

Zeolite Mineral Resource Base of Russia

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The article is devoted to the mineral resource base of zeolites in Russia. The main zeolite deposits in Russia and the other CIS nations are considered, large zeolite provinces are identified, and the most promising territories for expanding the mineral resource base of the Russian Federation are determined. Information on the reserves of deposits, the degree of their exploitation, and production rates is provided. The influence of formation conditions, composition and type of the parent material, on the textural-structural features of zeolites is established. The features of geological structure and composition of sedimentary, volcanogenic-sedimentary, and hydrothermal zeolite deposits are considered. A comparative analysis of zeolites from the most important industrial deposits in Russia and the CIS is given, characterizing their mineral and chemical compositions, thermal properties, volume of cation exchange capacity and specific surface area. This work is the result of the authors' own geological field work on various zeolite deposits in Russia and the CIS, as well as a summary of previously published materials.

Keywords: zeolite, clinoptilolite, industrial minerals, sorbents, mineral resource base

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Introduction

Zeolite rocks are an important subject for research, both from the scientific and applied standpoint. Translated from Greek, the word *zeolite* mean “boiling water”, which is associated with their property of actively absorb water with a characteristic hissing sound. Having a volcanic nature, they are formed similarly to bentonite clays - from different magmatic rocks under the action of weakly alkaline solutions.

From a mineralogical point of view, zeolites form a whole group consisting of more than 200 minerals, differing from each other primarily in the ratio of aluminum to silicon, the size of the entrance of their channels and the shape of their crystals (Distanov et al., 2000). The most common minerals of the zeolite group are clinoptilolite, mordenite, heulandite, stilbite and chabazite, which are found in most Russian deposits.

Unlike clay minerals, which have a layered structure capable of swelling, zeolites have a rigid crystalline framework. Defects in the crystal lattice, formed due

to isomorphic changes in the zeolite structure, lead to the appearance of a negative charge in the “channels” – hexagonal nanosized cavities that penetrate the entire body of the mineral. This feature allows zeolites to be used as a molecular sieve – to pass certain molecules and ions of small size through the structure of the mineral and retain large molecules (Kossovskaya, 1980; Distanov et al., 2000). Gas purification systems and the production of catalysts are based on this principle. In addition to the oil and gas sector, zeolites are widely used in agriculture and livestock farming, as an ameliorative soil additive and a source of useful micro- and macroelements that promote plant growth, as well as in the form of feed and hygienic bedding for livestock (Kordala, Wyszowski, 2024; Ming, Boettinger, 2001). The use of zeolites as a dietary supplement by humans has also proven its effectiveness. Finally, zeolite is also used in water filters, due to their powerful ion-exchange properties, being able to quickly and effectively purify polluted water (Burov et al., 1990; Milyutin et al., 2023; Gadore et al., 2024).

The main objectives of this work were to analyze the mineral resource base of zeolites in Russia and the CIS countries, identify zeolite provinces and determine promising territories. The conditions of the formation of zeolites of various genesis, their structural-textural and physicochemical features were also considered.

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Terminology issues

It is worth noting that the term “zeolites” has a generalized meaning when describing deposits and mineral raw materials. Various terms are often used in domestic literature, such as zeolites, natural zeolites, zeolitized tuffs, zeolite-containing rocks. The lack of a clear classification can lead to misunderstandings.

As noted above, from a mineralogical point of view, “zeolites” are a group of minerals, but this term is also used to refer to types of rocks.

In Soviet times, especially in geological reports on prospecting and exploration of deposits, it was common to use the name of the primary, parent rock with the addition of the prefix “zeolitized”, for example – “zeolitized tuffs”. Depending on the content of minerals of the zeolite group in the rock, the prefix was added – strongly, medium or weakly zeolitized. In modern literature, this terminology is used less often and only for rocks where minerals of the zeolite group are not the main ones. The State Commission on Reserves officially approved the term “zeolites” to designate the type of the rock. Thus, based on generally accepted classifications, as well as the terminology established in Russian and foreign modern geological and technical literature (Distanov, 2000; Chekryzhov, Popov, 2001; Zonkhoeva, 2018; Christidis, 2011; Marantos et al., 2011), the authors of this work believe that rocks in which minerals of the zeolite group predominate, and their content exceeds 40–50%, should be called “zeolites” and not “zeolitized tuffs”.

Often, zeolite group minerals are present in quantities not exceeding 40%, especially when it comes to opokas (silica clays) and tripoli, where they are formed from a siliceous substrate, and their content is approximately equal to other “useful” components of the rock. In this case, the decision about the classification of the deposit (whether it is zeolite or siliceous raw material), could be made based on the final industries where it would be used and, to some extent, on the commercial and marketing plans of the management making the decisions on the further sale of the products.

The use of the term “zeolite-containing” rock has an ambiguous meaning. In some cases, this terminology is used to emphasize the low content of zeolite group minerals in the rock, usually not exceeding 10–15%. On the other hand, when putting reserves of mineral deposits on the State Register, the use of this term is practiced for rocks with a content of zeolite group minerals of less than 40%, taking into account that their further industrial use is directly related to the useful properties of zeolites. As an example, we can cite the Khotynets deposit of zeolite-containing tripoli, which, despite the approximately equal content of zeolite and opal-cristobalite group minerals, was put on the Register as a deposit of zeolite, and not siliceous raw materials.

The term “zeolitized” rock is commonly used in modern geological literature to denote rocks with an average zeolite group mineral content of less than 40% (although, in some cases up to 60%), the further use of which is not directly related to the useful properties of zeolites, but there is a need to indicate the presence of the zeolite process itself. “Weakly zeolitized” rocks include rocks with a zeolite group mineral content of about 20–30%.

The term “natural” zeolite is a complete synonym for zeolite, with an emphasis on its natural origin, which is associated with the widespread use of synthetic varieties of zeolites in industry.

Formation conditions

Zeolites are widespread throughout Russia, they are found both as impurities in silicite deposits, where their content ranges from a few percent up to 20–40%, and as large independent deposits of “volcanic” zeolites.

The first type includes sedimentary-type zeolites, mainly found within the Russian and the Siberian platforms, and West Siberian plate. Sedimentary-type zeolite deposits are typically formed in marine platform basins with a calm hydrodynamic environment, in humid or semi-arid climates. The material for its formation is connected with amorphous chemobiogenic silica (diatoms, tripoli, opoka (silica clay)), as well as aluminosilicate gels and clay minerals (Distanov et al., 2000; Marantos et al., 2011), which enter sea and lake basins with river runoff from nearby land. Zeolites of this genesis are widespread and are associated with the removal of terrigenous material and weathering processes (Muravyov, 1987; Savko, Sviridov, 2014; Savko et al., 2019; Belousov et al., 2023), however, zeolite contents of 30–40%, in some cases, are likely associated with superimposed or secondary zeolite formation processes.

Large deposits of high-quality, “volcanic” zeolite are represented by volcanogenic-sedimentary and hydrothermal types. In most cases, the primary material for the formation of zeolites are acidic rocks, since amorphous opal-cristobalite is unstable in an alkaline environment. However, there are industrial deposits where the formation of zeolites is also associated with basic rocks. Structurally, deposits of volcanogenic-sedimentary and hydrothermal genesis are confined to the marginal parts of platforms, folded belts, and rift zones, and are formed during periods of increased volcanic activity (Distanov et al., 2000; Marantos et al., 2011).

Zeolites of the volcanogenic-sedimentary type are formed in marine and lake basins in an arid or humid climate. A necessary condition for the formation of zeolites of volcanogenic-sedimentary genesis is the presence of acid volcanism in the region, increased

pH of the sedimentation basin waters (> 7.5), a closed basin type or the presence of stagnant waters and excess of free silica (Distanov et al., 2000; Christidis, 2011). The process of zeolite formation is associated with the devitrification of volcanic ash and tuffs in alkaline solutions. The final formation of the zeolitized deposit occurs at the stage of diagenesis and catagenesis.

The hydrothermal type of zeolite deposits is formed due to metasomatic replacement of volcanogenic rocks under the influence of low-temperature ($< 200\text{ }^{\circ}\text{C}$) hydrothermal solutions. Deposits of this type are confined to the near-crater vent zones of volcanic belts, and rift structures, and are formed on the slopes of paleovolcanoes (Distanov et al., 2000; Christidis, 2011). The composition of the parent rocks can also be varied – rhyolites, dacites, and in some cases – andesites and basalts. Zeolitization occurs along fracture zones in tuffs and crushed lavas.

It is worth noting that zeolite deposits are often spatially associated with deposits of perlites, silicites, bentonites, or hard and brown coals. If in the first two cases the spatial connection can be explained by the fact that perlites and silicites are the initial source of easily soluble silica, then the spatial connection with coal basins is explained by the fact that the presence of brown or hard coals is a paragenetic feature indicating favorable conditions for the accumulation of ash material and further zeolite formation, such as in coastal sea basins, lagoons, bays and salt lakes (Distanov et al., 2000; Christidis, 2011). Bentonite clays are formed under the same conditions as zeolites, but at lower pH values and excess magnesium in the water (Distanov et al., 2000; Belousov, Karelina, 2022; Belousov et al., 2023).

Structural and textural features

Different formation conditions, as well as varying composition and type of original parent material, affect the color and textural-structural features of the resultant zeolite rocks.

Since zeolites of sedimentary genesis are mainly found in opal-cristobalite rocks in subordinate quantities, macroscopically they have an appearance identical to tripoli - lightweight rocks of light gray and beige color with a massive, thick-, or thin- platy texture (Fig. 1a). They have fairly high water absorption and low strength, being easily scratched with a fingernail.

Volcanogenic-sedimentary and hydrothermal zeolites often inherit the textural features of the parent rocks; they have a homogeneous, massive, or detrital brecciated texture (Fig. 1b, c). Moreover, the fragments can be composed of both the original untransformed volcanic substance and recrystallized zeolites (Fig. 1c). The color range of volcanogenic zeolites is diverse. They are mainly characterized by various shades of green, bluish, beige, gray and white colors. Pinkish varieties

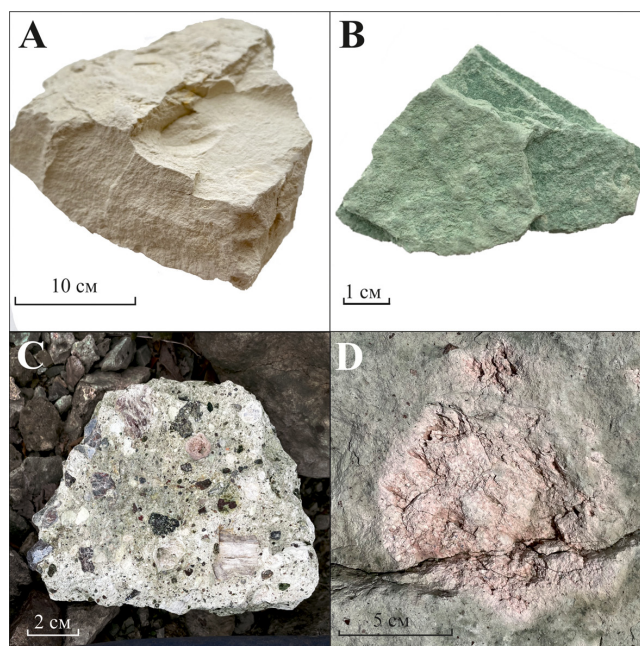


Fig. 1. Macro photographs of different types of zeolite rocks: A – massive, homogeneous zeolite-containing rock of light gray color (Khotynets deposit, Oryol Region); B – thin-platy, fine-grained zeolite of greenish color (Hongurru deposit, Republic of Sakha (Yakutia)); C – zeolitized tuff with breccia structure (Yagodninskoe deposit, Kamchatka Territory); D – pink pocket with increased smectite content in a zeolite rock (Yagodninskoe deposit, Kamchatka Territory)

are rarer. The color of zeolites depends not only on their chemical composition, but also on mineral impurities. As previously noted, smectite impurities of more than 20% can color zeolites in pink tones (Fig. 1d) (Belousov et al., 2024).

Volcanic zeolites are characterized by high strength – like hard-rocks, they are resistant to mechanical impact, but due to their natural porosity, they have fairly high water absorption of up to 50–70% of their own weight.

The microstructures of zeolites are diverse and are represented by both cryptocrystalline and well-crystallized varieties. Crystallization develops most actively in the cavities and pores of rocks. Zeolite rocks of sedimentary genesis are mainly characterized by siltstone and aleuropelitic structures with relics of diatoms and radiolarians (Fig. 2a, b). Minerals of the zeolite group are present either in the form of fine-crystalline needle-shaped aggregates or in cryptocrystalline form. Zeolite rocks of volcanogenic genesis are more characterized by well-crystallized aggregates of needle-shaped, prismatic or plate-shaped forms (Fig. 2c, d).

Mineral Resources Base

CIS Countries

Large zeolite deposits that were actively exploited back in the Soviet era are located in the CIS countries.

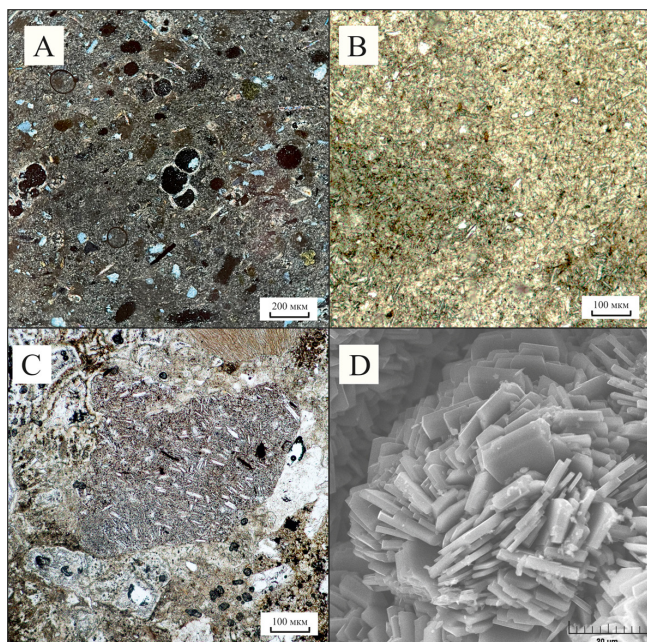


Fig. 2. Micrographs of zeolite rock samples from various deposits in Russia: A – radiolarian fossils with needle-shaped aggregates of clinoptilolite in a clayey-siliceous mass (Khotynets deposit, Oryol Region); B – vitroclastic tuff replaced by cryptocrystalline clinoptilolite (Honguruu deposit, Republic of Sakha (Yakutia)); C – rock fragment replaced by clinoptilolite crystals in zeolitized breccia (Yagodninskoe deposit, Kamchatka Territory); D – tabular clinoptilolite crystals (Yagodninskoe deposit, Kamchatka Territory)

They are mainly of the volcanic type, many of them are a source of high-quality raw materials imported not only to Russia, but also to European countries. These include the Noyemberyan and Shirak group of deposits in the Republic of Armenia, the Aidag deposit in the Republic of Azerbaijan, the Sokernitskoye deposit in Ukraine, the Tedzamskoye and Dzegvskoye deposits in Georgia, and the Tayzhuzgenskoye and Chankanayskoye deposits in the Republic of Kazakhstan.

The Noyemberyan and Shirak group of zeolite deposits is located in the Republic of Armenia. The zeolite content in the rocks is about 55–65%. Zeolite is mainly represented by clinoptilolite, and in some cases stilbite, mordenite and analcime. The reserves of the Noyemberyan group of deposits are about 25 million tons (Dzhrbashyan et al., 1999). At present, mining is carried out only at the Nor Koghb deposit, which is part of the Noyemberyan group. Zeolites from this deposit make up the bulk of Russian imports.

The Aidag zeolite deposit is located in the Tavuz region of Azerbaijan, its reserves are about 25 million tons. The clinoptilolite content is about 55–65% (Burov et al., 1990). By analogy with the Dash-Salakhinskoye and Ijevan bentonite deposits, the Aidag zeolite deposit is located in the same geological structure with the Noyemberyan group (Republic of Armenia), and is associated with the development of volcanism in

the northern part of the Gazakh trough of the Lesser Caucasus (Nasedkin, Shirinzade, 2008).

The Sokernitskoye zeolite deposit is the largest in Ukraine, it is located in the Zakarpattia region, and its reserves exceed 100 million tons. Zeolites there are of the volcanic type, their content is ~70%. The rocks are mainly represented by clinoptilolite (Burov et al., 1990).

The Tedzamskoye and Dzegva zeolite deposits are located in Georgia near the city of Tbilisi and are confined to the same geological structure. Zeolites are represented by clinoptilolite, its content is about 60–70%. The reserves of both deposits amount to several tens of millions of tons (Burov, 1990).

Zeolite deposits in the Republic of Kazakhstan are represented by the Tayzhuzgenskoye and Chankanayskoye deposits, located in the Tarbagatai and Kerbulak regions of Kazakhstan. Their reserves amount to 7 and 5.5 million tons, respectively (Vasilyanova, Lazareva, 2016).

Russian zeolite deposits

About 120 zeolite deposits and occurrences have been identified in Russia, but the State Register of Reserves takes into account only 18 deposits with category A+B+C₁ reserves of 594 million tons and category C₂ reserves of 799 million tons (State Reserves Committee of the Russian Federation: zeolites, 2019) (Fig. 3, Table 1). Zeolite rock extraction is small-scale. Only 4 deposits are being exploited: Khotynets (Oryol Region) with category A+B+C₁ reserves of 6.9 million tons, Honguruu (Republic of Sakha (Yakutia)) with category A+B+C₁ reserves of 11.3, as well as Kholinskoye (Zabaikalsky Territory) and Chuguevskoye (Primorsky Territory) with category A+B+C₁ reserves of 129.6 and 20.6 million tons, respectively. The total annual production is about 60–80 thousand tons (Belousov et al., 2020). The estimated resources of zeolites in Russia amount to hundreds of millions of tons. Almost all of the mined material is used to produce hygienic bedding for animals, soil for houseplants, as an additive to concrete, and for the production of foam glass, while the use of zeolites in high-tech industries is in the development stage.

Based on the administrative division, five large zeolite provinces are distinguished: Central, Southern, Ural, Siberian and Far Eastern.

Zeolites of the **Central and Southern provinces** are mainly of the sedimentary type and are confined to deposits of opal-cristobalite materials and carbonate rocks – diatomites, tripoli, opokas, limestones and marls, and are of Cretaceous age. The content of zeolites in most cases does not exceed 10–15% in the rock; they are found as impurities. In some cases, the zeolite content reaches 30–40%, as in the Khotynets (Oryol Region) and Tatarsko-Shatrashanskoye (Republic of Tatarstan) deposits of zeolite-containing rocks (Fig. 3, Table 1). Khotynets is the only deposit in the Central and Southern

regions listed on the Register with reserves of cat. A+B+C₁ about 6.9 million tons. The deposit is currently being exploited.

In general, it is worth noting that most terrigenous-siliceous deposits of Central Russia often contain a small admixture of zeolite group minerals (Savko et al., 2001, 2009, 2019a, b; Savko, Sviridov, 2014; Muravyov, Voronin, 1979; Muravyov, 1983, 1987; Bushinsky, Shumenko, 1970; Semenov et al., 1974; Senkovsky, 1977, 1980; Zhabin, Dmitriev, 2002). According to Zorina et al. (2008), a series of lithostratigraphic units have been identified in the Volgograd, Ulyanovsk, Saratov, Penza and Astrakhan regions, as well as in the Republic of Mordovia. These include carbonate and siliceous zeolite-containing rocks of the Cretaceous age. The content of zeolite group minerals averages 5–20%.

The studies of terrigenous-siliceous, clayey and volcanic rocks of the south of Russia, conducted by Khardikov et al. (2000), made it possible to identify a series of zeolite-containing areas in the stratigraphic interval from the Middle Jurassic to the Late Pliocene. They are located in Krasnodar Territory, Rostov Region, the Republic of Kabardino-Balkaria and the Republic of Dagestan.

The content of zeolite group minerals is also not high. Yusupov et al. (2021) studied zeolite-containing siliceous rocks in the Republic of Dagestan. The promising areas of Levashy and Dubek were identified, with an average zeolite content of about 20–40%. The predicted resources of zeolite-containing rocks

amounted to 119 million tons of categories P₁ and P₂.

From a geological point of view, by analogy with Transcaucasia, it is worth noting the high potential and prospects for further searches for zeolites in the Russian part of the Caucasus, where there are favorable conditions for zeolite formation within the young orogens.

The reserves of the **Ural province** of category A+B+C₁ and C₂ are about 34.6 and 27.7 thousand tons, respectively. The Lyulinskoe and Mysovskoe deposits are confined to volcanogenic-sedimentary deposits of the Middle and Upper Devonian, located in the Khanty-Mansiysk Autonomous District (Fig. 3, Table 1). Both deposits are listed on the balance sheet, but are not developed. The deposits are characterized by a high content of clinoptilolite 70–90%, but low reserves.

The reserves of the **Siberian province** amount to only 5.9 million tons of cat. A+B+C₁ and are represented by the Pegasskoe deposit (Zapadno-Pegassky district) in the Kemerovo Region (Fig. 3, Table 1) (Koretsky, Ignatova, 2010).

The deposits not listed in the State Register of Reserves include Sakhaptinskoe and Pashenskoe in the Krasnoyarsk Territory, Maloelanskoe, Oekskoe, Kudinskoe and Ushakovskoe in the Irkutsk Region (Fig. 3, Table 1) (Belitsky, Fursenko, 1992).

In terms of age, the deposits of the Siberian province belong to the Jurassic, Cretaceous and Carboniferous systems. Structurally, they are confined to folded belts. The formation of these deposits is directly related to volcanic activity.

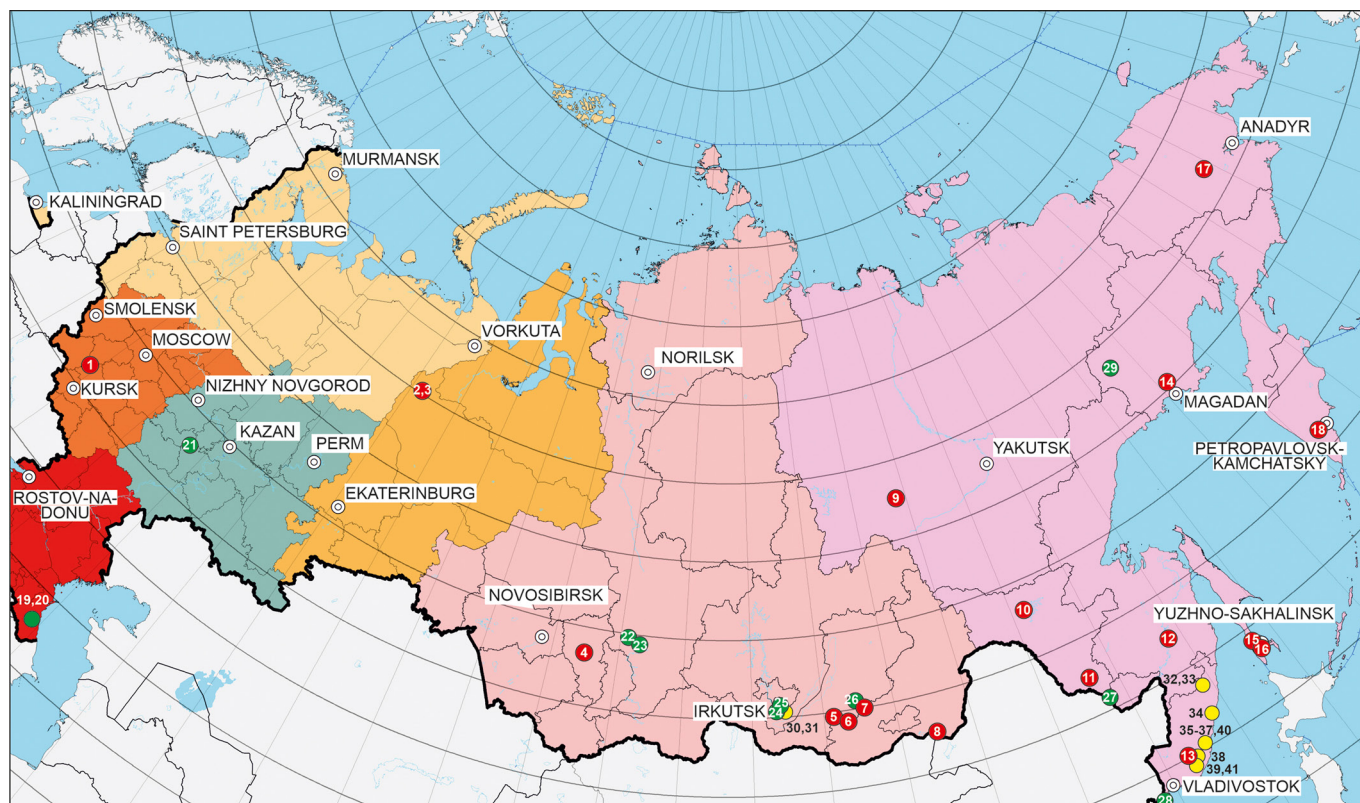


Fig. 3. Overview map of zeolite deposits and occurrences in Russia. For names of numbered items, see Table 1

№	Deposit	Region	Age	Genetic type	The main mineral of zeolites*	Average zeolite content, %	Reserves, mln tons **	Degree of development
Listed on the State Register of Reserves								
1	Khotynets (Obraztsovsky district)	Oryol Region	K ₂	volcanogenic-sedimentary	cpt	20-40	6.9	Under exploitation
2	Lulinskoe	Khanty-Mansiysk Autonomous District	D ₂₋₃	volcanogenic-sedimentary	cpt, mor, cbz	70	0.018	Unready for exploitation
3	Mysovskoe					>90	0.027	
4	Pegasskoe (Zapadno-Pegassky district)	Kemerovo Region	T	volcanogenic-sedimentary	hul, cpt	50-60	5.9	
5	Mukhor-Talinskoe (Mukhor-Bulyksky district)	Republic of Buryatia	J	hydrothermal	mor, cpt	60	1.7	Prepared for exploitation
6	Badinskoe	Transbaikali Territory	J ₃ -K ₁	hydrothermal	cpt, mor	70	9.8	Unready for exploitation
7	Kholinskoe (Moheisky district)				cpt	50-70	383.5	Under exploitation
8	Shivirtuiskoe			volcanogenic-sedimentary	cpt	50-80	803.2	Unready for exploitation
9	Hongurui	Republic of Sakha (Yakutia)	D ₃ -C ₁	volcanogenic-sedimentary	cpt, hul	70-80	11.3	Under exploitation
10	Vanginskoe	Amur Region	K ₁	? volcanogenic-sedimentary	cpt, hul	50-60	0.9	Unready for exploitation
11	Kulikovskoe		K ₂	? hydrothermal	mor, cpt	40	14.1	
12	Seredochnoe	Khabarovsk Territory	P ₁₋₃	? hydrothermal	mor, cpt	50-60	52.1	
13	Chuguevskoe	Primorsky Territory		hydrothermal	cpt	60-80	20.6	Under exploitation
14	Flora	Magadan Region	K ₂	hydrothermal	lmt	40	12.9	Unready for exploitation
15	Chekhovskoe (Tobutsky district)	Sakhalin Region	P ₃ -N ₁	volcanogenic-sedimentary	cpt	60	31.8	Unallocated reserves
16	Lyutogskoe					50-60	11.5	Unready for exploitation
17	Pastbischnoe	Chukotka Autonomous District	K ₂	volcanogenic-sedimentary	cpt	40-90	7.1	
18	Yagodninskoe	Kamchatka Territory	N ₂	hydrothermal	cpt	70	19.7	Under exploitation
Not listed on the State Register of Reserves								
19	Levashy Dubek	Republic of Dagestan	K ₂ -P ₁	sedimentary	no data	30-40	119	
20	Tatarsko-Shatrashanskoe	Republic of Tatarstan	K	sedimentary	cpt	35	100	
22	Sahaptinskoe	Krasnoyarsk Territory	C ₁	volcanogenic-sedimentary	hul, cpt	10-60		
23	Pashenskoe					30-60	414	
24	Maloelanskoe	Irkutsk Region	J	no data	hul, cpt	-	82	
25	Oekskoe					-	-	
26	Gavrilovskoe	Republic of Buryatia	J ₂	hydrothermal	cpt	60	21.4	
27	Raddenskoe	Jewish Autonomous Region	K	no data	cpt	60-75	30	
28	Novogorodskoe	Primorsky Territory	P ₂₋₃	hydrothermal	cpt, hul	50-70	3.5-4	
29	Khurchan	Magadan Region	K	volcanogenic-sedimentary	cpt, mor	70-90	30	
30	Kudinskoe occurrence	Irkutsk Region	J	no data	hul, cpt	20-30	393	
31	Ushakovskoe occurrence					20-30	203	
32	Vodorazdelnoe occurrence					30-80		
33	Losevskoe occurrence							
34	Shanduiskoe occurrence					45-90		
35	Kisinskoe occurrence							
36	Kolobyonkinskoe occurrence					60-70	2	
37	Shvedovskoe occurrence					40-90	1	
38	Furmanovskoe occurrence					<50		
39	Dorozhnoe occurrence							
40	Ustinovskoe occurrence						20	
41	Berezovoe occurrence							

Table 1. Deposits and occurrences of zeolites in Russia: *cpt – clinoptilolite; hul – heulandite; mor – mordenite; cbz – chabazite; lmt – laumontite; ** For deposits listed on the Register – reserves cat. A+B+C₁+C₂; not listed on the Register – predicted resources cat. P

By analogy with the Central and Southern provinces, deposits of siliceous raw materials, represented by opoka, diatomite and tripoli, are also widespread in the territory of Siberia, where zeolite group minerals are often found as an impurity of up to 5–15% (Smirnov, Konstantinov, 2016, 2017; Muravyov, 1983, 1987).

The **Far Eastern Province** ranks first in reserves and includes a number of zeolite deposits with reserves of category A+B+C₁ – 581.2 million tons and category C₂ – 799.7 million tons. These include the following deposits: Mukhor-Talinskoe (Mukhor-Bulyksky district) in the Republic of Buryatia, Badinskoe, Kholinskoe and Shivyrtuiskoe in the Zabaikalsky Territory, Honguruu in the Republic of Sakha (Yakutia), Vanginskoe and Kulikovskoe in the Amur Region (Sklyarova, 2021; Rogulina, Yurkov, 2006), Seredochnoe in Khabarovsk Territory, Chuguevskoe in Primorsky Territory, Flora in the Magadan Region, Lyutogskoe and Chekhovskoe in the Sakhalin Region, Pastbischnoe in the Chukotka Autonomous District and Yagodninskoe in the Kamchatka Territory. Deposits not listed on the balance sheet include Gavrilovskoe in the Republic of Buryatia, Raddenskoe in the Jewish Autonomous Region, Khurchan in the Magadan Region, and Novogorodskoe in Primorsky Territory (Fig. 3, Table 1).

All deposits of this province have hydrothermal or volcanogenic-sedimentary genesis, are confined to folded belts and have Jurassic, Cretaceous, Paleogene and Neogene age. The exception is the Honguruu deposit, which has Devonian-Carboniferous age. A more detailed description of this deposit is given in the next section.

Also along the coast of Primorsky Territory there is a series of zeolite occurrences - Vodorazdelnoe, Losevskoe, Shanduyskoe, Kisinskoe, Kolobyonkinskoe, Shvedovskoe, Ustinovskoe, Furmanovskoe, Dorozhnoe and Berezovoe. All of them are confined to depressions and hollows and likely have volcanogenic-sedimentary genesis (Fig. 3, Table 1).

Considering that the reserves of zeolite deposits in the Far East region are the largest in Russia and have high-quality raw materials, it is safe to say that the Far East is an underestimated and most promising region. For example, according to Mikhailov (Burov et al., 1990), the Far Eastern zeolite-bearing province is distinguished with five zeolite-bearing regions including volcanogenic complexes of different ages with reserves of zeolite raw materials in the hundreds of millions of tons: The *Primorsky zeolite-bearing region* includes the territories of Primorsky and southern Khabarovsk Territory and is represented by hydrothermal and, less frequently, volcanogenic-sedimentary deposits of the Paleogene age and is confined to the Sikhote-Alin volcanic belt. The *Okhotsk-Chukotka zeolite-bearing region* is located in the Magadan Region and the northern part of the

Khabarovsk Territory and is confined to the Upper Cretaceous volcanic rocks of the Okhotsk-Chukotka belt and geosynclinal terrigenous-tuffaceous deposits of the Penzhino-Anamyr and Koryak folded zones. The *Sakhalin zeolite-bearing region* is represented by volcanogenic-sedimentary Miocene zeolitized tuffs of various compositions. The *Kuril zeolite-bearing region* is represented by hydrothermal and volcanogenic-sedimentary zeolites of Neogene age. The *Kamchatka zeolite-bearing region* is mainly represented by hydrothermal deposits of Neogene zeolite, confined either to perlite rocks of the near-crater vent part of volcanoes or to terrigenous-tuffaceous deposits of volcanotectonic depressions.

Prospects for expanding the mineral resource base of zeolites in Russia

Despite the significant reserves of zeolites in Russia, the volumes of their production remain at a very low level. This is primarily due to the insufficient degree of study of already known deposit sites, the territorial remoteness of deposits of high-quality raw materials from logistics centers and large industries, as well as the lack of modern technologies that allow using zeolites not only in their original form, with minimal production costs, but also to obtain more science-driven products, such as ion-exchange filters for water and gas purification, nanocomposite fertilizers, means of delivering drugs to the human body, catalysts of various types, etc.

For a more complete understanding of the prospects for expanding the mineral resource base of zeolites in Russia, we will consider the most important sites taking into account the degree of their exploitation, the quality of raw materials and the remoteness from transport channels.

Deposits listed on the National Register of Reserves

It is worth noting that a fairly large part of the deposits listed on the Register of Reserves under the status of “not designated for exploitation” were prepared for exploitation or were being exploited at the end of the 20th or beginning of the 21st century. But for various reasons, the work was suspended. In most cases, this is due to the suspension of funding.

Over the past 30 years, zeolite mining has been carried out sporadically at the Badinskoe, Kholinskoe and Shivyrtuiskoe (Zabaikalsky Territory) deposits. However, due to the need for additional investment, as well as the low demand for zeolite raw materials in the early 2000s and less than ideal logistics, mining at most of these deposits was suspended. At the moment, mining is carried out only at the Kholinskoe deposit and does not exceed 1–2 thousand tons per year. Given the large reserves of the deposits, the high degree of

geological exploration conducted there, and quality of the raw materials, these sites deserve more detailed attention and reassessment of the possibility of their further exploration and increase in production volumes.

The Chuguevskoe hydrothermal zeolite deposit is currently in the exploitation status. However, the production volumes are low. This deposit is characterized by high operational properties and clinoptilolite content, as well as proximity to railways.

The Mukhor-Bulyksky district of the Mukhor-Talinskoe deposit (Republic of Buryatia) is listed in the distributed fund as “prepared for exploitation”. High-quality volcanogenic zeolites and its relative proximity to the railway (14 km Novoilinsk station) make it an attractive site in economic terms (Gordienko, Zhamoysina, 1995)

The Yagodninskoe hydrothermal zeolite deposit (Kamchatka Territory) was prepared for exploitation in the 1990s, but significant production was never established. The main problem at the deposit is its significant distance from industrial enterprises where this raw material could be used, as well as the need to build a road to Petropavlovsk-Kamchatsky. However, due to the presence of potassium zeolites with unique properties, the Yagodninskoe deposit can rightfully be considered one of the most promising sites.

The Lyulinskoye and Mysovskoe (Khanty-Mansiysk Autonomous District) deposits are listed on the Register of Reserves as “unallocated reserves”, although mining was previously carried out at the Lyulinskoye deposit. Despite the small reserves, some researchers noted the high quality of the raw materials (clinoptilolite content up to 90%) and the potential for a significant increase in reserves with additional geological exploration (Valieva, Nefedov, 2011; <https://www.uralinform.ru/>).

Deposits not listed on the Register of Reserves

In the Magadan Region, near the Kalym highway, there is a zeolite-bearing province represented by zeolitized vitro- and lithoclastic tuffs of acidic composition. The total predicted reserves of zeolites are about 100 million tons (Belitsky, Fursenko, 1992). The most promising is the Khurchan site, where the zeolite content is more than 70%. Thus, the zeolite-bearing province of Magadan is promising for staging work on prospecting and exploration of high-quality raw materials.

In Primorsky Territory, in addition to the Chuguevskoe deposit, zeolites are widespread within the East Sikhotealin volcanic belt, starting with the Novogorodskoe deposit in the south and ending with the Vodorazdelnoe occurrence in the north. In general, there are more than a dozen deposits including occurrences with a high zeolite content (Chekryzhov, Popov, 2001).

Also, during staging work on searching and exploring new sites of zeolite raw materials, it is worth paying attention to the Caucasus region, where there are favorable geological conditions for the localization of volcanic zeolites and the region has developed infrastructure.

Examples of the most important industrial zeolite deposits in Russia

In order to understand the differences in the formation conditions, geological structure and composition of deposits of various genesis, this paper will consider in more detail the most important industrial deposits of volcanogenic-sedimentary (Hongurui, Republic of Sakha (Yakutia)) and hydrothermal (Yagodninskoe, Kamchatka Territory) genesis. A separate article (Belousov et al., 2023) is devoted to the Khotynets deposit of zeolite-containing Tripoli, which belongs to the sedimentary type, therefore it will not be considered in this paper.

Yagodninskoye deposit (Kamchatka Territory)

The Yagodninskoe deposit of hydrothermal zeolites is located in the south of the Kamchatka Peninsula in the Yelizovsky district, 60 km west of Petropavlovsk-Kamchatsky. Geologically, the area is confined to the Verkhnekarymshinskaya volcanic zone, which is part of the South Kamchatka anticlinorium (Fig. 4). Along one of the large sublatitudinal faults, the thermal waters of the modern Bolshe-Bannaya hydrothermal system are discharged.

A deposits of perlite and zeolite are directly associated with an acidic volcanic massif of Upper Miocene-Pliocene age in the central part of the region (Nasedkin, Nasedkina, 1980; Nasedkin et al., 1985, 1988). The volcano is a complex system of lava flows, pyroclastic deposits and extrusive bodies. The zeolites are presented as altered vitroclastic tuff of rhyodacites, which lies at the base of the volcanic complex directly on dacites, as well as zeolitized perlites (Nasedkin, Nasedkina, 1980; Nasedkin et al., 1985, 1988).

The zeolites or strongly zeolitized tuffs are represented by homogeneous rocks of greenish and gray-greenish color with massive texture and relics of lithoclasts up to 10 cm in length. Depending on the content of minerals of the zeolite group, several types of rocks can be distinguished: 1) unaltered perlites with a characteristic perlite structure; 2) zeolitic rocks of greenish and gray-greenish color with massive texture and with a content of minerals of the zeolite group of about 60–70%; 3) zeolitized tuffs of pale green color with massive texture and a content of minerals of the zeolite group of 30–60%; 4) weakly zeolitized tuff breccias consisting of coarse-grained material and a zeolite content of 20–30% (Fig. 1c).

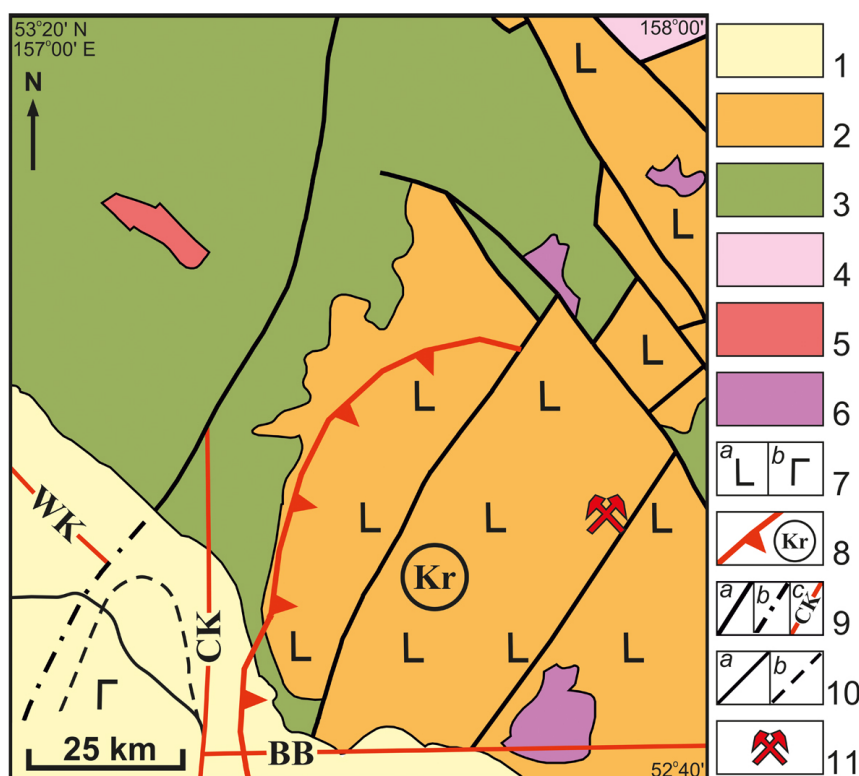


Fig. 4. Tectonic scheme of the Yagodninskoe deposit area, Kamchatka Peninsula, according to (Slyadnev et al., 2006, with modifications). 1–2 – Middle Miocene-Quaternary structural stage: 1 – coastal-marine and volcanic formations of the Pliocene-Quaternary substage, 2 – sedimentary deposits and volcanic formations of the Middle Miocene-Pliocene substage; 3 – metamorphosed terrigenous deposits, terrigenous-volcanogenic and volcanic formations of the Lower Cretaceous-Lower Eocene structural stage; 4 – metamorphic formations of the pre-Mesozoic structural stage; 5–6 – intrusive formations: 5 – Cretaceous-Paleocene age of acidic and intermediate composition, 6 – Eocene-Pliocene age of different composition; 7 – superimposed volcanic belts and zones (a – South Kamchatka belt; b – Tolbachik-Klyuchevskaya riftogenic volcanic zone); 8 – volcano-tectonic structure (Kr – Karymshinskaya); 9 – faults (a – main structure-forming faults exposed on the daylight surface; b – hidden under overlying formations; c – deep faults according to geophysical data (BB – Bolshe-Banny, ZK – West Kamchatka, CK – Central Kamchatka); 10 – boundaries (a – stages, substages, superimposed volcanic belts and zones, intrusive bodies; b – grabens and horsts); 11 – Yagodninskoe deposit

The zeolites are mainly represented by clinoptilolite and, to a lesser extent, heulandite, mordenite and stilbite. The bulk of the zeolite rock is composed of dense aggregates with a cryptocrystalline structure (Fig. 2b), but well-crystallized clinoptilolite of various morphologies is also found, filling the pore space (Fig. 2d) (Belousov et al., 2024).

The deposit's reserves of cat. A+B+C₁ are 7.3 million tons. At the moment, the deposit is not being exploited, but the studies carried out allow us to classify the zeolites of the Yagodninskoe deposit as high-quality raw materials.

Honguruu deposit (Republic of Sakha (Yakutia))

The Honguruu deposit is located in the Republic of Sakha (Yakutia), 91 km southeast of the village of Suntar and is of the volcanogenic-sedimentary type. Structurally, the deposit is confined to the western part of the Vilyui syncline and is located within the Kempendyay depression.

The geological structure of the territory includes Devonian volcanogenic-sedimentary rocks of the Kempendyay suite (D₃km) and Upper Devonian-Lower Carboniferous ones of the Kurunguryakh suite (D₃–C₁kr), to which the productive zeolite layers are confined (Kolodeznikov et al., 1992; Safronov et al., 2004) (Fig. 5).

The Kempendyai suite (D₃km) is represented by speckled volcanogenic-terrigenous-carbonate rocks. The suite is underlain by a rock salt layer and is conformably overlain by Upper Devonian-Lower Carboniferous formations. The thickness of the exposed part of the Kempendyai suite in the section is 174 m. The main part of the suite is composed of terrigenous rocks.

The Kurunguryakh suite (D₃–C₁kr) conformably lies on Upper Devonian formations. The thickness of the studied part is 166.3 m. In the section of the suite, layers of zeolite tuffs are distinguished. The main part of the section is composed of carbonate rocks.

In total, there are 4 zeolite layers at the deposit, which strike north-east and plunge monoclinaly at an

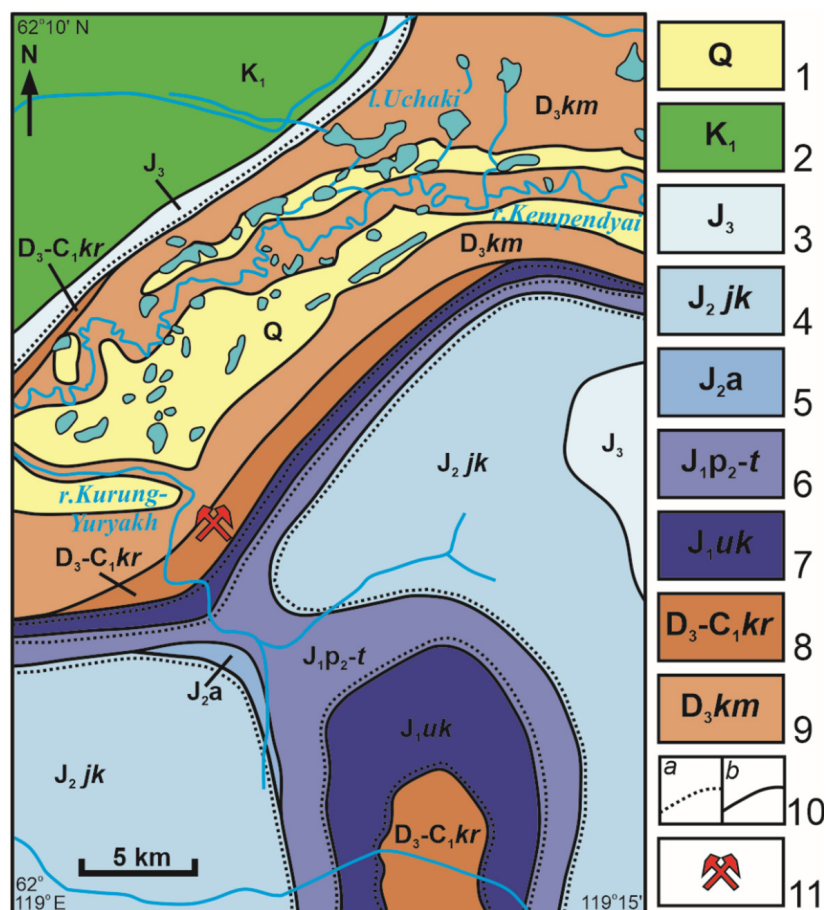


Fig. 5. Geological map of the area of the Honguruu zeolite deposit (Republic of Sakha (Yakutia)) according to (Nakhabtsev et al., 1975; Petrova et al., 1993 with additions and modifications). 1 – undifferentiated Quaternary rocks: loams, sandy loams, peat, sands, pebbles, silt; 2 – undifferentiated terrigenous rocks of the Cretaceous age: sands with interlayers of sandstones, siltstones, marls, limestones, pebbles and mudstones; 3–7 – terrigenous rocks of the Jurassic age; 3 – undifferentiated rocks: sands, clays, siltstones, mudstones, coals; 4 – sands, sandstones, siltstones, mudstones, gravelites of the Yakutian suite; 5 – sands with interlayers of sandstones of the Aalenian stage; 6 – mudstones, siltstones, sands, sandstones, limestones of the Upper Pliensbachian substage – Toarcian stage; 7 – sands with interlayers of sandstones, pebbles, gravelites, siltstones, mudstones, conglomerates of the Ukugut suite; 8 – Upper Devonian – Lower Carboniferous volcanogenic-sedimentary deposits of the Kurunguryakh suite: dolomites, limestones, marls, mudstones, tuffaceous siltstones, tuffites, tuffs, sandstones, anhydrites; 9 – Devonian volcanogenic-sedimentary rocks of the Kempendyay suite: siltstones, argillites, sandstones, marls, vitroclastic tuffs and tuffites, anhydrites, rock salt; 10 – boundaries: a – unconformable, b – normal; 11 – Honguruu deposit

angle of 25–45°. The thickness of the layers ranges from 5.6 to 11 m; they lie in conformity with the enclosing sedimentary and volcanic rocks. The layers have been traced over a distance of 6–8 km, their structure has been studied to a depth of 100–160 m. Reserves of category A+B+C₁ amount to 11.3 million tons. The deposit is being exploited, with annual production of about 30–50 thousand tons. (State Reserves Committee of the Russian Federation: Zeolites, 2019).

The zeolites are mainly light greenish, greenish-gray in color. In some cases, beige varieties are found. Massive, thin- and thick-slab textures predominate (Fig. 1b).

The content of zeolite group minerals in the average industrial sample is about 76%, they are mainly represented by clinoptilolite and heulandite. According

to the composition of exchange cations, rocks of both calcium-sodium and magnesium-calcium types are distinguished. Moreover, calcium varieties are mainly represented by heulandite.

The formation of zeolites of the Honguruu deposit is associated with the transformation of terrigenous and ash material accumulating in coastal lagoons and tidal zones with waters of high salinity.

It is worth noting that all the Upper Devonian-Lower Carboniferous rocks of the Kempendyay Depression contain zeolites. Back in 1983, K.E. Kolodeznikov identified the Kempendyay zeolite-bearing region (Nikolaev et al., 1993), where there are a number of zeolite deposits, but only the Honguruu deposit is listed on the State Registry of Reserves.

Comparative analysis of the composition and properties of zeolites from industrially important deposits of Russia and the CIS

This section presents a comparative analysis of the main industrially important zeolite deposits in Russia and the CIS using the example of the Khotynets (Oryol Region), Hongurru (Republic of Sakha (Yakutia)), Yagodninskoe (Kamchatka Territory), Kholinskoe (Zabaikalsky Territory), Nor Kokhb (Republic of Armenia) and Sokernitskoe (Ukraine) deposits.

In terms of mineral composition, the samples of all the studied deposits, with the exception of the Khotynets deposit, consist of more than 50% minerals of the zeolite group (Table 2, Fig. 6). As described above, the useful component of the Khotynets deposit is considered to be the sum of minerals of the opal-cristobalite, smectite and zeolite groups.

Since the diagnostics of a specific mineral from the zeolite group is not a trivial task, a set of methods was used, including X-ray phase analysis, X-ray fluorescence analysis, infrared spectroscopy and thermal analysis. For the rocks of the Khotynets, Sokernitskoye and Nor Kokhb deposits, the zeolites are represented mainly by clinoptilolite. In the rocks of the Yagodninskoe deposit, clinoptilolite is mainly found and, to a lesser extent, mordenite, stilbite and heulandite. The rocks of the Hongurru and Kholinskoe deposits are characterized by the content of both clinoptilolite and heulandite, and at the Hongurru deposit, heulandite forms independent varieties.

All samples of the considered deposits have a characteristic composition of rock-forming oxides. The silicon to aluminum ratio is on average 5–6 units, which corresponds to rocks of the clinoptilolite-heulandite

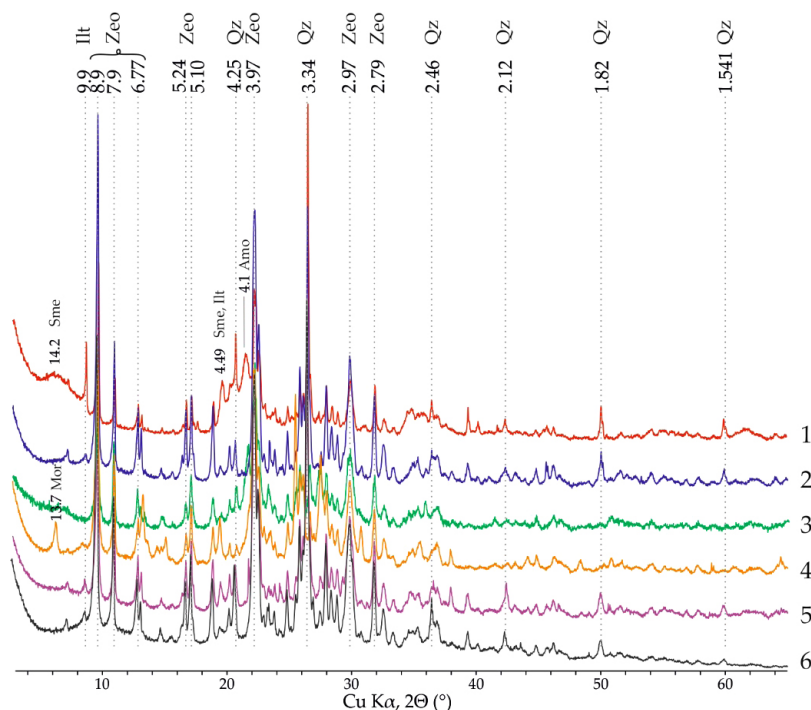


Fig. 6. X-ray diffraction pattern of zeolite samples: 1 – Khotynets; 2 – Khongurru; 3 – Kholinskoe; 4 – Yagodninskoe; 5 – Nor Kokhb; 6 – Sokernitskoe

Deposit	Zeolite	Smectite + mixed layered	Illite	Amorph SiO ₂	Cristobalite	Tridymite	Quartz	Feldspars	Calcite	Anatase
Khotynets	28.0	22.4	6.1	27.8	1.2	1	8.4	4.0	0.4	0.7
Khongurru	76.6	6.4	3.8	—	—	—	9.1	4.1	—	—
Kholinskoe	57.8	15.8	—	—	4.2	—	0.7	21.4	—	—
Yagodninskoe	69.3	—	14.1	—	7.8	—	—	8.8	—	—
Nor Kokhb	61.7	8.7	10.2	—	0.6	—	10.8	6.7	1.3	—
Sokernitskoe	71.8	1.4	8.4	—	—	—	15.0	3.4	—	—

Table 2. Mineral composition of zeolite samples, % by weight

series (Table 3). The exception is the Yagodninskoe deposit, the ratio of which is 8.9 units.

The specific surface area and porosity of the studied samples fluctuate within the range of 13–31 units, which is also typical for zeolite rocks (Table 4). Since nitrogen molecules cannot penetrate into the zeolite channels when determining the specific surface area, this value characterizes the macro- and mesopores which are most prevalent in the rocks. The presence of micropores is observed only in the samples of the Yagodninskoe and Khotynets deposits.

The most indicative characteristic of the sorption activity of zeolites is the cation exchange capacity (CEC). The maximum CEC value is found in samples from the Yagodninskoe, Hongurruu, Nor Kokhb and Sokernitskoe deposits, and is 205, 202, 199 and 190 mg-eq/100 g, respectively, which is primarily due to the high content of zeolite group minerals in the rocks (Table 5). The CEC value of the Kholinskoye and Khotynets deposits was 160 and 78 mg-eq/100 g, respectively.

Two the main groups of zeolites could be distinguished according to the composition of exchange cations: alkaline zeolites with predominant amounts of

exchange cations represented by potassium and sodium, and alkaline earth zeolites with a predominance of calcium and magnesium. Alkaline zeolites include the Yagodninskoe, Nor Kokhb and Kholinskoe deposits, and in the first two, potassium cations predominate over sodium. Zeolites of the Hongurruu deposit, as well as the Khotynets and Sokernitskoe deposits, belong to the alkaline-earth type.

It is worth noting that when using zeolites as sorbents, the most preferable are predominantly alkaline varieties, since sodium and potassium cations are more mobile and could easily be replaced during the purification of solutions and gases.

The thermal characteristics of the studied samples are also typical for zeolite rocks. Two main endothermic peaks are distinguished (Fig. 7). The endothermic effect within 100–110 °C is associated with the removal of surface moisture and, partially, water from the zeolite pores. The endothermic effect up to 500 °C is associated with the removal of water from the zeolite channels. It is important to note that some zeolites, such as clinoptilolite, have relatively high thermal stability; their crystal lattice is stable up to 750–900 °C, after

Deposit	LOI*	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	P ₂ O ₅	SO ₃
Khotynets	6.29	1.66	0.33	11.85	71.81	4.54	2.27	0.14	0.052	0.91	0.01	<0.01
Hongurruu	13.17	2.84	1.33	11.69	64.88	1.32	2.55	0.19	0.021	1.10	0.03	<0.02
Kholinskoe	6.03	2.22	0.26	13.11	70.77	4.53	1.63	0.13	0.070	1.11	0.01	<0.01
Yagodninskoe	10.27	0.11	1.53	8.09	71.97	1.50	1.98	0.50	0.004	3.58	0.27	<0.01
Nor Kokhb	9.53	2.65	1.09	11.93	66.91	2.32	3.29	0.24	0.023	1.72	0.06	<0.01
Sokernitskoe	8.56	1.48	0.65	13.14	68.62	3.35	2.38	0.16	0.041	1.11	0.02	<0.02

Table 3. Chemical composition of zeolite samples, % by weight. *LOI – loss on ignition

Deposit	Specific surface area, m ² /g	Pore volume, nm	Average diameter, nm	Micropore volume, cm ³ /g	Pore size distribution, %	
					micropores	meso-macropores
Khotynetskoe	26.8	0.089	3.77	<0.001	14	86
Khongurruu	13.3	0.042	8.46	<0.001	<1	100
Kholinskoe	31.9	0.109	7.58	<0.001	<1	100
Yagodninskoe	25.3	0.068	8.14	0.002	16	84
Nor Kokhb	20.1	0.073	4.72	<0.001	<1	100
Sokernitskoe	14	0.053	4.89	<0.001	<1	100

Table 4. Volume of specific surface area and pore size distribution of zeolite samples

Deposit	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Sum
Khotynets	12.3	18.7	40.2	7.2	78.4
Hongurruu	73.8	7.4	89.8	31.1	202.1
Kholinskoe	53.0	46.9	55.9	4.6	160.3
Yagodninskoe	43.5	71.3	81	10.1	205.9
Nor Kokhb	43.2	71.2	76.9	7.9	199.2
Sokernitskoe	34.5	38.4	94.8	22.7	190.4

Table 5. Cation exchange capacity of zeolite samples, mg-eq/100 g

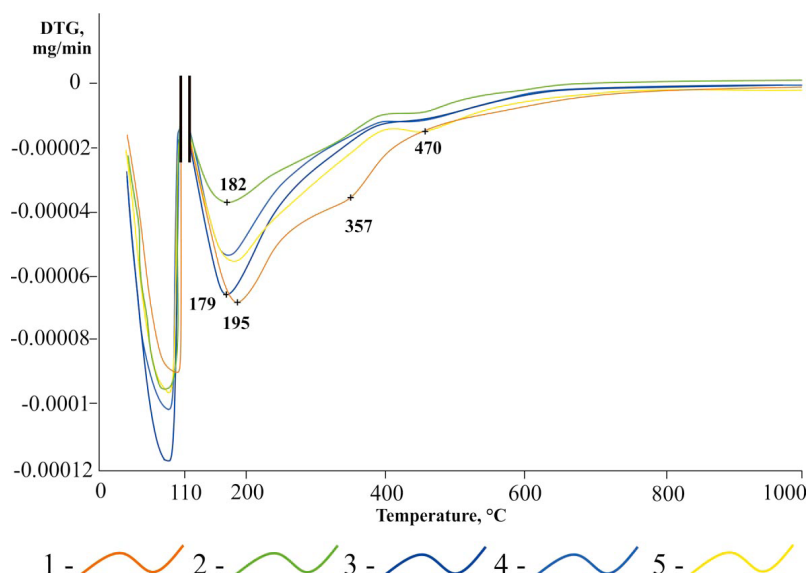


Fig. 7. Results of thermal analysis of zeolite samples from different deposits. 1 – Hongurou; 2 – Kholinskoe; 3 – Yagodninskoe; 4 – Nor Kokhb; 5 – Sokernitskoe

which the mineral undergoes amorphization. The zeolite from the Hongurou deposit is characterized by a distinct endothermic effect around 357 °C, which is associated with the presence of heulandite in the composition of the studied sample (Foldvari, 2011). The thermal effect in the region of 450–500 °C, noted to one degree or another in almost all samples, may be associated with an admixture of clay minerals, namely mixed-layer illite-smectite and illite.

Conclusion

About 120 deposits and occurrences of zeolites have been identified in Russia, however, the State Registry of Reserves includes only 18 deposits with reserves of category A+B+C₁ – 594 million tons, and category C₂ – 799 million tons. The extraction of zeolite rocks is small-scale, only the Khotynets (Oryol Region), Hongurou (Republic of Sakha (Yakutia)), Kholinskoe (Zabaikalsky Territory) and Chuguevskoe (Primorsky Territory) deposits are being exploited with a total annual production of about 60–80 thousand tons. Five zeolite-bearing provinces are distinguished: Central, Southern, Ural, Siberian and Far Eastern. Almost all of the mined material is used to produce hygienic bedding for animals, soil for houseplants, as an additive to concrete, and for the production of foam glass, while the use of zeolites in high-tech industries is in the development stage.

Zeolites are widespread, they are found both as impurities in deposits of silicites and carbonate rocks, where their content is insignificant, and forming large deposits of high-quality, so-called “volcanic” zeolite. The first type includes sedimentary zeolites, mainly found within the Russian and West Siberian plates and the Siberian platform. Deposits of high-quality “volcanic” zeolite are represented by volcanogenic-

sedimentary and hydrothermal types. They are directly related to volcanic activity, are formed on ash material, tuffs and perlites and are confined mainly to the Far Eastern and Siberian regions. Due to the peculiarities of their formation, deposits of volcanogenic zeolite are characterized by a spatial relationship with deposits of perlites, silicites, bentonites, hard and brown coals.

Despite significant reserves of zeolites in Russia, their production volumes remain at a very low level. Taking into consideration the degree of exploitation of the deposits, the quality of raw materials and the distance from transport channels, the most promising sites worthy of attention for prospecting/exploration work for high-quality zeolites were proposed.

One of the most promising regions in terms of the number of large sites with volcanic zeolites is the Transbaikal Territory. Of the sites put on the State Registry of Reserves, it is worth noting the Kholinskoe deposit. It is in the status of “being exploited”, but production at the deposit does not exceed 1–2 thousand tons per year. Given its large reserves, the high quality of its raw materials, as well as the availability of infrastructure, the Kholinskoe deposit belongs to the category of the most promising sites. The Badinskoe and Shivyrtuiskoe deposits are quite well studied and have high quality raw materials, and therefore they deserve more detailed attention and reassessment of the possibility of their further study and subsequent exploitation.

Zeolites of the Chuguevskoe deposit, located in Primorsky Territory, are distinguished by high performance properties. The Republic of Buryatia is also characterized by a high degree of zeolite content. In particular, the raw materials of the Mukhor-Talinskoe deposit are high-quality zeolites of volcanic origin, and

its relative proximity to railways makes it an attractive site in economic terms.

The hydrothermal zeolites of the Yagodninskoe deposit, located in the Kamchatka Territory, are unique in their properties, have a predominantly potassium composition of exchange cations and have increased sorption properties, and therefore can rightfully be classified as very promising sites. However, the development of the deposit is complicated by logistical difficulties.

Despite the small reserves, the Lyulinskoe and Mysovskoe (Khanty-Mansiysk Autonomous District) deposits can be classified as promising, since they have high-quality raw materials and the potential for a significant increase in reserves with additional geological exploration.

Also, sites with high potential include the zeolite-bearing province of the Magadan Region with predicted zeolite reserves of about 100 million tons, Primorsky Territory, where zeolite-bearing is associated with acidic volcanism within the East Sikhote-Alin volcanic belt, as well as the Caucasus region, where there are favorable geological conditions for the formation of volcanic zeolites and a developed infrastructure.

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References

- Belitsky I.A., Fursenko B.A. (1992). Natural zeolites of Russia: Geology, physical and chemical properties and application in industry and environmental protection. Novosibirsk: RAS, vol. 1, *Proc. Republic meeting "Natural zeolites of Russia"*, November 25–27, 1991, 171 p. (In Russ.)
- Belousov P.E., Chupalenkov N.M., Karelina N.D., Krupskaya V.V. (2020). Geological and structural position of bentonite and zeolite deposits in Russia. *Proc. Conf.: Rock, Mineral and Ore Formation: Achievements and Prospects of Research*. Moscow: IGM, pp. 826–829. (In Russ.)
- Belousov P.E., Karelina N.D. (2022). Volcano-Sedimentary and Hydrothermal Bentonite Deposits. *Journal of Volcanology and Seismology*, 16(6), pp. 451–461. DOI: 10.1134/S0742046322060021
- Belousov P.E., Karelina N.D., Morozov I.A., Rudmin M.A., Milyutin V.V., Nekrasova N.A., Rumyantseva A.O., Krupskaya V.V. (2023). Zeolite-containing tripoli of khotynets deposit (Orel region): mineral composition, sorption properties and formation conditions. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 334(5), pp. 70–84. (In Russ.) DOI: 10.18799/24131830/2023/5/4001
- Belousov P.E., Rumyantseva A.O., Kailachakov P.E. (2024). Volcanic Zeolites at the Yagodninskoe Deposit, Kamchatka. *Journal of Volcanology and Seismology*, 18(3), pp. 201–212. DOI: 10.1134/S0742046324700611
- Bushinsky G.I., Shumenko S.I. (1970). Refined definition of zeolite from chalk deposits of Bryansk. *Litologiya i poleznye iskopaemye = Lithology and mineral resources*, 6, pp. 111–114. (In Russ.)
- Burov A.I., Distanov U.G., Zainullin I.I., Konyukhova T.P., Mikhailov A.S., Nasedkin V.V., Plenkin A.P., Sabitov A.A. (1990). Natural sorbents of the USSR. Moscow: Nedra, 208 p. (In Russ.)
- Chekryzhov I.Yu., Popov V.K. (2001). Zeolites of Primorye: genesis and mineralogical-geochemical characteristic. *Uspekhi nauk o zhizni*, 1, pp. 82–96. (In Russ.)
- Christidis G.E. (2011). Advances in the Characterization of Industrial Minerals. *European Mineralogical Union Notes in Mineralogy*, v. 9. <https://doi.org/10.1180/emu-notes.2010.emu9>
- Distanov U.G., Aksenov E.M., Sabitov A.A. et al. (2000). Phanerozoic sedimentary paleobasins of Russia: problems of evolution and minerageny of non-metals. Moscow: Geoinformatika, 399 p. (In Russ.)
- Foldvari M. (2011). Handbook of thermogravimetric system of minerals and its use in geological practice. Budapest: Geol. inst. of Hungary, 180 p.
- Gadore V., Mishra R. S., Yadav N., Yadav G., Ahmaruzzaman Md. (2024). Advances in zeolite-based materials for dye removal: Current trends and future prospects. *Inorganic Chemistry Communications*, 66, 112606. <https://doi.org/10.1016/j.inoche.2024.112606>.
- Gordienko I.V., Zhamoysina L.G. (1995). Mukhortalinskoye perlite-zeolite deposit. Moscow: Geoinformmark, v. 1, b. 2, pp. 226–233. (In Russ.)
- Jrbashyan R.T., Mnatsakanyan A.Kh., Petrosov I.Kh. (1999). The main deposits of zeolites in Armenia. Yerevan: Academy of Sciences of the Armenian SSR, 190 p. (In Russ.)
- Khardikov A.E., Boiko N.I., Agarkov Yu.V. (2000). Zeolites of southern Russia. *Doklady Earth Sciences*, 371(5), pp. 469–472. (In Russ.)
- Kolodeznikov K.E., Novgorodov P.G., Matrosova T.V., Stepanov V.V. (1992). Kempendyai zeolite-bearing region. Yakutsk: YANTs SO RAN, 68 p. (In Russ.)
- Kossovskaya A.G. (1980). Natural zeolites. Moscow: Nauka, 224 p. (In Russ.)
- Kordala N., Wyszowski M. Zeolite properties, methods of synthesis, and selected applications. (2024). *Molecules*, 29, 1069. <https://doi.org/10.3390/molecules29051069>
- Koretsky D.S., Ignatova A.Yu. (2010). Study of the influence of zeolite from the Pegasus deposit on plant growth. *Vestnik KuzGTU*, 2(78), pp. 92–95. (In Russ.)
- Marantos I., Christidis G.G., Ulmanu M. (2011). Zeolite formation and deposits. *Handbook of Natural Zeolites*, pp. 19–36. <https://doi.org/10.2174/978160805261511201010028>
- Milyutin V.V., Belousov P.E., Nekrasova N.A., Krupskaya V.V. (2023). Sorption of radionuclides ¹³⁷Cs and ⁹⁰Sr on zeolites of various genesis. *Radiochemistry*, 65(3), pp. 346–353. DOI: 10.1134/S1066362223030104
- Ming D. W., Boettinger J.L. (2001). Zeolites in soil environmental. Berlin, Boston: De Gruyter, pp. 323–346. <https://doi.org/10.2138/rmg.2001.45.11>
- Muravyov V.I., Voronin B.I. (1979). Features of the composition of zeolites of the glauconite-siliceous formation and the problem of classifying the clinoptilolite-heulandite group. *Litologiya i poleznye iskopaemye = Lithology and mineral resources*, 2, pp. 75–82. (In Russ.)
- Muravyov V.I. (1983). Mineral parageneses of glauconite-siliceous formations. Moscow: Nauka, 208 p. (In Russ.)
- Muravyov V.I. (1987). Issues of abiogenic sedimentary silica accumulation. Origin and practical use of siliceous rocks. Moscow: Nauka, pp. 86–96. (In Russ.)
- Nasedkin V.V., Nasedkina V.Kh. (1980). Genetic and morphological types of clinoptilolite-mordenite mineralization in volcanic areas. *Natural zeolites*. Moscow: Nauka, pp. 122–134. (In Russ.)
- Nasedkin V.V., Solovyova T.N., Mager A.V. et al. (1985). Report. A comprehensive study of the raw material base and physical and mechanical properties of volcanic rocks (pumice, slag, tuff, perlite) of the Far East and Kamchatka. Moscow, 425 p. (In Russ.)
- Nasedkin V.V., Solovyova T.N., Nistratova I.E. et al (1988). Comparative characteristics of the mineral composition of zeolite rocks from Mount Yagodnaya and the products of modern mineral formation in the valley of the river. Bannaya Peninsula Kamchatka. Modern hydrotherms and mineral formation. Moscow: Nauka, pp. 70–85. (In Russ.)
- Nasedkin V.V., Shirinzade N.A. (2008). Dash-Salakhinskoe bentonite deposit. Formation and development prospects. Moscow: GEOS, 85 p. (In Russ.)

Nakhbatshev Yu.S., Korchagin V.P., Shcherbakov O.I. et al. (1975) State geological map at a scale of 1:200,000, Nizhnevilyuyskaya series, Sheet P-50-XVIII, FSUE VSEGEI, Yakutsk Geological Department.

Nikolaev A.V., Petrova A.I., Razumov A.N., et al. (1993). Report on the results of detailed exploration of the Honguruu zeolite deposit. TKZ N 417. Diamonds of Russia-Sakha AK.

Petrova A.I., Starygina T.T., Nikolaev A.V. (1993). Geological map of the work area. To the report on the results of detailed exploration of the Honguruu zeolite deposit. (In Russ.)

Rogulina L.I., Yurkov V.V. (2006). Features of the mineral composition of zeolites in the Amur region. *LITHOSPHERE (Russia)*, 1, pp. 149–157. (In Russ.)

Savko A.D., Zhabin A.V., Dmitriev D.A. (2001). Morphology of particles of zeolites of the heulandite group and free silica minerals (using the example of sediments of the Voronezh anticline). *Vestnik Voronezhskogo universiteta. Geologiya*, 12, pp. 51–56. (In Russ.)

Savko A.D., Dmitriev D.A., Ivanova E.O., Chigarev A.G. (2009). Lithology and minerals of the Santonian of the central part of the KMA. Voronezh: Voronezhskiy gosudarstvennyy universitet, 108 p. (In Russ.)

Savko A.D., Sviridov V.A. (2014). Geochemistry of lithogenesis. *Proc. All-Russian Meet. Syktyvkar*, pp. 206–209. (In Russ.)

Savko A.D., Dmitriev D.A., Sviridov V.A. (2019). Zeolite – siliceous weathering crusts on chalk rocks of the Voronezh anticline. Facies analysis in lithology: theory and practice. *Ekzolit*. Moscow, pp. 126–128. (In Russ.)

Savko A.D., Ivanova E.O., Chigarev A.G. (2019). Zeolites in the Upper Cretaceous deposits of the Belgorod and Kursk regions. *Sorbtionnye i Khromatograficheskie Protssy*, 10(3), pp. 433–439. (In Russ.)

Safronov A. F., Kolodeznikov K. E., Uarov V. F. (2004). Mineral resources of the Suntar region and prospects for their industrial development. Yakutsk: Izd-vo SO RAN, pp. 49–57. (In Russ.)

Semenov V.P., Askochinsky B.V., Seleznev V.N. (1974). Location, genesis and possibilities of using siliceous rocks of the Upper Cretaceous of the Voronezh anticline. *Raw material base of siliceous rocks of the USSR*. Moscow: Nauka, pp. 36–40. (In Russ.)

Senkovsky Yu.N. (1977). Lithogenesis of siliceous strata in the southwest of the USSR. Kyiv: Naukova Dumka, 127 p. (In Russ.)

Senkovsky Yu.N. (1980). Silicon accumulation in the Cretaceous on the continental margin of the Tethys part of the European block. *Sedimentary rocks and ores*. Kiev: Naukova Dumka, pp. 174–182. (In Russ.)

Sklyarova G.F. (2021). Zeolites - an unconventional multi-purpose type of agrochemical raw materials in the Far East. *Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal*, 5, pp. 36–44. (In Russ.)

Slyadnev V.I., Khasanov Sh.G., Krikun N.F. (2006). State geological map of scale 1:1000000 sheet N-57, VSEGEI, Kamchatgeologiya. (In Russ.)

Smirnov P.V., Konstantinov A.O. (2016). Comparative studies of Eocene and Paleocene diatomites of the Trans-Urals (using the example of the Kamyshevskoye deposit and the Brusyan section). *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 327(11), pp. 96–104. (In Russ.)

Smirnov P.V., Konstantinov A.O. (2017). Biogenic siliceous accumulation in Early Paleogene marine basins of Western Siberia: Factors and stages. *LITHOSPHERE (Russia)*, 17(4), pp. 26–47. (In Russ.)

State balance of mineral reserves of the Russian Federation: “Zeolites” (2019). Moscow: Rosgeolfond, 19 p. (In Russ.)

Valieva I.R., Nefedov V.A. (2011). Zeolites of the subpolar and polar Urals. *Nauka i sovremennost*. (In Russ.)

Vasilyanova L. S., Lazareva E. A. (2016). Zeolites in ecology. *Novosti nauki Kazakhstana*, 1(127), pp. 61–85. (In Russ.)

Yusupov A.R., Mamaev S.A., Yusupov Z.A., Mamaev A.S. (2021). Study of zeolite-containing siliceous rocks of Dagestan to obtain a mineral additive for cement. *Vestnik of Geosciences*, 10(322), pp. 42–46. (In Russ.) <https://doi.org/10.19110/geov.2021.10.5>

Zhabin A.V., Dmitriev D.A. (2002). Authigenic mineral formation in Paleocene and Upper Cretaceous deposits of the Voronezh anticline. *Proceedings of Voronezh State University. Series: Geology*, 1, pp. 84–94. (In Russ.)

Zonkhoeva E.L. (2018). Natural zeolites of Transbaikalia: properties and application. Ulan-Ude: BSC SB RAS, 192 p. (In Russ.)

Zorina S.O., Afanas'eva N.I., Volkova S.A. (2008). Zeolite potential of upper cretaceous-paleogene sedimentary rocks in the eastern and southeastern Russian plate. *Lithology and Mineral Resources*, 43(6), pp. 577–587. <https://doi.org/10.1134/S0024490208060059>

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