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PROSPECTS FOR SCANDIUM MINING IN UKRAINE

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B a c k g r o u n d ***. The prospects for scandium mining in Ukraine are discussed. The important role of scandium in modern industry, as one of the high-tech metals, is highlighted.***

M e t h o d s . ***Methods of collecting and analyzing published and archival materials, as well as methods of comparison and analogy were used in the study.***

R e s u l t s ***. It is emphasized, that Ukraine is among the world leaders in scandium resources. Ukrainian reserves of Sc are recorded in 13 host-rock (Zhovtorichenske, Stremyhorodske, Fedorivske, Torchynske) and placer deposits (Malyshivske, Valky Gatskivske, Vovchanske, Trostyanets, Zlobytske, Irshanske, Lemnenske deposit [West section], Lemnenske deposit [East section], Tarasivske). The geological structure and scandium mineralization of the Zhovtorichenske, Pershotravneve and Gannivske deposits are described. Other possible sources of Sc in Ukraine are also discussed. Potential technologies for scandium mining as a byproduct are considered.***

C o n c l u s i o n s . ***A conclusion was drawn regarding the significant prospects of Ukraine for scandium mining. The Zhovtorichenske complex iron-uranium-vanadium-scandium deposit was identified as the most promising Sc-bearing object. Ways and directions of further research were outlined.***

K e y w o r d s : ***scandium, mineral deposits, mineral resources, mining.***

Background

Problem statement. Scandium (Sc) is a chemical element located in group 3 of the periodic table of the elements, with atomic number 21. It occupies an intermediate position between rare and rare-earth metals in terms of its geochemical characteristics. Scandium is a strategic metal and is widely used in: aluminium and magnesium alloys, synthesis of superhard materials, metallurgy, aerospace, nuclear and chemical industries, rocket and automotive engineering, electronics, production of solid oxide fuel cells (SOFCs), lighting devices, high-temperature ceramics, thermoelements, lasers, oil cracking, etc. Aluminium-scandium alloys significantly exceed all known compounds in terms of strength, including titanium alloys. Together with rare earth elements (REEs), it is a necessary component of modern high-tech production. Considering the above, it is urgent and essential to explore new sources of scandium, including in Ukraine, where its significant reserves are expected.

World reserves and resources of scandium. There are 11 minerals known where scandium is a principal or essential component (thortveitite, befanamite, kolbeckite, sterrettite, etc.), but only ***thortveitite*** $(Sc, Y)_2 [Si_2O_7]$ (Sc_2O_3 – 25.0–47.9 %, Y_2O_3 – 0.5–17.7 %) is of significant industrial value. Scandium in the form of an isomorphic impurity can enter the crystal system of various rock-forming and trace minerals. Therefore, independent scandium deposits are practically absent, with a few exceptions (the Iveland and Tordal regions in Norway, and Befanamo in Madagascar). Scandium is mined as a byproduct with various ores, including iron, uranium, titanium, tin, tungsten, bauxites, laterites, and phosphorites. Significant scandium resources are also concentrated in waste from titanium-magnesium and tungsten production, waste from the processing of bauxite and uranium ores, tin smelting slags, and cast iron production.

According to various estimates, scandium reserves range from 0.5 to 1.8 Mt. They are concentrated in China, the USA, Norway, Australia, Russia, Ukraine, Kazakhstan, Madagascar, etc. Scandium world production ranges from 5–10 to 20–30 tons, which is supplied by China (up to 66 % of world production), Russia, the Philippines, Kazakhstan, and Canada (Global scandium market, 2020; Mineral commodity summaries, 2023; Review of the scandium market..., 2020; World reserves of scandium..., 2019).

In recent years, world production and prices for scandium have fluctuated significantly, reflecting the global market situation. However, their significant increase may be predicted in the near future. In recent years, the cost of 99.5 % scandium oxide has been $1,300–1,400/kg, and the price of scandium metal has been between $12,000/kg and $20,000/kg. The global scandium market is estimated to be approximately $650 million in 2024, and is expected to grow to nearly $1 billion by 2029.

Analysis of recent studies and publications. The topic of scandium in Ukraine has been discussed in a number of publications, which raised the issues of possible sources of scandium in Ukraine (Mineral resources of Ukraine, 2020;

Mykhailov et al., 2023), the distribution of scandium in rock complexes of the Ukrainian Shield (Kryvdik et al., 2000; Mitskevich et al., 1986; Pavlyshyn et al., 1993), the structure of the Zhovtorichenske complex iron-uranium-vanadium-scandium deposit (Mykhailov, 2010; Tarkhanov et al., 1991a; 1991b; Zagnitko et al., 2017), methods for extracting scandium from waste generated by titanium-magnesium production (Kolobov, & Koreneva, 2009).

Aspects of the general problem that have not been previously solved. The issue of geological and economic assessment of scandium mining prospects in Ukraine remains unresolved.

The purpose of this study is to assess the potential for scandium mining in Ukraine, provide recommendations, and establish the direction for further research.

Methods

The study uses methods of collecting and analyzing published and archival materials, as well as methods of comparison and analogy.

Results

Sources of scandium in Ukraine. In terms of scandium reserves, Ukraine is among the world leaders and ranks first in Europe. The State Balance of Mineral Resources of Ukraine has established scandium reserves in 13 deposits: 4 complex deposits in host rocks: Zhovtorichenske (uranium-vanadium-scandium metasomatites), Stremyhorodske, Fedorivske and Torchynske (apatite-titanomagnetite-ilmenite ores) and nine ilmenite placer deposits: Malyshivske, Valky Gatskivske, Vovchanske, Trostyanets, Zlobytske, Irshanske, Lemnenske deposit (West section), Lemnenske deposit (East section), Tarasivske. Six of them are currently being developed or have been developed recently (Mineral resources of Ukraine, 2020). The most interesting of them in terms of investment attractiveness is the Zhovtorichenske deposit.

The Zhovtorichenske complex iron-uranium-vanadium-scandium deposit in the Dnipropetrovsk region has a long and complex history of development. Iron ores were discovered there at the end of the 19th century; at first, they were mined by open-pit methods, and since 1934 – by underground mining. In 1945, uranium ores were discovered at this site, and together with iron ores they were mined underground from 1948 to 1989 in the Nova and Olkhovska mines. In 1976, scandium ores were discovered here, from which scandium was extracted together with uranium at the Eastern Mining and Processing Plant (SkhidGZK) until 1989.

In 1993, the Eastern Mining & Processing Plant (SkhidGZK) formed a joint venture with an American investor, the Ashurst Technology Ltd., which mined scandium in limited quantities as a byproduct. Based on the processing of uranium production tailings, a technology was developed for extracting scandium from uranium ore to produce an aluminium-scandium alloy with a 2 % scandium content. However, in 1995, due to financial problems, the company withdrew from the project and scandium mining ceased. From then until the beginning of the 20s of the 21st century, only iron ore was mined from the upper floors of the deposit, and the lower mine floors were flooded.

The Zhovtorichenske deposit lies in rocks of the Kryvorizhska series, which are folded into a narrow synclinal fold with steep wing dips (Fig. 1). The main ore-controlling structure is a fork-shaped fault zone, which is intersected by a gentle thrust zone. The deposit has a zonal structure: the upper floors, extending to a depth of 1105 m, are composed of iron ores, with total reserves estimated at 880 Mt. The lower floors are composed of uranium-vanadium-scandium ores, with total reserves of approximately 8 Mt. Information on the reserves of scandium ores is confidential. According to foreign experts, the total may reach 7.4 Mt, with scandium accounting for 900 tons, having an average content of 105 g/t (Bernard, 2001; Chao et al., 1992).

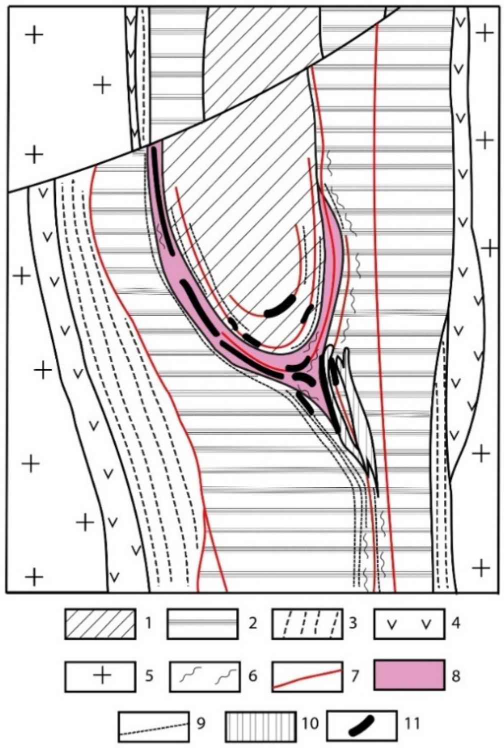

Fig. 1. The geological structure of the Zhovtorichenske deposit (Tarkhanov et al., 1991a):
1–4 – Kryvorizhska series: 1 – upper suite; 2 – middle suite, 3 – lower suite, 4 – amphibolites; 5 – granites and migmatites; 6 – crumpling, migmatization, and blastomylonite zones; 7 – crush zones; 8 – albitites; 9 – riebeckite and aegirine shists; 10 – iron ores; 11 – uranium ores

Uranium-vanadium-scandium ores are localized in a layered zone of carbonate-sodium metasomatites with uraninite and brannerite, about 100 m long along strike and up to 380 m along dip, with a thickness of up to 10–20 m (Tarkhanov et al., 1991a). Vanadium-scandium ores are confined to zones of carbonate-aegirine metasomatites in diopside quartzites, actinolite schists, and partly dolomites of the Paleoproterozoic Skelyuvatska suite, near its contact with the Gdantsivska suite (Fig. 2). They are represented by sublayered vein and lenticular bodies of alkali-amphibole-actinolite metasomatites composed of albite (6–15 %), aegirine (9–21 %), amphibole (riebeckite, arfvedsonite, tremolite, actinolite) (11–21 %), carbonate (21–46 %), quartz (6–26 %), talc (3–10 %), apatite (3–20 %), malacon, and tremolite (Tarkhanov et al., 1991b; Zagnitko et al., 2017).

Scandium and vanadium do not form their own minerals; they are isomorphically hosted in aegirine (up to 0.1 % Sc_2O_3; up to 3–5 % V_2O_5) and alkaline amphiboles (up to 0.1 % Sc_2O_3; up to 0.41–2.35 % V_2O_5). Two main types of ores are distinguished: vanadium-scandium and composite uranium-rare-earth (Table 1). The average content of scandium in vanadium-scandium ores is 0.072 %, in uranium-rare-earth ores – 0.042 %. The ores are composite; in addition to scandium, they also contain vanadium (0.036–0.54 %), yttrium (0.022–0.019 %), zirconium (1.1–1.2 %), and REE (0.036 %).

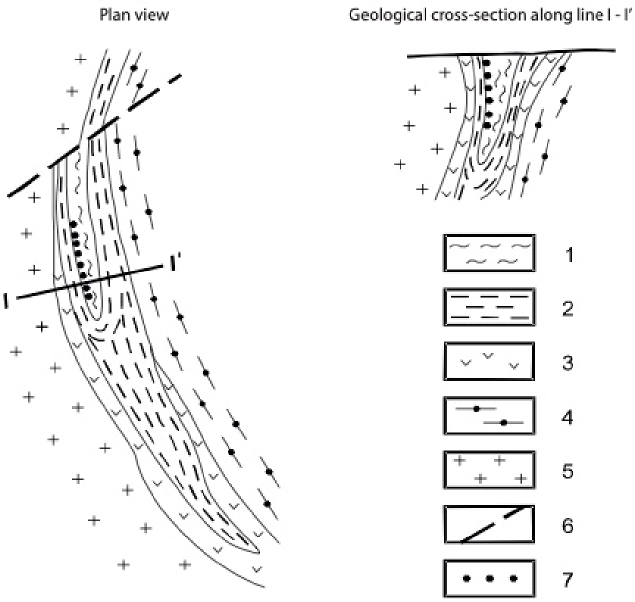

Fig. 2. Location of the scandium mineralization zone in the western wing of the Zhovtorichenska syncline (Tarkhanov et al., 1991b):
1 – Gdantsivska suite; 2 – Saksaganska and Skelyuvatska suites; 3 – Konkska series, amphibolites; 4 – granites, granite-gneisses of the Dnieper complex; 5 – granites of the Kirovograd complex; 6 – faults; 7 – scandium mineralization

Table 1

The content of scandium and related components in the hands of the Zhovtorichenske deposit, g/t (Tarkhanov et al., 1991a)

Ore	Sc	V	P_2O_5 %	TR_2O_3	Y	V_2O_5	Hf
Uranium-rare-earth	50–100	150–600	5.8	600–1000	20–500	1700	140
Vanadium-scandium	100–200	50–120	2.6	400–500	100–250	2700	150
Composite	100–150	100–200	3.4	500–600	150–250	2500	150

The main features of the Zhovtorichenske deposit are: its complex nature, the presence of various types of ores of different elements, an extremely wide range of minerals, such as actinolite, uranium-bearing apatite, arsenopyrite, baddeleyite, brannerite, rare-earth carbonates, coffinite, xenotime, malacon, monazite, pitchblende, nenadkevite, pyrochlore, spodumene, sphene, yttrium and uranium titanite, uraninite, zircon, cyrtolite, aegirine and many others.

Clay-rich weathering crust up to 40 m thick formed in the host ore rocks with an average Sc content of 0.01–0.013 %, Zr – 0.88–1.4 %, Y – up to 0.13 %, and increased content of Yb – up to 0.013 %, Lu and other lanthanides have been established. The Zhovtorichenske complex iron-uranium-vanadium-scandium deposit can be considered a highly promising object (Mykhailov et al., 2023).

In the ilmenite-apatite and titanomagnetite host rock ores of the ***Stremyhorodske*** and ***Torchynske*** deposits, scandium is present mainly in ilmenite (up to 0.015 % Sc_2O_3) and pyroxene (up to 0.024 % Sc_2O_3). The average Sc content in ores is 0.007–0.013 %. An increased scandium content up to 0.015 % was also recorded in the weathering crust of these deposits (Mitskevich et al., 1986).

The Stremyhorodske deposit was discovered in 1954, estimated in 1980, and re-estimated in 2016. It is represented by an ore body of gabbroids among the oreless anorthosites of the Paleoproterozoic intrusion, which is located in the zone of the deep Korosten fault. Gabbroids are recorded to a depth of 1378 m, although the reserves are approved to a depth of 500 m, which makes it reasonable for open-pit mining. The protocol of the State Commission of Ukraine on Mineral Resources №3725-DSK dated 11.29.2016 approved apatite reserves in the amount of 31,826.3 thousand tons; vanadium ores – 222.9 thousand tons; fluorine in apatite – 1,358.7 thousand tons; kaolin, grit, weathered gabbro – 32354 thousand tons; gabbro-anorthosite – 197736 thousand m^3. Titanium and scandium reserves are confidential. The average content of TiO_2 is 6.91 %; P_2O_5 – 2.42 %; vanadium – 0.2 %; fluorine in apatite – 2.22 %; scandium – 80 g/t (Mineral Resources of Ukraine, 2020).

In addition, scandium (up to 80 g/t) is present in ilmenite weathering crusts of this deposit. Their thickness can reach 35–40 m, and the ilmenite content varies from 30 to 130 kg/m^3.

The Torchynske deposit of eluvial titanium ores is located in the north of Zhytomyr region in the endocontact zone of the Volodarskiy massif of gabbro-anorthosites. It is localized in the weathering crust of gabbroids, represented by a strata-like layered deposit. It is 11.6 km long, 9 km wide, covers an area of about 100 km^2 and dips gently (2–12 degrees) to the east. The average content of ilmenite in the weathering crust of ore-bearing gabbro-norites is 110 kg/m^3. Apatite (on average 13 kg/m^3), titanomagnetite, as well as minor amounts of pyrrhotite, pyrite and chalcopyrite are found in addition to ilmenite (Yaremenko, 2020). Scandium is an associated component, its content in ilmenite is 27–67 g/t (on average 60 g/t). Vanadium can be extracted from ilmenite as a byproduct of titanium mining. The average content of V_2O_5 in ilmenite from the weathering crust is 0.224 %.

In placer ilmenite and rutile-zircon-ilmenite deposits (Malyshivske, Irshanske, Zlobytske, etc.) scandium is concentrated in ilmenite (0.005 %), rutile (0.003 %), zircon (0.007 %), and monazite (up to 0.03 %). The average content of scandium in placers is 0.001–0.01%. Years ago, scandium was extracted from concentrates at the Ust-Kamenogorsk Plant in Kazakhstan.

Scandium mineralization has been found in a number of deposits of ferruginous quartzites in Kryvyi Rih, in particular, in the ***Pershotravneve deposit***, where alkaline metasomatism is manifested in the rocks of the 6th ferruginous horizon of the Saksaganska suite. It occurs in the form of bodies of aegirinization of magnetite-cummingtonite ferruginous quartzites and cummingtonite ferruginous schists with zonal structure: outer carbonatization and quartzification zone; intermediate riebeckite zone; inner aegirinite zone (Fig. 3).

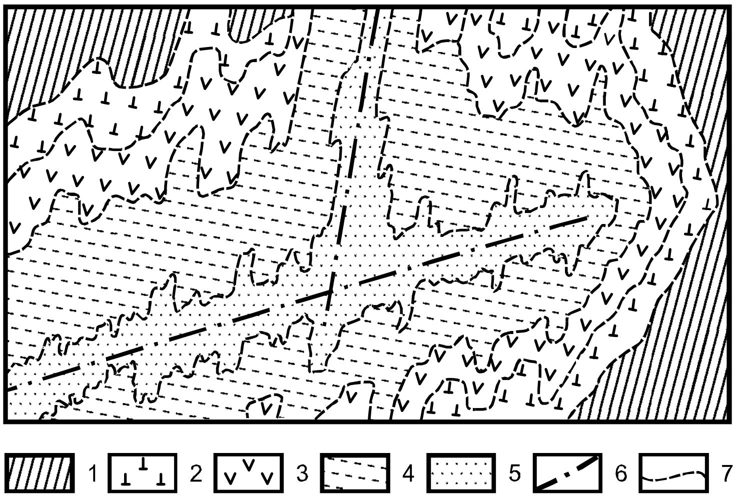

Fig. 3. Structure of the zonal body of scandium-vanadium bearing sodium metasomatites (Pavlyshyn et al., 1993):
1 – ferruginous quartzites; 2–5 – metasomatic zones: carbonatization (2), quartzification (3), riebeckitization (4), aegirinization (5); 6 – faults; 7 – boundaries of metasomatic zones

The main concentrator of scandium is cryptocrystalline brownish-green and bright-green aegirine, in which the scandium content reaches 5000–6000 g/t. The average scandium content in the ores of the deposit is 83 g/t, and vanadium – 742 g/t. They can be mined as byproducts during the mining of iron ores (Kharitonov, 2007).

At the ***Gannivske deposit*** in similar zonal bodies of sodium metasomatites among the ferruginous quartzites of the Saksaganska suite, the average scandium content is 79 g/t, vanadium is 701 g/t (Kharitonov, 2007).

The content of scandium and other elements in the zones of ore metasomatites is shown in Table 2.

Table 2

Scandium and other element content in ore metasomatite zones, g/t (Mykhailov, 2010)

Zone	Sc	V	Y	Zr	REE	P	Ti
Zhovtorichenske deposit							
Aegirine	**50–700**	**50–15000**	**60–400**	**500–5000**	**50–400**	**3000–40000**	**–**
Riebeckite	30–500	100–1500	50–300	500–3000	50–300	2000–50000	–
Actinolite	10–300	150–1500	50–300	500–2500	40–200	2500–50000	–
Tremolite	10–200	0–1000	10–150	100–2000	10–200	1000–20000	
Quartzification	**0–100**	**0–50**	**0–50**	**50–400**	**0–100**	**100–400**	**–**
Carbonatization	**0–100**	**0–50**	**0–90**	**50–300**	**0–100**	**1000–15000**	**–**
Diopside quartzites	**0–20**	**0–50**	**0–80**	**50–400**	**0–100**	**100–500**	**–**
Pershotravneve deposit							
Aegirine	10–210	50–3000	0–120	10–1300	–	50–4000	50–2000
Riebeckite	**0–100**	**0–500**	**0–10**	**0–10**	**–**	**0–50**	**50–3000**
Quartzification	**0–10**	**0–50**	**0–10**	**0–10**	**–**	**0–50**	**0–50**
Carbonatization	**0–10**	**0–50**	**0–10**	**0–10**	**–**	**0–50**	**0–50**
Ferruginous quartzites	**0–10**	**0–50**	**0–10**	**0–10**	**–**	**0–50**	**0–50**

The increased content of scandium was recorded in coal ash from the mine fields of the Luhansk region. Its average content is 74–90 g/t, and the reserves are estimated at 18.7 thousand tons. In addition to scandium, an increased content of REE, bismuth, copper, zinc, cobalt, molybdenum and other elements is recorded in coal ash.

In addition to the objects mentioned above, a potential source of scandium in Ukraine may include: the basic and ultrabasic intrusive and volcanic rocks of the Ukrainian Shield, rocks of bituminous domes and diapir structures of the Donbas region, phosphorites in the sedimentary cover of the Ukrainian shield, manganese ores in the Nikopol manganese ore basin, etc. (Kryvdik et al., 2000).

In addition to these sites, potential sources of scandium in Ukraine may include basic and ultrabasic intrusive and volcanic rocks of the Ukrainian Shield, rocks of bituminous domes and diapirs in the Donbas, phosphorites of the sedimentary cover of the Ukrainian Shield, manganese ores of the Nikopol manganese ore basin, and others.

The increased content of scandium has been found in peridotites (19–91 g/t), pyroxenites (56–75 g/t) and gabbros (32–66 g/t) of the Oktyabrskiy massif, picrite basalts of the Golovanivska suture zone (10–117 g/t), gabbro-norites of the Devladivska fault zone (32–56 g/t) (Mitskevich et al., 1986). Orthopyroxene (32–130 g/t), clinopyroxene (32–65 g/t), hornblende (50–150 g/t), actinolite (31–50 g/t), and biotite (30–50 g/t) are enriched with scandium in these rocks. In the granitoids of the Ukrainian Shield, the scandium content usually does not exceed 10 g/t, sometimes it is 15–47 g/t (Novoukrainskiy, Boguslavskiy, Korostenskiy, Kirovogradskiy granitoids), where scandium is concentrated mainly in biotite (up to 90–120 g/t), garnet (up to 130–

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300 g/t), zircon (up to 200 g/t in general, and even up to 1000 g/t in Berdychivskiy granites) (Mitskevich et al., 1986).

The issue of scandium extraction from ores of various metals and production waste can be solved by applying different technological schemes. One of the most common schemes involves leaching solid chloride waste (spent melt from titanium chlorinators) with hydrochloric acid, followed by settling and filtration of the resulting pulp, and the reduction of trivalent iron ions to divalent iron using magnesium powder. The solution is then directed to extraction with a 70 % solution of tributyl phosphate in kerosene. After extraction, the organic phase is washed with hydrochloric acid, and scandium is re-extracted with dilute hydrochloric acid. The obtained re-extract containing 0.45–0.9 g/L concentrations of Sc_2O_3 is neutralized with soda and then treated with oxalic acid. The resulting oxalates are filtered and calcined. As a result, a "crude" scandium oxide with a Sc_2O_3 content of 40–50 % is obtained.

This technology for extracting scandium from ilmenite of Ukrainian placers was developed back in the 1960s. It was used at the Ust-Kamenogorsk Titanium & Magnesium Plant (Kazakhstan), but can be also applied at the Zaporizhzhia Titanium & Magnesium Plant, where an experimental line for scandium production was launched in the 1990s, and the first batches of its oxide were produced. However, due to financial problems, it operated for only one month. Increased concentrations of scandium (up to 0.01 %) were also found in zircons of complex coastal-marine placers of Ukraine.

Scandium concentrate from titanium dioxide waste production was once obtained at the Sumy Production Association (PA) "Khimprom" and the PA "Titan" in Crimea, but its processing was carried out at the PA "Almaz" in Russia (Stavropol region). The following technological scheme was used at the PA "Titan". Sulfuric acid mother liquors after titanium hydroxide precipitation were directed to extraction for scandium recovery with diisooctyl methylphosphonate. The resulting re-extract with a Sc_2O_3 content of 2 % in liquid form was transported to the Lermontov Hydrometallurgical Plant, where it was mixed with industrial solutions of uranium production and a crude scandium oxide was precipitated.

Another source of scandium may be bauxites processed at the Mykolaiv Alumina Plant, where the scandium content in aluminium production waste (red sludge) reaches 50–100 g/t; in addition, yttrium, lanthanum, and neodymium are also present. Years ago, a scandium oxide production line was launched there, but it is currently not in operation. A potential source of scandium may be bauxites from Ukrainian deposits and occurrences (Vysokopilske, Pivdennonikopolske, Smilyanske). For example, in bauxites from the Vysokopilske deposit the average scandium content reaches 44.6 g/t.

Finally, a promising source for scandium extraction may be titanium-magnesium production waste, which has accumulated in large quantities (up to 1 Mt) in the dumps of the Zaporizhzhia Titanium & Magnesium Plant, from where scandium can be recovered by extraction with solid extractants (Kolobov, & Koreneva, 2009).

Special permits for scandium extraction as a byproduct in Ukraine have been issued for the mining of zircon-rutile-ilmenite placers of the Tarasivske deposit in Kyiv region (LLC "Rutile & Ilmenite Company") and ilmenite-zircon placers of the Valky Gatskivske deposit.

Discussion and conclusions

Ukraine has significant prospects to become a reliable source of scandium supply to European and global markets, primarily due to the presence of the large complex iron-uranium-vanadium-scandium Zhovtorichenske deposit; complex primary ilmenite-apatite and titanomagnetite ores of the Stremyhorodske and Torchynske deposits; placer ilmenite and rutile-zircon-ilmenite deposits such as Malyshivske, Irshanske, Zlobytske, etc.; as well as iron ore deposits such as Pershotravneve, Gannivske, and others, where an increased content of scandium has been recorded. To resume the development of Ukraine's own scandium mineral and raw material base, the following measures may be recommended:

1. Conducting revision work and additional exploration of all promising objects and structures with signs of scandium mineralization.
2. Conducting a geological and economic assessment of known objects of scandium mineralization and determining the feasibility study of extracting scandium as an associated component.
3. Improving existing and, if necessary, developing new technological schemes for the extraction of scandium from uranium, iron, titanium, and zirconium ores, bauxites, and technogenic waste from titanium and aluminium production.
4. Restoration and reconstruction of production facilities of the Zhovtorichenske deposit as the most promising object of scandium mineralization.
5. Attracting investments in the research and development of deposits with associated scandium mineralization.

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ПЕРСПЕКТИВИ ВИДОБУТКУ СКАНДІЮ В УКРАЇНІ

В с т у п . ***Розглянуто перспективи видобутку скандію в Україні. Показано важливу роль скандію в сучасній промисловості як одного з високотехнологічних металів.***

М е т о д и . ***В роботі використано методи збору та аналізу опублікованих і фондових матеріалів, методи порівняння та аналогій.***

Р е з у л ь т а т и . ***Наголошується, що Україна входить до числа світових лідерів із ресурсів скандію, запаси яких враховано на 13 корінних (Жовторіченське, Стремигородське, Федорівське, Торчинське) і розсипних родовищах (Малишевське, Валки-Гацківське, Вовчанське, Тростянецьке, Злобицьке, Іршанське, Лемненське-Західне, Лемненське-Східне, Тарасівське). Описано геологічну будову і скандієву мінералізацію Жовторіченського, Першотравневого і Ганнівського родовищ. Наведено інші можливі джерела скандію в Україні. Розглянуто можливі технології вилучення скандію як супутнього компонента.***

В и с н о в к и . ***Зроблено висновок про значні перспективи України щодо видобутку скандію, найперспективнішим об'єктом визначено Жовторіченське комплексне залізо-уран-ванадій-скандієве родовище. Намічено шляхи і напрями подальших досліджень.***

К л ю ч о в і с л о в а : ***скандій, родовище, запаси і ресурси, видобуток.***

Володимир Михайлов є членом редколегії видання, тому не брав участі у рецензуванні та прийнятті рішення щодо публікації цієї статті.

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