

Research and application of unique and rare earth elements in Ukraine: the way to innovation and sustainable development

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abstract

As environmental challenges have intensified, developed nations have increasingly focused on advancing technologies aimed at reducing environmental impacts. Consequently, minerals such as titanium, cobalt, and various rare and rare earth metals have become critical components of green technologies, playing a pivotal role in the energy transition from fossil fuels to alternative energy sources in advanced economies. Ukraine possesses substantial reserves of rare and rare earth elements, including tungsten, tantalum, niobium, indium, and others. These elements exhibit unique physical and chemical properties that render them essential for industrial applications, including use as alloying additives in steels and alloys, in electronics, magnetic materials, catalysts, and nuclear technologies. Nearly all titanium and iron ore deposits in Ukraine are complex, containing valuable rare-metal impurities such as vanadium, scandium, tantalum, niobium, zirconium, hafnium, thorium, tungsten, tin, gallium, indium, and yttrium. The present study identifies three primary sources of rare earth elements in Ukraine: primary apatite-ilmenite deposits, exogenous deposits resulting from weathering, and complex ilmenite-rutile and ilmenite-zircon deposits. The composition of valuable impurities in titanium ores varies depending on the specific deposit and geological conditions, underscoring the necessity of detailed mineralogical and geochemical analyses at each location. This research is based in investigations of titanium-bearing minerals within the Ukrainian crystalline shield, as well as the review of over 200 production reports. The paper outlines the formation patterns of various deposit types and emphasises the need for continued research into rare metals across diverse geological formations, including the exploration of alternative sources for extracting valuable impurities. Ukraine is preparing to implement modern, waste-free technologies for the extraction and comprehensive processing of its mineral resources. Failing to recognise the complex nature of these deposits can result in the loss of rare metals such as vanadium, hafnium, and zirconium. This paper further explores the potential of transitioning to environmentally sustainable methods for mining titanium and iron ores, with the concurrent recovery of rare metal by-products.

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Дослідження та застосування рідкісних і рідкісноземельних елементів в Україні: шлях до інновацій та сталого розвитку

Уляна Науменко, Віктор Мацуй, Олексій Науменко

Резюме. Зі зростанням екологічних викликів розвинені країни активізували розвиток технологій, спрямованих на мінімізацію впливу на довкілля. Як наслідок, важливими складовими «зеленого» виробництва стали мінерали, такі як титан, кобальт та різні рідкісні й рідкісноземельні метали, які набули ключового значення для країн із розвинутою економікою, що здійснюють енергетичний перехід від викопного палива до альтернативних джерел енергії. Україна володіє значними запасами рідкісних і рідкісноземельних елементів, включаючи вольфрам, тантал, ніобій, індій та інші. Ці елементи мають унікальні фізико-хімічні властивості, які забезпечують їх широке застосування в промисловості, зокрема як легувальні добавки у сплавах та сталях, в електроніці, магнітних матеріалах, каталізаторах і ядерних технологіях. Практично всі титанові та залізні рудні родовища України є комплексними, містять цінні рідкіснометалеві домішки, такі як ванадій, скандій, тантал, ніобій, цирконій, гафній, торій, вольфрам, олово, галій, індій та ітрій. Дослідження авторів виокремило три основні джерела рідкісноземельних елементів в Україні: первинні апатит-ільменітові родовища, екзогенні родовища, утворені в результаті вивітрювання, та комплексні розсипи ільменіт-рутилових і ільменіт-цирконових руд. Склад цінних домішок у титанових рудах варіюється в залежності від конкретного родовища та геологічних умов, що обумовлює необхідність детальних досліджень мінералогічного складу та вмісту металів конкретної локації. Наша робота базується на дослідженнях титановмісних мінералів Українського кристалічного щита та аналізі понад 200 виробничих звітів. У статті висвітлено закономірності формування різних типів родовищ і розглянута важливість подальших досліджень рідкісних металів в різних геологічних формаціях, включаючи альтернативні джерела вилучення цінних домішок. Україна планує впроваджувати сучасні безвідходні технології для видобутку й комплексної переробки мінеральних ресурсів. Недооцінка комплексності рудних розсипів може призвести до втрат рідкісних металів, таких як ванадій, гафній та цирконій. У роботі розглянуто перспективи переходу на екологічно чисті методи видобутку титанових і залізних руд з одночасним вилученням рідкіснометалевих домішок.

Ключові слова: Український щит, титанові поклади, домішки, рідкісні і розсіяні елементи, ільменіт.

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Introduction

Ukraine has large mineral resources, making it one of the richest European countries in terms of titanium, rare earth metals and lithium, estimated at between USD 3 and 11.5 trillion (according to the State Service of Geology and Mineral Resources of Ukraine). In 2021, the European Union signed a strategic partnership agreement with Ukraine on raw materials, which sparked a surge of interest from private companies in different countries. One of the fundamental features of Ukraine's geological structure is the diversity of its deposits. Rare and scattered elements are unevenly distributed, but significant quantities can be found in the Ukrainian Carpathians, Zakarpattia, Crimean Peninsula and other southern regions of the country. For example, the Ukrainian titanium province encompasses nine regions rich in titanium deposits: the north-eastern part of the Ukrainian Shield, the Dniro–Donetsk Depression and part of the south-western slope of the Voronezh crystalline massif, and the northern coast of the Black Sea and Sea of Azov [Atlas ... 2001] (Fig. 1). These deposits can be classified based on genetic types and the associated geological formations. Among these types are the following:

- deposits associated with intrusive gabbroic rocks,
- deposits linked to a gabbro weathered crust, as well as anorthosites and gabbro-anorthosites,
- deposits associated with weathered alkaline rocks and corresponding feldspar-mica metamorphic rocks, deposits formed by alluvial-deluvial placers during the Mesozoic Era and Palaeogene = Neogene periods,

- deposits related to coastal-marine (lateral) placers of the Novi Petrivtsi Formation and Sarmatian strata,
- deposits that formed modern alluvial and marine placers.

This geological diversity of deposits makes the Ukrainian titanium province a significant region for the extraction and processing of titanium resources.

Currently, over 200 deposits and occurrences of titanium- and iron-bearing minerals, such as ilmenite, leucoxene, titanium-magnetite, siderite, and many others, have been identified in Ukraine. However, in fact, the mineral resource base of titanium in Ukraine is represented by approximately 40 titanium deposits, of which 12 have been explored and commercial production has begun. Currently, titanium ore is mined in Ukraine by the main titanium ore resources concentrated in indigenous deposits, which can be sufficient for a long period of time for titanium ore mining companies to operate. However, there is a problem with the shortage of fresh ilmenite ores, which are mainly associated with the large Stremihorodske and smaller Fedorivske indigenous deposits in Ukraine. The main problem with the development of these deposits is that their exploitation requires significant capital investment to build new mines and processing plants. Placer deposits account for about 10% of all proven reserves [National Atlas ... 2010].

In the past, Ukraine played a crucial role in titanium concentrate production, accounting for 90% of the former Soviet Union's output. The historical maximum of titanium raw materials production in Ukraine was in 2008, when titanium production totalled at least 414 thousand tonnes of TiO_2 . In other words, actual titanium production in Ukraine is 10–15% higher than the estimate by the authoritative US publication Mineral Commodity Summaries (359 kt of TiO_2) and almost matches

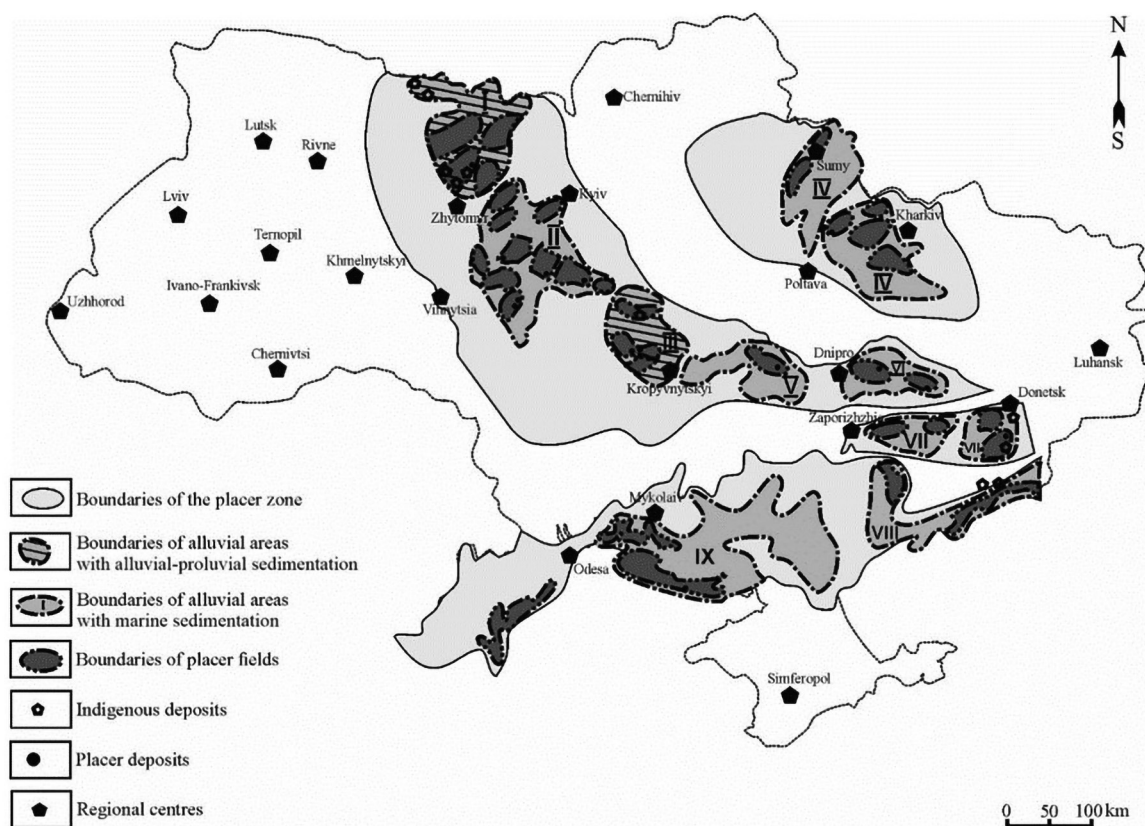


Fig. 1. Schematic map of titanium deposits in Ukraine (based on the map of titanium-zirconium deposits in Ukraine from the atlas 'Geology and Mineral Resources of Ukraine,' 2001).

Рис. 1. Схематична карта родовищ титану в Україні (за картою титано-цирконієвих родовищ України з Атласу «Геологія і корисні копалини України», 2001 р.).

the estimates of Ukrainian scientists (365–564 kt of TiO₂) [Mykhailov 2023]. In terms of reserves/annual production ratio in 2008 Ukraine became the world leader, significantly outstripping China, Brazil, and India, which follow it. Unfortunately, over the past 28 years, titanium sponge production in Ukraine has fallen by 50%, and titanium product production has fallen from \$630 million per year to \$350 million per year over the past 15 years [Concept ... 2023]. The Russian aggression against Ukraine has meant that strategic plans for the development of the Ukrainian titanium industry have been postponed until better times. However, despite the hostilities, Ukrainian titanium assets remain an attractive investment target. Analysts believe that titanium may become one of the elements of the foundation for Ukraine's post-war recovery.

The main value of titanium deposits lies in the presence of rare metal impurities such as vanadium, scandium, rutile, niobium, tantalum, tin, tungsten, gallium, thorium, etc., which are sometimes even more valuable than titanium or iron itself.

One of the main needs for rare earth elements is the production of electronic devices and components for the renewal and development of information technology. The amount of elements required can reach several hundred tons per year.

The use of rare earth metals in renewable green energy, such as niobium for the production of superconductors in wind turbines or neodymium for permanent magnets in solar panel generators, is key to stabilising the energy sector. In the restoration of medical infrastructure and the development of biotechnology, rare earths are used to produce magnetic resonators, lasers, and new materials for medical implants.

The development of the automotive industry and the production of electric vehicles use rare earth metals, in particular lithium and niobium, whose performance is important for the production of lightweight, energy-efficient batteries. Rare earth elements are used in the production of catalysts for the chemical industry, which is an important element for maintaining the production of chemicals and industrial processes.

This article does not discuss the associated valuable minerals of titanium ores, such as apatite or radioactive elements, but they are the target of further research in this area.

The objective of the research was to justify the real and extensive integration of new chemical elements, such as valuable impurities in titanium and iron ores, vanadium, scandium, tantalum-niobates, etc., into the post-war industrial production in Ukraine. Scientific research in the field of advanced technologies and materials science in Ukraine is actively contributing to the search for new methods of rare earth elements' extraction and use. This opens up new prospects for the development of high-tech industries such as electronics, solar energy, and medical equipment. Worldwide, the extraction of these resources significantly increased, but they remained unused in Ukrainian deposits. The assessment of the value of rare and scattered elements in Ukraine was conducted by scientists and producers, and reserves of these resources were partially calculated at deposits where they had not been utilised so far¹ [Borisenko 1957; Grinchenko 2006]. The demand for these resources in Ukraine was met through imports from Russia. Therefore, for the accelerated post-war development of Ukraine's resource base in new conditions, it is necessary to restructure industrial production by implementing comprehensive and zero-waste extraction of rare earth and scattered minerals. It is also crucial to employ advanced technologies for extracting titanomagnetite ores in the Korosten pluton, Stremigory and Torchin massifs, as well as Neogene ores of the Kerch region in Crimea and shales of the Menilite Formation in the Carpathians, and partially also iron ores in the Kryvyi Rih iron ore basin (Zhovtorichinsk raion), and so forth.

¹ Proskurin, G. P. *et al.* 1981. Stremihorodsk deposit of apatite-ilmenite ores. *Ukrainian Territorial Geological Fund*. Kyiv, 1–311. [Russian]; Shvayberov, S. K. 2002. Exploration of apatite-ilmenite ores of the Fedorivske deposit. *Ukrainian Territorial Geological Fund*. Kyiv, 1: 1–268. [Ukrainian]; Yarovoy, V. D. 2003. Recalculation of current reserves of sands of the Sarmatian Stage of the Malyshevsk deposit. *Ukrainian Territorial Geological Fund*. Kyiv, 1–1215. [Russian]

The relevance of the article lies in its focus on identifying new sources of useful components in the subsoil of Ukraine, which will give the potential to become a key player in the global rare earth metals market, and will determine new directions for its economic development.

History of studying valuable impurities in titanium minerals in Ukraine

Research on rare earth and scattered elements, their formation conditions, and the impact of geological-geochemical processes in the Earth's crust has been of interest to prominent scientists such as Vernadsky [2012], Fersman [1947], and Goldschmidt [1937]. Ukrainian geologists have studied these valuable elements as impurities in titanium minerals under both primary conditions and placers. In Ukraine, they were considered as impurities in titanium minerals, mainly described as new mineralogical discoveries. Thematic research is mainly reflected in production geological reports, articles, and scientific literature on the geology of titanium minerals² [Belevtsev *et al.* 1974; Bochai *et al.* 1998; Tyshchenko 2006].

The first practical steps towards developing Ukraine's raw material base were taken during survey work on the Dobrynsky and Hladkovsky titanium ore deposits in 1934–1935 [Pedan 1935; Piontkovsky 1935]. These works identified an elevated vanadium content in titanium minerals in the Hativskiy and Dobrynsky areas of Zhytomyr Oblast, estimated reserves of TiO_2 , and V_2O_5 , which had industrial significance. In subsequent years and up to the present, in the process of deeper exploration and development of titanium ores, geological practitioners and scientists from the National Academy of Sciences of Ukraine (Institute of Geological Sciences, M.P. Semenenko Institute of Geochemistry, Mineralogy and Ore Formation, etc.) continue to study titanium ores, discovering various valuable impurities such as scandium, tantalum, niobium, thorium, tungsten, hafnium, tin, and others. These efforts marked the beginning of practical steps in expanding Ukraine's raw material base through the extraction of rare and scattered elements [National ... 2011].

A significant contribution is the research of M. P. Semenenko³, who first summarised knowledge about the presence of beryllium, niobium, and tantalum in crystalline rock of the Ukrainian Carpathians. Special attention was given to their high stability in aggressive environments, determining their wide use in the chemical industry, metallurgy, rocket technology, and medicine.

V. G. Gevorkyan's work [Gevorkyan 1964; 2004], carried out in 1964 and 2002, is devoted to the study of rare elements found in ilmenite from the northern coast of the Sea of Azov. In these papers he notes that the ilmenite and ore concentrate contain a lot of niobium, tantalum, and rare earths. Gevorkyan emphasises that both ilmenite and its ore concentrate contain significant enrichments of niobium, tantalum and rare earth elements. These concentrations exceed typical levels in most samples, with Nb_2O_3 reaching 6900 g/t, Ta_2O_5 430 g/t, and rare earth elements (REE) 6400 g/t. The author provides a detailed geochemical analysis of waste and ilmenite concentrate from different deposits to better understand the technological possibilities of integrated processing. It was also emphasised that the ultimate goal should be the extraction of high-value mineral resources, including rare and scattered elements.

The monograph by Shnyukov *et al.* [2009] provides a characterisation of the geological study of vanadium, its sources of concentration, mineralogical-geochemical features, and types of industrial deposits and ore occurrences. The monograph particularly focuses on the concentration of vanadium in sedimentary rocks, including iron ores, bedded phosphorites, natural bitumens, the oil and gas condensate zone, organic products of humification, and adsorption in primary solutions in clays and sandstones. The research also shows the results of studying the vanadium in the Lviv–Volyn coal basin and uranium-vanadium-scandium metasomatic rocks of the Kryvyi Rih iron ore basin. The

² Vykhodtsev, M. K. 2007. Assessment of the prospects of titanium-zirconium placers of the northeastern slope of the Ukrainian Shield. *Fonds of Geological Survey Trust*, 1: 1–259. [Ukrainian].

³ Semenenko, N. P. et al. 1975. Geochemistry of beryllium, niobium and titanium in metasomatites of the USH (final report). *Ukrainian Territorial Geological Fund*. Kyiv, 1–218. [Russian].

monograph emphasises that the main source of vanadium extraction at present is titanomagnetites, magnetites, and some other iron minerals identified in the Ukrainian Shield and its slopes in complex titanium-vanadium deposits of the Korosten (Stremihorodske, Torchynske, and Zlobychivske deposits, etc.) and Korsun-Novomirhorod plutons (Nosachivske deposit). It is noted in the study that the industry in Ukraine does not extract vanadium from its own mineral raw materials, although the technological scheme for obtaining vanadium from Neogene ores of the Kerch region (Crimea, Ukraine) was developed in 1931. Under modern conditions, the extraction of vanadium impurities under these conditions requires the development of new unconventional technologies for cost-effective by-product or direct extraction.

The issue of studying and developing valuable impurities in ores has been the focus of Ukraine's geological service for the past 50 years, but the question remains open.

Material and Methods

In this study, the foundational information was derived from the results of prospecting and geological surveying conducted by the State Service of Geology and Mineral Resources of Ukraine (had different names in the past) from 1934 to the present day. A thorough analysis was carried out regarding the composition of titanium ore minerals, specifically rare-metal valuable impurities, as well as the overall results of prospecting, mineralogical and chemical composition, and reserve calculations of titanium-containing deposits in Ukraine. Special attention was given to the analysis of the chemical composition of ilmenite, rutile, zirconium concentrates in the original ores, and other titanium-containing minerals, including valuable impurities of rare-earth elements in Cretaceous, Palaeogene–Neogene, and Quaternary placer accumulations. The analysis included the percentage and grams per ton content of TiO_2 , Fe_2O_3 , FeO , P_2O_5 , and other trace elements in rocks and ores identified in the provinces of the Korosten and Korsun-Novomirhorod plutons in deposits and areas. We first collected the increased elevated concentrations of isomorphic impurities of vanadium, zirconium, niobium, tantalum, hafnium, scandium, cobalt, etc. Based on the unpublished survey reports we present for the first time to the wide public the presence of indium (average content of 0.0055%) and gallium (0.0033%) in ilmenite of the Korosten pluton with vanadium content ranging from 0.21 to 0.33 g/t and scandium from 63 to 100 g/t⁴.

Formation of rare and disseminated elements

The formation of rare and disseminated elements in titanium ore deposits in Ukraine is associated with the origin of these ore minerals from magmatic processes and tectonic events in the substrate, which included various chemical elements such as iron, aluminum, scandium, tantalum, niobium, hafnium, tungsten, tin, gold, and others. During the weathering of these magmatic sources and the alteration of minerals under the influence of factors such as weathering, valuable mineral concentrations were formed, creating extensive placers on the Earth's surface, especially in zones of geological formation processing from various geological periods [Ramdor 1962]. Under the influence of exogenous processes, minerals transitioned into kaolinite, montmorillonite, beidellite, but resistant minerals such as ilmenite, rutile, zircon, staurolite, sillimanite, disthene, quartz remained unchanged, persisting as fine disseminated particles in the moving mass of weathered crust rocks [Lazarenko 1971; Kulish 2005].

Ilmenite (titaniferous iron ore) and its leucoxene-altered varieties serve as the primary carriers of rare and disseminated elements, including impurities of varying concentrations of vanadium, scandium, tantalum, hafnium, and other elements. Regional weathering horizons formed during the Jurassic and Cretaceous periods became key areas for the formation of titanium placers (see Fig. 1).

⁴ Irshansky mining and processing plant. 1974. Report on geological exploration works carried out by Irshansky GOK in 1972 and 1973. Irshansk, *Ukrainian Territorial Geological Fund*, 66. [Russian].

The Korosten pluton is an important source of rare and scattered elements in Ukraine. Its geological structure and characteristics make it an object of interest for scientific research and industrial production, given the development of modern technologies and the growing demand for these valuable resources. The Korosten pluton is located in the central part of Ukraine, mainly in Zhytomyr and Kyiv oblasts. This geological object is important from the point of view of rare and scattered elements (REEs) extraction.

The Paromivske alluvial ilmenite deposit is an important resource in Ukraine that plays a key role in the production of iron, steel and titanium dioxide. The geological structure and structural-geological position of the Paromivske deposit are described and illustrated in [Yaremenko 2016.]. Its further development contributes not only to the region's economy but also provides the necessary raw materials for the country's industry and technological development.

According to the data of O. M. Bazaliyska⁵, obtained during the exploration of the Paromivsky placer deposit of ilmenite in the Mesozoic–Cenozoic deposits and weathering crusts of the basic rocks of the Korosten pluton intrusive complex, the following chemical composition was determined (Table 1).

Valuable components in ilmenite include Sc and V, with V₂O₅ content in ilmenite ranging from 0.24 to 0.28%. The industrial content of scandium in ilmenite is 30–50 g/t (0.003–0.005%) (Table 2).

In Table 3, the chemical composition of ilmenite from the Korosten pluton and titanium-zirconium placer deposits is presented, based on the data of Vykhdotsev *et al.* (report, 2007), who also provided a positive assessment of the prospects of titanium-zirconium placers on the northeast slope of the Ukrainian Shield.

Table 1. Chemical composition of the Paromivske placer deposit (in %) (from report of Bazaliyska⁵)

Таблиця 1. Хімічний склад Паромівського розсипного родовища (у %) (виробничий звіт, Базалійська⁵)

Deposit	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Fe ₂ O ₅	FeO	MnO	CaO ₅	MgO	Na ₂ O	K ₂ O	P ₂ O ₅	Cr ₂ O ₃	V ₂ O ₅
Paromivske	0.61– 1.29	50.96	0.20– 0.49	0.20– 0.49	6.62– 14.25	24.8– 35.56	0.53– 0.64	0.05– 0.06	0.28– 0.52	0.07– 0.08	0.57– 0.09	0.034– 0.082	0.021– 0.029	0.24– 0.28

Table 2. Reserves of V₂O₅ and Sc in ilmenite and zircon in alluvial ores of the Paromivsky placer deposit of ilmenite (C₂ category) (from report of Bazaliyska⁵)

Таблиця 2. Запаси V₂O₅ і Sc в ільменіті та цирконі в розсипних рудах Паромівського родовища ільменіту (категорія C₂) (виробничий звіт, Базалійська⁵)

Category of TiO ₂ component	Ilmenite reserves (in tonnes)	Average content			Inventories (in tonnes)		
		V ₂ O ₅ , t	Sc, gr/t	Zr, kg/m ³	V ₂ O ₅	Sc	Zr
Aluvium B+C ₁	801376	0.293	94.4	0.64	2348	no data	no data
Weathering crusts B+C ₁	1760762	0.257	84.8		4525	no data	no data
Total	2562138				6873	no data	no data

Table 3. Chemical Composition of ilmenite from the Korosten pluton and titanium-zirconium placer deposits (in %) (from report Vykhdotsev²)

Таблиця 3. Хімічний склад ільменіту з Коростенського плутону та титано-цирконієвих розсипів (у виробничий звіт, Виходцев²)

Deposit	TiO ₂	FeO	MnO	MgO	Al ₂ O ₃	Cr ₂ O ₃	V ₂ O ₅
Korosten pluton	50.2	42.5	0.55	0.82	0.38	0.03	0.20
Tarasivske placer	64.2	27.5	0.014	traces	2.1	0.10	0.18
Zelenoyarske placer	69.7	27.3	0.37	1.08	0.23	0.42	0.21

According to Mazurenko [2009], after enrichment of two samples of titanium-zircon sands from the Tarasivske deposit, the following significant impurities were found: in rutile: 0.145% Nb₂O₅, 0.013% Ta₂O₅, total rare-earth elements—0.01%, 0.25% V₂O₅; in ilmenite: V₂O₅: 0.018–0.83%, Ta₂O₅:

⁵ Bazaliyska, L. M. *et al.* 2016. Exploration of the Paromivske alluvial ilmenite deposit. *Ukrainian Territorial Geological Fund*. Kyiv. 3: 259. [Ukrainian]

0.015%, total rare-earth elements—0.041%; in zircon: 1.17% Hf, 0.15% V₂O₃, total rare-earth elements—0.43%.

Other elements, presented as associated impurities, include Mn, Pb, Sb, Mi, Cr, Sn, Mo, Cu, and Co.

The chemical composition of ilmenite in titanium-zirconium deposits refers to the elemental makeup and structure of the ilmenite mineral found within these deposits. Understanding the chemical composition is crucial for assessing the potential economic value of the deposit and for designing effective extraction and processing methods. The table below shows the chemical composition of ilmenite in the titanium-zirconium deposits of the Korosten pluton (Table 4).

Table 4. Chemical composition of ilmenite in titanium-zirconium deposits (in %) (from report, Mazurenko, 2009)

Таблиця 4. Хімічний склад ільменіту в титано-цирконієвих родовищах (у %) (виробничий звіт, Мазуренко, 2009)

Placer deposits	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	CaO ₅	MgO	P ₂ O ₅	Cr ₂ O ₃	V ₂ O ₅	ZrO ₂
Samotkanske	0.34	68.2	1.1	26.5	–	1.19	0.09	0.02	0.09	0.17	0.24	–
Vovchanske	–	63.4	2.0	29.0	1.0	0.83	0.26	–	0.06	1.35	0.25	–
Tarasivske	1.1	64.2	2.1	26.8	0.46	0.014	traces	traces	traces	0.1	0.18	–
Zelenoyarske	0.97	62.0	1.67	28.08	–	0.76	0.36	0.33	0.14	0.75	0.21	0.08

As seen from Tables 1–4, the comparison of the chemical composition of ilmenite in the gabbroids of the Korosten pluton and the placers indicates a significant similarity in chemical composition. However, analyses of bulk ilmenite samples from the placers differ markedly, showing higher contents of TiO₂, Al₂O₃, and Cr₂O₃, and lower iron content.

For example, in the Stremihorovske deposit (Zhytomyr Oblast), 90% of TiO₂ production comes from ilmenite. This deposit is located in gabbros, diabases, pyroxenites, and syenitic pegmatites, widely represented in weathering crusts, coastal-marine, and continental placers. Leucoxenised ilmenites include over 20 different elements, including rare, scattered, and rare-earth elements, the total content of which can reach 30 kg/t or even more [Proskurin *et al.* 1974]. Studies of conducted by V. H. Gevorkyan (2002) identified rare metals Co, V, Zn, Hf, Nb, Sn, Th, Sc, V, Zn, and Ga as impurities, as well as a significant amount of Ni, Cr, Cu, Pb, Ag, and Zn. Leucoxenised ilmenites tend to accumulate more impurities [Baranov 1961; Ramdor 1962; Gevorkyan 1964, 2002].

In addition to magmatic deposits associated with titanomagnetite ores containing rare and scattered elements, various types of epigenetic concentrations of these impurities exist in Ukraine. They are located in different age sedimentary rocks: Kimmerian iron ores, coals, bauxites, vanadium placers, limestones, red-colored and mottled formations, copper- and uranium-bearing sandstones, solid bitumens, etc. According to published reports [e.g. Kholodov 1968, 1973; Shnyukov 1977, 2008; Balance ... 2014], the largest vanadium reserves are found in sedimentary iron ores, exceeding the vanadium content in placers of titanium minerals several times. Unfortunately, the extraction of this valuable material, which plays a crucial role in the industry of many countries has not been carried out to date.

Conclusion

Our research has identified three significant sources of rare earth elements in Ukraine. The first source is primary deposits of apatite-ilmenite ores located in gabbroic rocks. The second source is exogenous deposits formed as a result of rock weathering. The third source is complex deposits of ilmenite-rutile and ilmenite-zircon placers.

In the post-war period, Ukraine's mining industry is preparing to use modern, integrated and waste-free technologies for the extraction of valuable mineral resources, and for this purpose it is important to use raw materials and beneficiation products in a comprehensive manner in the extraction and further processing of concentrates and associated rocks, such as clay, peat, sands, including quartz, lignite, apatite and others. Efficient use of mineral resources and maximising the extraction of

valuable products should be aimed not only at generating economic benefits, but also at preserving the environment and preventing its pollution by industrial waste.

Given that Ukraine primarily focuses on the development of titanium and iron ore deposits, which include rare and scattered elements, and the latter are not extracted (which is not economically viable), Ukraine should reconsider its approach to extracting vanadium and other minor elements from iron ores, bauxites, oil shales, phosphorites, various uranium deposits. To achieve this, detailed geological and geochemical studies of all identified sources and accumulators of valuable mineral impurities in Ukraine are required, including ilmenite concentrates and production waste.

Ukraine has large deposits of high-quality local raw materials. Using its scientific and production potential, as well as investment support from geopolitical partners, Ukraine is able to meet the demand for valuable elements by developing complex deposits for both domestic and international markets. In addition, it is necessary to continue to search for new methods of identifying sources of rare and scattered elements, and to explore alternative approaches to their extraction and use.

Declarations

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