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PROSPECTS FOR THE DEVELOPMENT OF LIGHT AND HEAVY RARE EARTH ELEMENTS FROM ZIRCON-ILMENITE DEPOSITS IN UKRAINE

Purpose. To identify the most promising mineral deposits in Ukraine containing light and heavy rare earth elements (REE) in accordance with the assessment criteria of the European Commission, considering the global demand for critical raw materials and the cost of their sale.

Methodology. The work used a set of research methods: generalization – systematization of information on world production and demand for light and heavy rare earth elements; analogy and comparison – generalization of experience in determining the distribution of rare earth elements in placer and core deposits; analysis and synthesis – to substantiate the feasibility of involving existing deposits of critical raw materials in development; empirical – to compare existing information on deposits of rare earth elements in Ukraine with the classification of the European Commission, in which they are divided into light and heavy materials.

Findings. The most promising primary and placer deposits of light and heavy rare earth elements in Ukraine have been identified, according to an assessment by the European Commission. It has been established that the leading light rare earth elements found in zircon-ilmenite deposits of Ukraine are lanthanum, cerium, praseodymium, and neodymium, while the heavy ones are represented by terbium, dysprosium, erbium, and ytterbium. The potential content of light and heavy REE in primary deposits of Ukraine has been determined, according to which the main concentrations were found for light elements. Of the total content of light REE in ore, the largest share is represented by cerium (up to 28 % of the total quantity of deposits), lanthanum (up to 21 % of deposits) and neodymium (up to 18 % of deposits). In the same deposits, the yttrium content of the total share of REE does not exceed 3 %, and the remaining elements require additional study. It has been established that in placer deposits, the largest share of the total content of light REE in the ore is represented by cerium (up to 16 % of deposits), lanthanum (up to 14 %) and neodymium (up to 11 %), and the yttrium content does not exceed 3 %.

Originality. For the first time, the division of rare earth elements contained in zircon-ilmenite deposits in Ukraine into light and heavy elements, according to the European Commission's classification, was carried out. Deposits of critical mineral raw materials in Ukraine have been identified, from which light and heavy rare earth elements can be extracted. The need for further study of mineral deposits in the Azov, Volyn, and Polissia regions, as well as the Dnipropetrovsk and Zhytomyr regions, was substantiated to identify new locations of light and heavy rare earth elements and expand their existing list.

Practical value. It has been determined that Ukraine has sufficient potential for the development of light and heavy rare earth elements from zircon-ilmenite deposits, as classified by the European Commission. However, for their effective exploitation, it is necessary to create a modern geological database, develop and implement the latest enrichment technologies, attract investments with the development of a transparent market, and organize a closed production cycle.

Keywords: *critical raw materials, rare earth elements, minerals, mining, resource supply*

Introduction. The development of high-tech industries of the *21st* century is impossible to imagine without the use of light (LREE) and heavy (HREE) rare-earth elements. That is why they belong to the category of critical mineral raw materials, which play a crucial role in ensuring global supply chains; their shortage, even for a short time, can lead to the shutdown of entire economic sectors [1].

The existing experience of manufacturing and providing consumers with these materials shows that until 2010, their production was not attractive due to low profitability, and almost all REE in the world was manufactured in China. A significant reduction in supply from Chinese companies led to a tenfold increase in global prices for REE in 2011, arousing interest in other countries in developing new or preserving mineral deposits.

The search for new deposits around the world led to the entry of REO producers from the USA, Australia, Myanmar, Thailand, Malaysia, and other countries into the market in 2018 [2]. This allowed for partial diversification of securing global supply chain risks and stabilization of the cost of rare earth elements.

The primary consumer of REE is the military-industrial complex (MIC), which utilizes materials with high strength characteristics, including special glass, ceramics, and various alloys, for the development of aviation. An integral part of aluminum alloys is ultralight scandium, which is used in the construction of aircraft. Aerospace, modern gadgets, nuclear energy, photo and computer technology – all of these are impossible without the use of REE [3].

The use of light rare-earth elements, such as neodymium and praseodymium, is indispensable in energy and electrical engineering technologies. Their properties allow the creation of powerful permanent magnets used in electric car engines, portable electronic devices, and wind turbines.

In the chemical industry, lanthanum and cerium are utilized as catalysts, particularly in the oil cracking process. Car exhaust gas purification systems are effective due to the action of catalysts that include cerium. In the production of optical lenses and displays, cerium is used as a polishing material [4]. In metallurgy, lanthanum is used as an alloying agent for cast iron and steel to enhance mechanical properties and corrosion resistance. Thanks to cerium, glass acquires different colors, which is essential for optical filters and laser systems technologies.

The use of heavy REE has become widespread in various industries, especially in high-tech processes. For example, terbium and dysprosium are part of high-temperature neodymium-based magnets [5]. The presence of these REE increases the stability of magnets when heated, which is significant for aircraft and automotive engines.

From the general group of heavy REE, gadolinium is worth highlighting, since, due to its neutron absorption properties, it can be used as a material for control rods of nuclear reactors [6]. It is also used in medicine as a component of contrast agents for magnetic resonance imaging (MRI), in the manufacture of diagnostic equipment, and in medical lasers.

Europium is used in the production of phosphors for LEDs and television screens, while thulium, erbium, and holmium are used in lasers and fiber-optic communication systems [7].

Of particular note is ultralight scandium, which, according to the European Commission classification, does not belong to light or heavy REE. It is widely used as an alloying element to produce aluminum-based alloys. Due to its unique physicochemical properties, the addition of this material to alloys reduces the weight of materials while increasing their corrosion resistance and strength [8]. It is ideal for producing alloys used in aircraft, spacecraft, and missiles. Scandium is also used in high-tech alloys for 3D printing (additive manufacturing). This enables the printing of robust and lightweight structures for military and industrial applications. This REE has promising applications in next-generation batteries and fuel cells, increasing their service life and improving energy efficiency.

Thus, it can be argued that the development of the raw material base for obtaining light and heavy REE is one of the key areas of providing high-tech industries with critical materials [9, 10], and countries with existing reserves of these minerals are becoming essential players in the world market. Participation in the diversification of risks in the functioning of REE supply chains to consumers from leading economies worldwide will enable Ukraine to receive additional security guarantees and economic benefits. In this regard, the country faces an essential task of exploring, evaluating, and developing REE deposits as a critical resource for the functioning of the technological industries of the economy [11].

Literature review. In the work [12], three primary sources of rare earth elements in Ukraine are identified, which include primary apatite-ilmenite deposits and exogenous deposits formed because of weathering. Attention is also paid to complex ilmenite-rutile and ilmenite-zirconium deposits, in which rare earth elements occur as associated raw materials. It is determined that the content of these elements in titanium ores can vary depending on the specific deposit and geological conditions, which emphasizes the need for analysis of each selected area. It is worth noting that the primary research in this work focuses on titanium-bearing minerals within the Ukrainian Crystalline Shield, which does not allow for coverage of their entire geography within the country.

In the conducted studies [13], the authors propose distinguishing four groups of critical raw materials, which have varying degrees of geological certainty, determining their further potential for commercial development. Rare earth element deposits are often combined with lithium deposits into a single group, which is characterized as being mostly explored and having significant reserves. According to the information provided, these deposits are currently not in commercial production but can be brought into production after an appropriate geological and economic assessment. Thus, the results of the above studies suggest that there is an insufficient level of certainty regarding the prospects for the development of rare earth material deposits, considering their classification into light and heavy elements.

In the studies [14], a general description of the metallic mineral deposits of Ukraine is provided, from which the largest Kryvyi Rih iron ore basin is distinguished, which is connected to the base of the Ukrainian crystalline shield. Also, general information is given on the location of complex primary deposits of ilmenite-apatite ores and deposits of precious and rare-earth metals. However, during the studies, insufficient attention was paid to promising deposits of critical raw materials, which include light and heavy rare-earth elements.

The paper [15] examines the impact of the war in Ukraine on global trade in rare earth elements and related critical metals (Nb, Ta, Sc, Co, Pd), as these events pose a risk to the production of key technologies. Disruptions to global supply chains for critical raw materials have led the United States and the European Union to intensifying the efforts to diversify their sources of supply and reduce dependence on Beijing. The results of the paper emphasize the importance of the emergence of new players in the global rare earth elements market; therefore, the role of Ukraine, a country with significant mineral reserves, should be reassessed to attract potential investors.

The research conducted in [16] highlights the crucial role of rare earth elements in achieving the United Nations' Sustainable Development Goals. They play a key role in implementing energy transition through renewable programs in various countries. The factors contributing to the global shortage of rare earth metals have been identified. One of the primary challenges for the functioning of rare earth metal supply chains, from producers to consumers, is the increasing growth of geopolitical risks and the intensification of international competition. Thus, the presented analysis of works in the field of research enables us to determine the relevance of involving Ukraine in the development of new rare earth element deposits. This will partially diversify the risks associated with supplying critical raw materials on the global market. The classification of these deposits into light and heavy rare earth elements, as assessed by the EU, will enable us to unify our existing raw material base in accordance with European Commission legislation.

In 2024, the world reserves of rare earth elements are estimated at 90 million tons [17], while according to the United States Geological Survey (USGS), almost half of the estimated oxides of these metals are in China (44 million tons). Brazil and India are in second and third places with 21.0 and 6.9 million tons, respectively. The presence of significant reserves of rare earth ores in China enables it to play a dominant role in providing global supply chains with critical raw materials. Table 1 presents the distribution of the leading global producers of light and heavy rare earth elements, as classified by the European Commission in 2023 [18].

The analysis of the distribution of REE production by country worldwide in 2023 (Table 1) confirms that China's share ranges from 66.7 to 84.4 %, depending on the specific critical element. At the same time, the production of REOs (Rare earth oxides) in Australia and the United States reaches 19 % for all aspects except terbium, dysprosium, and scandium. The largest share of production in China is for terbium and dysprosium, accounting for 84.4 % of the total, while the share of scandium oxide production is the smallest among the others, at 66.7 %.

According to the results of the assessment of the United States Geological Survey (USGS), the global production of REE oxides in 2024 amounted to 390 thousand tons [19], excluding the scandium processing portion. Compared to 2023, REOs production increased by 9 % due to the introduction of new plants in China, Nigeria, and Thailand into the global market.

The most significant difficulty associated with obtaining REE lies in the process of their extraction from ore deposits, since they are usually found in a dispersed state. Even though rare earth metals are on average 200 times more common than gold, their concentrations are, in most cases, economically infeasible for extraction under existing technologies.

The total number of rare earth elements is 17, but it is worth noting that promethium is the only one among them that is a radioactive and unstable metal with a defined half-life. Because of this, its use in industry is minimal and it does not belong to the critical raw materials according to the European Commission 2023 classification.

According to the results of research [20], in the production of REE oxides, their ratio among themselves in descending order is as follows: cerium 43.2 %; lanthanum 24.9 %; neodymium 16.2 %; yttrium 4.9 %; praseodymium 4.6 %; samarium 2.2 %; gadolinium 1.4 %; dysprosium 0.9 %; erbium 0.5 %; ytterbium 0.4 %; europium 0.3 %; holmium 0.2 %; terbium 0.2 %; thulium 0.1 %; lutetium 0.1 %. According to the source [21], the annual production of scandium oxide is approximately 40 t, or 0.01 % of the total production of REE oxides in the world. The obtained data enable us to roughly estimate the annual production volumes of REE oxides in 2024 for each element, considering the total production volume of 390 thousand tons (Fig. 1).

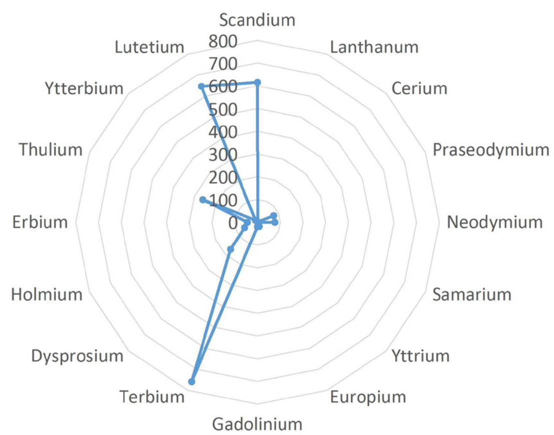
According to the established indicators (Fig. 1), the global production of REOs ranges from 40 tons of scandium to 168,500 tons of cerium. At the same time, almost 92 % of the total production volume of all REOs falls on light oxides of LREE. Among HREE, the most produced oxides are yttrium, gadolinium, dysprosium, erbium, europium, and ytterbium. The production of other REE oxides does not exceed 1,000 tons per year.

Since the production of REE oxides is extremely expensive, and the cost of extraction increases depending on the complexity of the technological processes and

Table 1

Central producing countries of rare earth oxides in 2023, %

REE	Share of production by country, %			
	China	Australia	USA	Myanmar
Light REE:				
- lanthanum, cerium, praseodymium, neodymium, samarium	68.3	9.9	9.2	–
Heavy REE:				
- yttrium, europium, gadolinium, holmium, erbium, thulium, ytterbium, lutetium	68.3	9.9	9.2	–
- terbium, dysprosium	84.4	–	–	9.3
Scandium:	66.7	–	–	–



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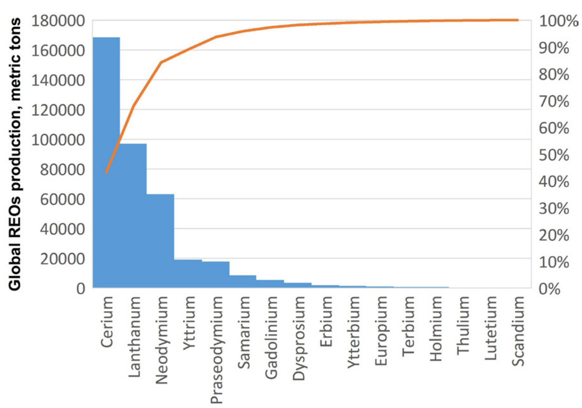


b

Fig. 1. Annual production volume of rare earth oxides (REOs) in 2024:

a – by atomic number; b – by production volume, tons the share of each element in the raw material, their value on the world market will vary significantly. To establish general indicators of the financial value of the oxides of each REE, they were ranked according to the current value on world markets, according to open source data [22, 23] (Fig. 2).

The ranking of REE oxides by cost (Fig. 2) allows us to state that terbium oxide is the most expensive, with a price of 758.6 USD/kg in 2025 [22]. The lowest costs are observed for the production of cerium oxide, 1.4 USD/kg. It has also been determined that the most expensive production is that of heavy REOs: lutetium at 646.9 USD/kg, thulium at 261 USD/kg [23], and dysprosium at 168 USD/kg. The cost of the remaining REE oxides does not exceed 80 USD/kg. These values correlate with the production volumes of REO oxides (Fig. 1), as metals produced in minimal volumes have the highest cost.

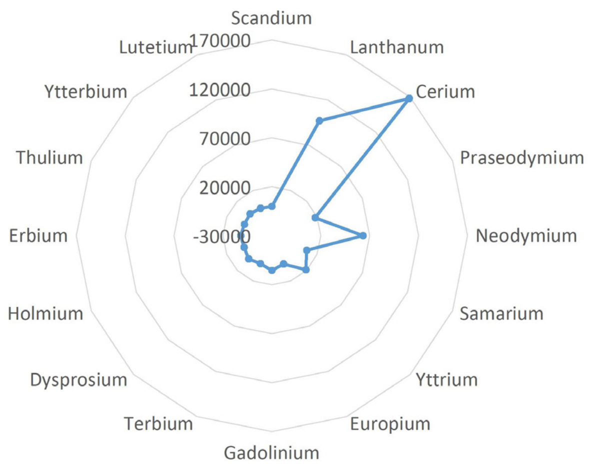
A similar relationship is observed for the rare earth element scandium, which, according to the EU classification, does not belong to either the light or heavy REE group. The production of its oxide is limited to 40 tons per year, while the cost reaches 615.40 USD/kg [22].

Analysis of the established production volumes of light and heavy REE oxides and scandium, and their market value in 2025, allows us to determine the total cost of manufactured raw materials in the world, as well as to rank the cost of fabricating individual rare earth metals by atomic number of chemical elements and market value of raw materials (Fig. 3).

The obtained results of ranking REE oxides by the total cost of manufactured raw materials (Fig. 3, *b*) enable us to establish that the most significant value in the raw materials market is 4.78 USD billion for neodymium oxide. This is due to its wide application in electric vehicles, turbines, laser glass, and electronics, as well as its lower cost of $ 75.6 USD/kg compared to terbium ($ 758.6 USD/kg) or dysprosium ($ 168.3 USD/kg). The following three positions are occupied by praseodymium (1.37 billion USD), terbium (591.7 million USD), and dysprosium (590.1 million USD). The lowest value of the raw material market is recorded for samarium, at 18 million USD. The market for scandium oxides is 24.6 million USD, with the smallest annual production volume (40 tons) compared to other REE oxides. The estimated total global market volume for REE oxides in 2025 is $ 8,573.2 million, which correlates with the 2024 data, which estimated the total at $ 8.7 billion [24].

To compare the technical and economic indicators of rare earth element extraction, a comparison of the cost and volumes of their production in relative terms was performed (Fig. 4).

The obtained generalized research results (Fig. 4) allow us to determine that the most expensive oxides are heavy REOs – terbium and lutetium, as well as scandi-



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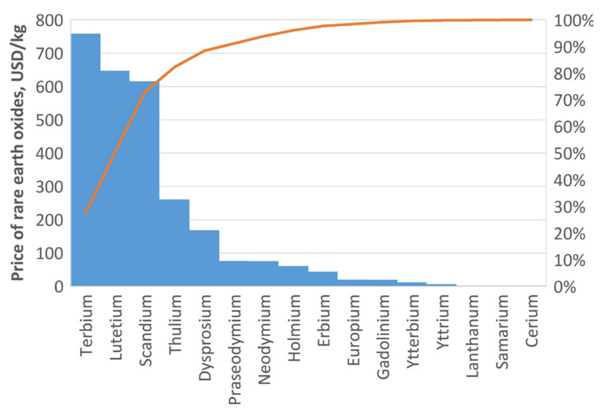

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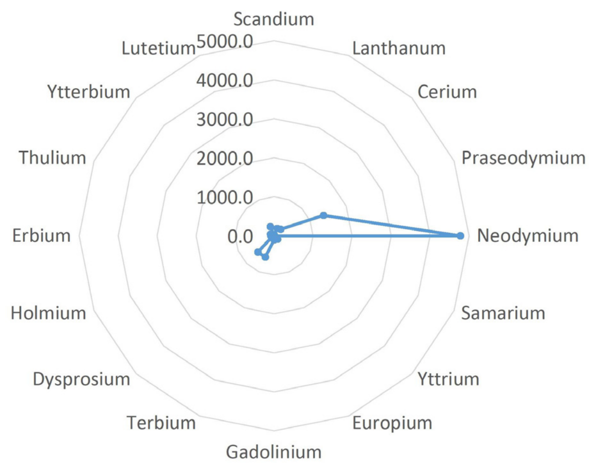
Fig. 2. The cost of rare earth metal oxides on the world market in 2025:

a – by atomic number; b – by product cost, USD/kg



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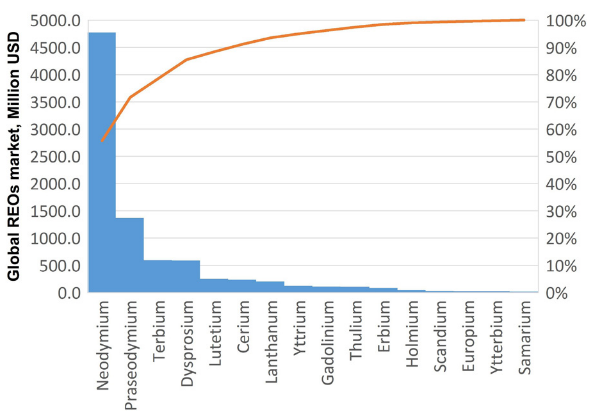

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Fig. 3. Total cost of rare earth raw materials in 2025:

a – by atomic number; b – by total market value of raw materials, Million USD

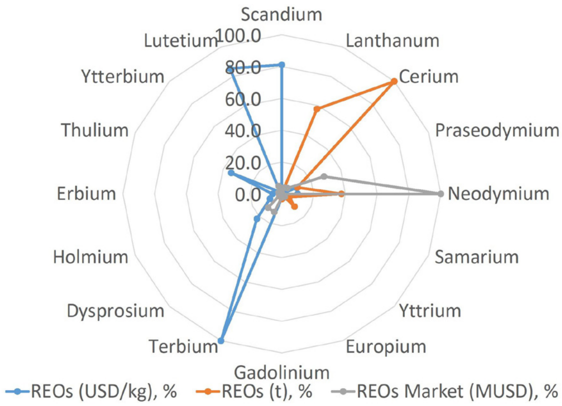

Fig. 4. Comparison of the cost and production volumes of rare earth materials in relative values:

REOs (USD/kg) – market value of rare earth oxides, terbium is taken as 100 % (758.6 USD/kg); REOs (t) – total production volume of rare earth oxides, cerium is taken as 100 % (168,000 t); REOs Market (MUSD) – total cost of manufactured critical mineral in 2025, neodymium oxide is taken as 100 % (USD $4 776M)

um; oxides of neodymium and praseodymium occupy the most significant sales market; the largest production volume is occupied by light REOs – cerium, lanthanum, and neodymium.

The established indicators enable further assessment of the attractiveness of new rare earth metal deposits through a feasibility study. The obtained cost indicators and world production volumes of each rare earth metal are necessary to determine the feasibility of organizing mining and enrichment operations at new mineral deposits that can potentially be involved in development in Ukraine.

To establish practical methods for developing deposits of light and heavy rare earth elements in Ukraine, an analysis of the mining and geological conditions of these deposits worldwide was conducted.

Today, more than 70 native rare earth minerals have been identified worldwide, belonging to the classes of phosphates, carbonates, oxides, fluorides, silicates, sulfides, and borates. A special group is composed of rare earth tungstates – yttrotungsite and arsenates – retschanite, which are very rare and have been practically unstudied. Most native REE minerals are found in pegmatites, hydrothermal veins, and weathering crusts. Additionally, rare earth elements are found as impurities in more than 280 minerals. By composition, REE minerals are divided into groups (the main minerals are given in brackets): cerium (bastnaesite, knoptite, loparite, monazite, parisite); gadolinium (samarskite); yttrium (euxenite, xenotime, yttrialite); yttrium-ytterbium (fergusonite). A group of complex minerals (apatite, orthite, gadolinite, pyrochlore, sphene) has also been identified. The accumulation of light lanthanides often occurs in feldspars, and heavy ones in dark-colored minerals.

The REE minerals themselves include (in brackets are examples of the most essential minerals for industry with the maximum possible content): phosphates (monacite, rhabdophanite, xenotime), carbonates (bastnaesite, parisite), oxides (fergusonite, loparite, euxenite), fluorides (yttrofluorite, yttrosynchysite), silicates (gadolinite, yttrialite), sulfates, borates, and tungstates. REEs can also be isomorphic impurities in other rock-forming and accompany minerals in deposit [25, 26].

The geochemical behavior of rare earth elements is shaped by their characteristics, namely crystallochemical bonds, ionic radii, changes in valence, tendency to complex formation, sorption properties, thermodynamic conditions of mineral formation, etc. [27, 28]. During the solidification of magmatic melt, there is a diffuse accumulation of REE, which is associated with their high solubility in fluoride systems. At the same time, during the post-magmatic stage, in pegmatites and carbonatites, their concentration increases due to the formation of their own minerals or isomorphic inclusion in other mineral phases. The probability of the formation of hydrothermal REE deposits, for example, at Bayan-Obo (China) and Wuke Hill (Tanzania), has also been proven. Similar deposits are also found in Ukraine. The mechanisms of salt melt separation can explain this at the final stages of magmatic system evolution. According to experimental data, REEs under equilibrium melt conditions with a fluid can disperse in the form of complex fluoride, phosphate, and halide forms, sometimes even at atmospheric pressure [25, 27]. At the same time, such complexes are not detected with chlorine; however, under conditions of chloride-sulfide separation, the elements can concentrate in silicate melts with significant distribution coefficients. Under such conditions, high-temperature salt solutions with high concentrations of rare-earth elements can form, which facilitates the development of their industrial clusters.

In the processes of hypergenesis, the nature of the distribution of rare earth elements is largely determined by their initial mineral form, susceptibility to hydrolysis, ability to form complexes, and the possibility of changing the valence state [25]. In mineral associations resistant to weathering, REEs can form eluvial placers. When combined with unstable components, they can be carried away or, conversely, accumulate in the weathering zone in the form of kaolinites, iron hydroxides, or newly formed mineral phases, serving as impurities. Under such conditions, it is possible to detect industrially significant concentrations of REEs even with a low content of elements in bedrock, which makes their development practical. The search and study of such objects in Ukraine have acquired particular importance in the context of growing global demand for rare earth raw materials.

According to available data [27, 28], the process of element accumulation in weathering crusts occurs during the early alkaline phase, primarily due to light lanthanides. In contrast, heavy elements and yttrium are partially removed. In the late acidic stage, on the contrary, light lanthanides, in particular lanthanum, are partially removed from rocks. In contrast, medium and heavy lanthanides, yttrium, are preserved in the form of sediments. This explains the broader distribution of light lanthanides in the upper part of the weathering crust.

Lanthanides are of critical geochemical importance due to their ability to isomorphically substitute both among themselves and with other elements with similar ionic radii. In the process of magmatic differentiation, their concentration increases from minimal in ultramafic and mafic rocks to the formation of their own minerals, such as orthite, monazite, and kainosite in granites, syenites, and nepheline syenites. Alkaline granites are characterized by an increased content of rare earth elements and are associated with the formation of bastnaesite, monazite, and sphene deposits. Pegmatites enriched in gadolinite, keelhautite, talenite, brytholite are associated with arfedsonite alkaline granites, and in pyrochlore- and columbite-bearing granites, fergusonite, xenotime, gagarinite, monazite are present as accessory components [27, 29]. The maximum concentrations of lanthanides are observed in nepheline and alkali syenites, which is due to the presence of their own minerals in significant amounts, mainly from the cerium subgroup.

Pegmatites are distinguished by the most incredible diversity and richness of rare earth mineralization among magmatic formations, including both their own REE minerals and apatite, sphene, garnet, etc. enriched with them.

During the process of bedrock exogenous destruction, some rare earth minerals, primarily oxides and anhydrous phosphates (such as monazite, xenotime, loparite, euxenite, samarskite, and orthite), are preserved and accumulate in placers. At the same time, the vast majority of REE-containing minerals, in particular silicates, anhydrous carbonates, and fluorides, are chemically unstable under weathering conditions and turn into hydrous carbonates and phosphates, rare earth colloidal forms (woodavrite), or hydrated compounds. In weathering crusts, REE are often concentrated in both their own minerals (rhabdophanite, bastnaesite, etc.) and as part of other hypergenic formations.

Unlike the lanthanides, yttrium is concentrated only in granitoids and related deposits, with its concentration increasing from ultramafic and basic rocks to acidic ones. In granitoids, yttrium is usually found in apatite, sphene, zircon, epidote, and also forms its own minerals (fergusonite, xenotime, gadolinite, kainosite). Yttrium mineralization typically accompanies the final stages of intrusive massif formation and aplite dike development. When weathering, most yttrium minerals are resistant to destruction and form placers, but the same fluorides and yttrium silicates, as a result of chemical weathering, pass into the form of unstable hydrous carbonates and phosphates [29].

According to the genesis of REE, three types of deposits are distinguished: endogenous, exogenous, and metamorphic [25], which are also characterized by their geographical features, connection with the corresponding groups of rocks, and other characteristics. In Ukraine, there are so-called traditional REE deposits associated with carbonatites (Novopoltavske) and Mariupolites (Mazurivske), as well as unconventional, enriched zirconium and rare-earth-zirconium ores formed in nepheline-free syenites (Azov and Yastrebetske deposits). In addition, within the Azov region, the Petrovo-Hnutivka occurrence of cerium group ores, represented mainly by parisite, calcite, and fluorite, was discovered, which is comparable to the Mountain Pass (USA) and Bayan-Obo (China) occurrences. The article then focuses on the characteristics of more promising REE deposits within Ukraine.

Purpose. The purpose of this work is to systematize the mineral deposits of Ukraine that contain light and heavy rare earth elements (REE) in accordance with the European Commission's assessment criteria, considering global demand for critical raw materials, the cost of realization, and sales volumes. This will enable unified approaches to categorizing 16 elements as light or heavy, thereby preventing further inconsistencies in assessing mineral raw materials within the context of Ukraine's European integration processes.

Setting the task. To achieve the set goal, the following tasks are planned: determining the annual volume of rare earth oxides (REOs) production with the establishment of their cost; comparing the price and production volumes of rare earth materials in relative values, which makes it possible to determine the most valuable and scarce among them; analyzing general information on the conditions of occurrence of light and heavy rare earth metal deposits, which allows investigating the most common conditions of their occurrence for further assessment; systematizing promising primary and placer deposits of Ukraine, in which light and heavy rare earth elements are concentrated.

Methods. The work used a set of research methods: generalization – systematization of information on world production and demand for light and heavy rare earth elements; analogy and comparison – generalization of experience in determining the distribution of rare earth elements in placer and root deposits; analysis and synthesis – to substantiate the feasibility of involving existing deposits of critical raw materials in development; empirical methods – to compare existing information on deposits of rare earth elements in Ukraine with the classification of the European Commission, in which they are divided into light and heavy materials.

Results. Analysis of open sources allows us to establish the distribution of REE in the rocks of the Ukrainian Shield. The accumulation of light lanthanides here is primarily associated with carbonate metasomatism [29]. In contrast, yttrium and heavy lanthanides are concentrated because of potassic metasomatism and greisenization processes. Of considerable interest are the carbonatite complexes of the Novopoltava, Malotersyanskyi, and Mazurivskyi massifs, as well as alkaline metasomatites. The Sushchano-Perzhanska zone, where intensive post-magmatic processes were recorded, contributed to the formation of secondary minerals that serve as carriers of rare earth elements (Fig. 5).

Depending on the type of host rocks, several main genetic types of endogenous mineralization are distinguished: zirconium-thorium-rare-earth type (in granites, syenites and pegmatites), represented by the Mykolaivske and Sabarivske deposits (Prydniprovske), Yastrebetske (Polissia) and the Uspenskyi manifestation in the Azov region; yttrium-rare-earth-zirconium and cerium-lanthanum type (in alkaline syenites), which include the Azov, Anadolske and Petrovo-Hnutivske deposits in the Azov region; uranium-thorium-yttrium-rare-earth type (in potassium and sodium metasomatites), characteristic of the Lozuvatske, Kalynivske and Pivdenne deposits of the Kirovohrad uranium-ore district, as well as for the Balka Korabelna manifestation [30].

A lot of the listed deposits' ores belong to the low-enriched category, which complicates their industrial development and requires improvement of enrichment methods.

Based on this, four primary areas of endogenous rare-earth mineralization development are distinguished – Podilskyi (Berdychivskyi, Zhytomyrskyi and Zvenyhorodskyi complexes), Perzhanskyi ore cluster (Yastrebetske deposit), Kryvyi Rih uranium-ore region (Korsun-Novomyrhorodskyi complex), and Pryazovskyi district (Novopoltavskyi, Azovskyi, etc.). Manifestations of

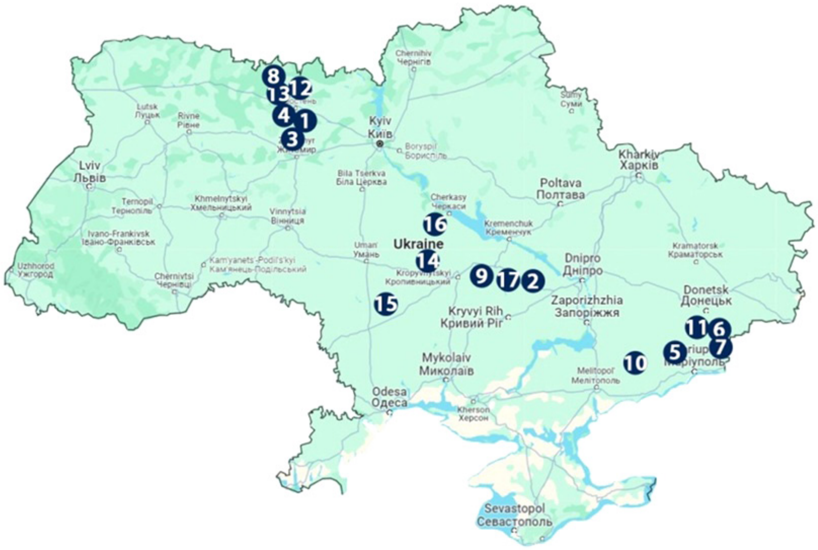

Fig. 5. Mineral deposits of Ukraine containing rare earth elements:

1 – Irshanske; 2 – Malyshevske; 3 – Fedorivske; 4 – Stremyhorodske; 5 – Azovske; 6 – Anadolske; 7 – Petrovo-Hnutivske manifestation; 8 – Yastrebetske; 9 – Zhovtorichenske; 10 – Novopoltavske (Muzykivska area); 11 – Mazurivske; 12 – Perzhanske; 13 – Sushchanske; 14 – Polokhivske; 15 – Lozuvatske; 16 – Smilianske; 17 – Motronivske

rare-earth mineralization associated with weathering crusts and placers containing monazite are also distinguished (Volyn-Podilskyi and Pryazovskyi districts).

The Azov region comprises granites and pegmatites of the Saltychanskyi, Anadolskyi, and Kamennomohylskyi complexes, as well as carbonatites of the Chernihiv and syenites of the South-Kalchytskyi complex. The rare-metal apatite Novopoltavske deposit is part of the carbonatites within the Chernihiv complex, located on the Orikhovo-Pavlohradskyi deep fault. The rocks of the deposit are represented by calcite and calcite-dolomite carbonatite ores, which form dike-like and rod-shaped bodies with sharply defined boundaries relative to the host phenites, nepheline syenites, and iolite-melteigites. The main ore component is apatite; associated minerals include monazite, pyrochlore, cerium fergusonite, columbite, zircon, and orthite, among others. The principal rare earth mineral is monazite, in which the REE content reaches 65 %. It is characterized by a low thorium content (0.1–0.3 %), which increases the technological value of its concentrate. Apattites of this deposit contain a significant amount of REE, with a content of up to 11 %. They are represented by cerium and lanthanum, and yttrium, samarium, europium, terbium, ytterbium, and lutetium are also present [27].

Within the deposit, a linear weathering crust is developed, the thickness of which in the central part of the fault zone reaches 370 m. There is a dependence on the increase in the concentrations of components in the weathering zone by several times. The average apatite content in carbonatites is 10 %, with small phosphate bodies reaching 50 %. According to forecast estimates, the extraction of REE from apatite alone can be promising for development. The resources of the deposit are estimated at 1 million tons of monazite and 200 million tons of apatite to a depth of up to 500 m [31], which allows us to consider the deposit relevant for the extraction of critical elements.

The Mazurivske deposit is a typical example of a zirconium-rare-earth-niobium complex, located within the massif of nepheline syenites, characterized by pyrochlore-zirconium ores in albitites and mariupolites. Ore minerals in this massif include pyrochlore, zircon, ferrioxonite, monazite, and brytholite, among others. The REE content in the ores varies from 0.2 to 65 %. The comprehensive development of the deposit as a source of alumina raw materials, along with the parallel extraction of REE, is promising.

Thus, the Novopoltavske and Mazurivske deposits are of considerable interest as sources of light and heavy REE within the limits of endogenous mineralization, with prospects for comprehensive development in the strategic resource balance of Ukraine. It should be noted that the industrial concentration of scandium has been found within several alkaline and ultrabasic complexes of the Ukrainian Shield. The highest values (up to 91 g/t) have been found in peridotites, pyroxenites, and gabbros. Oktiabrskyi massif, gabbro-norites Devladivka zone (up to 56 g/t), individual granites and their minerals. Special attention should be paid to pegmatites of the Ukrainian Shield, especially Saltychansk granites, where the scandium content in biotites reaches 90–120 g/t, in garnets – up to 300 g/t, and in zircons up to 200 g/t (there are data about 1,000 g/t in Berdychiv granites) [32].

A potential source of raw materials is also bauxite from deposits in Dnipropetrovsk and Mykolaiv regions (Vysokopilske, Pivdennonikopolske, Smilianske), where average scandium concentrations of 44.6 g/t in raw materials and up to 100 g/t in aluminum production waste have been detected.

Among the promising objects, deposits associated with alkaline and metasomatic formations also play an essential role. In particular, the Azov deposit (Fig. 5) represents a new industrial-genetic type, with no analogues in world practice. It is located in the northeastern part of the Azov block, composed of intrusive rocks of the Paleoproterozoic South Kalchytsia complex. Ore bodies are associated with a series of syenite stocks. Within the Azov block, nine ore bodies of varying thickness have been discovered, each containing rare earth elements at a content of up to 30 %. The ores are interspersed, polymineralic in composition, and are represented by brytholite, bastnaesite, orthite, zircon, monazite, chovkinite, ytrialite, magnetite, and fluorite [32].

The main rare-earth mineral is brytholite, represented by inclusions, intergrowths, and aggregates of prismatic crystals within pegmatoid areas, and is in paragenesis with zircon, orthite, and rare chevkite. Brytholite has a complex composition, with a predominance of cerium varieties, although yttrium forms are also present. A significant proportion of yttrium (up to 6–10 % of the total amount of REE) increases the industrial value of the raw material. It should be noted that brytholite is inferior to monazite in its properties and REE content, which determines its low extraction rates. According to preliminary estimates, the resources of the Azov deposit (to a depth of 300 m) are about 56 million tons of ore with an average content of rare-earth oxides from 0.4 to 1.27 %, as well as zirconium oxides of 1.5 %. Total forecast reserves are estimated at 710 thousand tons of TR_2O_3, of which approximately 20 % is in the yttrium-lanthanide group, and 840 thousand tons of Zr_2O_3 [25, 32]. In fact, within this deposit, weathering crusts are developed, formed in the disintegration and kaolinite-hydromica zones, where ore bodies of residual genesis, enriched in REE, are localized.

The geological analogue of the Azov deposit is the Yastrebetske deposit of zirconium ores (located in the southwestern part of the Perzhanskyi ore cluster). Still, at present, no industrial reserves of rare earth elements have been discovered here, although a similar mineral composition is observed in alkaline syenites, in particular, brytholite, orthite, and bastnaesite. Within the deposit, there are several crescent-shaped ore-bearing zones enriched in zircon. Their thickness ranges from 5 to 120 m with a maximum length of up to 2 km. The ores also contain ilmenite, apatite, bastnaesite, brytholite, magnetite, orthite, parisite, fluorite, and other minerals. The main ore minerals are brytholite and zircon. The total content of rare earth elements in individual ore bodies varies from 0.07 to 1.24 % [32]. Although the deposit is considered to be powerful, the depth of the ore bodies exceeding 500 m significantly complicates its prospects for development. It could be a source of alumina raw materials, accompanied by the concomitant release of rare earth elements, zircon, feldspars, and fluorite.

In the west of the Azov Sea is the Uspenivskyi occurrence, which refers to pegmatites and pegmatoid granites of albitized marginal areas of intrusive massifs. The thickness of the ore bodies varies from several centimeters to 59 m, while the depth of occurrence can reach up to 300 m. The ore occurrence is characterized by xenotime, cyrtolite, and uraninite associations in terms of mineral composition. The weathering crust at depths of up to 100 m contains up to 34 g/t of monazite and up to 5.45 kg/t of xenotime, but has increased radioactivity [25]. This occurrence is promising due to the presence of several elements, including yttrium, cerium, and neodymium. The presence of uraninite and cyrtolite indicates the concomitant content of uranium and thorium, which increases the strategic value of the object for the complex extraction of critical raw materials.

The ore zone, which cuts through metamorphic rocks and Anatolian granites to the southeast of the Mazurivske deposit, forms the Anatolian deposit. The structure of the zone is characterized by vein-vein mineralization of fluorite, apatite, orthite, in which the average TR_2O_3 content is 9.23 %. Among the rare earth minerals found are apatite, fluorite, orthite, and cerite [33]. The first two elements form thin layers with orthite in banded ores and belong to cerium varieties in chemical composition. According to geological and economic characteristics, this deposit can be attributed to promising objects with high resource availability.

The Petrovo-Hnutivskyi manifestation is located in the valley of the Kalmius River (northeast of Mariupol) and is associated with a fluorite-rare-earth-carbonate vein up to 3 m thick, which occurs in fenitized granosyenites of the Kalmius massif. The vein has a steep dip, composed of aggregates of calcite, bastnaesite, parisite and fluorite. The main ore minerals are bastnaesite and parisite, which form intergrowths with calcite in the form of nests and blocks (0.6–0.8 m). The content of fluorocarbonates of rare earth elements reaches 15–20 %, TR_2O_3 reaches 62.6 % in bastnaesite and 52.3 % in parisite [27].

Rare earth mineralization associated with feldspar metasomatites was discovered in the Kirovohrad uranium-ore district, particularly within the Lozuvatske, Kalynivske, and Pivdenne deposits. Here, both albitite and sodium-phosphorus metasomatites with uranium-thorium-yttrium-rare-earth mineralization were formed, represented by malacone, tsyrtolite, monazite, orthite, xenotime, and apatite [32]. It is necessary to separately note the scandium reserves; historically, its development began with the development of the Zhovtorichenske deposit within the Kryvyi Rih iron ore basin. Scandium reserves within it are estimated at 900 t (with an average content of 105 g/t) and are concentrated in aegirine and alkaline amphiboles, which are concentrated in fault zones. Vanadium, yttrium, zirconium, etc. are also present in industrial concentrations. In the same northern part of the Kryvyi Rih iron ore basin, a more homogeneous (unlike the Zhovtorichenske deposit) vanadium-scandium mineralization was discovered within the Pershotravneve deposit of ferruginous quartzites with the main mineral-concentrator aegirine and the content of scandium in ores up to 83 g/t, vanadium – 742 g/t. By genesis, both deposits are hydrothermal-metasomatic. Similarly to the Pershotravneve deposit, at the Hannivske deposit, scandium ores are associated with zonal bodies of sodium metasomatites, where the average content of scandium is 79 g/t, and vanadium is 701 g/t [25, 32].

Among rare earth and yttrium objects, the occurrence at Balka Korabelna (Ostapivske, Pobuzke) is of particular interest – a uranium ore region within the Ukrainian Shield, which falls within the field of granitoid development. Ore bodies are represented by granites and pegmatites. The deposit measures 70 m in length, 40 m in width, and ranges from 3.5 to 20.2 m in thickness, extending to a depth of up to 50 m. The ore mass is formed by fine-grained inclusions and accumulations of monazite, xenotime, and apatite in a rock represented by biotite, feldspar, and quartz with secondary almandine and magnetite. The main ore minerals are monazite and xenotime, with secondary minerals including zircon, apatite, and uraninite. The TR_2O_3 content in the ore bodies varies from 0.22 to 1.51 % [30]. REE phosphates are concentrated in biotite areas of rocks that have undergone microclinization. They form granular aggregates and veinlets localized near cracks or at contacts with microcline.

In connection with the carbonate and alkaline complexes of the Ukrainian Shield, it is also worth noting several deposits and objects of potential sources of rare earth elements in the Pridniprivia and Pobuzhzhia regions: the Malotersyanske pyrochlore-gatchetolite deposit, the Perzhanske beryllium deposit with rare earth mineralization, and the Proskurivsky and Antonivskyi massifs.

In addition to the primary deposits, significant titanium-zircon-ilmenite placers are also known in Ukraine, in particular within the Zhytomyr region and the Azov region, which can be considered as an additional source of rare earth raw materials. The average monazite content in these objects ranges from 120–144 g/t (for Volyn) to 450–900 g/t (in the Azov region).

It is worth noting that the Fedorivske deposit (Zhytomyr region) of titanium ores (Fig. 5), which are represented by ilmenite and rutile with impurities of vanadium, apatite, and rare earth elements (cerium, lanthanum, neodymium, praseodymium, etc.), belongs to the strategic objects of the mineral raw material base of Ukraine. This enables the extraction of related, valuable raw materials in parallel with titanium products. Preliminary geological and economic assessments (recorded ore reserves of about 171 million tons) provide grounds to attribute the Fedorivske deposit to potential objects of complex development of REE [34].

Additionally, the Malyshevske (in some sources, Muzykivske) deposit in the Dnipropetrovsk region is one of the largest deposits of ilmenite-rutile-zirconium sands in Ukraine, which serves as a source of titanium, zirconium, as well as potentially rare earth elements (tantalum, niobium, yttrium, cerium, neodymium, etc.). In particular, the deposit has been found to have an increased content of hafnium and related elements, such as phosphorus, yttrium, lanthanides, uranium, and thorium [25, 32].

The ilmenite-apatite and titanomagnetite Stremyhorodske, Torchynske deposits (Zhytomyr region), with an average scandium content of up to 0.015 %, the ilmenite and rutile-zircon-ilmenite alluvial deposits Zlobychske, Malyshevske and Irshanske, with a scandium content of up to 0.01 %, whose resources are capable of ensuring the production of scandium-containing concentrates, are considered promising.

Scandium has been found in coal mine ash in Luhansk Oblast, with an average content of 74–90 g/t, and total reserves of 18.7 thousand tons (excluding other elements). In addition, scandium has been found in hydrogoethite-ferrimontmorillonite oolite iron ores of Kerch with a content of 7–11 g/t, as well as in martite and goethite-hydrogoethite quartzites of Kryvyi Rih with an average content of 1–3 g/t [25].

When developing a systematization of light and heavy rare earth elements deposits in Ukraine, the most promising of the listed ones were considered, based on the European Commission's assessment (Table 2).

It is worth emphasizing that rare earth elements are concentrated in the primary and sedimentary (placer) deposits of light (lanthanum, cerium, praseodymium, neodymium) and heavy REE (terbium, dysprosium, erbium, and ytterbium). They are located directly within the Azov, Volyn, and Polissia regions, as well as in the Dnipropetrovsk and Zhytomyr regions. They are presented in the form of isomorphic impurities, which are components of ilmenite-apatite and titanium-zirconium ores.

In the Azov block, large deposits of rare and rare-earth metals have been discovered (Mazurivske and Azovske zircon-rare-metal deposits). The Zhovtorichenske scandium-vanadium, Novopoltavske apatite-rare-earth, Yastrebetske fluorite-zircon-rare-earth, Fedorivske, Stremyhorodske, Krapyvenkivske, and Vydyborzke apatite-titanomagnetite-rare-metal deposits should be highlighted as particularly promising.

Rare earth deposits do not form their own minerals, but are present as impurities in known ores. To extract REE from the main ores, it is necessary to extract and process significant volumes of rock. A feature of the above deposits is their complexity, which is evident in the fact that, along with the main mineral, associated minerals represented by REE are also extracted. The economic feasibility of comprehensively developing such deposits with the right approach increases significantly.

Within Ukraine, there are significant deposits of native ores, the extraction of REE from which involves the implementation of complex technological processes: loosening the rock massif, crushing, obtaining valuable elements. According to open sources of information, the content of light REEs cerium, lanthanum, neodymium, praseodymium, and samarium has been established, and only one heavy REE – yttrium (Fig. 6).

According to the analysis of the light and heavy REE distribution in primary deposits of Ukraine (Fig. 6), the largest share of their total content is represented by light elements – cerium (up to 28 % of deposits), lanthanum (up to 21 % of deposits), and neodymium (up to 18 % of deposits). In the same deposits, the content of yttrium (heavy REE) from the total share of elements does not exceed 3 %, and the remaining elements require additional study. The primary deposits with the largest reserves are Muzykivske and Stremyhorodske. It is worth

Table 2

Presence of deposits of light and heavy rare earth elements in sedimentary and primary zircon-ilmenite deposits of Ukraine

No.	Region	Name of the deposit	REE type	Main elements	Type of ore
1	Zhytomyr region	Irshanske	Light	Cerium, lanthanum, neodymium	Titanium-zirconium
2	Dnipropetrovsk region	Malyshevske	Light	Neodymium, praseodymium	Ilmenite-apatite
3	Azov region	Azovske	Heavy	Dysprosium, terbium	Rare metal
4	Polissia	Sushanske	Heavy	Erbium, ytterbium	Mineralogically complex deposits
5	Cherkasy region	Smilianske	Light; heavy	Cerium, neodymium, ytterbium	Loose titanium-zirconium
6	Dnipropetrovsk region	Motronivske	Light; heavy	Lanthanum, dysprosium	High potential, untapped

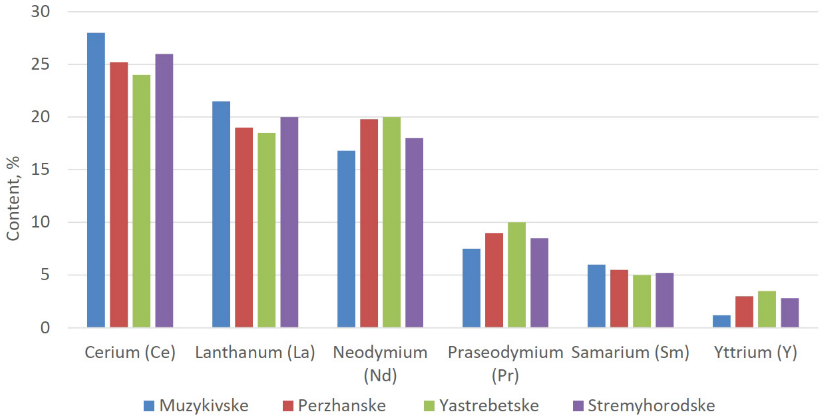

Fig. 6. Distribution of the main rare earth elements in ores of primary deposits of Ukraine

noting that the extraction of light and heavy REE requires multi-stage enrichment processes: flotation, sorption, and ion exchange.

The Stremyhorodske native deposit of rare earth elements in Ukraine is one of the largest in Europe and the world. Its mineralization extends to a depth of 1.5 km, utilizing a combined open-pit and underground mining method. This approach involves open-pit mining of the upper part of the deposit using a system of tranches, while the lower, deeper part is mined underground. High capital costs for developing this deposit can be offset by significant volumes of minerals, comprehensive development of the main and associated raw materials, and a long life for the quarry. At the same time, a substantial problem for the extensive development of native and sedimentary deposits of rare earth ores is the insufficient study of the deposits and inadequate geological exploration. That is, at the stage of obtaining a license for a specific site, the investor currently lacks a strategic vision for developing these critical deposits. Solving this problem will further ensure the creation of new jobs, filling budgets at all levels, and the development of strategic sectors of the economy.

Promising placer deposits include Motronivske, Malyshevske, Irshanske, and Smilianske, in the deposits of which previous studies have established the presence of several light and heavy REE (Fig. 7).

According to the analysis of the distribution of REE in placer deposits (Fig. 7), it was found that of the total content of light REE in the ore, the largest share is represented by cerium (up to 16 %), lanthanum (up to 14 %) and neodymium (up to 11 %), and the content of yttrium does not exceed 3 %. The placer deposits with the largest reserves include Motronivske and Irshanske.

As in the case of the development of primary deposits of rare earth elements, the development of placer deposits should be based on an integrated approach to the extraction of the main titanium-zirconium raw materials, as well as associated REE elements in the ore. Such an approach will significantly enhance the technical and economic indicators of placer deposit development, and will also reduce production waste and increase the level of circularity in development technologies.

Since scandium, according to the European Commission, does not belong to light or heavy REE and is positioned separately, deposits containing it are considered independently.

The significant scandium anomaly includes two powerful titanium structures: the Korostenskyi and Korsun-Novomyrhorodskyi plutons. Technological solutions for developing such deposits are known, but there is no industrial infrastructure in Ukraine for the effective extraction of scandium from ores. One of the main reasons is the low content of the element in ores and the high cost of the technological process, which makes the extraction of scandium economically unfeasible.

The analysis of Ukraine's REE resource base, combined with the high global demand for this critical raw material, necessitates the application of best global practices and advanced development technologies. Together with additional geological exploration, these actions will expand

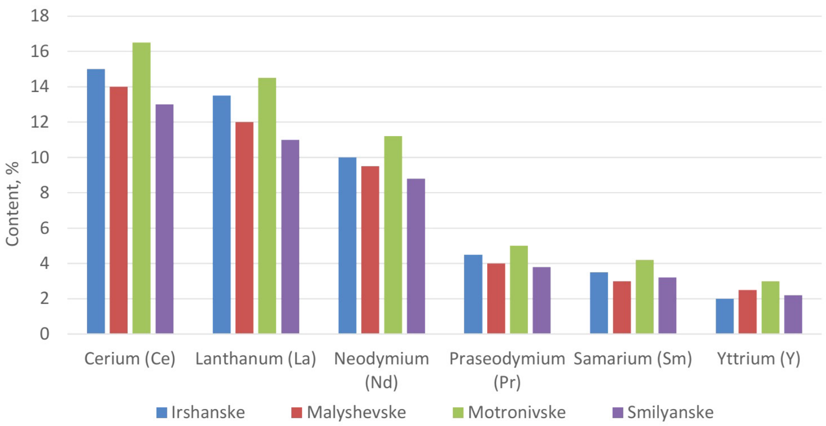

Fig. 7. Distribution of the main rare earth elements in ores of placer deposits of Ukraine

the supply chains of raw materials and the markets for finished products, ensuring diversification in global markets.

In Ukraine, scientific and technological solutions are currently being developed for the application of low-waste methods for the extraction of REE. Among the promising techniques, the use of membrane technologies and biosorbents should be highlighted, which lead to a reduction in reagent consumption and a negative impact on the environment.

Thus, Ukraine possesses light and heavy REE resources; however, to begin industrial development, it is necessary to go a significant way, which consists of creating a modern geological database, developing and implementing the latest enrichment technologies, attracting investments with the development of a transparent market, and organizing a closed production cycle mining-processing-production. The implementation of these measures will enable Ukraine to become a significant player in the global REE market and stimulate the development of knowledge-intensive sectors of the economy.

Conclusions. It was found that the highest value on the world market is held by oxides of heavy REOs – terbium and lutetium, as well as scandium. At the same time, the largest sales market is held by gadolinium, neodymium, and praseodymium, and the most significant production volume is held by light REOs – cerium, lanthanum, and neodymium. The obtained cost indicators and volumes of world production of each rare earth element allow us to determine the attractiveness of developing new mineral deposits in Ukraine.

It has been established that today, 280 REE minerals from the classes of phosphates, carbonates, oxides, fluorides, silicates, sulfides, and borates have been identified worldwide. A special group is composed of rare earth tungstates – ytrotungsite and arsenates – retschanite, which are very rare and have been practically unstudied.

Four main areas of endogenous rare earth mineralization development in Ukraine have been identified, and 17 mineral deposits, the ores of which have a potential content of light and heavy REE.

A systematization of light and heavy rare earth element deposits in Ukraine has been developed in accordance with the European Commission's assessment of the most promising primary and placer deposits. It has been established that the main light rare earth elements found in Ukrainian deposits are lanthanum, cerium, praseodymium, and neodymium. In contrast, the heavy ones are represented by terbium, dysprosium, erbium, and ytterbium.

It was determined that the core deposits with the largest reserves include Muzykivske and Stremyhorodske, in which the largest content of light REE in the ore is represented by cerium, lanthanum, and neodymium. The placer deposits with the largest reserves include Motronivske and Irshanske, in which the largest share of the total content of light REE in the ore is represented by cerium, lanthanum, and neodymium. In core and placer deposits, the content of yttrium from the total share of REE does not exceed 3 %, and the remaining elements require further study.

It has been determined that Ukraine has sufficient potential in the development of light and heavy REE; however, for their practical use, it is necessary to create a modern geological database, develop and implement the latest enrichment technologies, attract investments with the development of a transparent market, and organize a closed production cycle.

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Перспективи освоєння легких і важких рідкісноземельних елементів із циркон-ільменітових родовищ України

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Мета. Визначити найбільш перспективні родовища корисних копалин України, що містять легкі й важкі рідкісноземельні елементи (РЗЕ) у відповідності до критеріїв оцінки Європейської комісії з урахуванням світового попиту на критичну сировину та вартості її реалізації.

Методика. У роботі використано комплекс методів досліджень: узагальнення – систематизація відомостей про світовий видобуток і попит на легкі й важкі рідкісноземельні елементи; аналогія й порівняння – узагальнення досвіду щодо визначення розподілу рідкісноземельних елементів розсипних і корінних родовищах; аналіз і синтез – для обґрунтування доцільності залучення існуючих родовищ критичної сировини у розробку; емпіричні – для порівняння існуючих відомостей про поклади родовищ рідкісноземельних елементів України із класифікацією Європейської комісії, в якій вони поділяються на легкі й важкі матеріали.

Результати. Встановлені найбільш перспективні корінні й розсипні родовища легких і важких рідкісноземельних елементів України відповідно до оцінки Європейської комісії. Встановлено, що основними легкими рідкісноземельними елементами, що виявлені у циркон-ільменітових родовищах України, виступають лантан, церій, празеодим, неодим. У той же час важкі представлені тербієм, диспрозієм, ербієм й ітербієм. Визначено потенційний вміст легких і важких РЗЕ у корінних родовищах України, відповідно до якого основні концентрації виявлено для легких елементів. Із загального вмісту легких РЗЕ у руді найбільша частка представлена церієм (до 28 % від загальної кількості родовищ), лантаном (до 21 % родовищ) і неодимом (до 18 % родовищ). У тих же родовищах із загальної частки РЗЕ вміст ітрію не перевищує 3 %, а решта елементів потребує додаткового вивчення. Встановлено, що у розсипних родовищах із загального вмісту легких РЗЕ у руді найбільша частка представлена церієм (до 16 % родовищ), лантаном (до 14 %) і неодимом (до 11 %), а вміст ітрію не перевищує 3 %.

Наукова новизна. Уперше виконано поділ рідкісноземельних елементів, що містяться у циркон-ільменітових родовищах України, на легкі й важкі елементи за класифікацією Європейської комісії. Виділені родовища критичної мінеральної сировини України, в яких можуть видобуватися легкі й важкі рідкісноземельні елементи. Обґрунтована необхідність подальшого вивчення родовищ корисних копалин Приазовського, Волинського й Поліського регіонів, а також Дніпропетровської та Житомирської областей для виявлення нових місць розташування легких і важких рідкісноземельних елементів і розширення вже встановленого їх переліку.

Практична значимість. Визначено, що Україна має достатній потенціал в освоєнні легких і важких рідкісноземельних елементів із циркон-ільменітових родовищ згідно із класифікацією Європейської комісії. Проте для ефективного залучення їх в експлуатацію необхідне створення сучасної геологічної бази даних, розробка й впровадження новітніх технологій збагачення, залучення інвестицій із розвитком прозорого ринку та організація замкнутого виробничого циклу.

Ключові слова: *критична мінеральна сировина, рідкісноземельні елементи, корисні копалини, видобуток, ресурсозабезпечення*

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