well productivity based on these methods, have been actively developed by Russian Academy of Sciences institutes over the past decades. A prerequisite for the application of such methods is the creation of a depression of sufficient magnitude and duration in wells to form man-made microfractures. The resulting microfracture system significantly increases the permeability of a reservoir rock in a well vicinity zone that leads to a significant increase in well productivity. Such methods are most effective for deep-buried formations (more than 3 km deep) in compacted reservoir rocks with sufficient reservoir pressure reserve. An additional favorable factor for their application is an abnormally high reservoir pressure.

One of the first techniques of influencing a well bottom zone based on the methods under consideration is described in patent[1]. It is based on the results of laboratory experiments with carbonate rocks of the Tengiz field [1].

The most well-known methods are the geoloosening method and its further modification, the directional unloading of the reservoir (DUR), developed at the Ishlinsky Institute for Problems in Mechanics of RAS[2] [2, 3]. To justify the applicability of the DUR method, stresses arising on a wellbore wall (for an open hole design) and at the tip of a perforation (for a cased hole design) are simulated on a core sample in laboratory experiments[3] [4]. A distinctive feature of the DUR technique is the need to create additional perforation channels as stress concentrators, including for the open hole design. The technique application allows increasing well productivity by 1.5–2 times for the cased hole design and by 2–4 times for the open hole design[4].

An alternative method for creating a microfracturing zone by significant reducing pore pressure is Cyclic Geomechanical Treatment (CGT) method proposed by researchers at the Oil and Gas Research Institute of the Russian Academy of Sciences. The technique for increasing well productivity based on the

[1] SU 1609978. Bakirov E.A., Zakirov S.N., Shcherbakov G.A. et al. Method for treating the well bottom zone of a reservoir. Publ. on November 30, 1990. Bulletin No. 44 (In Russ.)

[2] RU 2645684 C1. Klimov D.M., Karev V.I., Kovalenko Yu.F., Titorov M.Yu. Method for directed formation relieving. Publ. on February 27, 2018. Bulletin No. 6 (In Russ.)

[3] Kovalenko Yu.F. Geomechanics of oil and gas wells. [Diss. … Dr. Sci. (Phys.&Math.)] Moscow; 2012. 314 p. (In Russ.)

[4] Ibid.

CGT method is described in patent[5]. Some practical implementation features are discussed in [5]. The main feature of CGT is a full cycle of the stimulation, including deep decreasing pore pressure and a subsequent increase in the pressure above the initial level to open microfractures. The increase in well productivity (PI – productivity index) as a result of field testing of the method in a formation with an initial reservoir pressure of about 11 MPa is estimated at 44–49%. A description of the programs and results of the laboratory experiments, numerical modeling, and field application is presented in paper [6].

The traditional theoretical explanation for the formation of a zone of increased permeability (microfracturing) due to a significant decrease in pore pressure is based on the mechanism of shear failure. It arises under the influence of excessive tangential stress when the maximum effective stress exceeds the minimum primary effective stress by a critical value[6]. At the same time, the technique for studying the CGT on core samples used in [6] involved changing only pore pressure at a constant pseudo-triaxial external load that corresponds to constant tangential stresses. Nevertheless, these experiments also detected an increase in the permeability of samples in the course of decreasing pore pressure after reaching its critical value.

The aim of this study is to substantiate the geomechanical mechanism of reservoir loosening consistent with the results of laboratory studies on core samples and the application of the considered methods in wells. The objectives of the study included analyzing the features of the laboratory experiments and their results, identifying possible mechanisms for the formation of microfracturing, and substantiating a geomechanical criterion, followed by the development of a coupled hydrogeomechanical model and calculation of the radius of a well vicinity zone of increased permeability.

Theory and Techniques

To analyze possible geomechanical mechanisms of microfracturing formation in a reservoir under the influence of DUR (Directional Unloading of the Reservoir) and CGT methods, we considered the features of the setup and results of laboratory experiments in framework of these methods.

[5] RU 2620099 C1. Zakirov S.N., Drozdov A.N., Zakirov E.S. et al. Method for increasing the productivity of production wells and the injectivity of injection wells. Publ. on May 23, 2017. Bulletin No. 15. (In Russ.)

[6] Kovalenko Yu.F. Geomechanics of oil and gas wells. [Diss. ... Dr. Sci. (Phys.&Math.)] Moscow; 2012, 314 p. (In Russ.); Khimulya V.V. Rheological and filtration properties of rocks under complex triaxial loading. [Diss. ... Cand. Sci. (Phys.&Math.)] 01.02.04. Moscow; 2021. 133 p. (In Russ.)

Method of Directional Unloading of the Reservoir

Experiment techniques

The purpose of the laboratory studies using the DUR method is to simulate, on a core sample, the stresses existing on a well wall for an open hole design or on the tip of a perforation for a cased hole design[7] [4].

The studies are conducted using a triaxial independent loading test system (TILTS). The TILTS installation creates effective stresses by acting on the faces of a cubic rock sample (Fig. 1, *a*). The loading stages are shown schematically in Fig. 1, *b*.

At each of the three stages, the effective stresses change due to external loads on a sample face. Pore pressure is maintained constant at a level of atmospheric pressure (or the first few atmospheres).

Stage 1. A sample is compressed evenly on all sides until the specified effective stress is reached (segment OA in Fig. 1, *b*). Point A corresponds to the effective stresses S_i acting in a rock matrix prior to drilling, under the simplifying assumption that vertical and lateral rock stresses are equal.

Stage 2. The average normal stress $S = (S_1 + S_2 + S_3)/3$ remains constant throughout the whole stage 2. Each point on segment *AB* corresponds to the well bottom-hole pressure greater than the formation pressure, i.e., a certain value of repression on the formation. The end point of the stage (point *B*) corresponds to the state when the well has been drilled and the bottom-hole pressure is equal to the formation pressure.

Stage 3. The process of creating depression, i.e., lowering the bottom-hole pressure (segment BC in Fig. 1, *b*), is modeled. The third stage continues until the sample is fractured.

During all stages, the sample strain is measured in three directions and its permeability is recorded (through gas pumping). The experiment is described in more detail in the thesis of Yu.F. Kovalenko[8].

In total, these three consecutive loading stages correspond to theoretical concepts of changes in effective stresses on the wall of an open hole during the drilling of a productive formation and subsequent creation of a depression. The changes in effective stresses on the surface of perforations for a cased well demonstrate similar regularities. It should be noted that in these studies and those discussed below, it is assumed that Biot's law for effective stresses is applicable in the Terzaghi form (Biot's coefficient is equal to 1).

[7] Ibid.

[8] Kovalenko Yu.F. Geomechanics of oil and gas wells. [Diss. ... Dr. Sci. (Phys.&Math.)] Moscow; 2012. 314 p. (In Russ.)

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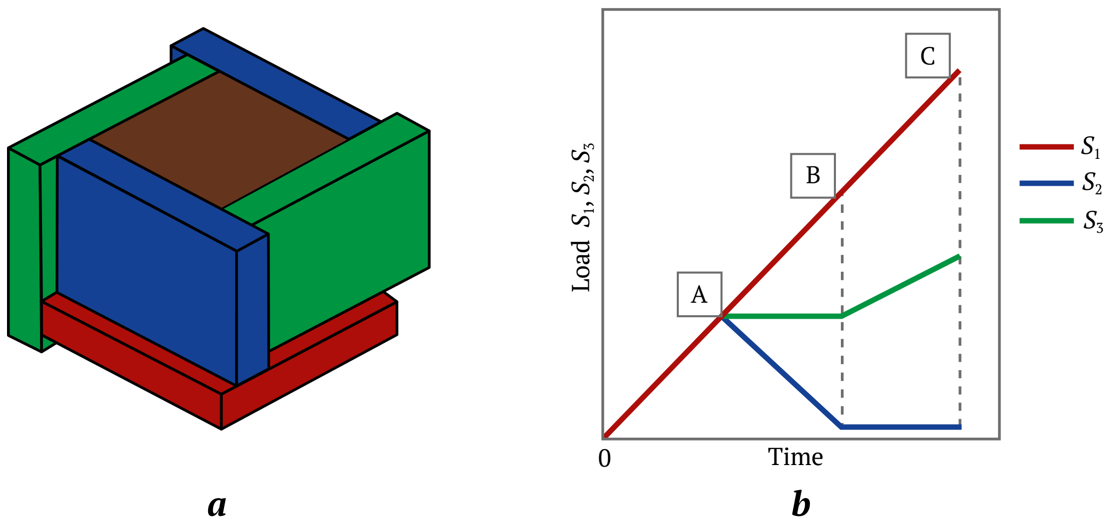


Fig. 1. Schematic diagram of the action on a cubic sample (*a*) and the stages of loading the sample (*b*) when modeling the effective stress field in the vicinity of a vertical open hole: S_1, S_2, S_3 are effective normal stresses on the cube faces
Source: Kovalenko Yu. F. Geomechanics of oil and gas wells. [Diss. ... Dr. Sci. (Phys.&Math.)] Moscow; 2012. 314 p. (In Russ.)

For a vertical open hole in the absence of fluid flow, the solution to the Lame's problem [7] is valid:

$$\begin{aligned} S_2 &= S_r = (\sigma_r - p_0)(1-(r_w/r)^2), \\ S_3 &= S_\theta = (\sigma_r - p_0)(1+(r_w/r)^2), \\ S_1 &= S_z = \sigma_r - p_0, \\ q\big|_{r=rw} &= \sigma_r - p_0, \end{aligned} \quad (1)$$

where S_1 is effective vertical stress; S_2 is effective radial stress; S_3 is effective tangential stress in a formation at a distance r from the well axis; r_w is the well radius; σ_r is initial rock (total) stress; p_0 is reservoir (pore) pressure; q is maximum effective tangential stress. As the pore pressure p_0 decreases, the effective stresses on the wellbore wall $r = r_w$ change in accordance with stage 3 of the experiment described (see Fig. 1, *b*).

Findings of experiments and their interpretation

The findings of the experiments using the directional unloading of the reservoir method are different for different types of core samples[9]. As typical examples, the thesis of Yu.F. Kovalenko[10] describes the results for sandstone samples with a high clay content and carbonate rock samples.

In the first case, the permeability of the core sample decreased steadily and reached zero by the end of the experiment. In the second case, the effect on the carbonate rock samples resulted in an increase in permeability. The loading stages and the permeability change curve for one of the carbonate samples are shown in Fig. 2.

The first stage, at which triaxial hydrostatic compression on the sample takes place, lasted until the 800th second. By the end of the stage, stress S_3 reached a value of 26 MPa. The sample permeability at this point is no more than 10% of the initial value that indicates inelastic strain. When stress S_3 exceeds 10 MPa, significant strains develop in the sample, the permeability decreases and drops to almost zero by the 400th second (see Fig. 2, *b*). This indicates that irreversible changes associated with compaction occur in the sample structure during the hydrostatic compression stage. Consequently, the elastic limit has been exceeded in the sample, and significant compaction has occurred. After 800 seconds, when tangential stresses begin to act on the sample, an intense increase in permeability begins.

It is assumed that the inelastic compaction and accompanying change in the structure of the sample at the first stage of the experiment led to shear fracture with a sharp increase in the sample permeability at the second stage. Otherwise, the failure of the internal structure of the rock would have begun at higher tangential stresses and the permeability would not have increased so significantly.

Thus, the cause of the decrease in sample permeability in the DUR experiments is considered to be elastic and inelastic compaction with an increase in effective stresses, and the cause of the subsequent increase in permeability is shear failure of the internal structure of the sample with the formation of microfractures upon reaching critical tangential stresses.

[9] Karev V.I. The influence of stress-strain state of rocks on the filtration process and well flow rate. [Abstr. Dr. Sci. (Eng.) Diss.] Moscow: IPMech RAS Publ.; 2010. 33 p. (In Russ.)

[10] Kovalenko Yu.F. Geomechanics of oil and gas wells. [Diss. ... Dr. Sci. (Phys.&Math.)] Moscow; 2012. 314 p. (In Russ.)

For porous materials, strain under compression can occur both in the absence of tangential stresses, i.e., under hydrostatic loading (compaction), and in their presence. Then it is called shear-enhanced compaction. The shear failure line for rocks in the "mean normal stress – maximum tangential stress" space can usually be approximated by a straight line according to the Mohr–Coulomb criterion (Fig. 3, *a*) [7].

In [8], two options for transition from shear-enhanced compaction to inelastic increase of stressed material volume due to fracture formation and opening are considered. The first option consists in applying tangential stresses to a sample from the very beginning of the experiment. The other option is that a sample can be hydrostatically compressed to a state of inelastic compaction strain. Then, when critical tangential stresses are created, sample failure begins. This is exactly the case for describing the above results of the experiment using the DUR technique. The red arrow in Fig. 3 schematically shows the direction of stress change in the experiment.

Method of Cyclic Geomechanical Treatment (CGT)

Routine of experiments

The essence of the CGT method consists in combining a half-cycle of deep depression to create a zone of loosening of the reservoir, followed by a half-cycle of repression on formation to open and further expand the microfractures created.

Let us consider the peculiarities of the laboratory experiments using the example of studies described in [6]. Carbonate samples from the Tournaisian stage rocks were selected for experiments on cores using the CGT method. Let us consider three cores samples

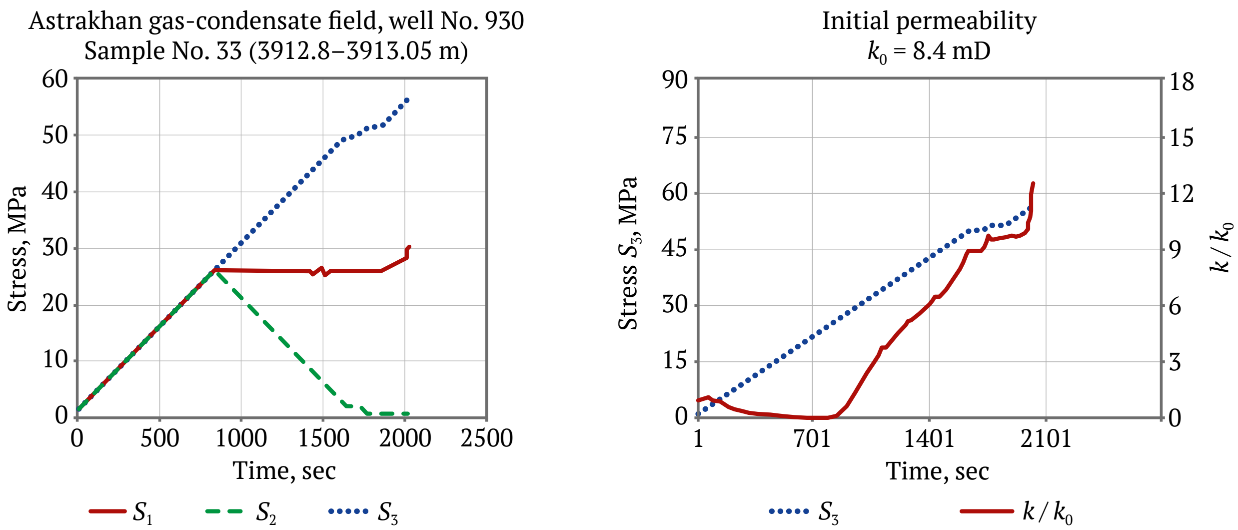


Fig. 2. Stages of loading and change in permeability of carbonate sample (Astrakhan gas-condensate field)
Source: Kovalenko Yu. F. Geomechanics of oil and gas wells. [Diss. ... Dr. Sci. (Phys.&Math.)] Moscow; 2012. 314 p. (In Russ.)

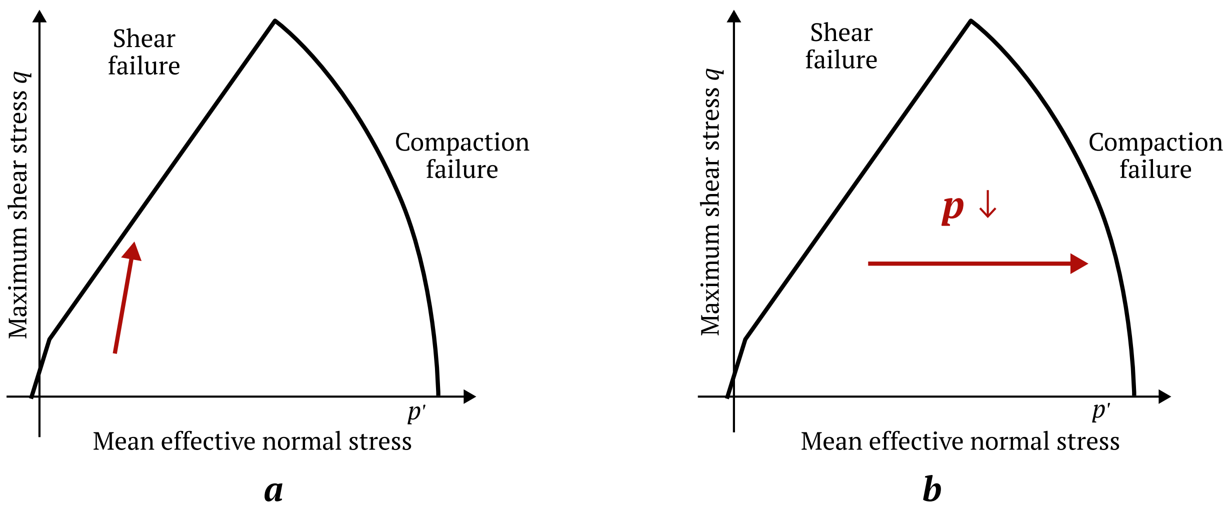


Fig. 3. Failure diagrams and direction of change in effective stresses in experiments simulating the effective stress field in the vicinity of a vertical open hole well (*a*) and in experiments with changing pore pressure (*b*)

after extraction saturated with kerosene in the presence of connate water saturation. After the experiment, they demonstrated a multiple increase in permeability relative to the initial value. The main characteristics of the core samples are given in Table 1. The other three core samples in the same studies were completely saturated with formation water (brine) model and did not show any increase in permeability. The effect of rock saturation on the nature of permeability changes during CGT tests is a positive factor for application of the method in oil wells [6].

The study was performed under pseudo-triaxial compression, simulating the vertical rock stress (axial load on a sample P_{vert}) and minimal lateral stress (confining pressure P_{comp}) typical for the formation. The initial pore (fluid) pressure P_{por} corresponded to the initial reservoir pressure of the formation. The experimental conditions are schematically shown in Fig. 4, *a*. In the experimental process, pore pressure cyclically changed. The stages of the experiment are shown in Fig. 4, *b*.

At each stage of the experiment, pore pressure was kept constant. The saturating fluid was pumped until the pressure difference stabilized, and the current permeability value was determined. The acoustic method was also used to evaluate the current values of dynamic elastic moduli, Young's modulus, and Poisson's ratio. The experiment is described in more detail in [6].

Findings of experiments and their interpretation

The results of the experiments for all core samples saturated with kerosene and containing connate water are in agreement at a qualitative level. At the initial stages of pore pressure reduction, rock compaction was observed, accompanied by a decrease in permeability and an increase in Young's modulus. However, with further growth of compressive stresses and a decrease in pore pressure below the critical level, signs of loosening of the internal structure of the rock were observed. This was followed by an increase in permeability with increasing pressure due to the opening of microfractures that had formed. Besides, in a number of samples, when the initial pressure was exceeded, a characteristic sharp increase in permeability was observed with a decrease in the Young's modulus, corresponding to the formation of a tensile fracture supported by the previous rock loosening. The permeability increase effect persisted during the stage of secondary pressure decline to initial or lower values. Core samples with reduced Young's modulus values and increased porosity values (initially more "loose" with probable presence of microfractures) are characterized by a more intense decrease in permeability during the initial pressure reduction. For more tight core samples, on the contrary, the greatest increases in permeability were observed as a result of CGT application [6].

Table 1

Parameters of the Tournaisian stage rock core samples

Sample No.	Depth, m	Lithology	Porosity, %	Gas permeability, mD	Fluid	Connate water saturation, %
2	1,224.29	Limestone	14.24	484	Kerosene	10.81
5k	1,224.67	Limestone	12.88	270	Kerosene	14.33
6	1,224.71	Limestone	12.31	60	Kerosene	19.04

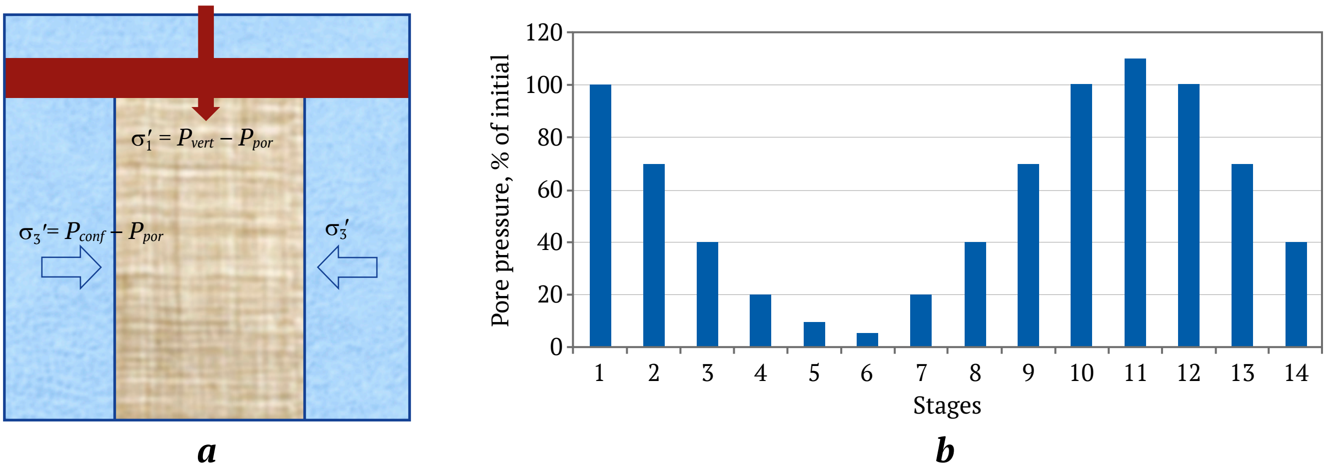


Fig. 4. Schemes of pseudo-triaxial loading in experiments (*a*) and the experiment stages (*b*): σ_i' are the effective stresses

The characteristic plots of Young's modulus and permeability are shown in Fig. 5 for sample 6.

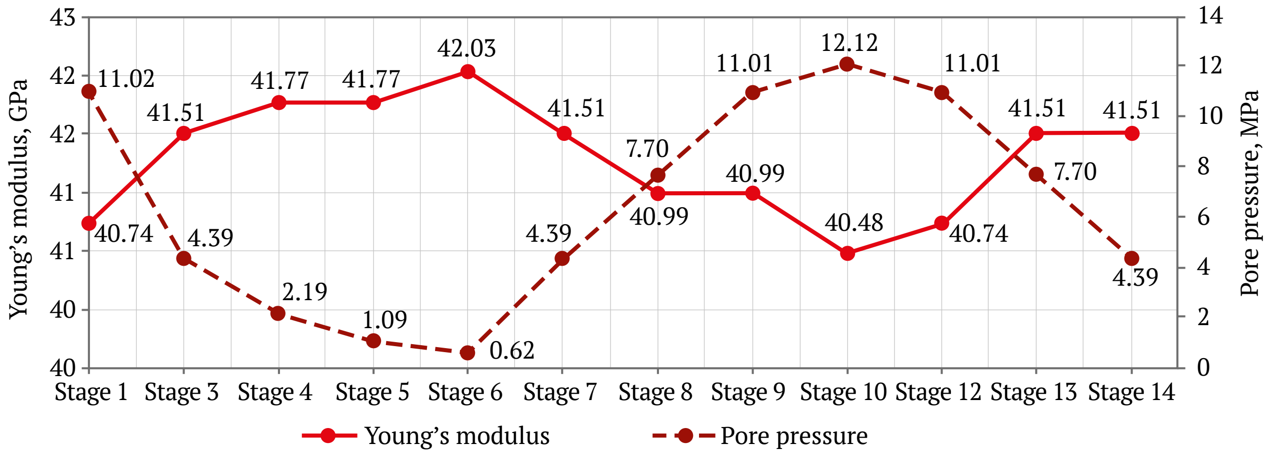
Let us consider the first six stages of the experiment, corresponding to the half-cycle of pore pressure reduction. Increased permeability in this case indicates exceeding the strength limit in the sample and beginning of the failure of the internal structure.

During the first three stages of the experiment, the increase in Young's modulus is accompanied by a decrease in permeability, i.e. the sample undergoes compaction. At stage 5, a simultaneous increase in Young's modulus and permeability takes place, and at stage 6, Young's modulus decreases that may indicate the formation of fractures in the sample, while the sample structure has become more compact. It should be noted that the joint growth of the Young's modulus and permeability could have already occurred during stage 4 but not recorded due to the discrete nature of the measurements. So the failure of the internal structure begins during stage 4 or stage 5.

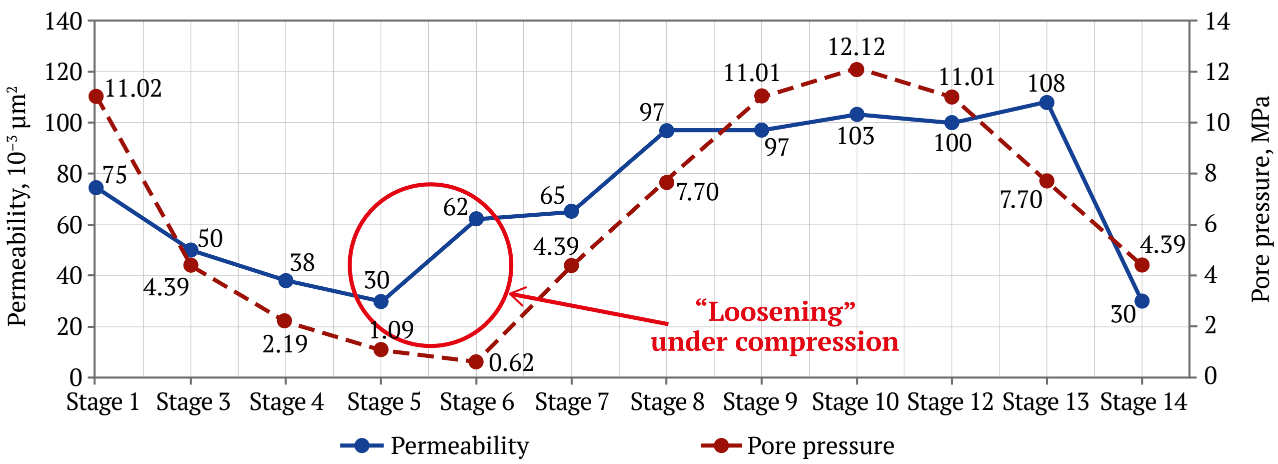
A distinctive feature of the experiments under consideration is that only the pore pressure changes while the confining stress and axial load remain constant. Consequently, there is a synchronous increase in effective normal stresses in all principal directions. At the same time, effective tangential stresses remain constant, so a decrease in pore pressure cannot cause shear failure. Under the influence of increasing effective normal stresses, compaction failure may occur.

In the "mean normal stress – maximum tangential stress" space, the compaction failure line corresponds to an arc of a circle, see Fig. 3, *b* [7]. The red arrow schematically indicates the direction of change in effective stresses in the experiments.

Fig. 6 compares the conditions for internal failure obtained in the experiment described above on a sample from the Tournaisian stage rocks with the compaction failure envelope curves for various carbonate rocks studied in [8]. This type of envelope curve



a



b

Fig. 5. Laboratory test results for sample 6 (kerosene-saturated with connate water): *a* – Young's modulus plot, *b* – permeability plot. The red line shows the pore pressure changes

is typical for carbonate reservoirs and is confirmed by lab experiments [9–11] and geomechanical modeling [12]. It should be noted that the increase in Young's modulus observed in Fig. 5, accompanied by a simultaneous increase in the permeability of the core sample (the beginning of microfracture formation) at the corresponding stage of the experiment, also corresponds to the characteristic features of rock behavior at the onset of compaction failure [13].

In Fig. 6, triangular and circular markers of three colors indicate the results of experimental determination of stress state corresponding to compaction failure for samples of three different carbonate rocks according to data [8]. The horizontal axis corresponds to the mean effective normal stress, while the vertical axis corresponds to the differential stress (the difference between the maximum and minimum normal stresses). The compaction failure envelopes for each of the three rock types are shaped like arcs of circles, with the circles for the orange triangles and green bubbles being similar. The red star marks the point corresponding to the effective stresses at the onset of permeability growth (loosening) in the above experiment on a carbonate rock sample from the Tournaisian stage rock, as described in [6].

Microfractures form primarily in the areas of rock that are characterized by high compaction. The most porous areas are more susceptible to non-elastic compaction. The strength of samples subjected to the experiments with the use of the CGT method could be affected by chemical effects arising from the interaction between the rock and the fluid (kerosene and connate water), as well as by the structural features of the reservoir rock. The presence of heterogeneous inclusions, cavities, and natural fracturing also affects the strength characteristics of the samples. All these factors influence the position of the point for the Tournaisian rock sample in Fig. 6 in comparison with dry carbonate samples of different porosity from [8]. At the same time, one may expect that the shape of the compaction failure envelope will remain unchanged and should pass through the red point in Fig. 6 parallel to the envelopes for the orange and green points.

Thus, in the experiments on CGT considered, the increase in the permeability of samples with a decrease in pore pressure below the critical level cannot be explained by shear failure under the action of tangential stresses. It is probably related to compaction failure. The envelope for compaction failure can be approximately obtained by aligning the obtained critical stress point with the envelope shape characteristic of other carbonate rocks.

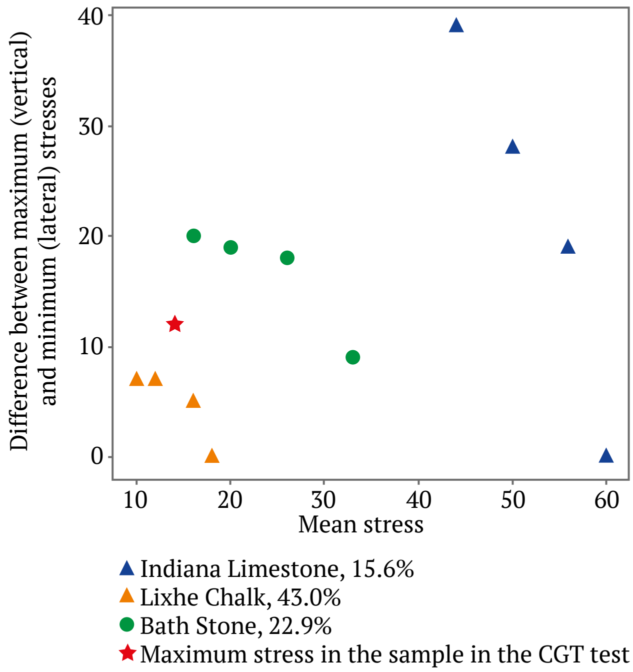


Fig. 6. Compaction failure envelopes according to [8] and ultimate stress state for a Tournaisian stage rock sample

Findings

Assessment of the radius of the increased permeability zone during shear failure

The main cause of fracturing in a well vicinity zone when creating a deep depression using DUR and CGT methods is a decrease in local reservoir pressure, which leads to an increase in effective stresses. When using the directional unloading method, low bottomhole pressure must be maintained for a rather long period of time. It is assumed that prolonged depression can cause pressure to drop to a level sufficient to trigger the shear failure at a sufficient distance from the well to achieve a noticeable increase in productivity[11]. Thus, evaluating the radius of the shear failure zone is important for calculating productivity gains and, consequently, the potential effect from the method application in terms of increasing productivity.

Such evaluation was performed by Yu.F. Kovalenko in his thesis[12] for open-hole conditions. The problem is similar to the Lame's problem, but the pore pressure is not constant; rather, it increases from the well wall toward the remote boundary in accordance with the steady-state solution for axisymmetric inflow with a given depression Δp_w (Dupuis solution).

[11] Kovalenko Yu.F. Geomechanics of oil and gas wells. [Diss. ... Dr. Sci. (Phys.&Math.)] Moscow; 2012, 314 p. (In Russ.)

[12] Ibid.

Thus, long-term operation of the well at a specified intensive mode is assumed. Rock deformation is considered elastic until the Mohr–Coulomb shear failure criterion is reached. Based on the calculation results, the radius of the failure zone R^* is evaluated, where, according to the Mohr–Coulomb criterion, shear failure with the formation of a fracturing region is predicted.

The Yu.F. Kovalenko's thesis presents graphs of the relative radius of the failure zone R^*/R_w (R_w is the well radius) as a function of the internal friction angle at three values of depression Δp_w for the characteristic conditions of the Astrakhan oil and gas-condensate field: formation depth of 3,800–3,900 m, initial reservoir pressure of 60 MPa, vertical overburden stress of 90 MPa.

The results of the calculations from the Yu.F. Kovalenko thesis show that, with values of internal friction angle characteristic of real rocks of 15° and above, the calculated radius of the failure zone does not exceed 3–4 times the radius of the well (~30–40 cm) even at a depression of 60 MPa.

Using the model developed by Yu.F. Kovalenko, the authors performed similar calculations for the initial data corresponding to the characteristic conditions of the Tournaisian stage carbonate reservoirs (formation depth of 1,200 m, initial reservoir pressure of 11 MPa, vertical overburden stress of 26.06 MPa, depression of 10 MPa). Fig. 7 shows graphs of maximum tangential stresses as a function of the distance from the well wall. The peak point corresponds to the boundary of the failure zone.

As can be seen in Fig. 7, *a*, even in the case of underestimated values of the cohesion coefficient and internal friction angle, the radius of the failure zone is about 35 cm from the well wall. For more typical parameter values (Fig. 7, *b*), it decreases to about 5 cm.

More complex features are characteristic of a formed failure zone for a cased well with perforation. In the V.V. Khimulya's thesis[13], the stress at the tip of a single perforation channel was evaluated using an analytical solution for a spherical cavity filled with a pressurized fluid [14]. The distribution of stresses in a well vicinity zone, taking into account the interference of perforation channels, can be assessed based on the results of numerical calculations published in the literature. The paper [15] examined the stability of a wellbore under different perforation densities across the formation thickness. Fig. 8 shows the failure region at a perforation density of 8 perforation holes per 0.3 m. The blue area indicates the elastic zone, while the green area indicates the failure zone. As can be seen from the Fig. 8, the tangential stresses are high enough to cause failure along the perforation hole, but it does not propagate into the formation outside the perforation zone. The stress field poses a high risk of damaging the cement column of the wellbore, but does not create conditions for the formation of an extended failure zone, which could cause the significant increase in productivity when using the DUR method in similar conditions.

[13] Khimulya V.V. Rheological and filtration properties of rocks under complex triaxial loading. [Diss... Cand. Sci. (Phys.&Math.)] 01.02.04. Moscow; 2021. 133 p. (In Russ.)

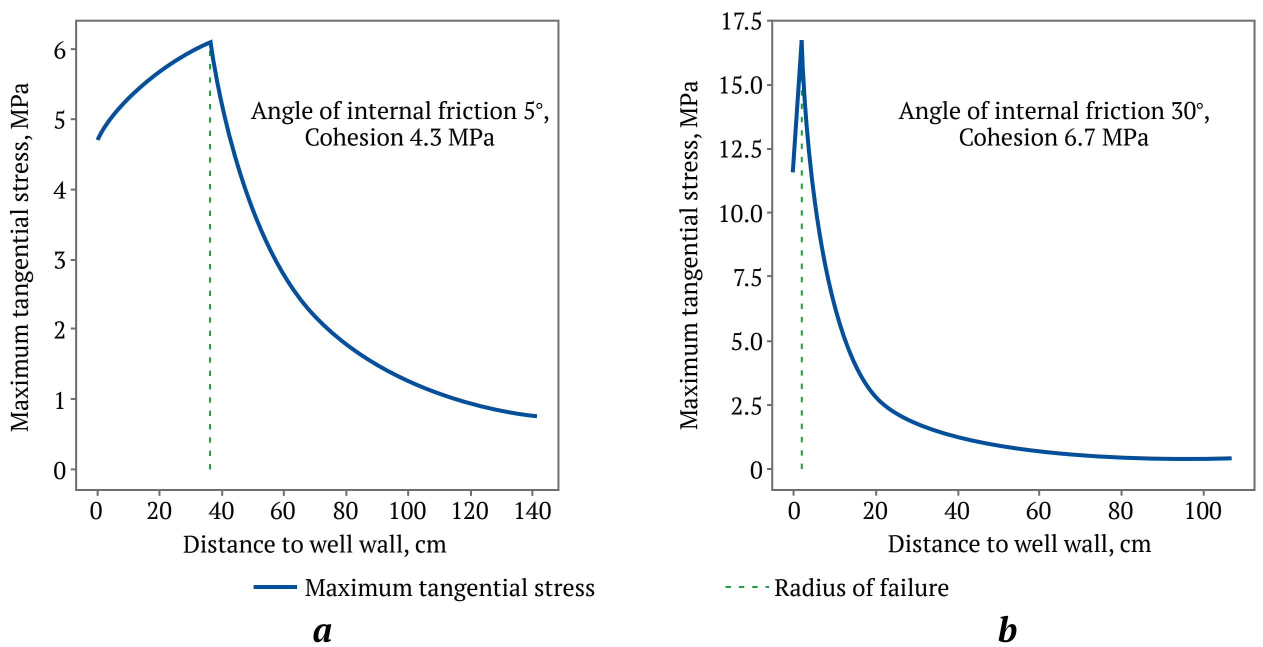


Fig. 7. Distribution of maximum tangential stresses in the vicinity of open-hole well for the following parameters: Poisson's ratio – 0.25; overburden rock stress – 26.06 MPa; initial pore pressure –11.0 MPa; depression – 10 MPa; wellbore radius – 0.1 m

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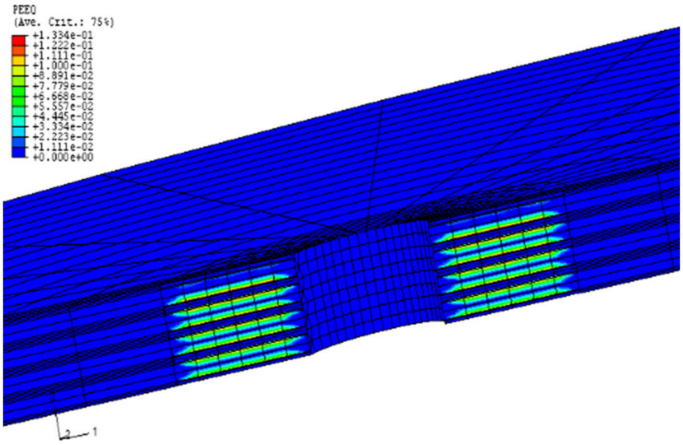

Fig. 8. Numerical solution of the problem of stress distribution in the vicinity of perforation channels at a perforation density of 8 perforation holes per 0.3 m for a cased well. The blue color indicates the elastic zone, while other colors indicate the zone where the shear failure criterion is met [15]

The simulation results presented below confirm that the estimates of the fracture zone size during shear failure (Figs. 7 and 8) cannot explain the achieved increases in the productivity index: 1.5 times during experimental testing of the CGT method (for a cased wellbore in shallow Tournaisian stage rocks [6]), and up to 3–4 times using the DUR method (for an open-hole wellbore, with additional perforation and in conditions of deeper sediments with a large reservoir pressure reserve[14]).

Coupled hydrogeomechanical modeling: evaluation of the radius of the increased permeability zone formed during compaction failure when using the CGT method

It has been shown above that the results of laboratory experiments on the CGT under constant pseudo-triaxial loading with changing pore pressure can be explained by the action of inelastic compaction mechanisms followed by compaction failure. To simulate the corresponding effects in a well vicinity zone when creating a depression in a well, the tNavigator flow simulation software package from Rock Flow Dynamics company (RFD) was used[15]. It enables the numerical solution of multiphase fluid flow problems in a reservoir during field development, together with the solution of a simplified geomechanical problem concerning changes in stress and strain distribution in reservoir rocks.

[14] Kovalenko Yu.F. Geomechanics of oil and gas wells. [Diss. ... Dr. Sci. (Phys.&Math.)] Moscow; 2012, 314 p. (In Russ.)

[15] TNavigator 23.1. Technical manual for the Simulator. RFD; 2023.

In the RFD tNavigator, there are two ways to solve flow and elasticity problems jointly: coupled and modular. The coupled approach was used, in which a single system of equations describing flow processes in the formation (continuity equations taking into account Darcy's law) and geomechanical effects (in this case, Lame's equations taking into account Hooke's law) is solved on a single computational grid[16].

To account for the effects of inelastic compaction and compaction failure, a script has been implemented in the Python language built into tNavigator, which processes the current effective stress fields at each computation step. The compaction was set by adjusting the current permeability multiplier in a grid cell (relative to the initial value) depending on the average effective normal stress. The corresponding decreasing dependence was assumed based on the first stages of the laboratory experiment (see Fig. 4, stages 1–5).

The compaction failure criterion under current changes in effective stresses in the grid cell was controlled by intersecting the envelope curve passing through the experimental point corresponding to the increase in permeability in the laboratory experiment (red dot in Fig. 6). The shape of the envelope curve was adopted by analogy with the experimental data from [8] (see Fig. 6). Fig. 9 shows an example of an envelope curve for one of the samples, approximated with sufficient accuracy by a circular arc with selected parameters, in this case, with the radius in stress coordinates of 13.4 MPa and the center at the point: 7 MPa; 0 MPa. Fig. 9 also shows the Mohr-Coulomb straight line for the shear failure criterion, which was not achieved in the computations. The burgundy horizontal arrow indicates the direction of change in effective stresses as pore pressure decreases.

When the compaction failure criterion was met (intersection of the envelope curve), the cell permeability increased fourfold that corresponds to the final increase in permeability after CGT application according to the results of one of the experiments on the Tournaisian stage rock core samples.

The characteristics of a Tournaisian stage reservoir in one of the fields in the Republic of Tatarstan were used as input data for modeling. The reservoir model had horizontal dimensions of $2{,}000 \times 2{,}000$ m, a nominal thickness of 1 m, with a vertical well located in the center. Along the axes *Ox* and *Oy*, the grid was densified towards the well with a constant coefficient of 1.1. The minimum cell size (the central cell with a well) was 0.5×0.5 m.

[16] Ibid.

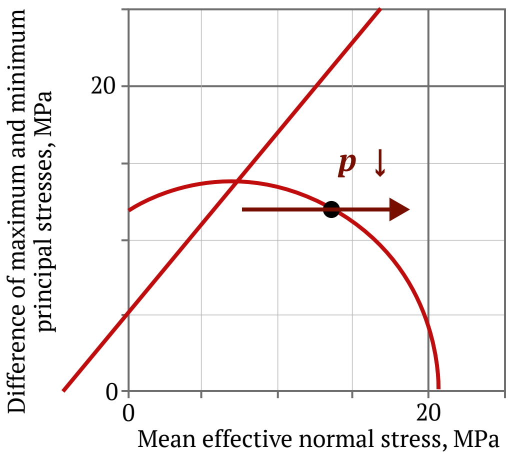

Fig. 9. The envelope for the compaction failure criterion and the criterion's activation point obtained experimentally, as well as the Mohr-Coulomb straight line for shear failure

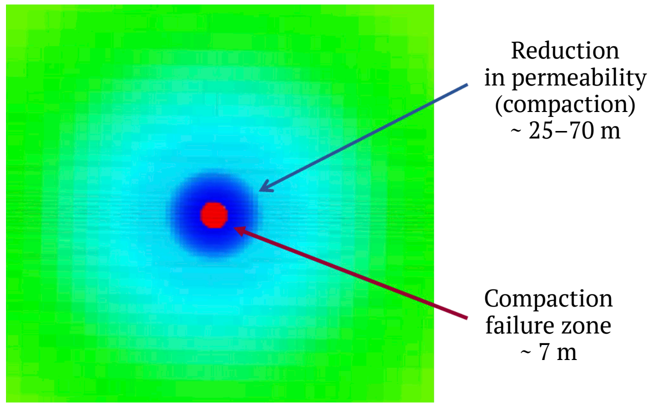

Fig. 10. Permeability multiplier distribution based on the computations using a coupled model in tNavigator (hydrodynamics + geomechanics) with a script to account for compaction and compaction failure through effective stress analysis. The colors are explained in the text

The parameters of the reservoir and fluids were set in accordance with the characteristics of the accepted Tournaisian stage reservoir. The flow was assumed single-phase (oil). The boundary conditions at the outer boundaries of the model corresponded to no-flow condition and constant vertical and lateral rock stresses. The oil flow rate corresponding to the maximum possible depression for a given reservoir was set at the well.

The central fragment of the permeability multiplier distribution obtained as a result of the modeling is shown in Fig. 10. The area with the initial permeability value (multiplier 1) is marked in green. The blue shades indicate the region of compaction. The average decrease in permeability in the blue zone (the radius of approx. 70 m) is ~5%, and that in the dark blue zone (the radius of approx. 25 m) is ~8%.

The red area shows the failure zone (the radius of approx. 7 m), where permeability increased fourfold as a result of the compaction failure criterion being triggered.

Thus, for the conditions of the Tournaisian formation, through the mechanism of compaction failure, which allows explaining the results of the CGT laboratory experiments, the origination of a well vicinity zone of increased permeability with a radius of about 7 m is predicted. This value is at least 20 times greater than the radius of the similar zone predicted based on the shear failure mechanism (see Fig. 7).

Findings discussion and practical application

Let us compare the evaluated size of the loosening zone (~7 m) obtained through simulation of CGT application with the actual results of applying this method in a well exploiting the Tournaisian formation [6].

Let us determine the calculated increase in the well productivity index. The magnitude of the skin factor formed as a result of CGT application can be approximately estimated using the well-known formula for a two-zone axisymmetric reservoir:

$$S = \left(\frac{k}{k_s} - 1\right) \ln \frac{r_s}{r_w} \approx -3.19, \tag{2}$$

where r_s is the radius of the near zone with permeability k_s, r_s = 7 m; r_w is the radius of the well, r_w = 0.1 m; k/k_s is the ratio of permeability in the remote zone (unchanged formation) to permeability in the near zone (fractured zone), k/k_s = 1/4. The effect of compaction outside the fractured zone can be neglected due to its minor impact on the average permeability of the remote zone (the first few percents).

The skin factor value obtained allows estimating the increase in the *PI* (productivity index) relative to its initial value PI_0. For a perfect well and a nominal external boundary radius r_e = 500 m, using Dupuis' formula, one obtains:

$$\frac{PI}{PI_0} = \frac{\ln \frac{r_e}{r_w}}{\ln \frac{r_e}{r_w} + S} \approx 1.6. \tag{3}$$

Thus, modeling the CGT application effect based on the compaction failure mechanism provides an approximate estimate of the increase in well productivity index by a factor of 1.6. This estimate is consistent with the actual productivity increase of 1.45–1.5 times obtained during field tests in the Tournaisian reservoir [6]. It should be noted that, since the mechanism of compaction failure is determined mainly by the increase in average effective normal stresses due to a decrease in pore pressure, a different type of well completion (cased well with perforation) does not significantly affect the assessment of the effect.

The value of 1.6 obtained using the compaction failure criterion also fully corresponds to the results of the hydrodynamic calculations performed in [6], where the increase in permeability from the CGT application was set depending on the pore pressure, without analyzing geomechanical effects.

At the same time, it is clear from formulas (2)–(3) that the sizes of the loosening region obtained by the shear failure mechanism (see Figs. 7 and 8) cannot explain the actual increase in the productivity index in the experimental application of the method described in [6].

Conclusions

The analysis presented in this paper allows drawing a number of conclusions regarding the probable geomechanical mechanism of formation of a well vicinity zone of increased permeability when creating a deep depression using the CGT method and the related DUR method.

1. Laboratory experiments on the TILTS installation simulate loading conditions corresponding to the stress state on the wall of an open-hole wellbore or a perforation channel. It is assumed that the well vicinity zone of increased permeability arises due to shear failure as tangential stresses increase. Estimates of the extent of this effect do not exceed 30–40 cm from the wellbore wall, at least for the typical parameters and reservoir conditions of carbonate reservoirs in the Ural-Volga region.

2. The effect of permeability increase when creating a critical depression in laboratory experiments with constant pseudo-triaxial loading and changes in pore pressure can be explained by the mechanism of compaction failure due to an increase in effective normal stresses.

3. According to the results of coupled hydrogeomechanical modeling for typical conditions of the Tournaisian reservoirs in the Republic of Tatarstan, taking into account the effects of inelastic compaction and compaction failure through the analysis of effective stresses, a well vicinity microfracturing zone (increased permeability zone) reaches ~7 m. This is at least 20 times greater than the area predicted based on the shear failure mechanism.

4. Taking into account the permeability increase according to the laboratory data, the estimated size of the fractured zone based on the compaction failure mechanism is consistent with the productivity increase observed in the field test on the well.

Thus, the results of this study improve understanding of the geomechanical mechanism of increasing permeability in a well vicinity zone due to applying the CGT method and other methods based on the creation of deep depression. This will enable more accurate predictions of the expected effect based on laboratory studies and modeling, and also improving the effectiveness of the methods for increasing well productivity and oil recovery from carbonate reservoirs.

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Assessment of the elemental status of the young population in Solnechny, Khabarovsk krai, as part of mining environmental monitoring

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Abstract

Prolonged operation of the mining and processing plant in Solnechny District, Khabarovsk Krai, led to the formation of a technogenic mining system. Biogeochemical zones with elevated concentrations of chemical compounds, including heavy metals and arsenic, developed in the area. Monitoring revealed that soil samples taken at varying distances from the second tailings dump of the Solnechny Mining and Processing Plant (MPP), including within the settlement of Solnechny, contained heavy metals – Cu, Zn, Pb, and Hg – at levels exceeding the maximum permissible concentrations (MPCs) by factors of 1.4 to 12.36. Arsenic levels reached 571 times the MPC. Surface water bodies showed excess concentrations of Cr, Cu, Fe, and Zn, ranging from 2 to 110 times the MPC. No arsenic excess was found in water samples. The elemental status of a developing child reflects the health of the surrounding ecosystem. Hair samples from children under 14 years of age residing in the settlement of Solnechny were analyzed. Girls showed elevated levels of Hg, Cr, Pb, and Cu, along with reduced concentrations of the essential element Zn. Boys showed increased levels of Hg, Fe, Cr, Zn, and Cu. To reduce the spread of pollutants from tailings dumps, including those of the Solnechny plant, technical solutions have been proposed.

Keywords

mining, beneficiation, tin ore, waste, tailings dump, environment, technogenic pollution, soil and subsoil, water, sample, heavy metals, chromium (Cr), iron (Fe), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd), tin (Sn), mercury (Hg), lead (Pb), spectrometry, spectrophotometer, child population, elemental status, land reclamation, waste containment, Khabarovsk Krai, settlement of Solnechny

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ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Исследование элементного статуса молодого населения посёлка Солнечный Хабаровского края в рамках горно-экологического мониторинга

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Аннотация

В Солнечном районе Хабаровского края в результате длительной работы горно-обогатительного комбината сформировалась горнопромышленная техногенная система. Здесь образовались биогеохимические зоны с высоким содержанием соединений химических элементов, в том числе тяжёлых металлов и мышьяка. Установлено, что в мониторинговых точках, расположенных на различном расстоянии от второго хвостохранилища Солнечного ГОКа, в том числе на территории посёлка Солнечный (Хабаровский край), концентрации определяемых тяжёлых металлов в почвах превышают нормативные значения по Cu, Zn, Pb и Hg от 1,4 до 12,36 ПДК, содержание As составило 571 ПДК. В водных объектах отмечается превышение по Cr, Cu, Fe и Zn от 2 до 110 ПДК. Превышение содержания As в исследуемых пробах воды не обнаружено. Элементный статус в растущем организме человека является индикаторным показателем состояния экосистем, в связи с чем была проведена оценка элементного состава волос жителей посёлка Солнечный в возрасте до 14 лет. Показано, что особенностью элементного статуса для девочек в исследуемой группе являются высокие показатели содержания тяжёлых металлов Hg, Cr, Pb, Cu, а также пониженное содержание важного эссенциального элемента Zn. Для мальчиков отмечаются превышения по концентрациям Hg, Fe, Cr, Zn и Cu. В связи с этим предложены технические решения с целью снижения распространения загрязняющих веществ от хвостохранилищ, в том числе Солнечного ГОКа.

Ключевые слова
горное дело, обогащение, оловорудное сырье, отходы, хвостохранилище, окружающая среда, техногенное загрязнение, почва, грунт, вода, проба, тяжелые металлы, хром (Cr), железо (Fe), медь (Cu), цинк (Zn), мышьяк (As), кадмий (Cd), олово (Sn), ртуть (Hg), свинец (Pb), спектрометрия, спектрофотометр, детское население, элементный статус, рекультивация, консервация, Хабаровский край, поселок Солнечный

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Introduction

Since the early 1970s, intensive mineral resource development by mining enterprises in the Far Eastern Federal District has led to significant technogenic pollution of all environmental components [1, 2]. In the vicinity of mining operations, which have been affected to varying degrees by technogenic impact, biogeochemical zones have developed with elevated concentrations of chemical element compounds, including heavy metals and arsenic.

One such industry-forming enterprise of the past century was the Solnechny Mining and Processing Plant (MPP) in Khabarovsk Krai. During the economic transition of the 1990s, the plant failed to adapt and was declared bankrupt [3, 4].

The first tailings dump of the Solnechny Concentration Plant (SCP) is located about 100 meters from the settlement of Gorny, in the Silinka River valley, near its confluence with the Amut River. Tailings were deposited there from 1963 to 1997. The accumulated waste layer reaches a thickness of 20–25 meters. The dump covers an area of 20 hectares and contains 10.6 million tons of tailings. It is currently used for reprocessing by the SCP. The second tailings dump of the SCP lies across from the mining settlement of Solnechny. It covers 40.3 hectares and contains 24.09 million tons of accumulated waste. The former assets of the Solnechny MPP – including the Festiválnoye and Pereválnoye deposits – are currently managed by the Tin Ore Company, which has resumed tin and tungsten mining and continues to fill a third tailings dump. Meanwhile, GeoPromInvest LLC is actively reprocessing waste from the second dump and has constructed a new tailings storage facility behind it. Previous studies have shown that tailings dumps, containing vast quantities of waste, have a harmful impact on the environment and pose a serious threat to human health, biodiversity, and water bodies [5–7] due to the accumulation of toxic heavy metals in living organisms.

Hair is recognized as an informative and reliable biological material that reflects the environmental conditions as well as the presence of diseases and health deviations in the human body [8]. The chemical composition of hair reflects both the internal physiological state and the impact of various exogenous factors [9]. Due to the slow growth rate of hair, its analysis provides an average concentration of macro- and microelements over several months. According to A.Ye. Pobilat et al. [10, 11], monitoring trace element content in hair can address a wide range of scientific challenges, including the indication of environmental pollution and the assessment of harmful factors affecting human health.

The aim of this study is to assess the distribution of Pb, Hg, Cu, Cr, Fe, Zn, Cd, Sn, and As compounds using the elemental status of the child population in a mining settlement. Based on this aim, the following objectives were defined: 1. To analyze and systematize literature data on technogenic pollution of the ecosphere caused by waste from tin ore processing. 2. To assess the distribution of chemical elements in environmental components in the impact zone of the Solnechny tailings dump. 3. To investigate the

Fig. 1. Surface of the second tailings dump of the Solnechny Concentration Plant

elemental status of the population under the age of 14 in the settlement of Solnechny, Khabarovsk Krai, as part of mining-related environmental monitoring.
4. To develop proposals aimed at reducing the spread of technogenic pollution within the ecosystem.

The study focuses on technogenically impacted mining areas resulting from the operations of the Solnechny MPP, as well as the elemental composition of hair in children and adolescents residing in the mining settlement.

The second tailings dump of the Solnechny MPP is situated at elevations ranging from 286 to 303 meters, approximately 6.5 kilometers southwest of the confluence of the Kholdomi and Silinka rivers, directly opposite the second processing facility. The mining settlement of Solnechny lies on the opposite side of the valley, at a higher elevation (Fig. 1).

Methods

To characterize the technogenic conditions within the impact zone of the tailings dump, soil and ground samples were collected to determine the total content of heavy metals and arsenic in the vicinity of the second tailings dump of the Solnechny MPP. Sampling was conducted in accordance with GOST 17.4.3.01–2017[1].

Water samples were also collected from the impact zone of the second tailings dump, at various points within the Silinka River basin[2]. Element concentrations were determined using atomic absorption spectrometry, employing a Thermo Solaar M Series atomic absorption spectrophotometer and an Agilent 720 ICP-OES spectrometer.

Fig. 2 presents the map of soil and water sampling points within the impact zone of the second tailings dump.

Hair samples were collected from children and adolescents aged 3 to 14 (both boys and girls) residing in the settlement of Solnechny. The elemental status was determined for 45 children, including 20 boys and 25 girls under the age of 14. The mean age was 6.68 ± 2 years. Among them, boys aged 7 or younger accounted for 26.7%, girls of the same age group for 33.3%, boys aged 8–14 for 22.1%, and girls aged 8–14 for 17.9%. The sample included only permanent residents of the settlement. All hair samples were collected and prepared according to standard procedures for trace element determination in biological substrates[3], and were analyzed at the accredited Information and Analytical Center of the Institute of Tectonics and Geophysics, Far Eastern Branch of the Russian Academy of Sciences (Khabarovsk). The concentrations of the following elements were measured: Cr, Fe, Cu, Zn, As, Cd, Sn, Hg, and Pb. The data were processed using Microsoft Office software tools.

[1] GOST 17.4.3.01–2017. Interstate Standard. Nature Protection. Soils. General Requirements for Sampling.

[2] R 52.24.353–2012. Sampling of Surface Land Waters and Treated Wastewater.

[3] Guidelines for the Determination of Trace Elements in Diagnostic Biosubstrates by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Methodological Recommendations. Moscow: Federal Center for State Sanitary and Epidemiological Supervision, Ministry of Health of Russia; 2003. p. 22.

Results and discussion

Between 1969 and 2001, approximately 24.1 million tons of waste were deposited in the second tailings dump of the Solnechny MPP. As of 1990, the site contained the following amounts of recoverable metals: 46,392 tons of tin (average grade: 0.183%), 707,000 tons of copper (0.28%), 39,356 tons of zinc (0.156%), 47,853 tons of lead (0.188%), 6,742 tons of tungsten (0.015%), 5,874 tons of bismuth (0.013%), and 339 tons of silver (116 g/t), along with various rare elements and gold. According to previous assessments, the dewatered tailings are classified as highly hazardous in terms of toxicity[4] [2]. No land reclamation activities have been undertaken in the disturbed area, despite the requirements set forth by the Subsoil Law of the Russian Federation[5]. Based on our calculations, which considered the sampling depth (up to 20 cm), contamination level, area of polluted land, and applicable assessment coefficients, the total estimated environmental damage to the soil amounts to 19,306 rubles per square meter [13].

At monitoring points located at varying distances from the second tailings dump, the concentrations of heavy metals and arsenic in the 10–20 cm soil layer substantially exceeded regulatory thresholds (Table 1).

[4] Order of the Ministry of Natural Resources of Russia No. 238 of 08.07.2010 (as amended on 18.11.2021) "On Approval of the Methodology for Calculating the Amount of Damage Caused to Soils as an Environmental Protection Object." Re-|gistered with the Ministry of Justice of Russia on 07.09.2010, No. 18364. URL: https://docs.cntd.ru/document/902227668

[5] On Subsoil. Law of the Russian Federation No. 2395-1 of 21.02.1992. Latest revision: 2024. Moscow: CENTRMAG; 2024. 136 p.

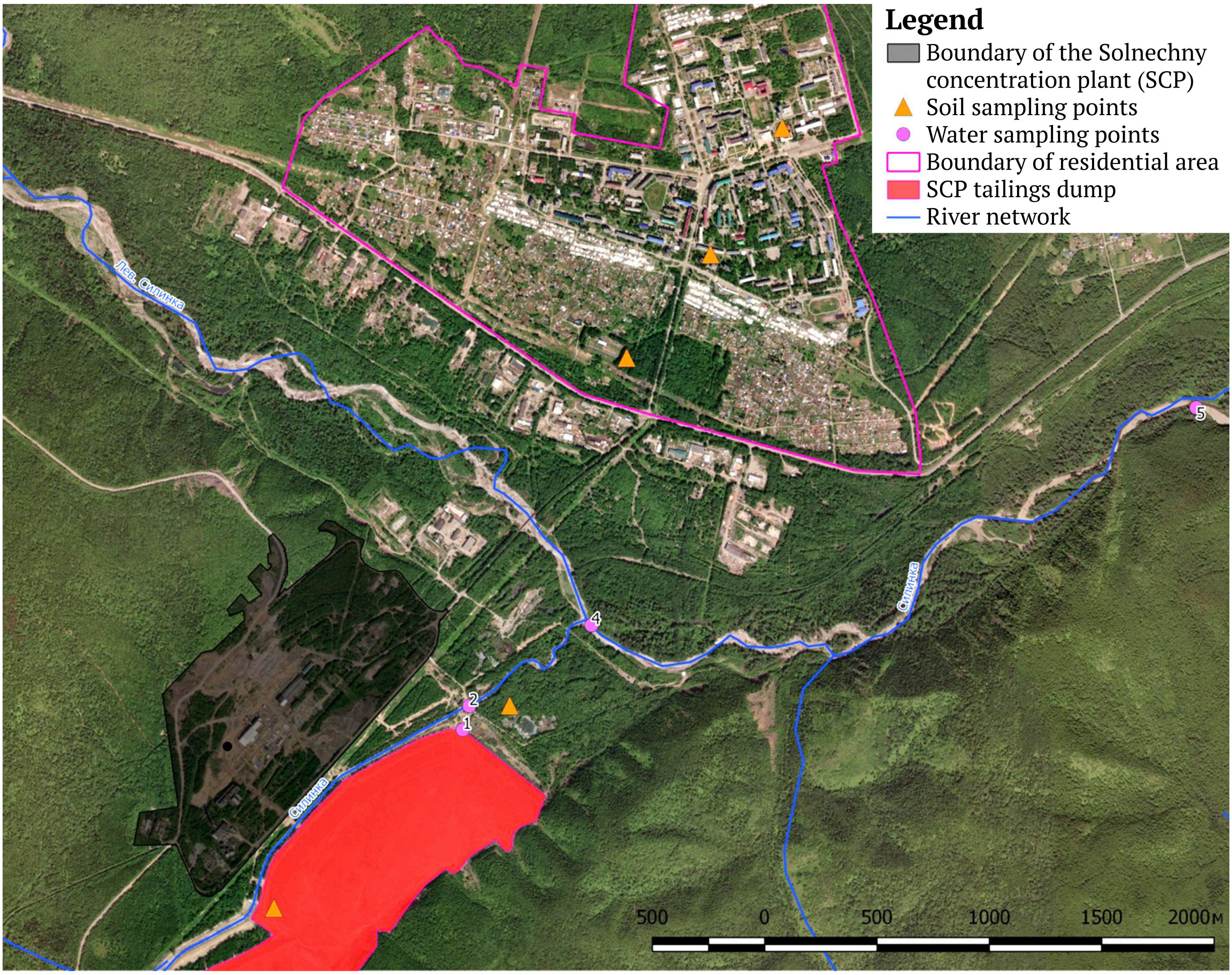

Fig. 2. Map of sampling points for soil and water in the vicinity of the second tailings dump of the Solnechny MPP

An unfavorable environmental situation was identified within the residential area located in close proximity to the site (1.5–3.0 km), where average concentrations exceeded regulatory limits by the following factors: Cu – 12.36 MPC, Zn – 2.73 MPC, Pb – 9.71 MPC, Hg – 1.40 MPC, and As – 569.09 MPC.

Water samples from both technogenic (T1) and natural sources (T2–T5) were collected (see Fig. 2) and analyzed for concentrations of the following elements: As, Cd, Co, Cr, Cu, Fe, Mn, Pb, Sn, and Zn. The analytical results are summarized in Table 2.

In natural waters downstream of the Silinka River, beyond the second tailings dump of the Solnechny MPP, concentrations of several elements exceeded the maximum allowable concentrations (MACs) for surface waters designated for fishery use: chromium exceeded MACs by 4 to 11.5 times, copper by 110 times, iron by 2 to 24.2 times, and zinc by 31 to 46 times. No exceedance of arsenic levels was detected in the water samples.

Thus, the residents of the Solnechny mining settlement live in an environment where contaminant levels in soil and soil substrate and water bodies exceed regulatory standards.

To identify regional geochemical characteristics of the natural environment, element ratios were calculated by comparing the concentrations of chemical elements in hair samples from the local child population with the average concentrations of these elements in hair by sex (see Fig. 3).

Table 1

Concentrations of selected heavy metals and arsenic in soil (10–20 cm depth) at various distances from the second tailings dump of the Solnechny MPP (mg/kg)

Elements	Zn	Cu	Pb	Hg	As
At the tailings dump	140.00	620.18	713.22	5.78	7792.60
0.3 km from tailings dump	168.30	749.79	282.74	2.29	2306.47
1.5 km from tailings dump	71.68	319.76	642.22	8.3	3254.48
2.5 km from tailings dump	264.16	643.56	195.37	0.3	105.12
3 km from tailings dump	119.62	260.91	36.31	0.22	54.95
Regulatory limit (MPC)	55. 5	33.0	30.0	2.1	2.0
Background level	60.46	38.78	81.5	0.58	42.49

Table 2

Concentrations of selected heavy metals and arsenic in water samples from the Silinka River basin at varying distances from the second tailings facility of the Solnechny MPP, mg/L

Sampling points	P. 1	P. 2	P. 3	P. 4	P. 5	MAC*, mg/L
As (total)	0.0180 ± 0.0076	0.0240 ± 0.0101	0.0090 ± 0.0038	0.0050 ± 0.0021	0.0050 ± 0.0021	0.05
Cd	0.20	< 0.01	< 0.01	< 0.01	< 0.01	0.005
Co	3.78	< 0.05	< 0.05	< 0.05	< 0.05	0.01
Cr (VI)	0.18	0.09	0.19	0.23	0.20	0.02
Cu	166.30	0.11	< 0.03	< 0.03	< 0.03	0.001
Fe (III)	292.90	2.42	0.38	0.20	0.20	0.1 (general)
Mn	104.79	2.22	0.42	0.28	0.37	0.01
Pb	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.006
Sn	0.0390 ± 0.0133	< 0.005	0.0090 ± 0.0031	0.0060 ± 0.0020	0.0110 ± 0.0037	0.112
Zn	51.09	0.46	0.37	0.35	0.31	0.01

* Order of the Ministry of Agriculture of Russia No. 552 of 13.12.2016 (as amended on 13.06.2024) "On Approval of Water Quality Standards for Water Bodies of Fisheries Importance, Including Maximum Permissible Concentration Limits for Harmful Substances in the Waters of Such Water Bodies".

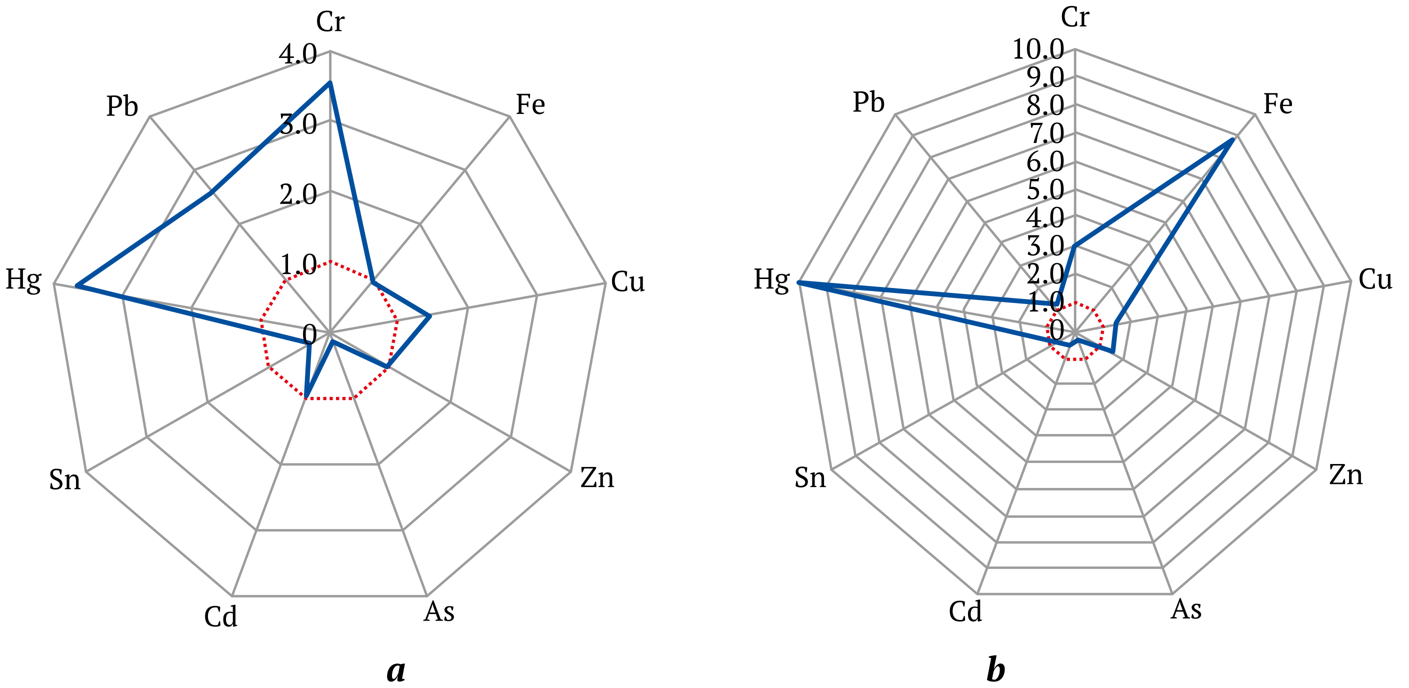

Fig. 3. Elemental composition of hair in the young population of Solnechny compared to average levels across Russia: *a* – girls; *b* – boys

The data obtained allowed us to identify the specific geochemical profile of hair samples from children and adolescents residing in the Solnechny mining settlement:

For girls: $Hg_{3.66} > Cr_{3.52} > Pb_{2.61} > Cu_{1.43} > Cd_{0.95} = Fe_{0.95} > Zn_{0.94} > Sn_{0.32} > As_{0.13}$;

For boys: $Hg_{9.81} > Fe_{8.75} > Cr_{2.95} > Zn_{1.54} > Cu_{1.45} > Pb_{1.06} > Sn_{0.87} > Cd_{0.57} > As_{0.33}$.

The elemental status of children in this study group is characterized by elevated levels of toxic metals such as Pb, Hg, and Cr. Notably, the Zn content in girls' hair was found to be close to the minimum reference range (124–320 μg/g).

To reduce the dissemination of pollutants in environmental components, the implementation of environmental management strategies using innovative technological solutions is recommended. Over the past 10 years, researchers at Pacific State University have proposed conducting reclamation or containment of tailings using substrates made from shredded spruce, larch, and birch bark, supplemented with a nitrogen-based activator and *Trichoderma* fungi[6]. These substrates have since been modified with additional components. In 2015, a Russian patent was granted for a tailings reclamation mixture incorporating phototrophic bacteria[7]. Other effective mixtures included additives such as biochar[8] and spent oyster mushroom mycelium[9]. The use of organic substrates derived from industrial by-products significantly reduces the cost associated with acquiring fertile soil, which is typically required for reclamation. In recent years, over one million tons of forestry and wood-processing waste have accumulated in the region. Therefore, reclamation or conservation of tailings surfaces using these materials is particularly relevant for Khabarovsk Krai. Further development and implementation of this technology are essential to reduce reclamation costs and prevent erosion processes.

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Conclusion

The results of this study, supported by a review of previous research, indicate that the second tailings dump of the Solnechny MPP is a significant source of technogenic pollution in the surrounding environment. Concentrations of heavy metals in soil samples exceeded maximum permissible concentrations (MPCs) as follows: Cu by 12.36 times, Zn by 2.73 times, Pb by 9.71 times, and Hg by 1.4 times. The average arsenic concentration in soil exceeded the MPC by a factor of 569.09. In surface water bodies, the highest exceedances were recorded for Cr, Cu, Fe, and Zn. Arsenic concentrations in water samples did not exceed regulatory limits.

An assessment of the elemental status of local residents under the age of 14, based on hair analysis by sex, revealed elevated concentrations of Hg, Pb, and Cr. A distinctive feature among girls was a reduced level of the essential element Zn, while boys exhibited elevated levels of Fe.

To mitigate the spread of pollutants from tailings dump, including the one operated by the Solnechny MPP, the study proposes the use of forest industry waste as an alternative substrate for reclamation, providing a cost-effective and sustainable solution.

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Reducing mine water contamination at the local drainage facility of a kimberlite mine

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Abstract
The clarification of contaminated mine water by means of sedimentation in designated water collectors is accompanied by a gradual decrease in their effective volume due to siltation. The operation of pumping units within the drainage facility under conditions of silted water collectors at underground mining site adversely affects both their service life and energy efficiency. To prevent severe degradation in pump operating conditions, silted underground water collectors are regularly taken out of operation for cleaning, using self-propelled equipment. As Russian kimberlite mines reach their design capacity, the interval between cleaning cycles of the local drainage system's water collectors has significantly decreased. Currently, at kimberlite mines, the cleaning of silted water collectors is routinely carried out using all available load–haul–dump (LHD) machines operated by the mine's Mechanical and Power Service. The expansion of the LHD fleet is constrained by the high cost of these machines. In this context, reducing the intensity of mine water contamination entering the water collectors of the local drainage system has become a pressing and practically significant objective. Mathematical modeling has shown that a substantial reduction in mine water contamination within the local drainage system of a kimberlite mine can be achieved by eliminating sludge formation caused by ore spillage during transfer from the feeder to the main level conveyor belt. To eliminate this source of sludge formation, a mechanized system for collecting ore spillage has been developed, with a specially designed collecting and loading unit as its key component.

Keywords
kimberlite mine, mine water, local drainage facility, water collector, water clarification, siltation, sludge formation, ore spillage, energy efficiency, mathematical modeling, technological solution

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ГОРНЫЕ МАШИНЫ, ТРАНСПОРТ И МАШИНОСТРОЕНИЕ

Научная статья

Снижение загрязнения шахтных вод в системе участкового водоотлива кимберлитового рудника

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Аннотация
Осветление загрязненных шахтных вод путем отстаивания в специальных водосборных емкостях сопровождается постепенным снижением их рабочего объема из-за заиления. Эксплуатация насосных агрегатов комплекса водоотлива в условиях заиленных водосборников подземного горного предприятия негативно отражается на их долговечности и энергоэффективности. Для недопущения сильного ухудшения условий эксплуатации насосного оборудования заиленные водосборные емкости регулярно выводятся из работы в целях чистки от осевших продуктов заиления с помощью самоходной техники. С выходом кимберлитовых рудников РФ на проектную мощность периодичность работы водосборников участкового водоотлива между чистками заметно снижается. В настоящее время на кимберлитовых рудниках чистка заиленных водосборников систематически происходит с задействованием всех имеющихся погрузочно-доставочных машин механоэнергетической службы. Уве-

личение рабочего парка указанных машин сдерживается их дороговизной. В связи с этим снижение интенсивности загрязнения шахтных вод, поступающих в водосборники участкового водоотлива, является актуальной задачей и представляет практический интерес. По результатам математического моделирования установлено, что добиться существенного снижения интенсивности загрязнения шахтных вод в системе участкового водоотлива кимберлитового рудника можно путем ликвидации шламообразований, возникающих в результате просыпа руды при перегружении с питателя на ленту конвейера основного горизонта. Для устранения указанного источника шламообразования был разработан механизированный комплекс по сбору просыпанной горной массы, где ключевым элементом является заборно-погрузочное устройство.

Ключевые слова
кимберлитовый рудник, шахтные воды, участковый водоотлив, водосборник, осветление, заиление, шламообразование, просып руды, энергоэффективность, математическое моделирование, технологическое решение

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Introduction

At present, a significant share of solid mineral deposits worldwide is being developed using underground mining methods. In the foreseeable future, the number of mining operations transitioning to underground extraction of mineral resources is expected to grow steadily.

Underground mining of solid minerals is typically accompanied by the inflow of mine water into underground workings. Ultimately, this water is pumped to the surface by the drainage facility's pumping equipment [1, 2].

One of the key characteristics of mine water is the presence of insoluble mechanical impurities, which cause abrasive wear on metal components when they come into contact with pump elements [3–5].

At underground mining sites, mine water is clarified by sedimentation in designated water collectors and settling tanks [6].

Sedimentation of contaminated water gradually reduces the storage capacity of these collectors due to siltation. A decrease in their effective volume inevitably lowers the efficiency of water clarification and adversely affects both the service life and energy efficiency of the drainage system's pumps [7–10]. In critical cases, this may even lead to suspension of mining operations due to flooding risks. The main cause of such scenarios is the accelerated hydroabrasive wear of pump flow-path components [11, 12]. To prevent this, silted water collectors are regularly taken out of service for removal of settled sludge, using self-propelled equipment operated by the mine's Mechanical and Power service (MPS), primarily load–haul–dump (LHD) machines [13, 14].

Operational experience at Russian kimberlite mines indicates that, as these mines reach their design capacity, the interval between cleanings of water collectors within the local drainage facility is significantly reduced and may, in some cases, be as short as three days [15]. This situation clearly underscores the need to expand the fleet of LHD machines operated by MPS, as the collection and hauling of settled sludge often require the full set of available equipment. The failure of even a single LHD unit can severely disrupt the cleaning process. However, the procurement of additional LHDs for the MPS is currently under review due to their high cost. Moreover, the reduced operating interval between cleanings increases the operational expenses associated with maintaining the existing MPS fleet [16].

A decrease in the rate of siltation in the water collectors of the local drainage facility – under conditions where the kimberlite mine is operating at design capacity – can be achieved by limiting the entry of sludge-forming materials.

Notably, no prior studies have been conducted to identify and quantify the contribution of individual sludge formation sources to mine water contamination at kimberlite mines.

The aim of this study is to determine the primary sources of sludge formation that accelerate siltation in the water collectors of the local drainage facility at kimberlite mines, and to propose a technological solution to mitigate their impact.

To achieve the stated objective, the following key **tasks** must be addressed:

– to develop mathematical models of sludge formation within the local drainage facility, taking in;

– to assess the relative contribution of individual sludge formation sources to mine water contamination within the local drainage facility at kimberlite mines, and to identify the most significant among them;

– to develop and substantiate a technological solution aimed at minimizing the impact of sludge formation sources on mine water contamination within the local drainage facility at kimberlite mines.

The primary research methods employed in this study were visual observation and mathematical modelling.

Study site description

Extensive observations of mine water contamination processes at the water collectors of the local drainage facilities at kimberlite mines operated by ALROSA indicate that the origins of sludge formation are highly diverse.

At Russian kimberlite mines employing the conventional (layered) mining method, typical sources of sludge formation include secondary by-products of backfilling operations. In particular, this refers to slurry generated during the flushing of clogged pipeline segments with water, and, less frequently, to leakage of backfilling mixture from damaged sections of the isolation wall in the backfilled workings. Occasional failures of the isolation wall are typically attributed to violations of standard backfilling procedures [17].

At water-bearing kimberlite mines that implement backfilling of the mined-out voids, another common source of sludge formation is sludge composed of broken rock mass particles excavated by a tunnelling roadheader during production activities.

A distinct feature of sludge formation at the Udachny kimberlite mine, which operates using the block caving method, is the systematic spillage of sludge materials from the skip during hoisting to the surface. This issue is caused by the low structural reliability of the bottom discharge gate responsible for emptying the skip [18].

Regardless of the selected underground mining method, conventional sources of sludge formation at kimberlite mines include: pulp containing kimberlite ore spilled during transfer from the feeder to the belt conveyor; sludge discharged from the bucket of an MPS-operated LHD during the transportation of settled sludge; and sludge generated during high-pressure washing of the working strand of the conveyor belt, performed to eliminate or mitigate damage caused by a rupture [19, 20]. Conveyor belt ruptures typically result from wear caused by shaft construction debris or from overloading.

Mathematical models of sludge formation within the local drainage facility at a kimberlite mine

According to visual observations of mine water contamination processes within the local drainage facility of a kimberlite mine, the total daily volume of sludge formation during diamond-bearing ore extraction can be estimated for two mining methods: cut-and-fill mining with backfilling of mined-out voids – V_{cf}, m^3, and block caving – V_{bc}, m^3, as follows:

$$V_{cf} = V_{flush} + V_{leak} + V_{exc} + V_{spill} + V_{wash} + V_{LHD}; \quad (1)$$

$$V_{bc} = V_{spill} + V_{wash} + V_{skip} + V_{LHD}, \quad (2)$$

where V_{flush} – volume of sludge formation resulting from the flushing of clogged segments of the backfilling pipeline, m^3; V_{leak} – volume of sludge formation caused by leakage of backfilling mixture from a damaged section of the isolation wall, m^3; V_{exc} – volume of sludge formation, in which the solid phase consists of broken rock mass excavated by a tunnelling roadheader during production operations, m^3; V_{spill} – volume of sludge formation whose solid phase consists of kimberlite ore spilled during transfer from the feeder to the conveyor belt, m^3; V_{wash} – volume of sludge formation resulting from washing of the working strand of the conveyor belt, m^3; V_{skip} – volume of sludge formation resulting from the spillage of settled solids from the skip, m^3; V_{LHD} – volume of sludge formation resulting from the spillage of settled solids (sludge) from the bucket of an MPS-operated LHD machine, m^3.

The value of V_{flush} is defined as:

$$V_{flush} = k_{backfill} n_{flush} S_{pipe} k_v, \quad (3)$$

where $k_{backfill}$ is the coefficient accounting for the time required for stope mining t_1, preparation t_2, and filling with backfilling mixture t_3; n_{flush} is the number of times the backfilling pipeline is flushed during the filling of a single mined-out stope with backfilling mixture; S_{pipe} is the cross-sectional area of the backfilling pipeline, m^2; l_{pipe} is the length of the backfilling pipeline section being flushed, m; k_v is the coefficient accounting for the total volume of clogged pipeline segments.

The coefficient $k_{backfill}$ is calculated as:

$$k_{backfill} = \frac{1}{t_1 + t_2 + t_3}. \quad (4)$$

According to observations of backfilling operations at the Mir and Internatsionalny mines, the residual coefficient k_{resid} is taken as 0.2.

The value of V_{leak} is determined as follows:

$$V_{leak} = k_0 k_{backfill} \frac{86400}{t_{flow1}} V_l, \quad (5)$$

where k_0 is the coefficient accounting for the risk of drainage of the backfilling mixture from the isolation wall of the backfilled working; t_{flow1} is the time required for the water flow to carry the volume of backfilling mixture leaking per second from the damage V_l, s.

The time t_{flow1} is calculated as:

$$t_{flow1} = \frac{b_w h_w l_{fow1}}{q_{prod}}, \quad (6)$$

where b_w and h_w are the width and depth of the water flow entraining the backfilling mixture into the local drainage water collector, m; l_{flow1} is the horizontal distance from the leakage point of the backfilling mixture to the water collector, m; q_{prod} is the water inflow at the production level, m³/s.

The volume V_l is equal to:

$$V_l = \frac{V_{layer}}{t_l}, \quad (7)$$

where V_{layer} is the volume of the backfilling mixture layer, m³; t_l is the time during which the mixture layer leaks from the isolation wall, s.

The volume V_{layer} is given by:

$$V_{layer} = b_k l_k h_{layer}, \quad (8)$$

where b_k and l_k are the width and length of the mined-out stope, m; h_{layer} is the height of the backfilling mixture layer in the mined-out stope, m.

The time t_l is calculated as:

$$t_l = \frac{V_{layer}}{86400 S_{crack} h_{layer}} \cdot \sqrt{\frac{2h_{layer}}{g}}, \quad (9)$$

where S_{crack} is the area of the crack in the isolation wall of the backfilled chamber through which the backfilling mixture leaks, m².

The volume V_{exc} is calculated as follows:

$$V_{exc} = k_{sl} k_{trans} \frac{A_0}{t_{flow2} \rho_r}, \quad (10)$$

where k_{sl} is the coefficient accounting for the ratio of solid to liquid phases in the sludge; k_{trans} is the coefficient accounting for the proportion of excavated rock mass transferred from the production level to the main level of the kimberlite mine; t_{flow2} is the time it takes for the excavated rock mass to be transported by water flow per second, s; A_0 is the mine's output, kg/day; ρ_r is the average density of the excavated rock mass, kg/m³.

The time t_{flow2} is determined as:

$$t_{flow2} = \frac{b_w h_w l_{flow2}}{q_{prod}}, \quad (11)$$

where l_{flow2} is the average horizontal distance between the site of broken rock accumulation and the water collector of the local drainage system, m.

The volume V_{spill} is calculated as:

$$V_{spill} = k_{sl} \cdot \frac{10 A_0}{t_{flow3} \rho_r} \cdot k_{loss}, \quad (12)$$

where t_{flow3} is the time it takes for kimberlite ore spilled during transfer from the feeder to the conveyor to be transported by water flow, s; k_{loss} is the coefficient accounting for the quantity of spilled ore.

The time t_{flow3} is calculated as:

$$t_{flow3} = \frac{b_w h_w l_{flow3}}{q_{main}}, \quad (13)$$

where l_{flow3} is the average horizontal distance from the location of kimberlite ore spillage to the local drainage water collector, m; q_{main} is the water inflow at the main production level, m³/s.

The coefficient k_{loss} is calculated as:

$$k_{loss} = \frac{86400 m_{spill}}{A_0}, \quad (14)$$

where m_{spill} is the mass of spilled rock material per second, kg.

According to field studies conducted at the Udachny and Mir mines, $m_{spill} \approx 0.5$ kg at $A_0 = 11{,}000$ t/day, $m_{spill} \approx 0.1$ kg at $A_0 = 2{,}700$ t/day.

The volume V_{wash} is determined as:

$$V_{wash} = k_{failure} k_{sl} V_{conv}, \quad (15)$$

where $k_{failure}$ is the coefficient accounting for the conveyor belt service life; V_{conv} is the conveyor belt capacity, m³.

The coefficient $k_{failure}$ is calculated as:

$$k_{failure} = \frac{24}{t_{belt}}, \quad (16)$$

where t_{belt} is the average conveyor belt service life, h.

The volume V_{conv} is defined as:

$$V_{conv} = b_{conv} l_{conv} H_{layer}, \quad (17)$$

where b_{conv} and l_{conv} are the width and length of the conveyor belt, m, respectively; H_{layer} is the height of the transported rock mass layer, m.

The volume V_{skip} is calculated as follows:

$$V_{skip} = k_{spill,skip} k_{fill,skip} n_{skip} V_{vessel}, \quad (18)$$

where $k_{spill,skip}$ is the coefficient accounting for the spillage intensity of the skip contents during the hoisting of sludge to the surface; $k_{fill,skip}$ is the coefficient accounting for the skip filling with sludge; n_{skip} is the number of skips hoisted to the surface per day; V_{vessel} is the capacity of the skip, m³.

The coefficient $k_{spill,skip}$ is calculated as follows:

$$k_{spill,skip} = \frac{V_{spill,skip}}{k_{fill,skip} V_{vessel}}, \quad (19)$$

where $V_{spill,skip}$ is the volume of sludge spilled from the skip during a single hoisting cycle, m³.

According to field studies conducted at the Udachny mine, $V_{spill,skip} \approx 0.05$ m^3 at A_0 = 11,000 t/day (skip carrying capacity = 30 t).

The volume V_{LHD} is determined as follows:

$$V_{LHD} = k_{spill,LHD} k_{fill,LHD} n_{trip} V_{bucket}, \tag{20}$$

where $k_{spill,LHD}$ is the coefficient accounting for the spillage intensity of LHD machine bucket contents; $k_{fill,LHD}$ is the coefficient accounting for the filling rate of the LHD bucket; n_{trip} is the number of trips made by one machine per day; V_{bucket} is the bucket capacity of the LHD machine, m^3.

The coefficient $k_{spill,LHD}$ is calculated as follows:

$$k_{spill,LHD} = \frac{V_{spill,LHD}}{k_{fill,LHD} V_{bucket}}, \tag{21}$$

where $V_{spill,LHD}$ is the volume of sludge spilled from the bucket of the MPS-operated LHD during a single trip (m^3)

According to field observations conducted at the Udachny and Mir mines, $V_{spill,LHD} \approx 0.02$ m^3 at V_{bucket} = 3.5–4 m^3.

Taking into account the transformation of expressions (3)–(21) through arithmetic operations, the values of V_{cf} (1) and V_{bc} (2) take the following form:

$$V_{cf} = \left\{ \begin{aligned} &\left(\frac{0,2 n_{leak} S_{pipe} l_{pipe}}{t_1 + t_2 + t_3} \right) + \\ &+ \frac{1}{t_1 + t_2 + t_3} \cdot k_0 \cdot \frac{86400 q_{prod}}{b_w h_w l_{flow1}} \cdot \frac{86400 S_{crack} h_{layer}}{\sqrt{\frac{2 h_{layer}}{g}}} + \\ &+ \left(k_{sl} \frac{q_{prod} A_0}{b_w h_w l_{flow2} \rho_r} k_{trans} \right) + \\ &+ \left(k_{sl} \frac{10 q_{main}}{b_w h_w l_{flow3} \rho_r} \cdot 86400 m_{spill} \right) + \\ &+ \left(\frac{24}{t_{belt}} k_{sl} b_{conv} l_{conv} h_{layer} \right) + \\ &+ \left(V_{spill,LHD} n_{trip} \right) \end{aligned} \right\} \tag{22}$$

and

$$V_{bc} = \left\{ \begin{aligned} &\left(k_{sl} \frac{10 q_{main}}{b_w h_w l_{flow3} \rho_r} \cdot 86400 m_{spill} \right) \\ &+ \left(\frac{24}{t_{belt}} \cdot k_{sl} b_{conv} l_{conv} h_{layer} \right) \\ &+ \left(V_{spill,skip} + n_{skip} \right) \\ &+ \left(V_{spill,LHD} n_{trip} \right) \end{aligned} \right\}. \tag{23}$$

Thus, two mathematical models of sludge formation were developed, taking into account the specific conditions of the local mine drainage system and the characteristics of underground kimberlite ore mining.

Classification of sludge formation sources within the local mine drainage system in a kimberlite mine

The proportional contribution of each individual sludge formation source, Δ_i, to mine water contamination within the local drainage system of a kimberlite mine is determined as follows:

$$\Delta i = \frac{V_i}{V_{sludge}} \cdot 100\%, \tag{24}$$

where V_i is the daily sludge volume from source i, m^3; V_{sludge} is the total daily sludge volume, i.e., V_{cf} or V_{bk}, depending on the selected underground mining method for the kimberlite ore deposit, m^3.

To determine the values of V_i and V_{sludge}, the previously derived mathematical models (22) and (23) are used.

Table 1 presents the calculated values of V_{cf} and V_{bk}, as well as their components, with reference to the Mir and Udachny kimberlite mines.

Fig. 1 shows the contribution of previously identified sludge formation sources to mine water contamination within the local drainage systems of the Mir and Udachny mines.

According to the conducted studies, the main contributors to mine water contamination at the Mir

Table 1

Results of calculations of sludge formation volumes V_i, V_{cf}, and V_{bk}

Mir Mine		Udachny Mine	
V_{flush} = 3.96 m^3	V_{spill} = 3.33 m^3	V_{spill} = 23.19 m^3	V_{LHD} = 0.14 m^3
V_{leak} = 0.64 m^3	V_{wash} = 0.77 m^3	V_{wash} = 0.0024 m^3	–
V_{exc} = 4.84 m^3	V_{LHD} = 0.01 m^3	V_{skip} = 7.5 m^3	–
V_{cf} = 13.55 м^3		V_{bk} = 30.83 м^3	

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mine are sludge formation volumes V_{exc}, V_{flush}, and V_{spill}, while at the Udachny mine they are V_{spill} and V_{skip}. In both cases, V_{spill} represents a major contributor, accounting for 24% and 75% of the total sludge formation volume, respectively.

These findings are relevant to both operating and future water-bearing kimberlite mines operated by ALROSA.

Development and justification of a mechanized system for collecting spilled rock mass

To minimize the impact of sludge formation volume V_{spill} on mine water contamination under local drainage conditions at kimberlite mines, a mechanized system for collecting spilled kimberlite ore (hereinafter referred to as "the mechanized system") has been developed. This system is most effectively installed in the ore transfer zone between the feeder and the conveyor belt, as the majority of spillage occurs beneath the conveyor in this area. This zone accounts for 65–70% of the total solid phase contributing to sludge formation volume V_{spill}.

In view of the above, it can be concluded that under conditions of underground kimberlite ore mining using backfilling systems, practical implementation of the proposed technological solution can reduce the intensity of mine water contamination in the local drainage system by approximately 16%. In mines that use block caving methods, the expected reduction may reach a factor of two.

The operating principle of the mechanized system is illustrated in Fig. 2 [19].

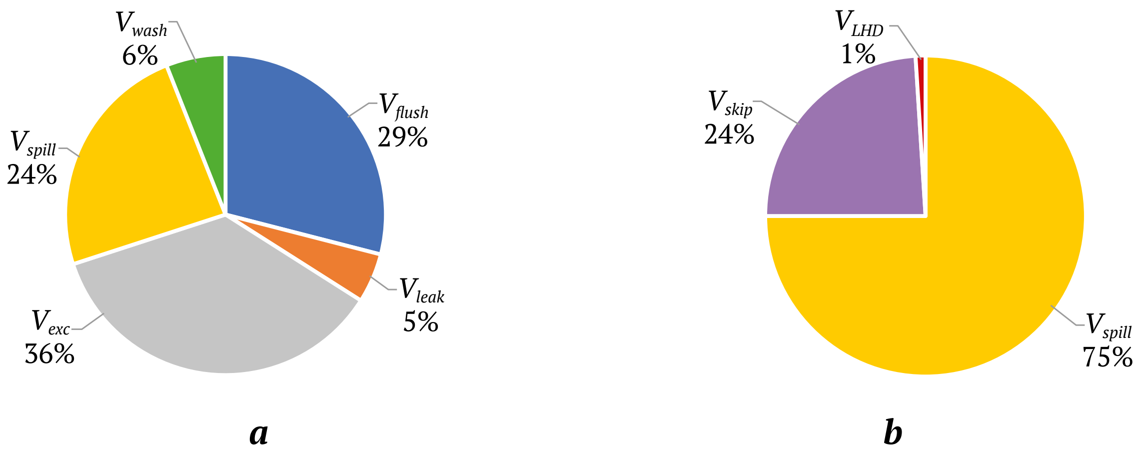

Fig. 1. Contribution of sludge formation sources to mine water contamination at the Mir (*a*) and Udachny (*b*) mines: *1* – V_{flush}; *2* – V_{leak}; *3* – V_{exc}; *4* – V_{spill}; *5* – V_{wash}; *6* – V_{skip}; *7* – V_{LHD}

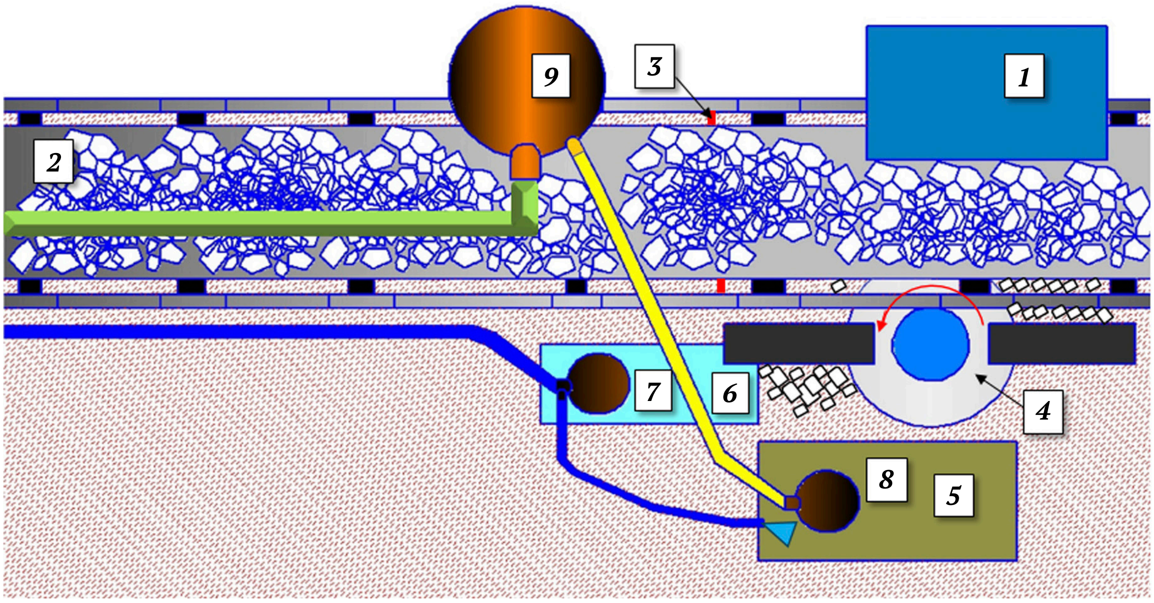

Fig. 2. Mechanized system for collecting spilled ore: *1* – feeder; *2* – belt conveyor; *3* – partition; *4* – collection and loading unit; *5* – sludge collector; *6* – water collector; *7* – submersible pump; *8* – submersible pump with agitator; *9* – pulp collection tank

During the transfer of kimberlite ore from feeder *1* to conveyor belt *2*, the spilled rock mass accumulates on the floor of the level in an area separated from the rest of the under-conveyor space by partition *3*. The collection and loading unit *4*, mounted on the side of the conveyor support frame, gathers the spilled ore. Using rotating arms, this unit moves the sludge-forming material into the sludge collector *5*. Mine water flowing into the level, which previously carried the spilled material toward the local drainage system, is now diverted into the water collector *6*, thus avoiding contact with the settled solids. From the water collector, the water is pumped by submersible pump *7* into the local drainage facility's water collectors. A portion of this water is systematically diverted via a branch of the pump 7's discharge pipeline into the sludge collector *5*, where it is mixed with the accumulated rock material by the agitator of submersible pump *8*, forming a slurry. This slurry is then pumped into the pump collection tank *9*. Through the tank's drain valve, it is evenly redistributed onto the conveyor belt.

To control the flow of water into sludge collector *5*, the end of the branch pipeline from pump *7* is equipped with a ball valve.

Submersible pumps *7* and *8* must be fitted with automated control systems to ensure timely startup and shutdown based on the fill levels of the water collector *6* and sludge collector *5*.

The collection and loading unit consists of a gear motor *1*, a disc *2*, a shaft *3*, arms *4*, and couplings *5* (Fig. 3). The shaft, threaded at one end, is screwed into a central threaded hole in the disc. A coupling is mounted on the opposite end of the shaft. The arms are press-fitted into the disc slots. Components *2*, *3*, and *4* form the sweeping star. The gear motor is secured using bolted connections *6* inserted into slotted holes *7* of a channel section *8* welded to the side of the conveyor support frame *9*. This slot design allows for both vertical and horizontal adjustment of the gear motor when connecting it to the sweeping star via the couplings.

To reduce the energy consumption of the unit, the arms *4* are made of lightweight materials such as wood or composites. Additionally, these materials are less susceptible to the aggressive effects of highly mineralised mine water.

The recommended ratios between the geometric parameters of the collection and loading unit components are as follows:

$$R_{disk} : l_{arm} - 1:3;\ l_{arm\text{-}in\text{-}slot} : R_{disk} - 1:2;\ b_{arm} : l_{arm-in-slot} - 1:4,$$

where R_{disk} is the radius of the disk; l_{arm} is the length of the arm; $l_{arm\text{-}in\text{-}slot}$ is the length of the arm section inserted into the disk groove; b_{arm} is the thickness of the arm.

The operating parameters of the collection and loading unit depend on the number of arms z_{star}, the diameter d_{star}, and the rotational speed n_{star} of the sweeping star [21, 22]. The number of arms z_{star} ranges from 1 to 8, and the rotational speed n_{star} is 24–45 rpm [22].

The operating costs of the mechanized system are largely determined by the electricity consumed by the gear motor of the collection and loading unit.

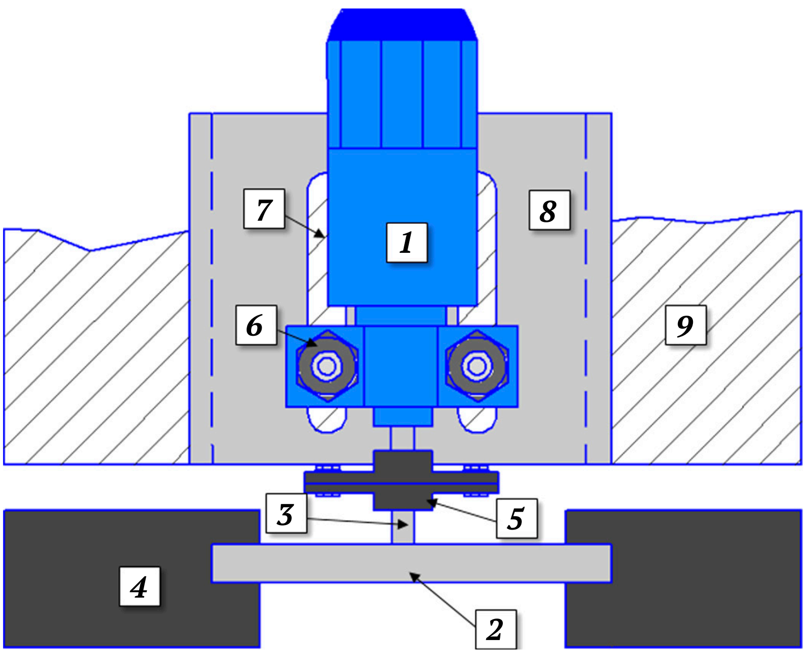

Fig. 3. Collection and loading unit: *1* – gear motor; *2* – disk; *3* – shaft; *4* – arm; *5* – coupling; *6* – bolted connection; *7* – slotted hole; *8* – channel section; *9* – side of the conveyor frame

The power consumption of the gear motor P_{mot}, kW, is determined as follows:

$$P_{mot} = \frac{(M_1 + M_2)n_{star}}{9550 \cdot \eta}, \quad (25)$$

where M_1 is the static torque on the sweeping star, N·m; M_2 is the resisting torque on the sweeping star, N·m; η is the efficiency of the gear motor.

The torque M_1 is given by:

$$M_1 = \frac{2\pi I n_{star}}{60 t_{time}}, \quad (26)$$

where I is the moment of inertia of the sweeping star, kg·m²; t_{time} is the set time for acceleration or deceleration of the sweeping star, s.

The moment of inertia I is calculated as:

$$I = \frac{(m_{star} + m_{coupling})R_{star}^2}{2}, \quad (27)$$

where m_{star} is the mass of the sweeping star, kg; $m_{coupling}$ is the total mass of the two couplings, kg; R_{star} is the radius of the sweeping star, m.

The radius R_{star} is determined as follows:

$$R_{star} = R_{disk} + l_{arm} + l_{arm\text{-}in\text{-}slot}. \quad (28)$$

Since the spilled ore accumulates between the center and the far edge of the under-conveyor zone, the optimal radius R_{star} is calculated using the following expression:

$$R_{star} - d_{mot} - b_{chan.sect} \geq \frac{b_{conv}}{2}, \quad (29)$$

where d_{mot} is the diameter of the gear motor housing (m); $b_{chan.sect}$ is the width of the channel section, m; b_{conv} is the width of the conveyor belt.

The torque M_2 is calculated as follows:

$$M_2 = k_{resist} F_{capt} h_{arm} z_{star} \rho_{ore} g d_{star}, \quad (30)$$

where k_{resist} is the coefficient accounting for the resistance of the spilled ore encountered by the arm of the sweeping star during movement, depending on its moisture content w; F_{capt} is the average capture area of spilled ore per arm of the sweeping star, m²; ρ_{ore} is the ore density, kg/m³; g is gravitational acceleration, m/s².

After multiplying F_{capt} and h_{arm}, equation (30) takes the following form:

$$M_2 = k_{resist} V_{spill} z_{star} \rho_{ore} g d_{star}, \quad (31)$$

where V_{spill} is the average volume of spilled rock mass per second, m³.

Practical data obtained at the Udachny kimberlite mine indicate that the moisture content w of the spilled ore does not exceed 20%. Laboratory experiments using a physical model of the collecting arm demonstrated that the power consumption P required to handle wet material may increase by approximately 15% (at w = 20%) compared to the power required for handling dry material P_0 (Fig. 4).

Based on the results of physical modelling, the coefficient k_{resist} is assumed to be 1.15. The volume V_{spill} is calculated as follows:

$$V_{spill} = k_{zone} \frac{m_{spill}}{\rho_{ore}}, \quad (32)$$

where k_{zone} – coefficient accounting for the volume of spilled ore directly in the transfer zone from the feeder to the conveyor belt; m_{spill} is the mass of the spilled ore per second, kg.

Estimation of the expected technical and economic effect from the implementation of research results (case study: Udachny Mine)

A significant portion of the solid phase of mine water usually settles at the bottom of drainage workings in the form of sludge and silt deposits. These are subsequently removed using LHD machines and, depending on the mining technology adopted for kimberlite deposits, either used as one of the components of the backfilling mixture or hoisted to the surface using shaft hoisting equipment [15].

A characteristic feature of the settled sludge pulp in drainage workings at kimberlite mines is the presence of voids filled with mine water. During removal of the pulp by the LHD machine's bucket, these voids tend to rupture, causing water to spill. This leads to extensive contamination of the machine's units and components – particularly the suspension bearing of the articulated frame and the electrical equipment – resulting in a shortened service life.

Operational data show that the mean time to failure for such LHD machines is 30–40% lower than that of similar equipment used in other production areas of kimberlite mines.

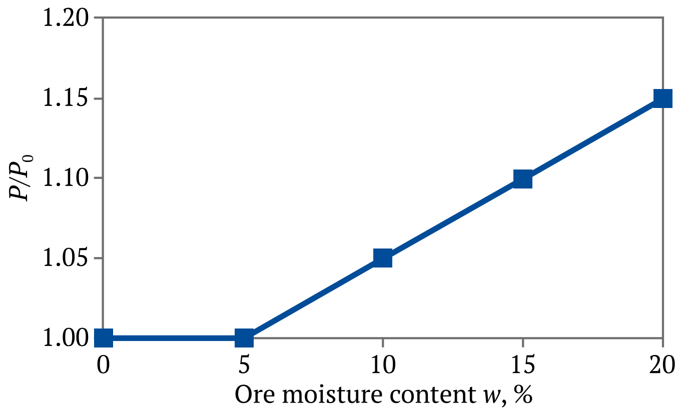

Fig. 4. Dependence of the P/P_0 ratio on the moisture content w of the spilled ore

Therefore, when calculating the main operating costs of the drainage system at a kimberlite mine, it is essential to factor in the annual repair costs of LHD machines (Z_{LHD}, million RUB/year), which result from cleaning sludge-filled drainage workings and hauling the removed pulp:

$$Z_{LHD} = k_{failure} Z_{LHD^*}, \quad (33)$$

where $k_{failure}$ is the coefficient accounting for the average share of equipment failures caused by contact with sludge pulp ($k_{failure} \approx 0.35$); Z_{LHD^*} is the total annual operating costs of the LHD machines.

According to statistical studies [16], the dependence of Z_{LHD} on the volume of sludge material transported by LHD machines V_{sludge}, m^3 is described by the following regression equation (Fig. 5).

Implementation of the mechanized system is expected to significantly reduce Z_{LHD} costs associated with mine water drainage operations at kimberlite mines.

Its estimated payback period $T_{payback}$, months, is calculated as follows:

$$T_{payback} = \frac{Z_1 + Z_2}{\Delta Z_{LHD}} \cdot 12, \quad (34)$$

where Z_1 is the estimated cost of developing and installing the system, million RUB; Z_2 is the estimated operating cost of the system, million RUB; ΔZ_{LHD} – difference between the current and expected LHD repair costs Z_{LHD} after implementation of the system.

The expected annual technical and economic benefit Z_0 from the practical implementation of the proposed technological solution (after the payback period) is determined by the following expression:

$$Z_0 = \Delta Z_{LHD} - Z_2. \quad (35)$$

According to the calculations, implementation of the mechanized system at the Udachny mine is expected to pay off within 10 months. The projected annual technical and economic benefit from its use is estimated at 4 million RUB.

Given that the implementation of the proposed technological solution eliminates the need to purchase an additional loading and hauling machine for the drainage system at the studied mine, its expected technical and economic efficiency increases significantly.

Conclusion

The following key findings were obtained based on the research results:

1. Mathematical models of sludge formation within the local mine drainage system of a kimberlite mine were developed, allowing for the identification of the main sources of suspended solids in mine water, depending on the adopted ore extraction technology. It was found that at mines employing backfilling of mined-out voids, the primary sources of mine water contamination are:

– sludge generated from flushing blocked sections of the backfilling pipeline (29%);

– sludge from continuous miner operations (36%);

– sludge formed due to ore spillage during its transfer from the feeder to the conveyor belt at the main haulage level (24%).

At mines that extract kimberlite ore using block caving, the dominant source of contamination is ore spillage from the conveyor belt, accounting for 75% of the total sludge volume.

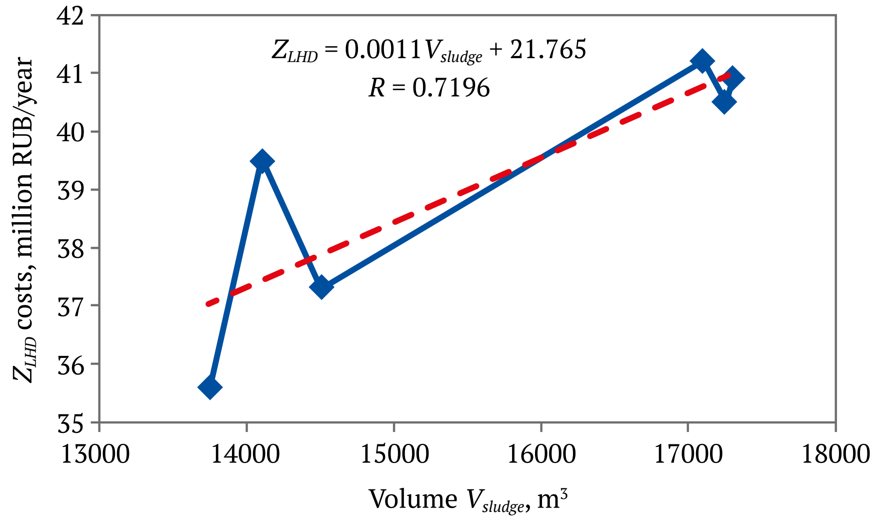

Fig. 5. Dependence of LHD repair costs Z_{LHD} on the annual volume of transported sludge material V_{sludge}

2. To reduce the rate of mine water contamination within local drainage systems at kimberlite mines, a mechanized system for collecting spilled rock mass from the under-conveyor area was proposed. The system's working unit – a collection and loading device – is mounted in the ore transfer zone between the feeder and conveyor belt. In the context of underground mining with backfill systems, the implementation of this system is expected to reduce mine water contamination intensity by approximately 16%, and by a factor of two at mines employing block caving. The estimated payback period for the technological solution is less than one year (10 months), and the projected annual technical and economic benefit is 4 million rubles (based on data from the Udachny Mine).

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EXPERIENCE OF MINING PROJECT IMPLEMENTATION

Research paper

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Economic incentive instruments for the development of technogenic deposits

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Abstract
Russia possesses a significant but underutilized technogenic mineral potential, the development of which could expand the country's mineral resource base and reduce environmental pressure. The aim of this study is to develop an effective economic mechanism – including instruments suitable for small businesses – to stimulate investment in the development of technogenic deposits. The study analyzes existing economic instruments for incentivizing the processing of technogenic mineral accumulations (TMA), proposes a methodological approach for selecting the optimal set of instruments, and presents an integrated economic model. Special attention is given to a project prioritization system based on three key criteria: budgetary efficiency, economic efficiency, and environmental efficiency. For different project categories (green, yellow, red), the most effective instruments were identified, including tax incentives, state guarantees, and credit mechanisms. The proposed model of the economic mechanism is built on six fundamental principles: clarity, transparency, teamwork, modularity, controllability, and efficiency. The implementation of the proposed measures is expected to stimulate small business involvement in the development of technogenic deposits.

Keywords
small business, economic mechanism, instruments, project ranking, model, technogenic deposits, public-private partnership (PPP), incentives, technogenic mineral accumulations

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ОПЫТ РЕАЛИЗАЦИИ ПРОЕКТОВ В ГОРНОПРОМЫШЛЕННОМ СЕКТОРЕ ЭКОНОМИКИ

Научная статья

Инструменты экономического стимулирования освоения техногенных месторождений

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Аннотация
Россия обладает значительным, но недостаточно используемым техногенным минеральным потенциалом, освоение которого способно расширить сырьевую базу и снизить экологическую нагрузку. Цель исследования – разработка эффективных экономических механизмов (включая решения для малого бизнеса), стимулирующих инвестиции в освоение техногенных месторождений. В работе проанализированы существующие инструменты стимулирования переработки техногенных минеральных образований, разработаны методический подход к отбору оптимальных инструментов и комплексная экономическая модель. Особое внимание уделено системе ранжирования инвестиционных проектов по трем ключевым критериям: бюджетной эффективности, коммерческой выгоде и экологическому эффекту. Для разных категорий проектов (зеленые, желтые, красные) определены наиболее эффективные инструменты поддержки, включая налоговые льготы, государственные

гарантии и кредитные механизмы. Разработанная модель экономического механизма основана на шести принципах: ясности, транспарентности, командной работе, модульности, контролируемости и эффективности. Реализация предложенных мер позволит активизировать развитие малого бизнеса в сфере освоения техногенных месторождений.

Ключевые слова
малый бизнес, экономический механизм, инструментарий, ранжирование, модель, техногенные месторождения, ГЧП, стимулирование, техногенные минеральные образования

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Introduction

According to economic theory, small and medium-sized enterprises (SMEs) are the driving force behind the development of any national economy [1, 2]. However, the criteria for classifying businesses as small or medium vary across countries, as noted by D.A. Pletnev, V.I. Barkhatov, and K.A. Naumova[1]. In Russia, such classification is based on annual revenue and average headcount, which are used to distinguish micro, small, and medium-sized enterprises (hereinafter collectively referred to as "small enterprises" or SEs). It has been demonstrated that SEs serve as a foundation for the formation of the middle class and are a key factor in stabilizing and minimizing social tension, as they create jobs for the local population [3]. The mining sector is no exception [4, 5]. In recent years, amid the growing relevance of the circular economy concept, increasing geological complexity of developing new mineral deposits, and depletion of the country's mineral resource base – particularly in terms of processing technogenic mineral accumulations, including small placer deposits (in this case, the focus is on the industrial and consumer waste management sector) – a noticeable upward trend has emerged [6, 7]. The main areas of activity for such small-scale subsoil users include the recovery of valuable components from industrial and consumer waste, as well as the improvement and development of new technologies for processing such waste [8]. This trend is characteristic not only of Russia, but also of Western countries. However, while abroad the share of small-scale subsoil users among all SEs ranges between 15% and 30%, in Russia this figure remained between 0.3% and 1.6% over the period from 2010 to 2021 [9] (Fig. 1).

Fig. 1 shows the relative stability in the number of small and medium-sized enterprises operating in the mining and metallurgical sector over the past decade. Nevertheless, a modest but notable increase can be observed in the number of small businesses specifically involved in resource development, with their share rising from 0.3% to 0.5%. A more detailed analysis of these figures reveals that this growth was

[1] Pletnev D., Barkhatov V., Naumova K. SME's Criteria in National Economies and Its Scale: A Comparative Study. 2021. URL: https://www.researchgate.net/publication/355331587_SME's_Criteria_in_National_Economies_and_Its_Scale_A_Comparative_Study

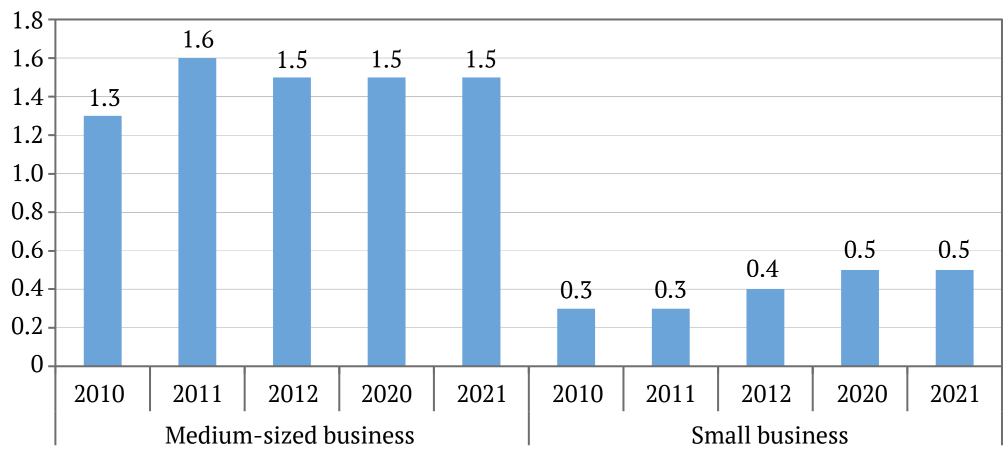

Fig. 1. Share of subsoil users among SMEs in the Russian Federation, %

Source: compiled by the authors based on: Nadymov D. S. Development of an organizational and economic mechanism for the development of technogenic deposits using state development instruments. [Diss. ... Cand. Sci. (Econ.)] St. Petersburg; 2015. 157 p.; Small and Medium-Sized Enterprises in Russia. Statistical Yearbook. Rosstat. Moscow; 2022. 101 p.

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driven primarily by enterprises engaged in the oil industry, as opposed to the mineral (ore) sector [10, 11], not to mention innovative startups focused on waste processing. Unfortunately, even among these oil-related enterprises, the majority operate at a loss[2] [12]. All of this points to a range of persistent challenges in the development of small and medium-sized enterprises in the field of resource development and the processing of industrial and municipal waste. One of the fundamental problems, from the standpoint of resource-use economics, is the inadequacy of the existing economic regulation mechanism that governs this area of activity.

Review of regulatory frameworks for the management of technogenic mineral accumulations: Russian and international experience

The lack of incentives for activities related to the management of industrial and consumer waste is reflected in the rather fragmented guidance provided in official policy documents such as the "Foundations of the State Policy in the Field of Environmental Development of the Russian Federation for the Period up to 2030" (approved by the President of the Russian Federation on April 30, 2012) and the "Environmental Doctrine of the Russian Federation". These documents limit the promotion of technogenic mineral object processing to secondary processing of industrial waste, focusing on waste collection, sorting, and subsequent use as secondary raw materials and energy sources. As a result, resource conservation is prioritized, while the environmental consequences are largely overlooked. This approach aligns with the concept of a circular economy, which emphasizes the reuse of resources, but neglects key aspects of environmental sustainability, such as pollution reduction and biodiversity conservation[3]. Thus, the existing system of incentives is narrowly focused on the economic efficiency of waste processing, while disregarding broader environmental imperatives recognized in international agreements and national development strategies.

Policy documents, legislative acts, and conference recommendations addressing the use of technogenic mineral accumulations repeatedly emphasize the need to develop and implement mechanisms for economically incentivizing their processing[4]. In particular, regional sustainable development strategies consistently highlight the importance of creating economic stimuli for enterprises engaged in the processing of mining and metallurgical industry waste. The legislation governing the management of industrial and consumer waste also provides for the possibility of granting tax incentives and subsidies to organizations involved in the processing of technogenic mineral resources[5]. The outcomes of scientific conferences and expert discussions confirm that an effective system of economic incentives is a key factor in increasing the profitability and scalability of technogenic mineral accumulation (TMA) processing, which in turn contributes to reducing environmental impacts and promoting the rational use of natural resources. For example, in the recommendations of the 2013 All-Russian Conference, it was proposed that federal legislative and executive authorities should:

– implement a set of measures to economically incentivize the rational use of waste;

– include waste disposal facilities from mining and related processing industries in the list of facilities eligible for public-private partnership (PPP) agreements [13].

As part of the Strategy's implementation[6], lawmakers emphasize the importance of incorporating the use of economic and administrative instruments for waste management into the list of fundamental principles, as well as promoting the active use of PPP mechanisms at the stage of waste generation[7]. Key areas recognized as crucial for attracting investment in the development of technogenic deposits include the formulation of economic regulatory instruments to support sectoral growth and the introduction of incentives for stakeholders and enterprises engaged in waste processing – such as tax benefits and preferential treatment. These measures are intended to create favorable conditions for the development of processing infrastructure and to improve the investment attractiveness of projects in the waste management sector.

[2] Small and Medium-Sized Enterprises in Russia. 2013: Statistical Yearbook. Rosstat. Moscow; 2013. 127 p.

[3] UNEP (2011). Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication. United Nations Environment Programme.

[4] Regional Target Program "Processing of Technogenic Formations of Sverdlovsk Region". 1996; Republican Target Program "Ecology and Natural Resources of the Republic of Bashkortostan (for 2004–2010 and the period until 2015)". Ufa; 2004; Federal Target Program "Waste". Moscow; 1996.

[5] Federal Law "On Industrial and Consumer Waste" No. 89-FZ of June 24, 1998.

[6] Strategy for the Development of the Industry for the Treatment, Recycling, and Neutralization of Industrial and Consumer Waste for the Period up to 2030. Order No. 84-r dated January 25, 2018. Moscow, 2018.

[7] Federal Law "O Industrial and Consumer Waste" No. 89-FZ.

During the Soviet era, the issue of economic incentives for the use of by-products and production waste was also a subject of considerable attention. The main objective of incentive measures was to motivate enterprises to engage in activities aimed at reducing resource consumption and improving the environmental safety of production processes[8], specifically:

– rational use of mineral resources;

– more complete extraction and utilization of associated minerals, overburden, host rocks, and primary processing waste;

– prevention of environmental pollution;

– minimizing land withdrawal for the storage of by-products and waste”[9].

A broad set of mechanisms was historically employed to promote waste utilization, including price regulation, strategies for integrating secondary raw materials into the economic cycle, and the establishment and distribution of material incentive funds for employees involved in waste processing. The utilization process was largely governed by directive management methods typical of a centrally planned economy.

The resolution of the CPSU Central Committee and the Government of the USSR dated January 7, 1988, “On a Fundamental Restructuring of Environmental Protection in the Country” is considered the first attempt to introduce economic instruments into environmental management. This document emphasized the priority of using economic methods in the regulation and governance of natural resource use and environmental protection. The first legal codification of economic instruments for regulating waste-related activities appeared in Section III of the RSFSR Law “On Environmental Protection”, which introduced payments for negative environmental impact, including fees for the disposal of industrial and consumer waste. This section also outlined the procedures for financing targeted environmental programs implemented at various levels of government – from regional to federal[10]. These measures were intended to encourage environmental protection activities and reduce anthropogenic pressure on ecosystems. However, according to most experts, these initiatives were not sufficiently developed and did not fulfill their intended role. With the transition to a market economy, emphasis shifted to other economic levers, such as taxation, monetary policy, and related financial instruments[11] [14]. Overall, the situation has remained largely unchanged. Amendments to the Federal Law “On Industrial and Consumer Waste” and the Federal Law “On Environmental Protection” have been widely regarded by experts as ineffective, as these revisions do not constitute direct-action norms and thus require the subsequent adoption of additional subordinate legislation[12] [15].

The current economic mechanism for waste utilization is widely characterized as ineffective [16, 17]. Elements of economic incentives in the existing legislation are fragmented and lack coherence, as evidenced by the predominance of declarative provisions that have not been followed by practical implementation[13] [18]. Relevant authorities, such as the State Duma Committee on Natural Resources and the Ministry of Natural Resources and Environment of the Russian Federation, have failed to fulfill their responsibilities in improving the legal framework for incentivizing activities related to the management of industrial and consumer waste and the remediation of historical environmental damage [19]. As a result, appropriate federal legislation in this area has yet to be enacted [20], which hinders the formation of an effective waste management system and delays the creation of incentives necessary for the development of this sector.

It is also regrettable that Federal Law No. 209-FZ “On the Development of Small and Medium-Sized Enterprises in the Russian Federation”, adopted on July 24, 2007, explicitly excludes SMEs engaged in subsoil use, including the development of technogenic mineral accumulations, from the list of entities eligible for state benefits and preferences. Furthermore, under the provisions of Federal Law No. 224-FZ of July 13, 2015 “On Public-Private Partnerships,

[8] Resolution of the Council of Ministers of the USSR No. 65 of January 25, 1980 “On Measures to Further Improve the Use of Secondary Raw Materials in the National Economy”; Resolution of the Council of Ministers of the RSFSR No. 237 of May 7, 1980 “On Measures to Further Improve the Use of Secondary Raw Materials in the National Economy of the RSFSR”.

[9] Methodological Recommendations for the Economic Stimulation of the Comprehensive Use of Associated Raw Materials and Processing Waste. Donetsk: Institute of Economic and Industrial Research, Academy of Sciences of the Ukrainian SSR; 1986. 46 p. P. 5.

[10] Law of the RSFSR No. 2060-1 of December 19, 1991, “On Environmental Protection”.

[11] Belik I.S. Economic Mechanism for Incentivizing the Use of Industrial Waste. [Abstr. Cand. Sci. (Eng.) Diss.] Yekaterinburg; 1993. 24 p.

[12] Yastrebkova O.A. Organizational and Legal Issues in Environmental Protection from Pollution by Mining and Rela-|ted Processing Industry Waste. [Diss. ... Cand. Sci. (Law)] Yekaterinburg; 2000. 189 p.

[13] Seleznev S.G. Waste Dumps of the Allarechensky Sulfide Copper-Nickel Ore Deposit: Specific Features and Development Challenges. [Diss. ... Cand. Sci. (Geol.&Min.)] Yekaterinburg; 2013. 141 p.

Municipal-Private Partnerships in the Russian Federation, and Amendments to Certain Legislative Acts of the Russian Federation", small enterprises are excluded from the list of entities authorized to enter into public-private partnership (PPP) agreements. This legislative restriction deprives SMEs of the opportunity to participate in PPP projects and limits their access to financial support from development institutions established to promote economic growth and innovation. In turn, this may constrain competition in the PPP sector and reduce the involvement of small businesses in projects of significant socio-economic importance.

Under such conditions, it is only natural to turn to international experience in applying market-based economic instruments to stimulate the processing of technogenic mineral accumulations. However, it is important to adopt the best practices of industrially developed countries in a balanced and thoughtful manner, rather than through blind replication.

The efficiency of economic instruments used in these countries to promote waste processing can be evaluated based on statistical data. For instance, due to the implementation of advanced technological solutions, over 40% of the annual copper output, 35% of gold, and significant portions of other strategically important metals in foreign countries are obtained from secondary raw materials. According to researchers, this share continues to grow and, in some cases, exceeds the volume extracted from primary raw materials. At the same time, the cost of metal recovery is reduced by a factor of 1.5 to 3.0 [21, 22]. In the material flow balances of the United States and Japan, secondary raw materials account for up to 26% of input resources. In most developed economies, the contribution of recycled materials ranges from 16 to 20%. These figures reflect the growing importance of recycling in meeting industrial needs and reducing dependence on primary raw material sources [23]. According to V. V. Chainikov, the recycling rates of ash and slag dumps are as follows: 53% in the United Kingdom, 65% in France, 75% in Germany, and 25% in the United States. The recycling of blast furnace slag reaches up to 100% in Germany, the United States, and the United Kingdom, and up to 90% in France [24]. The recycling rate of steelmaking slag is 55% in Japan and up to 35% in the United States [25]. The experience of government support for entrepreneurial activity that has yielded significant results in the field of advanced waste processing and disposal deserves unequivocal recognition. For example, Germany – previously mentioned – offers a wide range of economic incentives, including free access to information on waste and recycling technologies, along with active use of specialized exchanges and auctions [26]. In the United States, economic instruments include subsidies, tax incentives, loans, investment tax credits, and more [27].

Some countries also employ direct public investment in industrial and consumer waste management. For instance, under the condition of applying advanced technologies, entrepreneurs in Sweden can receive direct subsidies covering up to 50% of the costs of constructing or upgrading their waste recycling facilities. The German model, similar to that of Sweden, focuses on implementing zero-waste technological processes [28]. In Japan, the government funds centralized research projects dedicated to developing waste utilization methods. Japanese entrepreneurs engaged in waste recycling also benefit from a special depreciation system for writing off environmental equipment and enjoy local tax exemptions. In addition, such enterprises can obtain concessional loans from specialized banks and funds at reduced interest rates. Similar mechanisms operate in Germany, where the national development bank provides targeted loans for waste recycling and processing projects. If a project involves recycling waste from multiple industrial sectors, entrepreneurs may apply for funding from specialized regional foundations. All these economic instruments are aimed at creating conditions in which recycling becomes more profitable for entrepreneurs than paying levies and fines for landfilling, storing, or incinerating waste. Moreover, foreign countries have developed not only economic but also legal mechanisms to promote waste recycling. As early as the late 20th century, countries such as Austria and Germany enacted dedicated legislative acts – namely, the "Circular Economy and Waste Act" (Germany) and the "Packaging Decree" (Austria). These legal frameworks are designed to assign producers full responsibility for their products across the entire life cycle. The implementation of these provisions has led to a measurable reduction in both total waste volumes and the amount of unprocessed packaging. In Austria, for instance, this approach yielded substantial results: over a ten-year period, the total volume of waste and packaging was reduced threefold, while some waste categories saw a 30- to 40-fold decrease [28]. These outcomes clearly demonstrate the effectiveness of the extended producer responsibility concept in tackling waste management and environmental protection challenges.

The organizational framework has also been adjusted to intensify waste recycling activities, with dedicated institutions established in various countries. For example, in Japan, responsibility for waste management lies with the Ministry of Economy, Trade and Industry (METI). A key component of this system is the Clean Japan Center, which operates under METI. The center coordinates the efforts of businesses, non-profit organizations, and government agencies involved in the collection and recycling of industrial and municipal waste. It also conducts expert evaluations of emerging technologies and supports local authorities in developing waste recycling systems. In addition, the center maintains a specialized database of waste recycling technologies applied in Japan and abroad[14]. In the United States, a specialized agency within the Department of the Interior is responsible for the reclamation of mine sites and the enforcement of the Surface Mining Control and Reclamation Act[15]. In France, issues related to waste recovery and recycling are addressed through joint efforts by national and regional agencies for ecological transition[16] (Agence de la transition écologique, 2024) [29]. In the Russian Federation, despite the urgency of the waste problem, the sector remains outside centralized state regulation [30, 31].

Given the specific features of the economic regulatory framework for subsoil use – particularly in relation to technogenic mineral accumulations (TMAs) – t***here is a clear need to develop a more effective set of economic instruments, including those applicable to small enterprises, to stimulate investment in the development of technogenic deposits***. This objective shaped the following research tasks: (1) to review existing economic instruments that support TMA processing; (2) to develop an original methodological approach for identifying the optimal set of instruments for technogenic deposit development; and (3) to propose a comprehensive model of an economic mechanism that incentivizes TMA processing.

Methods

Methodological issues in the analysis of socio-economic systems, including economic analysis, have been at the center of scholarly debate in recent years, as evidenced by numerous publications from the New Economic Association. Key works are featured on the website of the community of "scholar-economists from various academic schools and traditions across the Russian Federation"[17], who argue that the social sciences are currently experiencing a methodological crisis. The study of socio-economic and human-centered systems – such as waste management regulation or subsoil use governance, which are the main research subjects of the present paper – requires a wide range of methodological tools. This toolkit includes not only methods of mathematical statistics and game theory, but also specific approaches for analyzing complex human-centered systems, such as foresight methods (from the English foresight, meaning to look ahead or anticipate the future). In the methodology proposed by Rafael Popper[18] [32, 33] foresight methods are structured as a hierarchical system of specific research techniques (see Fig. 2) employed in the course of scientific inquiry. These foresight methods are traditionally classified into three types: qualitative (methods aimed at subjective understanding and evaluation of research objects), quantitative (methods allowing for objective measurement of phenomena, followed by mathematical or statistical analysis), and mixed methods (which involve quantifying qualitative judgments, opinions, and expert or survey-based assessments).

One of the key advantages of the foresight methodology lies in its flexibility and methodological pluralism, enabling researchers to choose from a diverse set of tools based on the specific goals of the study and to validate results through various approaches. In this research, the following foresight methods were employed to develop the most effective set of economic incentives (including those accessible to small businesses) for encouraging investment in the development of technogenic mineral deposits: 1) to analyze the existing economic incentives aimed at promoting the processing of technogenic mineral accumulations (TMAs), qualitative methods were used, including a literature review and participation in thematic conferences and workshops; 2) to develop both an original methodological approach designed to justify and substantiate the optimal set of incentives for the development of technogenic deposits and a model of the economic mechanism for incentivizing the processing of technogenic mineral accumulations (TMAs), the full range of foresight methods was employed. These included qualitative techniques such as brainstorming sessions and expert workshops, the mixed Delphi method, and a quantitative approach involving modelling and scenario construction using hypothetical examples. It is worth noting that the model of the economic mechanism for incentivizing the processing of technogenic mineral accumulations (TMAs) –

14 Ministry of Economy, Trade and Industry, Japan, 2025. URL: https://www.meti.go.jp/english/

15 Office of Surface Mining Reclamation and Enforcement, 2025. URL: https://www.osmre.gov/

16 Agence de la transition écologique, 2024. URL: https://www.ademe.fr/

17 New Economic Association. URL: https://econorus.org/sub.phtml?id=182

18 Rafael Popper. URL: https://scholar.google.co.uk/citations?user=Z5gep-0AAAAJ&hl=es

including for small enterprises – was developed based on the findings obtained through all of the aforementioned research methods. In particular, it incorporated insights from the literature review as well as participation in seminars and conferences.

Results and discussion

Using a content analysis approach based on keywords such as "economic instruments," "technogenic mineral accumulations (TMA)," "mining waste," "small business," "small enterprises," "tax incentives," and "public-private partnership (PPP)," approximately 50 academic publications were selected for review. The information base for this study included research by both Russian and international scholars, sourced from library collections and scientometric databases such as Scopus, Web of Science (via ResearchGate), and the eLibrary portal. This provided a structured foundation for developing the most effective set of economic instruments (including those relevant to small businesses) aimed at attracting investment in the development of technogenic deposits.

1. Overview of economic instruments that stimulate TMA processing

The core set of economic instruments that encourage TMA processing – applicable broadly, including to small businesses – can be summarized as follows: 1) corporate income tax; 2) mineral extraction tax (MET); 3) VAT; 4) one-time payments; 5) cost write-offs; 6) subsidies; 7) loans; 8) property tax; 9) municipal property lease payments; 10) credits; 11) PPP. It should be noted that the general list of economic instruments and the logic behind its construction do not depend on the size of the enterprise – whether small, medium, or large. However, the efficiency of these instruments may vary depending on company size. As mentioned earlier, the only significant distinction concerning small businesses lies in the inapplicability of PPP mechanisms, which currently require adjustments to the national regulatory framework. Otherwise, the full range of economic instruments remains identical. In the Russian Federation, the limited efficiency of existing economic incentives for waste recycling

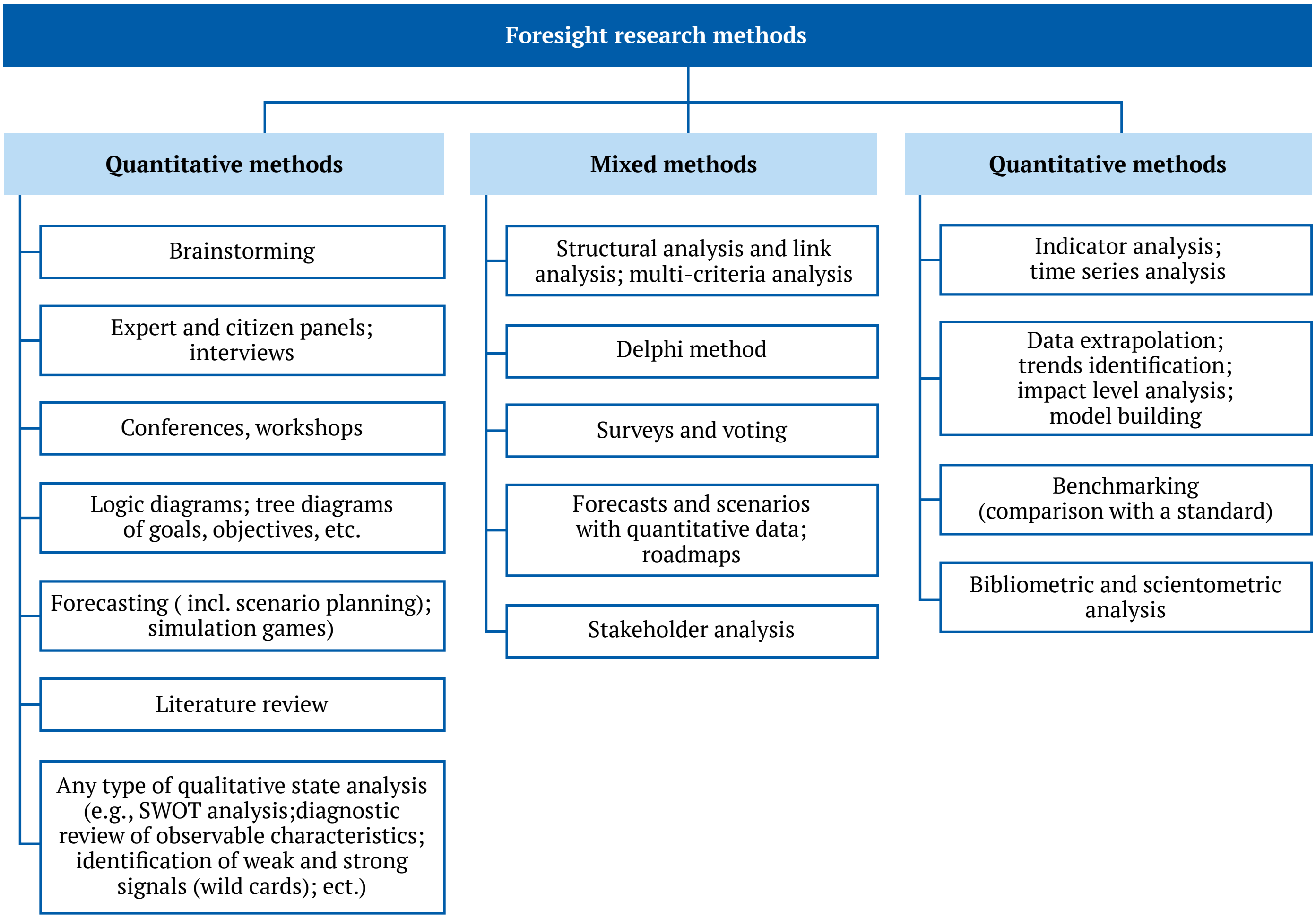

Fig. 2. Hierarchical structure of foresight research methods
Source: compiled by the authors based on the works of R. Popper [32, 33].

has led to increased research activity focused on modernizing these mechanisms. This, in turn, has generated numerous proposals for amendments to the legal framework. Most of these proposals focus on optimizing tax policy and the financial and credit system (see Table 1). Analysis of the available data highlights a particular emphasis on corporate income tax and MET. For example, it has been proposed to exempt from corporate income tax any profits derived from the sale of products made from technogenic raw materials. Some experts recommend granting this tax benefit for a period of 1.5 to 2 years for newly established small enterprises. Regarding the MET, opinions vary – from full cancellation to a reduction in tax rates or the application of lowering coefficients. Criticism of MET has repeatedly been voiced in policy recommendations submitted to governmental authorities. Nonetheless, none of these proposed amendments have been adopted to date. The fiscal nature of the current MET hinders the development of recycling activities. Thus, either a full repeal or a comprehensive revision of the tax calculation methodology is needed. Other proposals of interest include eliminating one-time payments and involving national development institutions in funding R&D activities in this area.

Table 1

Economic incentive instruments for TMA processing

Authors	Economic instruments proposed by researchers
Nadymov D. S.[19]	Deduction of geological exploration expenses from MET; Elimination of one-time payment
Chernyavsky A. G. [12]	Exemption from MET
Kubarev M. S., Ignatieva M. N. [16]	Exemption of marketable products derived from TMAs from income tax; Tax rate reduction or full exemption for 1.5–2 years upon introduction of new technologies; Full exemption for eco-friendly technologies (investment tax credit); Subsidies for clean tech development and interest payment on loans; Loans for installation of eco-tech equipment; Reduction or exemption of property tax; Reduction or exemption of municipal property lease fees; Concessional loans (guaranteed by regional government)
Kiperman Y. A., Komarov M. A. [30]	Exemption from income tax and MET
Seleznev S. G., Boltyrov V. B. [39]	Elimination of income tax
Mirzekhanov G. S. [40]	Reduction of taxable income base when purchasing new technological equipment; Elimination of MET; Deduction of exploration expenses for technogenic deposits
Boyarko G. Yu. [41]	50% reduction of VAT rate
Klemez T. N. [42]	Use of environmental coefficients in MET calculation
Seleznyov S. G. [43]	Exemption from income tax and MET
Sukhoruchenkov A. I., Kornilov N. P., Evsin V. G. [44]	Income tax exemption on revenue allocated to advanced technologies; Reduction of MET rates
Ochilov S., Kadirov V., Umirzoqov A., Karamanov A., Xudayberganov S., Sobirov I. [45]	Deduction of exploration expenses for technogenic deposits (from tax base)
Machado C. [46]	Elimination of income tax; Concessional loans
Ignatyeva M. N., Yurak V. V., Dushin A. V., Strovsky V. E. [35]	Implementation of the PPP mechanism
Potravny I., Novoselov A., Novoselova I., Gassiy V., Nyamdorj D. [47]	Reduction of TMA exploration costs
Butkevich G. R. [48]	Subsidies for clean tech development; Loans for the installation of clean technologies; Concessional loans and state guarantees
Goldyrev V., Naumov V., Kovyrzina U. [49]	Reduction of TMA exploration costs

[19] Nadymov D.S. Development of an organizational and economic mechanism for the development of technogenic deposits using state development instruments. [Diss. ... Cand. Sci. (Econ.)] St. Petersburg; 2015. 157 p.

Most research studies tend to focus on individual components of the economic mechanism. For instance, one study[20] examines the optimization of the system of environmental impact fees. Another research[21] analyzes the interaction between government agencies and oil and gas companies within the framework of public-private partnerships. A separate study[22] explores the pricing methodology for by-products of industrial activity. In [34], the author evaluates the effectiveness of programs financed through earmarked funds, while study [35] investigates the potential of using PPPs as an economic policy instrument for regulating subsoil use, including by small enterprises.

Given the limited availability of financial resources, it is necessary to establish prioritization criteria when allocating state support. One possible approach, described in a separate study[23], proposes classifying potential beneficiaries based on positive financial indicators and the volume of economic damage potentially avoided, and distributing funding proportionally to this value. In this model, the likelihood of receiving public funding is directly proportional to the scale of the anticipated avoided damage. In calculating avoided damage, a range of factors is taken into account, including losses resulting from land alienation, the negative effects of air, water, and soil pollution, and elevated risks to public health and mortality associated with environmental degradation.

The monetary valuation of land withdrawn from productive use serves as an indicator of the economic damage resulting from its requisition. The key methodological principles for assessing such damage are based on the following considerations: first, priority is given to the effective use of land assets; second, only losses related to the loss of the land's functional capacity are considered; third, the temporal aspect must be accounted for, including changes in land value over time; and fourth, various valuation methods may be used, provided they comply with current legislation and regulatory standards.

Requisition may affect lands used for agriculture, forestry, and game management, as well as land within the boundaries of populated areas. Methodologies for assessing economic damage vary depending on the land category. In calculating the financial burden caused by the pollution of natural resources (ambient air, water bodies, and soil), the use of aggregated indicators is recommended. To estimate economic damage resulting from increased population morbidity, methodologies outlined in [36] may be applied. The adoption of the "avoided economic damage" principle as an evaluation criterion is motivated by the urgent need to improve environmental conditions in industrialized regions, which often exhibit significant accumulated damage and unfavorable environmental conditions [37]. The proposed recommendations were successfully tested in Sverdlovsk Region as part of the targeted program *Processing of Technogenic Formations in Sverdlovsk Region* (1996). However, the methodology does not take into account the economic effect or profitability of the investments implemented.

In study [38], the authors emphasize the importance of waste recycling from the perspectives of economic, environmental, and social efficiency, as well as the generation of positive externalities (see Fig. 3).

To encourage secondary waste processing, the establishment of regional support funds is proposed. These funds would be financed through targeted contributions from profitable commercial ventures. Priority funding should be directed to projects that demonstrate both economic and environmental efficiency. Projects delivering economic, environmental, and social benefits should be supported not only through these targeted funds but also through employment assistance programs. Support for projects with cumulative effects and positive externalities is warranted when there is substantial potential to generate benefits in related sectors of the economy. Beyond measurable outcomes, project prioritization criteria should take into account regional characteristics and the broader implementation context. For instance, in regions with adverse environmental conditions, both economic efficiency and environmental impact must be considered in line with the United Nations' sustainable development principles. In contrast, in areas where there is a risk of social tension, priority should be given to projects that generate social benefits from the development of technogenic deposits – even though such benefits are often difficult to quantify. Evaluating positive externalities – especially spillover effects in adjacent sectors – is even more challenging and resource-intensive. As a result, economic and environmental effciency are generally

[20] Umerov R.Z. Mechanisms of Economic Improvement in the Management of Industrial Waste in the Regions. [Abstr. ... Cand. Sci. (Econ.) Diss.] Moscow; 2000. 25 p.

[21] Ledovskikh V.A. The Economic Mechanism of State Regulation of the Oil Refining Sector in Russia. [Abstr. ... Cand. Sci. (Econ.) Diss.] St. Petersburg; 2010. 20 p.

[22] Belik I.S. Economic Mechanism for Incentivizing the Use of Industrial Waste. [Abstr. ... Cand. Sci. (Econ.) Diss.] Yekaterinburg; 1993. 24 p.

[23] Pakhalchak G.Yu. Improvement of the Economic Mechanism for Processing Waste from Mining and Processing Industries. [Abstr. ... Cand. Sci. (Econ.) Diss.] Yekaterinburg; 1998. 19 p.

accepted as the primary evaluation criteria. This viewpoint is also presented in a study[24], where the author suggests that, in addition to these core criteria, two more should be included when allocating resources to potential subsoil users – public or private investors aiming to develope technogenic deposits. These are the technological foundation and the organizational framework of the project (see Fig. 4). However, the author does not justify the choice of instruments and instead focuses on outlining the procedures for obtaining investment.

The issue of formulating an effective set of economic instruments for the exploitation of technogenic deposits has been further addressed in more recent studies[25]. One such study proposes a range of

[24] Mudretsov A.V. Economic Feasibility of Prioritizing Investment Projects for Mining Waste Recycling and Disposal. [Diss. ... Cand. Sci. (Econ.)] Moscow; 2003. 138 p.

[25] Bogatyreva E.Yu. Toolkit for the Development of Environmental Entrepreneurship in the Field of Waste Management. [Abstr. Cand. Sci. (Econ.) Diss.] Yekaterinburg; 2015. 28 p.; Nadymov D.S. Development of an Organizational and Economic Mechanism for the Development of Technogenic Deposits Using State Development Instruments. [Diss. ... Cand. Sci. (Econ.)] St. Petersburg; 2015. 157 p.

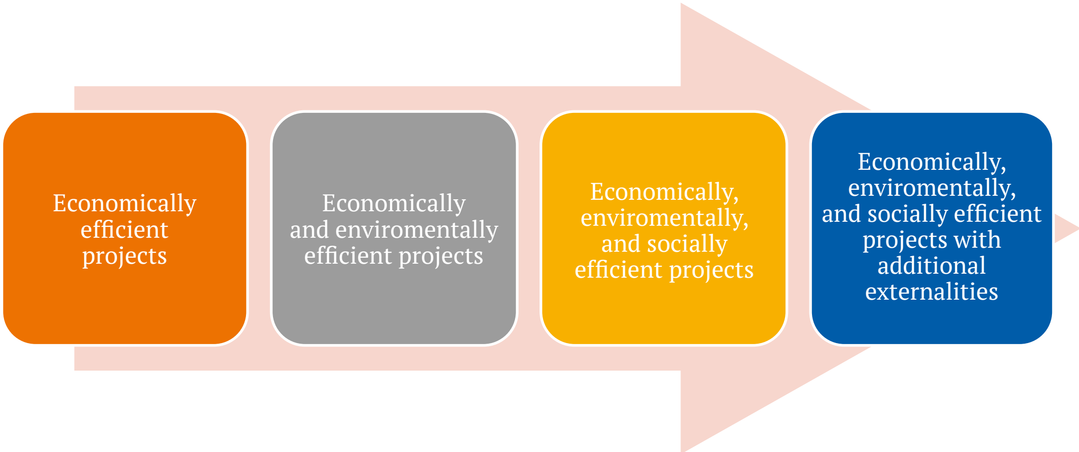

Fig. 3. Classification of waste recycling projects by type of efficiency
Source: authors' compilation based on data from [38].

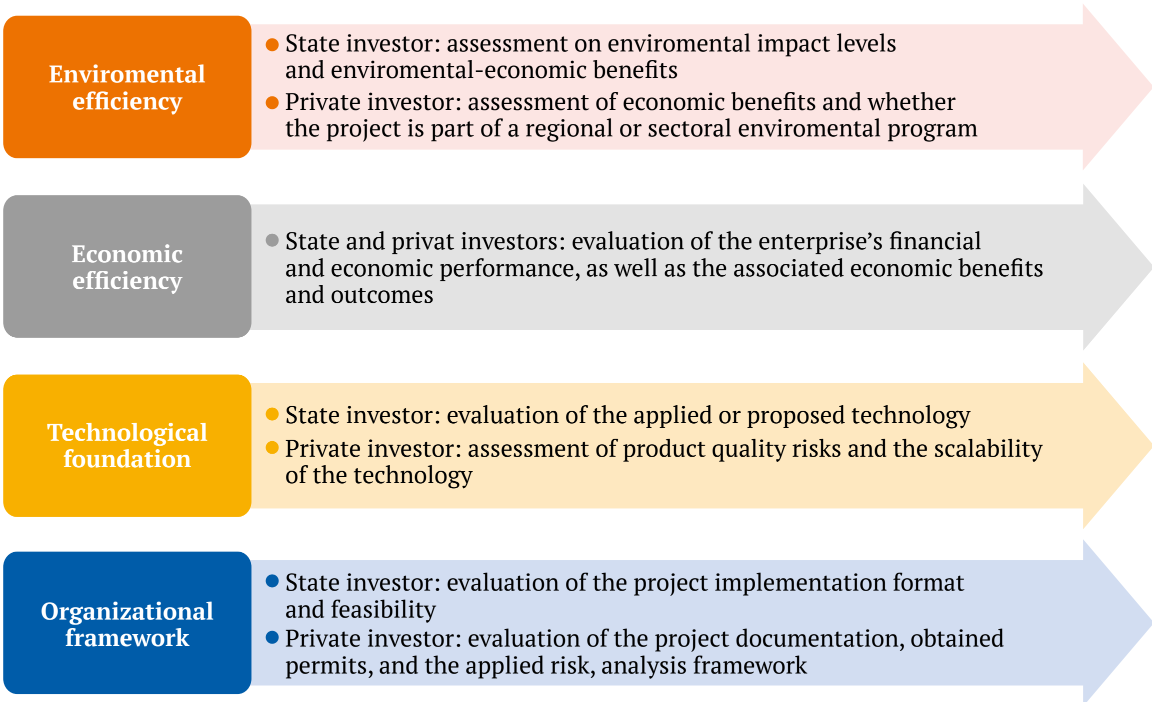

Fig. 4. Criteria for evaluating investment eligibility of projects for the development of technogenic deposits
Source: compiled by the authors based on the work by Mudretsov A.V. Economic Feasibility of Prioritizing Investment Projects for Mining Waste Recycling and Disposal. [Diss. ... Cand. Sci. (Econ.)] Moscow; 2003. 138 p.

instruments based on the criteria of economic and environmental efficiency of the processed waste. For high-profitability waste, the recommended incentives include various forms of credit – such as tax credits – and the use of an environmental entrepreneurship support fund. For moderately profitable waste, the suggested measures comprise tax incentives, credit guarantees, accelerated depreciation, and again, support from the same fund. In the case of low-profitability waste, the study proposes the use of subsidies, grants, tax incentives, and continued reliance on the environmental entrepreneurship support fund. Notably, this study does not offer a clear rationale for the selection of the proposed instrument – unlike the second study, in which the recommended instruments are aligned with the stages of R&D. In that work, the final selection of a specific incentive package is advised to be based on an evaluation of both commercial and budgetary efficiency, with priority given to maximizing commercial efficiency under conditions of positive – or at least neutral – budgetary effect.

Another study[26] roposes a method for ranking investment projects for subsequent funding based on eleven evaluation criteria, each scored using a point-based system (see Table 2).

Table 2

Evaluation criteria for investment project selection

Criterion	Score (points)
Net present value (NPV)	10
Involvement of the local population / creation of new jobs	10
Environmental impact	9
Evaluation of the technology used in the project	9
Environmental and economic efficiency (environmental effect vs. CAPEX)	8
Extent of project documentation development	7
Profitability index	6
Positive attitude of authorities and local communities	6
Investment payback period	5
Internal rate of return (IRR)	5
Scale of the project's environmental impact	4

The authors examine eight potential sources of funding and justify the optimal financing structure for the investment projects under consideration, based on the use of equity financing. The identified funding sources include:

– the federal budget;
– regional budgets;
– funds from subsoil users;
– private investment;
– loans and credits;
– green bonds;
– public–private partnership (PPP) mechanisms;
– compensation funds (e.g. damage compensation to Indigenous Peoples);
– repatriated offshore assets.

To achieve this objective, the authors propose a three-stage algorithm. In the first stage, priority project initiatives are identified based on the needs and expectations of key stakeholders. The second stage involves ranking these projects using a predefined set of criteria. In the final stage, the most suitable projects are selected for implementation, taking into account the feasibility of equity financing. This structured approach helps optimize resource allocation while reducing the financial burden[27].

2. Author's methodological approach to oustifying an optimal set of instruments for technogenic deposit development: a model of the economic mechanism to stimulate TMA processing

A review of academic literature on enhancing economic instruments for the development of technogenic deposits – whether by small, medium, or large businesses – reveals that the issue is still addressed in a rather fragmented way. The sets of proposed instruments are often neither well-substantiated nor systematically classified. Instead, most studies tend to focus on refining procedures for accessing financial resources to implement projects aimed at integrating technogenic deposits into economic circulation. Nevertheless, there is broad agreement among researchers that under market conditions, the core criteria for evaluating such projects and determining the appropriate set of instruments should be economic efficiency and environmental benefits. The authors of this study previously attempted to develop a simple and practical methodological approach for defining an optimal set of instruments for technogenic deposit develop-

[26] Chávez Ferreira Katerine Yeshia. Development of an Economic Mechanism for Attracting Investment in Projects for the Integrated Development of Technogenic Mineral Deposits. [Diss. ... Cand. Sci. (Econ.)] Moscow; 2020. 156 p.

[27] Ross S., Westerfield R., Jordan B. Fundamental of Corporate Finance. 12th Edition. 2019. GCTU Repository. URL: https://repository.gctu.edu.gh/items/show/720

ment[28], However, that approach did not take budgetary efficiency into account as a key criterion for project prioritization. Given the 2024 federal budget deficit of 1.7% of GDP and the planned 2025 deficit of 3.225 trillion rubles (1.5% of GDP), along with substantial ongoing national defense expenditures, budgetary efficiency has become the top priority. It is followed by commercial (or economic) efficiency, particularly in the context of international sanctions and the growing strategic importance of raw materials. Environmental impact remains important but takes a lower position in the hierarchy of criteria. This updated prioritization is supported by the findings of a brainstorming session involving 32 experts, including 12 representatives of public-sector institutions responsible for waste management and natural resource regulation, including subsoil use. At the first stage of the session, participants identified the most important criteria for evaluating investment projects in the mining sector focused on technogenic deposit development. The final results are presented in Fig. 5.

Based on these findings, the project ranking matrix for allocating resource support has been revised and is presented in a modified form (see Fig. 6).

[28] Komarova O.G. Toolkit of the Organizational and Economic Mechanism for the Development of Technogenic Mineral Deposits. [Cand. Sci. (Econ.) Diss.]. Yekaterinburg; 2025. 224 p.

In this figure, environmental impact is represented along a notional range (−∞; +∞). In practice, the environmental impact may also be negative (−∞), as there are cases where unscrupulous subsoil users cause environmental damage during TD development that exceeds the mitigated impact. The middle and upper thresholds for commercial (economic) efficiency and budgetary efficiency are set at 10%, 30%, and 100%, in line with standard investment analysis and project ranking practices. Budgetary efficiency is mathematically defined within the range (−100%; 100%). Projects marked in green are high-priority and recommended for funding first, based on the comparison of criteria (budgetary efficiency, commercial efficiency, and environmental impact). Yellow indicates medium-priority projects in terms of access to financial resources, while red denotes the low-priority group.

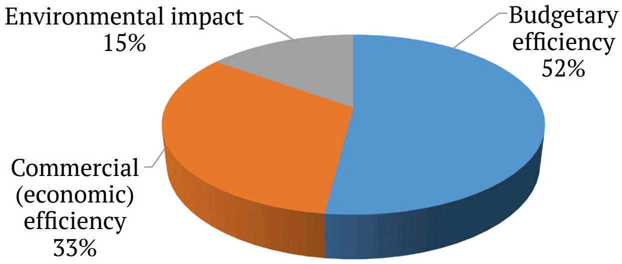

Fig. 5. Brainstorming session results
Source: Compiled by the authors.

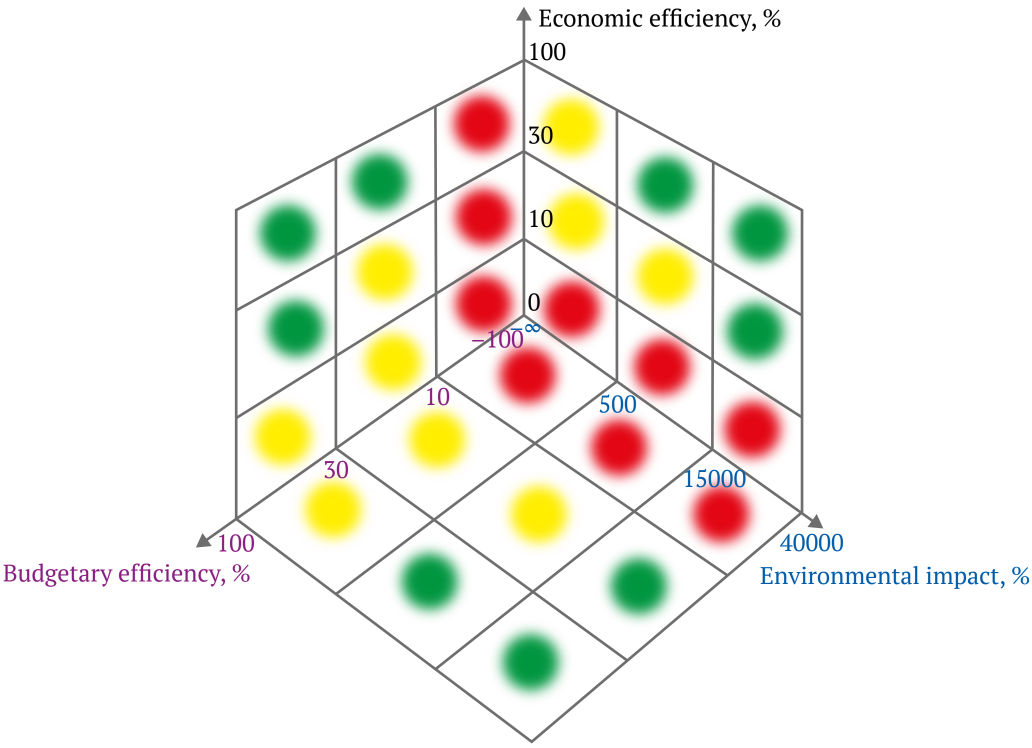

Fig. 6. Project ranking for resource support allocation:
green zone – high-priority projects; yellow zone – medium-priority projects; red zone – low-priority projects
Source: compiled by the authors.

If we assign the variable *D* for commercial (economic) efficiency with subscript *a*, *E* for environmental impact with subscript *b*, and *B* for budgetary efficiency with subscript *c*, then the grid cells in the matrix shown in the figure can be described as follows: for commercial (economic) efficiency *DHa*, *DMa*, *DLa*, for environmental impact *EHb*, *EMb*, *ELb*, for budgetary efficiency *BHc*, *BMc*, *BLc*, where the second letters *H*, *M*, and *L* stand for high, medium, and low levels, respectively.

Accordingly, the green zone includes projects with the following combinations of evaluated criteria: [*BHc*; *DHa*]; [*BHc*; *DMa*]; [*BMc*; *DHa*]; [*BHc*; *EHb*]; [*BHc*; *EMb*]; [*BMc*; *EHb*]; [*DHa*; *EHb*]; [*DHa*; *EMb*]; [*DMa*; *EHb*]. The yellow zone includes: [*BMc*; *DMa*], [*BHc*; *DLa*], [*BMc*; *DLa*], [*BHc*; *ELb*], [*BMc*; *ELb*], [*BMc*; *EMb*], [*DHa*; *ELb*], [*DMa*; *ELb*], [*DMa*; *EMb*]. The red zone includes: [*BLc*; *DHa*], [*BLc*; *DMa*], [*BLc*; *DLa*], [*BLc*; *ELb*], [*BLc*; *EMb*], [*BLc*; *EHb*], [*DLa*; *ELb*], [*DLa*; *EMb*], [*DLa*; *EHb*].

The second stage of the brainstorming session focused on establishing the rationale for applying specific incentive instruments within the economic mechanism regulating the integration of technogenic mineral accumulations into economic circulation. The survey was conducted using a Delphi method (a simplified version by D. Peskov) involving the previously mentioned group of experts. The experiment included five rounds of consensus-building for each project group. Only those incentive instruments that received 53% or more of the expert votes (i.e., 17 or more experts) were selected. The results are presented in Table 3.

Verification of the obtained results for medium-priority projects using brainstorming and the Delphi method was performed by comparing them with the model-building approach (hypothetical case studies) employed in the study by D.S. Nadymov[29]. In his work, Nadymov addressed the task of developing an optimal selection of government support instruments aimed at incentivizing the development of technogenic deposits within a limited set of feasible solutions under discrete optimization and uncertainty. To test the proposed solutions, he selected the Allarechensk technogenic deposit development project, classified as a medium-priority project according to the author's classification (see Fig. 6). Based on his calculations, the maximum net present value (NPV) can be achieved under Scenario 4 (Table 4).

Table 3

Incentive instruments

Project Group (see Fig. 6)	Incentive instruments	Frequency of expert support, %
High-priority projects (green zone)	Concessional loans	97
	Reduced costs for TMO exploration	56
	Investment tax credit	100
	Preferential taxation (income tax, MET, one-time payment)	91
Medium-priority projects (yellow zone)	Preferential taxation (income tax, MET, one-time payment)	94
	Cost write-off for TMA exploration	78
	State guarantees	100
Low-priority projects (red zone)	Loans	84
	Subsidies	91
	Preferential taxation (income tax, MET, one-time payment, property tax, land tax)	97
	Reduced lease payments	72
	Cost write-off for TMA exploration	66

In essence, the incentive instruments for the development of TMDs proposed and substantiated by D.S. Nadymov – based on detailed quantitative modeling – are largely consistent with the results obtained through the brainstorming session and the Delphi method for the medium-priority project group. The primary difference lies in the type of tax from which exploration expenses are deducted: in the present study, the deduction is applied to corporate income tax, whereas Nadymov's analysis considered deductions from the mineral extraction tax (MET). Another distinction is the inclusion of government guarantees among the expert-identified support instruments, which were not accounted for in Nadymov's study. Otherwise, the sets of instruments show substantial overlap.

D.S. Nadymov also compared the Allarechensk TD with two hypothetical deposits of larger scale (1.5 and 1.25 times greater in reserves, respectively), which were classified as high-priority projects (green zone). He concluded that NPV for both the subsoil user and the state may vary significantly in absolute terms. This suggests that a different configuration of economic instruments may be required to maximize

[29] Nadymov D.S. Development of an Organizational and Economic Mechanism for the Development of Technogenic Deposits Using State Development Instruments. [Cand. Sci. (Econ.) Diss.]. St. Petersburg; 2015. 157 p.

NPV for both parties. This finding is in line with the results of the present study, which identified the following as the most effective instruments for high-priority projects: concessional loans, deduction of exploration expenses, and the investment tax credit.

The expert survey conducted among leading specialists in TMA processing also provided the basis for a subsequent analysis of the data presented in Table 1, aimed at developing a general model of the economic mechanism for incentivizing TMA processing. As an initial step, the identified instruments were categorized according to the key components of the mechanism (Table 5), resulting in the following classification: direct instruments (subsidies, loans, etc.), indirect instruments (preferential tax treatment), financial and credit instruments, program-based support, and PPP.

During the prioritization of incentive instruments for TMA processing within the brainstorming framework, it was established that the efficiency of each instrument depends on the conditions of its implementation. This highlighted the need to develop a system of fundamental principles for constructing an economic mechanism that promotes the development of technogenic deposits. From the perspective of management theory, the principles can be categorized according to key functions: planning, organization, motivation, and control. Accordingly, the foundational principles include: clarity – the precision and comprehensibility of each instrument's purpose and functioning; transparency – openness in the management of instruments from both organizational and legal standpoints. When both the regulator and subsoil user have a clear understanding of the nature and application rules of these instruments, and when roles and responsibilities are well-defined, the planning and organizational levels of the economic regulation mechanism for technogenic deposit development can function effectively. At the levels of motivation and control, the following principles are proposed: teamwork, which implies joint involvement of subsoil users and public legal entities in organizing development activities, with an emphasis on the government's role in actively supporting subsoil users; modularity, which ensures the flexibility to easily replace, supplement, or remove instruments; controllability, which, although related to transparency, differs in that transparency ensures process visibility, while controllability focuses on managing the processes and their key parameters. The final principle in the proposed framework is efficiency, defined as the economic mechanism's ability to deliver maximum outcomes with minimal costs for all stakeholders – subsoil users, regulators, the natural environment, and society at large. Thus, the principles form a kind of Maslow's hierarchy (see Fig. 7), in which the failure to meet foundational (lower-level) principles prevents the realization of higher-level ones, ultimately making the achievement of the final principle – efficiency – unattainable.

Table 4

Scenarios for developing the Allarechensk TD using various government support instruments

Resulting value (NPV), thousand RUB	Scenarios						
	0	**1**	**2**	**3**	**4**	**5**	**6**
Subsoil user's NPV	–5072.5	548.4	5370.9	6033.9	12670.1	15557.2	19142.1
State NPV	6135	0	18809.6	18146.6	13839.6	10944.7	5046.2
Total NPV	1062.5	548.4	24180.5	24180.5	**26509.7**	26501.9	24188.3
Support instruments	No support	Zero one-time payment	Zero one-time payment	Zero one-time payment	Zero one-time payment	Zero one-time payment	Zero one-time payment
					Deduction of exploration costs from MET	Deduction of exploration costs from profit tax	Zero MET rate
			Deduction of exploration costs from MET	Deduction of exploration costs from profit tax	Concessional R&D loan	Zero MET rate	Deduction of exploration costs from profit tax
							Concessional R&D loan

Source: Compiled from: Nadymov D.S. Development of an organizational and economic mechanism for the development of technogenic deposits using state development instruments. [Diss. … Cand. Sci. (Econ.)] St. Petersburg; 2015. p. 122.

Table 5

Economic incentive instruments for TMA processing by mechanism element

Authors	Economic instruments proposed by researchers	Corresponding mechanism elements
Nadymov D. S.[30]	Deduction of geological exploration expenses from MET	Tax incentives
	Elimination of one-time payment	Tax incentives
Chernyavsky A. G. [12]	Exemption from MET	Tax incentives
Kubarev M. S., Ignatieva M. N. [16]	Exemption of marketable products derived from TMAs from income tax	Tax incentives
	Tax rate reduction or full exemption for 1.5–2 years upon introduction of new technologies, Full exemption for eco-friendly technologies (investment tax credit)	Tax incentives
	Subsidies for clean tech development and interest payment on loans	Direct government regulation / Government support programs
	Loans for installation of eco-tech equipment	Direct government regulation / Government support programs
	Reduction or exemption of property tax	Tax incentives
	Reduction or exemption of municipal property lease fees	Government support programs
	Concessional loans (guaranteed by regional government)	Financial and credit policy
Kiperman Y. A., Komarov M. A. [30]	Exemption from income tax and MET	Tax incentives
Seleznev S. G., Boltyrov V. B. [39]	Elimination of income tax	Tax incentives
Mirzekhanov G. S. [40]	Reduction of taxable income base when purchasing new technological equipment	Tax incentives
	Elimination of MET	Tax incentives
	Deduction of exploration expenses for technogenic deposits	Tax incentives
Boyarko G. Yu. [41]	50% reduction of VAT rate	Tax incentives
Klemez T. N. [42]	Use of environmental coefficients in MET calculation	Tax incentives
Seleznyov S. G. [43]	Exemption from income tax and MET	Tax incentives
Sukhoruchenkov A. I., Kornilov N. P., Evsin V. G. [44]	Income tax exemption on revenue allocated to advanced technologies	Tax incentives
	Reduction of MET rates	Tax incentives
Ochilov S., Kadirov V., Umirzoqov A., Kara-manov A., Xudayber-ganov S., Sobirov I. [45]	Deduction of exploration expenses for technogenic deposits (from tax base)	Tax incentives
Machado C. [46]	Elimination of income tax	Tax incentives
	Concessional loans	Financial and credit policy
Ignatyeva M.N., Yurak V.V., Dushin A.V., Strovsky V.E. [35]	Implementation of the PPP mechanism	Public–private partnerships (PPPs)
Potravny I., Novoselov A., Novoselova I., Gassiy V., Nyamdorj D. [47]	Reduction of TMA exploration costs	Tax incentives / Government support programs
Butkevich G. R. [48]	Subsidies for clean tech development	Direct government regulation / Government support programs
	Loans for the installation of clean technologies	Direct government regulation / Government support programs
	Concessional loans and state guarantees	Financial and credit policy
Goldyrev V., Naumov V., Kovyrzina U. [49]	Reduction of TMA exploration costs	Tax incentives / Government support programs

[30] Nadymov D.S. Development of an Organizational and Economic Mechanism for the Development of Technogenic Deposits Using State Development Instruments. [Diss. ... Cand. Sci. (Econ.)] St. Petersburg; 2015. 157 p.

Based on the findings from all of the methods outlined above – including the expert survey conducted using the Delphi method – and the set of foundational principles formulated by the authors, the proposed economic mechanism for incentivizing the processing of TMAs takes the form presented in the model below (Fig. 8).

Among the indirect instruments (i.e., tax incentives), the experts identified several particularly relevant measures: full or partial exemption from corporate income tax, full or partial exemption from the mineral extraction tax (MET), exemption from the one-time payment, exemption from property tax, and exemption from or reduction of land tax rates. A certain ambiguity remains regarding policy planning in the field of waste management at various levels: federal government support programs, as well as regional, sectoral, and local-level programs. Previously, the development of such target programs was considered part of the economic incentive mechanism. However, according to Federal Law No. 122-FZ of October 22, 2004 "On Amendments to Legislative Acts of the Russian Federation and Invalidation of Certain Legislative Acts," target programs were excluded from the list of economic instruments. This may have been associated with the adoption of Federal Law No. 115-FZ of July 20, 1995 "On State Forecasting and Programs of Socio-Economic Development of the Russian Federation," which sets out requirements for forecasting and planning socio-economic development, including aspects related to the management of industrial and consumer waste. The authors support the position of researchers who argue that excluding waste management planning from the list of economic instruments is unjustified.

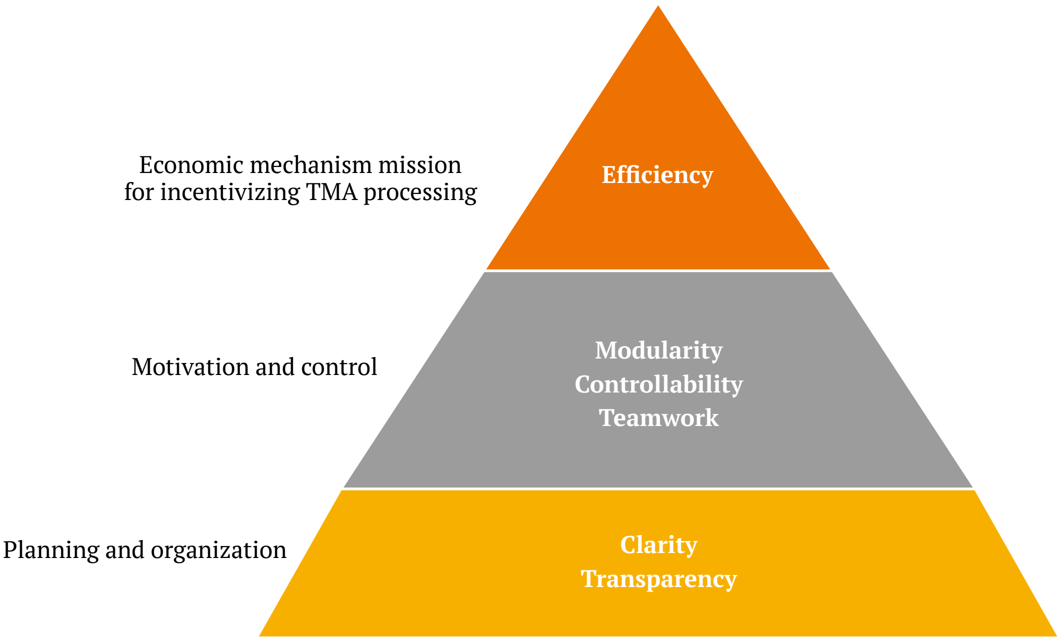

Fig. 7. Fundamental principles of the economic mechanism for incentivizing TMA processing
Source: compiled by the authors.

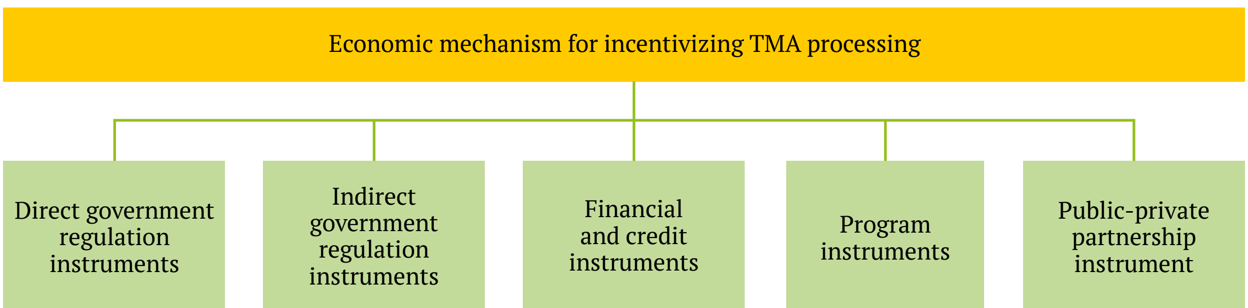

Fig. 8. Model of the economic mechanism for incentivizing TMA processing
Source: compiled by the authors.

Public–private partnerships (PPP) are recognized by many researchers as a promising instrument within the economic mechanism for incentivizing TMA processing [50, 51]. Such partnerships involve pooling resources and sharing risks between the state and private business[31], ultimately resulting in mutual benefit [52–54].

Promising PPP formats and mechanisms may include:

– government equity participation (i.e., investment of public funds in a company's charter capital);

– government lending for innovation projects;

– tax incentives;

– state guarantees;

– interest rate subsidies[32] [55].

Conclusion

Thus, the aim of this study – to develop more effective instruments of the economic mechanism (including for small businesses) to incentivize investment in the development of technogenic mineral accumulations (TMA) – was achieved through the following steps: analyzing the instruments of the economic mechanism that stimulate TMA processing; developing an original methodological approach to justify an optimal set of instruments for TMA development; and proposing a model of the economic mechanism for incentivizing TMA processing. The authors' approach was enhanced by incorporating three key evaluation criteria, prioritized in the current geopolitical context of the Russian Federation in the following order: (1) budgetary efficiency, (2) commercial (economic) efficiency, and (3) environmental impact.

The proposed hypothesis – that an efficient set of economic instruments (including those accessible to small businesses) would promote investment in TMA development – was confirmed both by international experience and by the results of a brainstorming session involving 32 experts. Among them, 12 were representatives of public legal entities involved in managing industrial and consumer waste and regulating natural resource use, including subsurface use; the remainder represented the academic and business communities.

The expert survey based on the Delphi method (adapted using D. Peskov's simplified format) produced the following ranking of efficient instruments – also relevant to small businesses – tailored to three project groups for TMA development:

– for the green project group, the most efficient and preferred instruments were: investment tax credit (100%), followed by bank loans (97%), preferential taxation (corporate income tax, mineral extraction tax (MET), and one-time payments) (91%), and lastly, deduction of technogenic deposit (TD) exploration expenses (56%);

– for the yellow project group, the top-rated instrument was state guarantees (100%), followed by preferential taxation (94%) and deduction of TD exploration expenses (78%);

– for the red project group, the instruments were ranked in descending order of efficiency and preference as follows: preferential taxation (corporate income tax, MET, one-time payments, property tax, and land tax) (97%), subsidies (91%), concessional loans (84%), reduced lease payments (72%), and deduction of TD exploration expenses (66%).

The authors' findings for the yellow project group are consistent with the detailed calculations and rationale provided in the study by D.S. Nadymov, where the highest net present value (NPV) (26.51 million RUB for the Allarechensk TD project) was achieved in scenario 4. This scenario incorporated economic instruments such as zero one-time payments, deduction of geological exploration expenses from MET, and concessional loans for R&D. Nadymov also compared these results with two hypothetical deposits of 1.5 and 1.25 times greater reserves (green project group) and concluded that both the NPV for subsurface users and the state can vary significantly depending on the instruments applied. Therefore, a different set of economic instruments is required to increase both values, which is also confirmed by the current study – since for the green group, a different set of instruments proved most efficient. This supports the objectivity of the results obtained via the brainstorming and Delphi methods.

The study also proposed a set of fundamental principles to underlie the overall model of the economic mechanism for incentivizing TMA processing. These include: Clarity – the essential purpose and operational logic of each instrument must be clearly defined and understandable; transparency – the management of instruments must be transparent in both organizational and legal aspects; teamwork – collaboration between subsoil users and public legal entities in organizing TMA development efforts, with active support from public authorities; modularity –

[31] Nadymov D.S. Development of an Organizational and Economic Mechanism for the Development of Technogenic Deposits Using State Development Instruments. [Diss. ... Cand. Sci. (Econ.)] St. Petersburg; 2015. 157 p.

[32] Ivanov V.S. Public–Private Partnership as a Factor of Government Support for the Innovative Development of the Region and Enterprises. [Abstr. Cand. Sci. (Econ.) Diss.] St. Petersburg; 2009. 18 p.

the flexibility to replace, add, or remove instruments with ease; controllability – the ability to manage and monitor key governance parameters; efficiency – the capacity of the economic mechanism to deliver maximum benefits for subsurface users, regulators, the environment, and society at large, while minimizing costs. As a result, the baseline economic mechanism for incentivizing TMA processing – including for small businesses – consists of the following blocks: preferential taxation, financial and credit policy, program instruments, and public–private partnerships (PPP). It should be noted that the list of instruments does not vary by company size: whether small, medium, or large, the same set of instruments applies. However, their efficiency will differ depending on company size. The only exception for small businesses is the limited applicability of PPPs, which require amendments to the existing regulatory framework. In all other respects, the economic instruments available to small businesses are identical to those for larger enterprises.

Thus, implementing the proposed recommendations for ranking investment projects enables two outcomes: first, it allows projects to be grouped and matched with a tailored package of economic instruments to promote investment in TD development; second, it provides a general model for an economic mechanism that incentivizes TMA processing. Enhancing this mechanism's toolset will undoubtedly stimulate more active engagement in the management and processing of technogenic mineral accumulations.

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