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Exploration and mining perspectives of the critical elements for green technologies in Ukraine

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Abstract: The state of the mineral resource base of Ukraine for a number of elements that are essential for the development of 'green power energy' in Europe is analysed. Four groups can be distinguished that differ in degree of geological certainty, available reserves and stages of potential and/or commercial development. (1) Iron, manganese and graphite – large-scale deposits that have been developed for a long time in Ukraine and have almost unlimited resources/perspectives for further production. (2) Lithium and rare-earth elements (REEs) – deposits that have mostly been explored and possess considerable reserves; these deposits are not under exploitation but can be brought into commercial production pending appropriate geological and economic evaluation. (3) Cobalt and nickel – deposits that have been discovered but their reserves are rather small and some technological problems of ore beneficiation exist; these deposits can be developed only in the case of additional confirmation of their economic feasibility by objective economic and geological evaluation. (4) Aluminium and lead – small deposits and manifestations that are known but their reserves and ore grades are rather low, and, as a result, their exploitation is doubtful and perspectives for commercial output are not clear.

Supplementary material: The list of mining regions and ore deposits of strategic and critical raw materials of Ukraine is available at https://doi.org/10.6084/m9.figshare.c.5913018

The criticality of mineral resources, as well as 'critical' or 'green' raw materials, has been discussed widely over the last decade, with the European Commission updating the list of critical minerals every 3 years; the latest list was presented in 2020 in the communication 'Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability' (European Commission 2020). Although the materials that fall within the critical group for a particular country or region do vary, the general principle for distinguishing the group of critical minerals is widely accepted.

Ukraine possesses a unique mineral resource potential and holds a leading position for a number of useful minerals (e.g. iron, manganese, titanium and uranium). About 8000 deposits and more than 20 000 occurrences of 120 types of minerals are known in Ukraine, including those that are considered to be essential in 'green technologies'. Based on commercial value and perspectives for development, they can be classified into four groups:

(1) Types of raw materials that form the basis of ore mining in Ukraine. These are studied in detail, include large reserves and are intensively developed: iron, manganese and graphite.
(2) Types of raw materials for which deposits have been discovered, and reserves and resources have been evaluated. They are viewed as highly prospective for commercial production but have not yet been developed: lithium and rare-earth elements (REEs).
(3) Types of raw materials for which deposits are known and reserves and/or resources are established. They are prospective for commercial production but have not yet been developed: cobalt and nickel.
(4) Types of raw materials for which deposits are known, and reserves and/or resources are established. Their perspectives as to commercial production are not so clear: aluminium and lead.

Almost all of these critical minerals deposits are associated with structures in the Ukrainian Shield and its margins; except for the lead deposits, which are known to occur within the Carpathian folded region and Dnipro–Donetsk Rift (DDR).

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Descriptions of important mineral deposits are given below with regard to the four groups outlined above, and their relevance to the concepts of 'critical raw materials' (CRMs) and 'Green Age' minerals will further require additional evaluation that is outside the scope of this paper.

Brief outline of the geology of Ukraine

Ukrainian territory comprises diverse tectonic units and displays complicated geology. Most of the onshore belongs to the platform areas that include, or are partly surrounded by, comparatively younger fold belts.

In the Eastern European Platform the following major tectonic units are differentiated: the Ukrainian Shield and the Voronezhska anticline, with their margins overlain by younger sediments, and the Dniprovsko–Donetska Depression (DDD) (Fig. 1).

The largest domain is the Ukrainian Shield, which extends from the NW to the SE through the entire country. In the Ukrainian Shield, the folded Precambrian basement and the overlying Phanerozoic sedimentary cover, with an irregular distribution and total thickness up to 120 m, are distinguished.

The Ukrainian Shield is composed of six megablocks with different geological histories and various rock complexes: Volyn (NW), Dnister–Boug, Ros–Tykych, Kirovograd, Middle Dniprean and Azovian.

Fig. 1. A sketch of the main mining regions and ore deposits of critical elements for green technologies in Ukraine. Mining regions: I, Kryvyj Rig (Fe); II, Kremenchuk (Fe); III, Bilozirka (Fe); IV, Nikopol (Mn); V, Tokmak (Mn). Ore deposits: 1, Zavallivske (Gr); 2, Petrivske (Gr); 3, Balakhivske (Gr); 4, Burtynske (Gr); 5, Troitske (Gr); 6, Mariupilske (Gr); 7, Yastrubetske (Zr, REEs); 8, Polokhivske (Li); 9, Dobra site (Li); 10, Novopoltavske (Ta, Nb, REEs); 11, Shevchenkivske (Li); 12, Azovske (Zr, REEs); 13, Mazurivske (Ta, Nb, Zr, REEs); 14, Kapitanivske (Cr, Ni, Co); 15, Ternuvatske (Ni, Co); 16, Devladivske (Ni, Co); 17, Prutivske (Ni, Co, Cu); 18, Vysokopolske (Al); 19, Yuzhnonikopolske (Al); 20, Beregivske, Biganske and Muzhyivske (Pb, Zn, Au); 21, Biliavske (Pb, Zn). See the text descriptions and Table 1 for location details.

They are mostly composed of Archean and Proterozoic high-grade granite–gneiss complexes, whereas lower-grade Archean greenstone belts are locally developed in the Middle Dniprean and Azovian megablocks. Lower Proteozoic low-grade volcanic-sedimentary complexes are developed at the western margin of Middle Dniprean megablock (Kryvyi Rig and Kremenchuk mining areas), and sublongitudinal tectono-metasomatic zones, composed of metamorphosed terrigenous and volcanic rocks, are confined to the folded area at the eastern margin of the Kirovograd megablock. The least metamorphosed sedimentary rocks are developed in the Volyn megablock. Mafic and ultramafic rocks are present in the Archean greenstone belts and in some folded areas of the Dnister–Boug megablock. Granitoid rocks and pegmatites are widespread, while their mineralized bodies are mostly located in the Azovian and Kirovograd megablocks. A detailed description of the Ukrainian Shield can be found elsewhere (Bobrov *et al.* 2006).

In the folded rim of the Eastern European Platform, Herzinian (the Folded Donbas, fragments of the Fore-Dobrugean Trough and the Marmaroshskiy massif in Trans-Carpathians), Kimmerian and Alpine domains (Crimean Mountains and folded Carpathians) can be distinguished.

The Volyno–Podilska Plate and the Lvivskiy Trough adjoin the Fore-Carpathian Trough from the north. The thickness of the Paleozoic–Mesozoic sedimentary cover of the Volyno–Podilska Plate reaches 9–10 km. The Vednian part of the section is well exposed in the Middle Dnister region. It has been studied in detail and is considered in publications as a unique geological object and etalon of the Vendian System. Similarly, in the south, the Fore-Black Sea Depression and adjacent Scythian Plate separate the Ukrainian Shield from the folded units of the Alpine Crimean Mountains.

In the NE, the Ukrainian Shield adjoins the DDD, which is filled with Paleozoic, Mesozoic and Cenozoic sedimentary rocks. The Herzinian Folded Donbas to the SE can be differentiated from the DDD. Another Herzinian folded Dobrugean Trough is located in the SW of the Odesa region.

A region of Kimmerian Alpine folding (Late Mesozoic–Early Cenozoic) includes the Crimean Mountains and their eastern subsided elongation in the Kerch Peninsula. The Crimean Mountains are composed of Triassic, Jurassic, Cretaceous, Paleogene and Neogene rocks.

Description by mineral types

Iron

Iron is one of the most widely used metals and provides 95% of world metallurgical production. In addition, the unique ferromagnetic properties of a number of iron alloys support their broad application in electrical equipment as cores of electromagnets and anchors, plates for accumulators, and in magnetic conductors for transformers and electric motors. Iron is applied as the anode in iron–nickel accumulators and iron–air accumulators. Iron powder and cast iron are used as spark generators and fuel in pyrotechnics.

Iron ores deposits are known in more than 130 countries of the world, with the largest proven reserves (more than 3 BT (billion tons)) being located in Russia, Ukraine, Australia, China, USA, Brazil, Canada, Kazakhstan, Sweden and India. These countries are also the largest producers of saleable iron ores (USGS 2020).

Thus, Ukraine is one of the leading global sources for iron reserves and production. Five iron ore basins and regions can be identified: the Kryvyj Rig and Bilozirka regions that include rich hematite–martite and magnetite ores; the Kremenchuk and Near Azov regions with magnetite quartzite; and the Kerch region that has brown iron ores. However, only the first three regions have commercial significance (locations I, II and III in Fig. 1; mining regions I, II and III in Table 1).

As of 1 January 2020, the State Commission on Mineral Reserves of Ukraine holds 60 deposits of which 25 are under exploitation: e.g. Inguletske, Skelevatske, Saksaganske, Valyavkinske, Gleyuvatske and Kremenchutske. They are described in detail in numerous geological publications (e.g. Gursky *et al.* 2006; Mykhailov *et al.* 2007; Gursky 2008; Rudko *et al.* 2010; Dovgy *et al.* 2017; Mykhailov and Hrinchenko 2018). Total reserves of iron ore are 18.8 BT. In 2019, 157.4 MT (million tons) of ore were extracted in Ukraine (Geoinform of Ukraine 2020). The reserves completely meet the requirements of the ore-mining industry of Ukraine and form a reliable base for many years ahead, including the requirements for the 'green power industry' in Europe.

Manganese

Besides metallurgy, a significant amount of manganese dioxide is used in the electrical engineering industry for the production of manganese–zinc galvanic cells, where MnO_2 is used as an oxidizer–depolarizer. Among the countries that lead in the reserves and output of manganese ores are the Republic of South Africa, Ukraine, Kazakhstan, Gabon, Brazil, Georgia, China and Australia (Reichl and Schatz 2021).

Ukraine has the world's largest proven reserves of manganese ores (2.4 BT), although ore grades in Ukraine are much lower than those of Brazil, Australia and Africa. Ore reserves are mainly located within

Table 1. *List of mining regions and ore deposits of strategic and critical raw materials of Ukraine*

Numbers	Name	Longitude (°N)	Latitude (°E)	Commodity name	Resources	Figure reference
Mining regions						
I	Kryvyj Rig	33.38	47.97	Iron ore	40.8 Bt with 33.3–34.2% Fe	Figure 1
II	Kremenchuk	33.70	49.17	Iron ore	39.5 Bt with 27.4–58.5% Fe	
III	Bilozirka	34.98	47.17	Iron ore	6.7 Bt with 55.7–62.8% Fe	
IV	Nikopol	34.37	47.65	Manganese ore	2.42 Bt with 23.9% Mn	
V	Tokmak	35.64	47.36	Manganese ore	1.73 Bt with 23.4–31.0% Mn	
Ore deposits						
1	Zavallivske	30.00	48.22	Graphite	94.64 Mt with 6.5% graphite	Figure 2
2	Petrivske	33.27	48.32	Graphite	9.22 Mt with 7.18% graphite	
3	Balakhivske	33.22	48.47	Graphite	42.41 Mt with 5.36% graphite	
4	Burtynske	27.30	50.31	Graphite	152.82 Mt with 6.7% graphite	
5	Troitske	36.88	47.03	Graphite	2.28 Mt with 2.17% graphite	
6	Mariupilske	37.50	47.17	Graphite	4.79 Mt with 3.92% graphite	
7	Yastrubetske	27.90	51.42	Zircon, REEs	0.21 Mt REEs	
8	Polokhivske	31.40	48.65	Lithium	0.75 Mt Li_2O*	Figure 3
9	Dobra (Stankuvatske, Nadiya)	31.06	48.33	Lithium	0.76 Mt Li_2O*	Figure 4
10	Novopoltavske	36.30	47.25	Tantalum, niobium, REEs	0.5 Mt REEs in monazite	
11	Shevchenkivske	36.70	47.90	Lithium	0.40 Mt Li_2O*	
12	Azovske	37.25	47.18	Zircon, REEs	0.71 Mt REEs	Figure 5
13	Mazurivske	37.51	47.52	Tantalum, niobium, zircon, REEs	0.20 Mt REEs	
14	Kapitanivske	30.58	48.18	Chromium, nickel, cobalt	6.1 Mt with 26.02% Cr_2O_3	
15	Ternuvatske	30.53	48.12	Nickel, cobalt	10.90 Mt with 0.91% Ni, 0.046% Co	Figure 6
16	Devladivske	33.77	48.10	Nickel, cobalt	10.31 Mt with1.06–1.24% Ni, 0.05% Co	
17	Prutivske	28.08	50.32	Nickel, cobalt, copper	36 Mt with 0.58% Ni, 0.02% Co, 0.26% Cu	
18	Vysokopolske	33.33	47.55	Bauxite	18.9 Mt with 38% Al_2O_3	Figure 7
19	Yuzhnonikopolske	34.15	47.64	Bauxite	0.535 Mt	
20	Beregivske, Biganske, Muzhyivske	22.67	48.20	Lead, zinc, gold	0.92 Mt Pb, 2.17 Mt Zn	Figures 8, 9
21	Biliavske	36.34	49.24	Lead, zinc	0.14 Mt Pb, 0.56 Mt Zn	

*Information on reserves is still confidential and the values given have been obtained by expert assessment.

the Nikopol Basin on the southern slope of the Ukrainian Shield. Some small occurrences of manganese ores are also known on the Kerch Peninsula, the Near Carpathians, Volyn–Podillia, the Crimean Mountains and other regions, but they do not have any commercial value. The manganese ores of Ukraine are described in many geological publications (e.g. Shnyukov *et al.* 1993; Gursky *et al.* 2006; Mykhailov *et al.* 2007; Gursky 2008).

The Nikopol Basin comprises the Nikopolske, Fedorivskre and Velikotokmatske deposits (locations IV and V in Fig. 1; IV and V in Table 1) located within an arc-like structure up to 250 km long and 20 km wide. Total reserves of the manganese ores in these deposits reach 2.4 BT (please note that metric tonnes (t) are used in place of tons (T) hereinafter unless otherwise specified). The Nikopolske deposit is currently under exploitation; 3.9 Mt of manganese ore was extracted in 2019 (Geoinform of Ukraine 2020). Any further increase in manganese ore reserves requires additional exploration work to be carried out at the western flanks of the basin.

Thus, explored reserves of manganese ores in Ukraine are sufficient to provide production for a long period of time and almost unlimited exports to European countries and the rest of the world.

Graphite

Graphite is used in electrical engineering in the production of galvanic cells, alkaline accumulators, electrodes, mobile contacts, and for the production of heating elements, contact brushes and slip rings in different electrical machines.

The largest reserves and resources of graphite are located in Russia, Ukraine, China, Mexico, Czech Republic, India, Madagascar and Brazil. Countries such as China, India, Brazil, Russia, North Korea, Canada, Madagascar, Czech Republic and Ukraine are among the leading producers of graphite in the world.

Ukraine is the largest graphite-bearing country, the main deposits of which are confined to structures in the Ukrainian Shield (Mykhailov *et al.* 2008). They are located within four ore districts: Pobuzhzhia (Zavallivske in Kirovograd Oblast), Kryvyj Rig (Petrivske and Balakhivske in Kirovograd Oblast), Volyn (Burtynske in Khmelnytskyi Oblast) and Near Azov (Troitske in Zaporizhzhia Oblast and Mariupolske in Donetsk Oblast) (locations 1–6 in Fig. 1; 1–6 in Table 1). Total reserves of graphite are estimated to be 306 Mt of ore and 17.9 Mt of graphite (Table 2). Two deposits, Zavallivske and Balakhivske, are under current exploitation. However, a recent production profile was extremely irregular (Table 3).

There are also numerous graphite occurrences found in different ore districts: Kosharo-Oleksandrivske, southern Hashchuvatske and Dubynivske in Pobuzhzhia; Babenkivske, Lozuvatske and Ovnyanske in Kryvyj Rig; Temryutske, Karatyukhinske and Sachkinske in Near Azov; and Makharynetske and Dubovetske in Volyn.

Zavallivske deposit. The Zavallivske deposit (location 1 in Fig. 1; 1 in Table 1) is confined to biotite–graphite gneisses of the Hashchevato–Zavallya Archean suite, which comprises limbs of a large synclinal fold that strikes from NW to sub-latitudinal directions (Fig. 2). About 40 tabular ore bodies ranging from 200 to 1200 m in length and from 3.5 to 80 m in thickness can be distinguished. By mineral composition, the ore-bearing gneisses can be divided into biotite, amphibole–biotite, biotite–chlorite, a chlorite-sericite, chlorite-talc and chlorite varieties. Graphite occurs as large flakes (2–4 mm) distributed rather irregularly in ores; and the graphite content reaches 6–14% (6.5% on average). Total reserves

Table 2. *Reserves of graphite deposits (in kt) (Geoform of Ukraine 2020)*

Deposit	$A + B + C_1$*		C_2	
	Ore	Graphite	Ore	Graphite
Zavalyivske	80 026.8	5036.0	14 613.0	744.2
Petrivske	7523.0	540.0	1696.0	115.0
Balakhivske	23 936.0	1302.0	18 469.0	820.0
Burtynske	113 390.9	6584.7	39 429.7	2405.9
Troitske	2027.0	163.0	252.0	14.0
Mariupolske	3440.0	135.0	1347.0	41.0
Total	230 343.7	13 760.7	75 806.7	4 140.1

*Hereinafter, the figures of reserves are given in the Russian codes A–B–C unless otherwise specified. The authors have to follow official data approved by the State Commission of Ukraine on Minerals Reserves. The reader is encouraged to take a look at the communication by Mr Stephen Henley and to attempt CRIRSCO, Russian codes mapping using the following link: https://mrmr.cim.org/en/library/magazine-articles/new-guidelines-for-international-reporting-of-russian-mineral-resources-and-reserves

Table 3. *Graphite production in Ukraine during 2010–19 (in kt)*

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Ore		18.7	91.9	28.1	104.0	111.2	103.0	263.5	218.9	27.4
Graphite		0.9	7.0	2.0	8.0	7.9	6.1	13.9	12.2	1.5

of graphite ore are 94 639.8 kt (thousand tonnes) containing 5780.2 kt of graphite.

The deposit is developed by open-pit mining, with the Zavallya ore-processing and beneficiation plant located nearby, which operates at an annual rated capacity of 800 kt of graphite ore or 35 kt of graphite concentrate. In the early 1990s, the production rate exceeded 40 kt and then sharply decreased; the current annual production reaches 4–8 kt. Rated capacities of both open pit and plant allow an increased production of graphite concentrate to meet the raw material requirements for the production of galvanic cells and alkaline accumulators (ash content 10–14%; humidity up to 1%; yield of volatiles up to 1%; copper up to 0.05%; admixtures of cobalt, nickel, lead and arsenic, traces). Large-flake graphite is used in the production of alkaline accumulators, concentrated by flotation (ash content up to 2%; humidity 1%; remaining balance on a sieve of 0.15 mm no more than 15%; sieve residue (0.063 mm) 30–50%; contaminating admixtures are not allowed).

Petrivske deposit. The Petrivske deposit (location 2 in Fig. 1; 2 in Table 1) is composed of a graphite accumulation that is 1.2–1.3 km long and 200–250 m wide. It occurs at the contact between crystalline limestones and Archean gneisses of the Rodionivka Suite and the Paleoproterozoic Ingulo-Ingulets Group intruded by veins of granites of the Ingulets Complex. The ore bodies reach 7–50 m-thick graphite gneisses that include 2–15% (7.18% on average) of fine-flake (0.001 to 2–5 mm) graphite. In the upper part of the geological column the graphite ores are weathered, resulting in the formation of loose kaolinized clays that include graphite lenses and veinlets (1.3–6.0%).

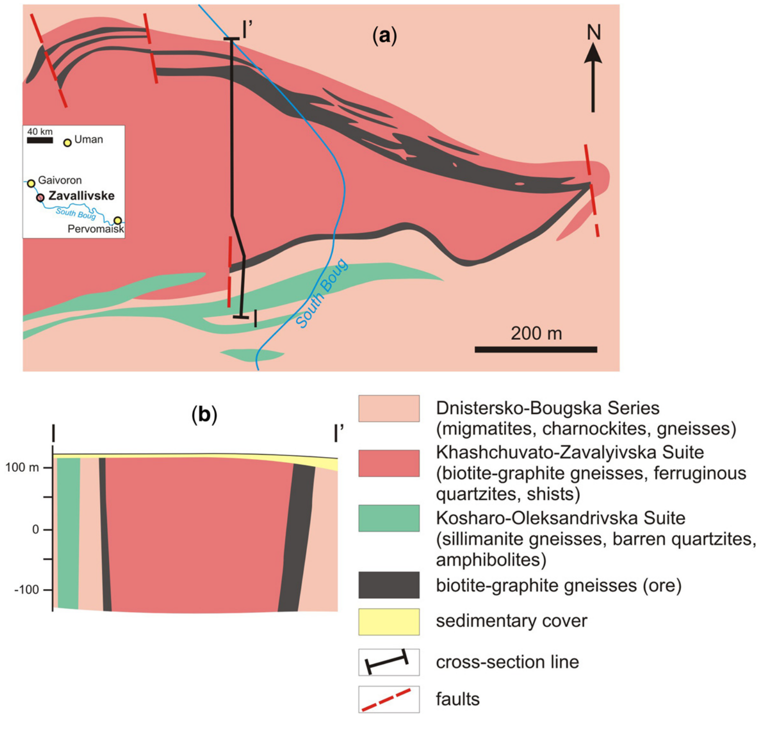

Fig. 2. Sketch of the geological map (**a**) and cross-section (**b**) of the Zavallivske graphite deposit.

Balakhivske deposit. The Balakhivske deposit (location 3 in Fig. 1; 3 in Table 1) comprises a tabular-like accumulation that reaches 600 m in thickness and occurs in gneisses of the Rodionivka Suite. Five ore bodies, 10–300 m thick and 400–2890 m long, have been traced to a depth of 300 m. The ores are intensively weathered, resulting in the formation of loose and semi-loose ore bodies. The average content of graphite reaches 5.36%.

Burtynske deposit. The Burtynske deposit (location 4 in Fig. 1; 4 in Table 1) occurs within an up to 18 km-long zone of graphite gneisses. The ore accumulation is up to 49 m thick and the average content of graphite is 6.7%. The ore is free milling and yields a concentrate that contains 90–95% flaky-crystalline graphite. The deposit can be mined using the open-pit method.

Troitske deposit. The Troitske deposit (location 5 in Fig. 1; 5, Table 1) is confined to the zone of graphite gneisses in the Temryk Suite, which extends for more than 25 km along the western limb of the Berestovetska syncline. The graphite gneisses form two ore zones with thicknesses ranging from 10 to 300 m; they strike over 3.5 km. The ore bands reach thicknesses of 5–140 m and include graphite that is heterogeneous in composition with up to 2–17% graphite.

Mariupolske deposit. The Mariupolske deposit (location 6 in Fig. 1; 6 in Table 1) is composed of graphite gneisses intercalated with amphibolites, quartzites and carbonates of Archean age, which are intruded by subalkaline granitoids and syenites of the Paleoproterozoic Yuzhnokalchik Complex. The 950 m-long by 250 m-wide ore zone includes six ore bodies with an average graphite content of 3.92%, three of which could have commercial significance.

Thus, based on the graphite resources, the size of the deposits and the quality of the ore grades, Ukraine is capable of meeting the graphite requirements of European countries for ‘green technologies’.

Lithium

Lithium is a critically important element for human civilization. Most of the lithium extracted in the world is used in the production of lithium accumulators. By calculation, 63 kg of lithium with a purity of 99.5% is required to produce one Tesla Model S battery. In addition, lithium is used in the production of, for example, air conditioners, refrigerating machines, accumulator and dry batteries, and hard-surfaced galvanic cells.

Most of the world’s reserves of lithium are concentrated in the salt lake brines of Bolivia and Chile, and rare-metal pegmatites of the USA, Australia and Canada. A distinctive feature of almost all lithium deposits is their complex nature. Tantalum, niobium, rubidium, cesium, tin and beryllium from rare-metal pegmatites, as well as potassium, sodium, bromine, boron and magnesium, are extracted as by-products from the brines in addition to the lithium.

The world’s lithium resources are estimated at *c.* 80 Mt, including (in Mt): Bolivia (21), Argentina (17.0), Chile (9.0), USA (6.8), Australia (6.3), China (4.5), Congo (Kinshasa) (3.0), Germany (2.5), Canada (1.7), Mexico (1.7), Czech Republic (1.3), Mali (1.0), Russia (1.0), Serbia (1.0), Zimbabwe (0.5), Brazil (0.4), Spain (0.3), Portugal (0.25), Peru (0.13), Austria (0.05), Finland (0.05), Kazakhstan (0.05) and Namibia (0.09) (USGS 2020).

Ukraine also hosts significant lithium resources. Ukraine’s lithium deposits are associated with early Precambrian rare-metal pegmatites of the Ukrainian Shield. Three deposits with reserves recognized by the State inventory of minerals reserves of Ukraine have been explored: Shevchenkivske (spodumene ore) of the Sorokino–Shevchenkove pegmatitic belt in Donetsk Oblast; Polokhivske (petalite ores); and the Dobra site (spodumene–petalite ores) deposits of the Shpolyano–Tashlyk ore district in Kirovograd Oblast. They mostly comprise petalite and spodumene–petalite, and rarely spodumene ores. The Li_2O grade ranges from 0.25 to 2.23%, rarely reaching 6.55% (average of 1.0–1.25%). Other deposits include Balka Kruta of western Near Azov, Lipnyazke and Nadiya of the central part of the Ukrainian Shield, and Zhovta Richka and Komendantivske of the Kryvyj Rig–Kremenchuk zone.

Shevchenkivske deposit. The Shevchenkivske deposit (location 11 in Fig. 1; 11 in Table 1) is located to the NE of the Near Azov block of the Ukrainian Shield (Isakov and Bobrov 2000). It occurs within the Shevchenkove graben-like structure and consists of schists and gneisses of the Upper Archean–Lower Proterozoic Soroky Suite of the Osipenkovo Group. These rocks have been metamorphosed to greenschist and amphibolite facies, and include rare-metal pegmatites. Six pegmatitic bodies, which form a vein system of sub-meridional strike and 85°–88° downdip to the west, have been discovered. These pegmatitic bodies have swells and twitches, and they range in size from 144 to 1076 m in length and from 2 to 84 m in thickness. In general, they pinch out at a depth of 350–500 m. Two vein bodies contain almost all the reserves of lithium within the explored part of the deposit. On average, they reach 40 m in thickness and 600–700 m in length. The ore-bearing pegmatites have a zonal structure (from the outer zone): (1) a contact zone with a fine-grained quartz–albite aggregate; (2) albite–microcline pegmatite; (3) a quartz–albite inequigranular zone; (4) albite–spodumene; (5) microcline–spodumene; (6) petalite–spodumene; and (7) a block zone with microcline. The pegmatite bodies show a simple composition, with 90–95% of their volume being composed of rock-forming minerals (albite, microcline and quartz), and 5–10% by spodumene and, to lesser extent, petalite, which makes up less than 4% of the lithium reserves. Rare lithium mica and phosphates, and rare-metal minerals of niobium, tantalum, beryllium and tin are also found. A quartz–albite–spodumene association (with microcline and petalite) that mainly hosts lithium forms the main mineral complex of the inner zones of the pegmatitic bodies. Here, spodumene forms blocks 8–10 cm in size and petalite occurs as fine-grained nests up to 5–20 cm in size. The lithium oxide content reaches 1.1–1.5%, with more than 95% of reserves being associated with spodumene. Lithium ores are classified into two types: spodumene (albite–microcline–spodumene) and petalite–spodumene. The lithium oxide content of the ores varies between 0.3 and 0.4%, and reaches 1.22% on average.

Investigations of technological samples indicate complete extraction of spodumene at an enrichment of 88–92%, with a total average yield of concentrate of 22.8%. The concentrate includes 4.9% lithium and corresponds to 'Spodumene concentrate; 4.0–7.0% of Li_2O' of the European market.

Information on the reserves of the deposit remains confidential. By analogy with similar deposits elsewhere, we estimate resources to be 30–35 Mt of ore and 400–450 kt of Li_2O.

Polokhivske deposit. The Polokhivske deposit (location 8 in Fig. 1; 8 in Table 1) of petalite ores is located within a Paleoproterozoic syncline that borders the Korsun–Novomirgorod pluton from the SW (Ivanov *et al.* 2000). The ore occurs in the folded cordierite–biotite, garnet–cordierite–biotite, biotite-garnet and diopside–biotite plagiogneisses with injections of aplite–pegmatite and two-feldspar inequigranular biotite granites of the Kirovograd Complex (2.1–1.9 Ga). The deposit comprises three steeply dipping ore bodies that occur concordantly with the banding of gneisses and the elongation of granitic injections (Fig. 3).

The largest ore body, which has an average thickness of 60 m, can be traced 550 m along strike and 800 m along dip. The second ore body, which is 13–75 m thick, can be traced 350 m along strike and 400 m along dip. The third ore body has considerably smaller dimensions. The average content of Li_2O is 1.25% in the first ore body, 1.21% in the second and 1.04% in the third. The mineral composition of the ore bodies is simple: petalite (27.6–36.2%),

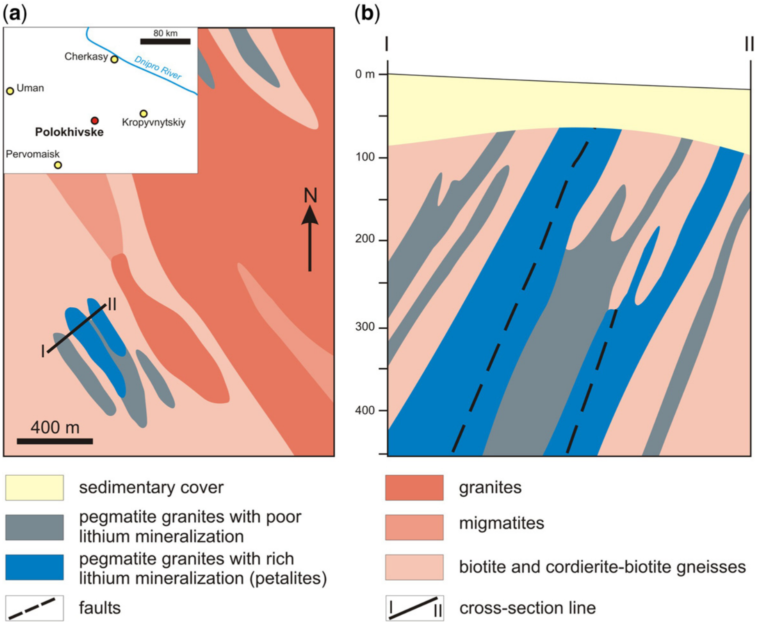

Fig. 3. Sketch of the geological map (**a**) and cross-section (**b**) of the Polokhivske deposit (modified after Eremenko *et al.* 1996). See Figure 1 for the location of this figure.

Table 4. *Major element composition of spodumene in the Polokhivske and Stankuvatske deposits (in %) (Voznyak et al. 2000)*

Component	Polokhivske deposit 1	2	3	4	Stankuvatske deposit 5
SiO_2	63.58	63.74	63.75	64.17	64.17
Al_2O_3	26.34	26.89	27.06	26.99	27.18
Fe_2O_3	0.84	0.25	0.10	0.34	0.09
FeO	0.72	0.57	0.72	0.26	0.48
MnO	Trace	Trace	Trace	0.04	0.05
MgO	0.08	Trace	Trace	0.08	
CaO	0.34	Trace	0.06	0.12	0.03
Na_2O	0.46	0.96	0.46	0.67	0.84
K_2O	0.21	0.34	0.10	0.07	0.03
Li_2O	6.70	6.99	7.10	7.04	7.14
H_2O^+	0.56	0.04	0.44	0.08	0.57
Total	99.50	99.91	99.93	100.08	99.16

1, Microcline–albite pegmatite with spodumene, drill hole 26-90, depth 134 m; 2, microcline–albite pegmatite with spodumene and petalite, drill hole 26-90, depth 270–274.3 m; 3, quartz–spodumene segregations in microcline–albite–petalite pegmatite, drill hole 26-90, depth 303 m; 4, quartz–spodumene segregation in albite–petalite pegmatite, drill hole 7-92, depth 381.5 m; 5, quartz–plagioclase zone with scarce segregations of spodumene at the near-contact zone with the host amphibolite, drill hole 32-91, depth 282.8 m.

albite (26.3–28.0%), perthitic K-feldspar (19.1–20.9%) and quartz (15.8–21.7%). Petalite is the main lithium-bearing mineral and contains 91–95% of total lithium in ore. It forms fine-grained monomineralic granoblastic aggregates up to 10–20 cm in size or occurs as disseminated small inclusions in a microcline-quartz–albite matrix. The mineral composition is shown in Table 3.

The spodumene content of the ores does not exceed 2%; it shows an irregular distribution and occurs mainly in intensively corroded relicts of primary pegmatite together with quartz. The composition of the ores is shown in Tables 4, 5 and 6.

The petalite concentrate can be extracted from the Polokhivske deposit ore using ecologically safe gravity separation.

The ore reserves are confidential; however, using expert assessment methods and analogies with similar deposits in the world, we can estimate its resources to be *c.* 65 Mt of ore and 800 kt of Li_2O.

Dobra site. The Dobra site (location 9 in Fig. 1; 9 in Table 1) is a deposit of spodumene–petalite mineralization that includes two ore occurrences – Stankuvatske and Nadiya – located at the western outer zone of the Lipnyazke granite dome (Fig. 4). The core part of the dome comprises granites of the Kirovograd Complex and the peripheral part includes granitic pegmatites. Lithium-rich pegmatites occur at the western border of the dome in amphibolites and mafic–ultramafic rocks that have been metamorphosed to amphibolite facies.

The deposit includes a group (between eight and 12) of contiguous, steeply dipping bodies of lithium pegmatites that range in thickness from the tens of centimetres up to 25–30 m. The total thickness of the productive zone reaches 140–150 m; thicker ore bodies are concentrated in the central part. The content of Li_2O in the single ore bodies varies between 0.345 and 2.23%, with an average of 1.26%. Unlike the Polokhivske deposit, ores are complex spodumene–petalite mixtures, with up to

Table 5. *Major and trace element composition of ores of the Polokhivske and Stankuvatske deposits (in %) (Eremenko et al. 1996)*

Component	Polokhivske Petalite ore	Stankuvatske Spodumene ore	Stankuvatske Petalite–spodumene ore
SiO_2	74.94	72.03	72.12
TiO_2	0.22	0.27	0.36
Al_2O_3	15.58	16.91	16.62
MgO	0.08	0.14	0.09
CaO	0.32	0.35	0.47
Na_2O	3.66	3.67	3.86
K_2O	2.71	2.58	2.18
Li_2O	1.10	1.79	1.49
Pb_2O	0.04	0.10	0.10
H_2O^-	0.11	0.11	
H_2O^+	0.26	0.86	0.49
CO_2	0.35	0.14	0.22
P_2O_5	0.48	0.89	1.14
Total	99.85	99.84	99.14
Ta_2O_5	0.002		0.006
Nb_2O_5	0.002	0.006	0.006
SnO_2	0.008	0.05	0.04
BeO	0.032	0.012	0.033

Table 6. *Mineralogy of ores of the Polokhivske and Stankuvatske deposits (in %) (Eremenko* et al. *1996)*

Mineral	Polokhivske	Stankuvatske	
	Petalite ore	Spodumene ore	Petalite–spodumene ore
Quartz (%)	14.3	14.0	14.1
Microcline (%)	23.5	18.8	14.8
Albite (%)	34.0	31.1	33.9
Petalite (%)	24.9	6.6	14.0
Spodumene (%)	0.8	25.3	20.3
Trifillite (%)	0.2	1.5	1.4
Apatite (%)	0.8	0.1	0.3
Muscovite, garnet, calcite, cordierite and sillimanite (%)	1.5	2.7	1.2
Chrysoberyl (g t^{-1})	1165	1125	1650
Cassiterite(g t^{-1})	90	450	400
Ferrocolumbite (g t^{-1})	55	500	500

20–25% spodumene. The presence of two lithium minerals is the factor that complicates the ore beneficiation technology as it requires selective extraction of the spodumene and petalite concentrates.

Resources are estimated to be *c.* 60 Mt of ore and 750 kt of Li_2O.

Thus, the total lithium resources of Ukraine's deposits could reach 2.0 Mt, which puts Ukraine along with a number of leading countries in terms of the resources of this metal, and enables Ukraine to fully provide the production volumes necessary to ensure 'green technologies'.

REEs

In recent years, the issue of REE mineralization has become especially urgent, and has acquired some strategic importance for a number of industrialized countries (e.g. the USA, the EU, Japan and Australia) where REEs are included in the list of CRMs. This

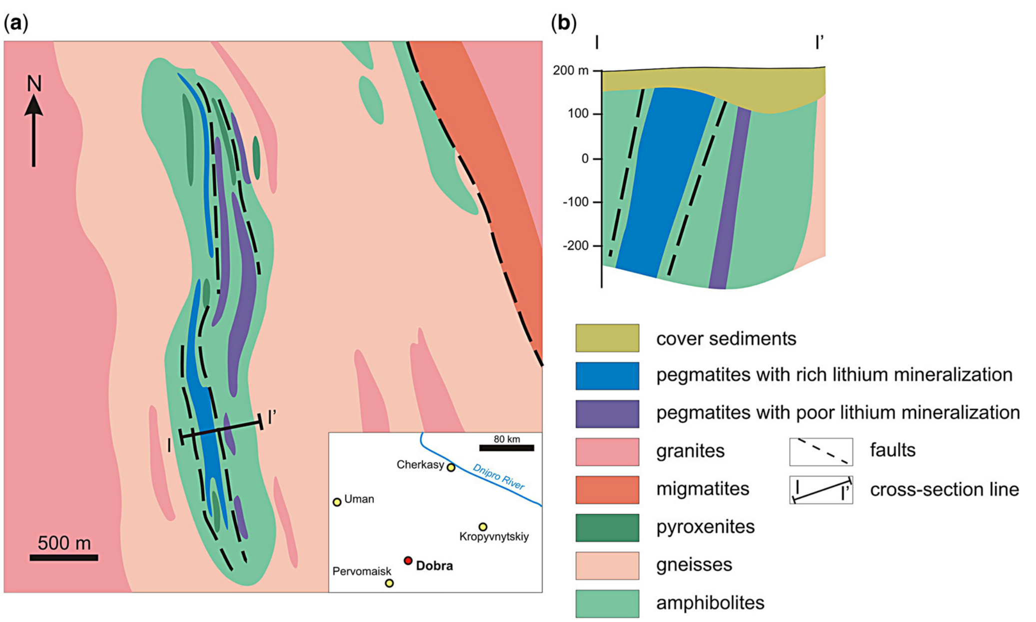

Fig. 4. Sketch of the geological map (**a**) and section (**b**) of the Dobra site (modified after Eremenko *et al.* 1996). See Figure 1 for the location of this figure.

trend reflects two main factors. First, the range of application of REEs in modern high-tech processes, including 'green technologies' has expanded. For example, REEs are used in the production of mobile phones, computer disks, electric and hybrid vehicles, batteries for electric vehicles, monitors and TVs with flat screens, equipment of renewable power engineering (e.g. solar panels and wind turbines), systems for missile guidance, and in the construction of the ships and submarines. Second, in recent years China, as the main producer of REEs because of the development of the unique Bayan-Obo deposit (Chao *et al.* 1997; Smith and Chengyu 2002), has introduced significant restrictions on the export of REE products that has forced the governments of many countries to enhance the prospecting and exploration of REEs within national territories.

Some of the largest reserves of REEs (in Mt) occur in: China (44), Brazil (22), Vietnam (22), Russia (12), India (6.9), Australia (3.3), Greenland (1.5) and the USA (1.4). In 2019, the world production of REEs reached *c.* 210 kt, including (in kt): China (132), the USA (26), Myanmar (22), Australia (21), India (3), Russia (2.7), Madagascar (2.0) and Thailand (1.8) (USGS 2020).

Ukraine is one of the largest REE metallogenic provinces in Europe (Mykhailov 2010). It has considerable REE resources of REE, although thus far they have not been explored. Ukraine possesses both traditional deposits associated with carbonatite (Novopoltavske) and mariupolites (Mazurivske), and unconventional resources such as zirconium and REE–zirconium ores of nepheline-free syenites (Azovske and Yastrubetske). Moreover, there some occurrences of cerium-rich parisite, calcite and fluorite ores (Petrovo-Gnutivske) located in Near Azov.

Novopoltavske carbonatite REE and apatite deposit. The Novopoltavske carbonatite REE and apatite deposit (location 10 in Fig. 1; 10 in Table 1) located in Near Azov is localized in carbonatites of the Chernigiv Complex within the Orihovo–Pavlograd Fault Zone. Apatite carbonatites, nepheline and alkaline syenites form en-echelon-like steeply dipping bodies that range in thickness from 10–20 to 100 m and extend over distances of hundreds of metres to kilometres. Calcite- and calcite–dolomite-hosted apatite ores occur as dykes and stocks. Among other minerals, monazite, pyrochlore, cerium fergusonite, columbite, gatchetolite, zircon, baddeleyite, orthite, aeschynite and fersmite are found. The average content of apatite in carbonatites is 10%, at times reaching 30–50% in small phoskorite bodies. The total content of REE reaches 0.17–4.6%: Nb_2O_5 (0.06–0.3%), Ta_2O_5 (0.002–0.003%) and P_2O_5 (4.3%). Monazite is the main REE-bearing mineral, for which the REE content reaches 65%. The monazite has a low thorium content (0.1–0.3%) that increases the value of the mineral concentrate. Moreover, REEs are concentrated in apatite (average content 1.0–1.5%; maximum content 8–11%), with Ce (0.6–1.1%) and La (0.1–1.6%) being most predominant. Y (150–600 g t^{-1}), Sm (250–400 g t^{-1}), Eu (40–150 g t^{-1}), Tb (40–100 g t^{-1}), Yb (10–20 g t^{-1}) and Lu (0.3–0.7 g t^{-1}) are also found. Sr usually does not exceed 0.5–0.7%, although sometimes it can reach 1.5–2.5% or even 5%. The age of mineralization has been dated at 2.19–1.99 Ga. The content of useful components rises several times in the linear weathering crusts (up to 50–370 m). According to S.G. Krivdik (Mykhailov and Kryvdyk 2004), inferred resources of the deposit, by analogy with similar world deposits, could reach 1 Mt of monazite and 200 Mt of apatite (up to a depth of 500 m).

Mazurivske (Oktiabrske) deposit. The Mazurivske (Oktiabrske) deposit (location 13 in Fig. 1; 13 in Table 1) belongs to the complex class of zirconium–REE–niobium ore deposits. It is confined to the Oktiabrsky massif of nepheline syenites that include pyrochlore–zirconium ores in albitites and mariupolites (Fig. 5). Ore minerals of mariupolites and associated albitites are represented by pyrochlore, zircon and britolite. The REE content averages 0.2% in ores, 65% in britolite and 1–5% in pyrochlore. A complex extraction of ores as aluminous raw materials with a bypass extraction of REEs is planned. Inferred resources could reach 200 kt of REE_2O_3.

Azovske deposit. The Azovske deposit (location 12 in Fig. 1 No. 12 in Table 1) is confined to a group of syenitic stocks, with the largest, Azovske (1.3 km^2), composed of alkaline feldspar, pyroxene–amphibole and quartz syenites, as well as pegmatites of the Paleoproterozoic Yuzhnokalchikskiy Complex. Nine crescent-shaped, several-metre-thick, ore bodies have been discovered. The main ore body has a length of 1640 m and an average thickness of 32 m. Ore-bearing varieties are represented by mesocratic and melanocratic (with ferrohastingsite, hedenbergite and fayalite) and, less commonly, leucocratic syenites. The ores are of an impregnated type. Among the ore minerals are britholite (predominant), bastnasite, orthite, zircon, monazite, chevkinite, yttrialite, magnetite, rhabdophanite and fluorite. The average REE_2O_3 content reaches 1.27% and 1.5% ZrO_2 (Melnikov *et al.* 2000). Technological samples contain following elements (% of total REE): Ce (46.8), La (19.0), Nd (18.5), Pr (4.3), Sm (3.3), Dy (1.7), Er (0.4), Tb (0.3), Ho (0.3), Tm (0.1), Lu (0.1) and Y (0.5). U (0.0012–0.0142%) and Th (0.0035–0.094%) are also found in the ores.

Inferred resources of the deposit are estimated up to a depth of 300 m, and reach 56 Mt of ore with 1.27% of REE_2O_3 (cut-off grade equals 0.4%) and

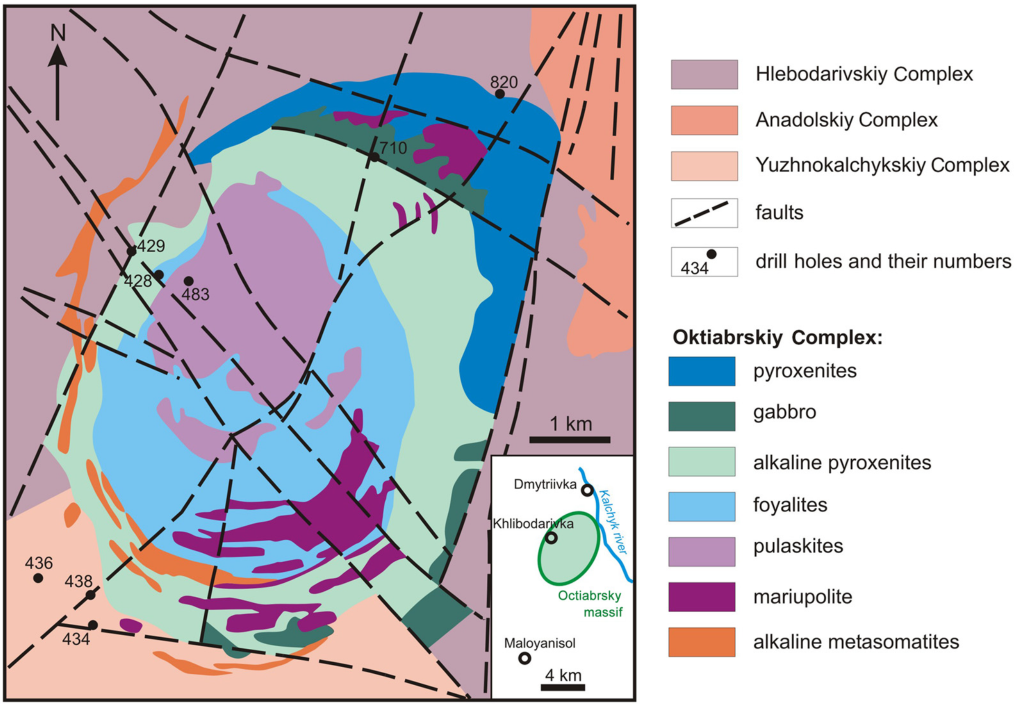

Fig. 5. Sketch of the geological map of the Octiabrsky massif (modified after Donskoy *et al.* 2004). See Figure 1 for the location of this figure.

1.5% of Zr_2O_3; or 710 kt of REE_2O_3 from which 20% are represented by Y-lanthanides, and 840 kt of Zr_2O_3.

Technological investigations have proved a possible application of gravitational and magnetic separation for the granular ore fraction and flotation for the slimes. Concentrate processing for the selective REE products is possible at the Dnipro Chemical Plant (Dneprodzerzhinsk). The technology of hydrometallurgical cleaning allows dissolution of about 72–97% of REEs, which can be easily extracted using ion-exchange technology. Zircon concentrate meets the requirements of ‘zircon metallurgical concentrate’; feldspar is suitable for application in the glass industry.

Yastrubetske deposit. The Yastrubetske deposit (location 17 in Fig. 1; 7 in Table 1) of zirconium ores is similar to the Azovske deposit. Regardless of the fact that syenites include the same set of minerals (britholite, orthite and bastnasite), the rich REE ores have not yet been discovered here. The deposit is located in the SW part of the Perzhansky ore node and is associated with the massif of alkaline syenites of the same name. Several crescent-like ore-bearing zones up to 2 km long and 5–120 m thick, and enriched with zircon, are confined to the massif. Other minerals such as ilmenite, magnetite, apatite, orthite, bastnasite, parisite, fluorite and britholite are also found. The total REE content in the single ore bodies reaches 0.07–0.3%, sometimes up to 1.24% (Gursky 2008).

Britholite and zircon are the main ore minerals. Britholite contains up to 50.2% of REE_2O_3, namely (in %): Y_2O_3 (10), ZrO_2 (5–6), Se_2O_3 (15–16), La_2O_3 (6–7), Gd_2O_3 (1), Yb_2O_3 (0.6), Tu_2O_3 (0.4) and Eu_2O_3 (0.1) (Kryvdyk and Tkachuk 1990). Zircon includes 1.24% of $REE_2O_3 + Y_2O_3$ and 0.8% of Hf. The composition of the REEs is as follows (from 100%): La (1.30), Ce (2.26), Pr (0.6), Nd (1.54), Sm (2.86), Gd + Eu (4.46), Tb + Y + Dy (65.86), Ho (2.66), Er (5.14), Tu (1.95), Yb (11.10) and Lu (0.27) (Nechayev *et al.* 1986). Zircon is significantly enriched in yttrium, and britholite is enriched in yttrium and cerium.

The deposit is considered to be large; however, the considerable depth of the ore bodies (over 500 m) complicates its possible commercial development. This deposit could be a source of bypass mining for such non-metallic raw materials as feldspars and fluorite.

In addition to these deposits, a number of REE occurrences such as Uspenivske, Anadolske and Petrovo–Gnutovske are known in the Near Azov region.

Thus, this type of raw material is strategically important not only for Ukraine but also for the development of 'green power engineering' in Europe. At the same time, these deposits are not yet developed and their commercial development requires considerable investment. A positive feature is the developed infrastructure of the mining industry in almost all regions and the proximity to the the European market.

Nickel

Nickel is widely used in electrical equipment in the production of alkaline iron–nickel, nickel–cadmium, nickel–zinc and nickel–hydrogen accumulators, and in the cores of electromagnets.

The world's main reserves of nickel are associated with two geological–industrial types: oxide silicate (lateritic) and copper–nickel sulfide. The largest reserves of nickel are located in Indonesia, New Caledonia, Australia, Brazil, Russia and Cuba. The reserves of cobalt are located in Congo (Kinshasa), Australia, Cuba, the Philippines, Russia and Canada.

Ukraine possesses exogenic deposits of silicate nickel that are associated with the weathering crust, and are distributed in the two districts of Middle Pobuzhzhya and Middle Dnipro. Silicate ores are low grade (0.38–1.24% nickel) and are suitable only for ferro-nickel smelting. The Pobuzhsky Ferronickel Plant, which rated the capacity of ore treatment at 1.5 Mt and a production rate of 9.3 kt of ferro-nickel, was operating with the resource base of the Middle Pobuzhzhya deposits. However, the plant has never reached the rated capacity. In 1997, the plant stopped working and since 2004 it has produced ferro-nickel from imported raw material.

Deposits of nickel and iron–nickel ores are associated with the weathering crusts developed on Precambrian ultramafic rocks, with typical thickness of the order 25–35 m, sometimes up to 100 m. The age of the weathering crust formation is Jurassic and early Cretaceous. Ochreous-nontronite, ochreous and ochreous-siliceous weathering profiles of ultrabasic rocks have developed. Most deposits are characterized by an ochreous-nontronite profile that is characteristic of the ultramafic rocks of the Pobuzhsky and Devladivsky complexes.

Pobuzhska Group. The Pobuzhska Group consists of six deposits (Derenyukhinske, Kapitansvske, Lipovenkivske, Pushkivske, Grushkivske and Ternuvatske) situated in Kirovograd Oblast. The bodies of ultramafic rocks up to several square kilometres in size are confined to the zone of Pobuzhsky faults situated in the central part of the Golovanivsky block. The ore bodies are confined to the weathering crust of ultramafic rocks of Archean age and are 50–80 m thick. Host rocks are represented by gneisses and mafic gneisses of the Dnister–Boug Group, and gneisses and quartzites of the Boug Group. The ore bodies are blanket-like in shape, and reach 200–2000 m in length, 40–500 m in width and an average thickness of 2.9–8.7 m. The depth of the ore body ranges from 1 to 10 m. The average nickel content is 0.9–0.99%, although some sites show 5% nickel. Cobalt is the most important by-product element. Iron varies over a wide range, sometimes reaching 45–50%. The main rock-forming mineral of the nickel ore is nontronite. In addition, beydelite, montmorillonite, chlorite (pennine and clinochlore), jefferisite and vermiculite are found. Relict minerals such as chrysotile, antigorite, magnetite and chromite are also commonly found.

Ternuvatske deposit. The Ternuvatske silicate nickel deposit (location 15 in Fig. 1; 15 in Table 1) is located within the central part of the Golovanivskiy block, on the right bank of the South Boug River. It occurs within an area of a serpentinite massif of the same name that has a NW strike and a discontinuous structure. It is subdivided into three parts by narrow pinches: northern, central and southern (Fig. 6).

Serpentinized dunites prevail in the northern part of the massif. The total thickness of the serpentinites reaches 600 m. The upper section consists of pyroxenites and amphibolites with a total thickness of up to 300 m. The serpentinites change to slightly serpentinized dunites in the middle part of the array (drill hole 1514) at a depth of 535 m. Host rocks are represented by Archean mafic gneisses, sillimanite gneisses, amphibolites, plagiomigmatites and Paleoproterozoic aplite–pegmatite granites. Sublatitudinal faults with an amplitude of 200 m separate the northern part of the massif from the central part. A group of low-amplitude faults causes the block structure of the massif. The central and southern parts are monoclines with rocks dipping to the SE at an angle of 70°–75°. The serpentinite column is characterized by an interlayering of serpentinized dunite and peridotite varieties that include interbeds of pyroxenites with a total thickness of 300 m.

The weathering crust of the serpentinites reaches 15 m in thickness and is nontronite in composition. It is overlain by sedimentary rocks (Neogene sands and clays, and Quaternary loams) with a thickness of 10–25 m. The average nickel content is 0.91%, and the cobalt content is 0.046%. Judged by reserves, the deposit is medium in size.

Devladivka Group. The Devladivka Group is represented by four deposits (Devladivske, Nove, Ternivske and Krasny Yar) that are located in Dnipropetrovsk Oblast, within the boundaries of

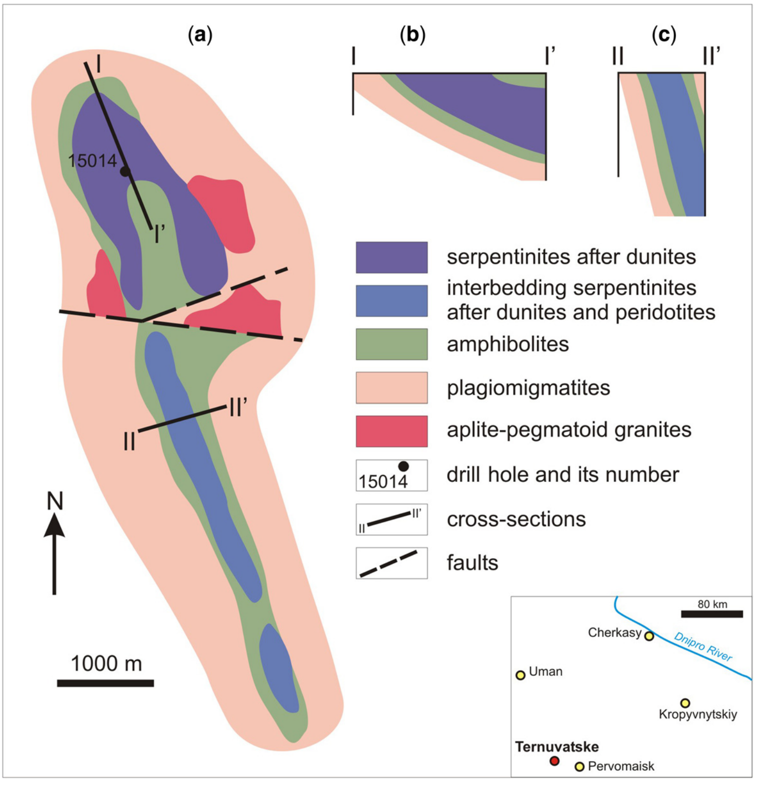

Fig. 6. Sketch of the geological map (**a**) and cross-sections (**b**) and (**c**) of the Ternuvatske deposit (modified after Mykhailov *et al.* 2007). See Figure 1 for the location of this figure.

the Middle Dnipro megablock of the Ukrainian Shield. The ultramafic rocks from which the weathering crust is developed have an Archean age and belong to the main greenstone belt formation (3.2–2.8 Ga) or post-greenstone (2.8–2.6 Ga) stages. The ultramafic rocks are widely distributed within the Belozerka greenstone structure but show a much lesser distribution within the Konka greenstone structure. The Devladove–Ternovsky district of ultramafic rock development is confined to the sub-latitudinal Devladivskiy Fault Zone that is 4–7 km wide and up to 50 km long.

The Devladivske body of ultramafic rocks (9.0 × 0.35–0.4 km) is extended in the sub-latitudinal direction and is composed of extensively serpentinized dunites, dunite–harzburgites, lherzolites and aluminous olivine harzburgites, with minor (up to 10%) norite harzburgites, pyroxenites and tremolite–actinolite rocks. Ultramafic rocks with a high Ni (0.15–0.35%) and low Cr_2O_3 (0.1–0.3%) content, and ultramafic rocks with a low Ni (0.25–0.05%) and increased Cr_2O_3 (0.3–0.5%) content can be distinguished.

In the SW limb of the Ternovska syncline, a unit of ultramafic rocks (4.5 × 0.3 km) of the same sub-latitudinal strike is distinguished. This unit is composed of serpentinites and serpentinized dunites, as well as minor actinolites and chlorite schists. Serpentinite contains 0.22–0.25% Ni, 0.48–0.56% Cr_2O_3 and 0.014–0.024% CoO.

Devladivske deposit. The Devladivske deposit (location 16 in Fig. 1; 16 in Table 1) is a complex deposit of nickel, iron and refractory clay. The deposit ore field comprises peridotites and gabbro-peridotites, porphyry-like granites of Kirovograd type, plagioclase granites and their migmatites, and polymigmatites of Dnipro granites of Proterozoic age. The nickel deposit is confined to the weathering crust formed from peridotites and gabbro peridotites that form a steeply dipping dyke-like body.

Weathering crusts include the following zones (from the bottom): (1) completely altered serpentinized peridotites of variable thickness; (2) nontronites (8–10 m thick) with nickel mineralization; and (3) yellow earth (15–20 m thick) that is treated as commercial iron ore. Nickel ores occur in seven separate ore bodies consisting of from two to four horizontally occurring ore layers confined to the upper parts of the nontronite zone. The average nickel content is 1.06–1.24%, with single sites showing 1.5–2.0%; the cobalt content reaches 0.04–0.05%.

There are also some other regions of the Ukrainian Shield that contain mafic–ultramafic rocks where commercial accumulations of copper–nickel ores can be found. All of these massifs are confined, foremost, to regions of Paleoproterozoic tectonomagmatic activation situated within the Volyn, Ingulets and Near Azov megablocks of the Ukrainian Shield.

Cobalt

Cobalt and its compounds are used in nickel–cadmium and some schemes of lithium-ion accumulators. Cobalt silicide (CoSi) in an excellent thermoelectric material that enables the construction of thermoelectric generators with a high efficiency. The largest reserves of cobalt are located in Congo (Kinshasa), Australia, Cuba, the Philippines, Russia and Canada (USGS 2020).

In Ukraine, cobalt is associated with nickel silicate ores in weathering crusts formed from ultramafic rocks of the Middle Pobuzhzhya region of Kirovograd Oblast and the Middle Dnipro region in Dnipropetrovsk Oblast, as described in the previous subsection. Their total reserves are estimated at 9.8 kt with an average cobalt content reaching 0.04% (which is rather low). In addition to these, there are a number of occurrences of endogenic nickel–cobalt mineralization that are closely associated with mafic intrusions: Prutivsky and Kamensky in Zhytomyr Oblast; Varvarivsky, Alferivsky, Volnokhutorsky, Granovsky, Adamivsky and Pototsky in the Middle Dnipro region; Demovjyarivsky in Pobuzhzhya; and Nikolaevsky and Novotroitsky in the Near Azov region. All of these are underexplored.

The Prutivske ore occurrence (location 17 in Fig. 1; 17 in Table 1) of copper–nickel sulfide ores is situated in the Volyn megablock of the Ukrainian Shield, within the Krasnogorsk–Zhytomyr zone, where it is associated with a Paleoproterozoic intrusion of the same name. The intrusion forms a sill-like body that is 1000–1500 m wide and 130–160 m thick. The body occurs in the core part of the anticlinal fold that comprises biotite migmatites and gneisses of the Teterev Group. It dips to the NE at an angle of 25°–35° and can be traced over 3 km to the NW. Gabbroides do occur as predominant rock varieties. Shleiren-like segregations and relatively thin layers of gabbronorites, troctolites and gabbro-pegmatites are also present.

Ore zones with sulfide mineralization are confined mainly to the footwall endo- and exocontacts of the intrusion. Their thicknesses vary from a few metres up to 15.1 m. The sulfide impregnation content ranges from 3 to 20%, sometimes reaching 50–70%. In some places veinlet ores with thicknesses in the range of a few centimetres are found. The average nickel content makes up 0.58%, cuprum is 0.26% and cobalt is 0.022%. The Ni/Co ratio varies from 10–15 to 35–37 in the ore bodies.

Characteristic ore mineral associations include chalcopyrite–pentlandite–pyrrhotite, pentlandite–cubanite–chalcopyrite–pyrrhotite and pyrite–violarite–mackinawite. The third association is secondary in origin and develops during the course of the epigenetic alteration of minerals of the first and the second paragenesis.

The Kamensky massif is located in the northern part of the Volyn megablock. It includes a zone of pentlandite–chalcopyrite–pyrrothite-impregnated mineralization, which is more than 60 m thick, where the cobalt content reaches 0.145%, the copper content is up to 0.55% and the nickel content ranges from 0.1 to 0.46%. According to geophysical data, the extent of the mineralized zone is 6.3 km (up to a depth of 2.4 km) and the northern part of the massif could include sulfide bodies that are up to 100 m thick.

Some prospective ore occurrences with cobalt–copper–nickel mineralization are found in the Middle Dnipro district: for example, Varvarivske, Alferivske, Volnokhutirske, Granivske, Adamivske and Pototske. They are structurally confined to the Varvarivsky ultramafic massif where impregnation by nickel sulfides is found. Grades of up to 0.5–1.5% nickel and 0.1% cobalt are found.

The Demovyarivske occurrence is located in Middle Pobuzhzhye within the Golovanivska suture zone. The Nikolayivske and Novotroitske occurrences are situated in Near Azov, within the Volnovakhska Fault Zone.

Prospective areas of Ukraine for endogenic copper–nickel mineralization with cobalt can be associated with retrograde-metamorphosed and layered mafic–ultramafic intrusions that are confined to areas of Paleoproterozoic tectonomagmatic activation that occur within the Volyn, Ingul and Near Azov megablocks of the Ukrainian Shield.

Aluminium

Aluminium is widely used in the electrotechnical industry for the production of wire for high-voltage power lines, in the winding of engines and transformers, and in cables, condensers and many other products. In the energy industry, aluminium is used as the universal secondary energy carrier. It is used for: (1) oxidation of aluminium in water for the production of hydrogen and thermal energy; and (2) aluminium oxidation by oxygen for electricity production in air–aluminium electrochemical generators.

Bauxite is the main commercial type of aluminium raw material in the world. More than 90% of the total and proven reserves of bauxite are distributed in 18 countries with a tropical and subtropical climate: for example, Guinea, Brazil, Australia, Jamaica, India, Vietnam, China and Guyana. Bauxites have a limited distribution in northern territories. In Europe, the largest reserves are found in Greece and Russia.

Ukraine is not endowed with domestic aluminium raw materials, therefore the enterprises that produce alumina and primary aluminium use raw materials imported from Guinea, Jamaica, Australia and other countries. Thus, the problem of supplying industry with a domestic aluminium raw material is urgent for Ukraine, despite the available resources that are represented by bauxites, alunite rocks, nepheline syenites, kyanite–andalusite–sillimanite quartzites, gneisses and schists.

The Ukrainian Shield and its slopes are the main areas of bauxite distribution, where they are associated with Mesozoic weathering crusts formed from Archean greenstone rocks. Alunite ores are confined to the Trans-Carpathian province, where they are associated with polymetallic ores of Neogene deposits. Nepheline ores are confined to Proterozoic syenites distributed in the Near Azov area of the Ukrainian Shield. Accumulations of andalusite–kyanite–sillimanite schists and quartzites occur in metamorphic rock masses of the Ukrainian Shield.

The formation of bauxite by primary lateritic weathering crusts, as represented by accumulations of bauxites forming deposits and a number of occurrences within the Middle Dnipro territory, is the most important type of aluminium resource for Ukraine. The reserves of two deposits – Vysokopilske and Yuzhnonikopolske – have been approved by the State Commission on Mineral Reserves of Ukraine.

Vysokopilske deposit. The Vysokopilske deposit (location 18 in Fig. 1; 18 in Table 1) is located on the southern slope of the Ukrainian Shield within a junction zone with the Black Sea Depression (Dnipropetrovsk Oblast). The deposit represents an ancient weathering crust that has been dissected by a network of small palaeovalleys (Fig. 7). Bauxites form an upper zone of the lateritic profile of the weathering crust that formed from gabbro-amphibolites and quartz–chlorite–amphibolite schists of Archean age. The bauxite accumulations are overlain by Eocene and younger loose flat-lying rocks of sedimentary cover, which have a total thickness ranging from 15 to 100 m. The age of the bauxites is Aptian–Albian.

The bauxite accumulations have an irregular shape, and their contours show a wavy configuration. The ore bed consists of separate flattened block masses up to 4–5 m in a diameter. Its upper part forms a firm shield consisting of stony red-brown cavernous bauxite (curass) that passes into loose argillaceous varieties below. The total thickness of the ore body is 10–12 m; the weathering crusts reach 30–40 m.

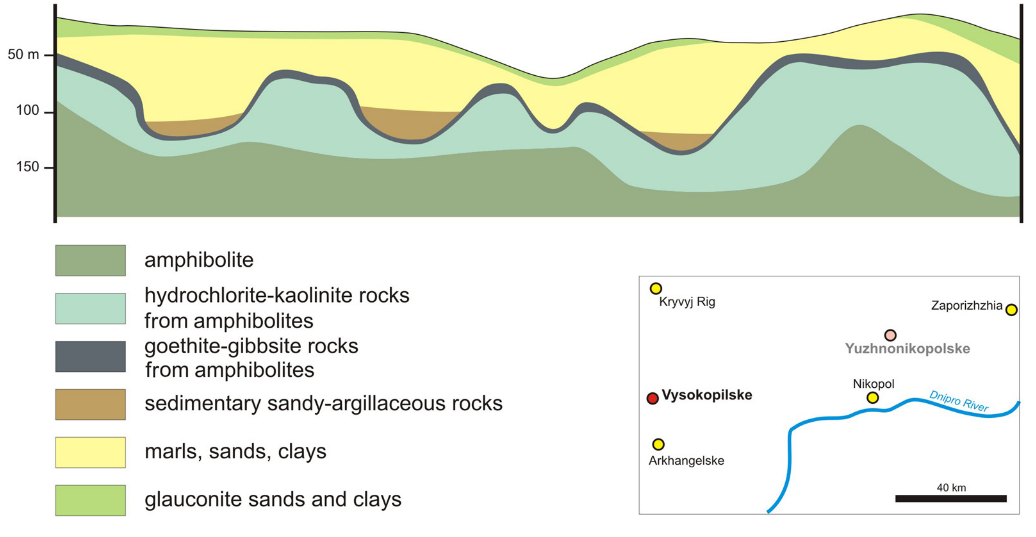

Fig. 7. Sketch of the geological cross-section of the Vysokopilske lateritic bauxite deposit. See Figure 1 for the location of this figure.

The bauxites are related to a hydrogoethite–boehmite–gibbsite type. Their average chemical composition is as follows: 38% Al_2O_3, 28% Fe_2O_3 and 8.5% SiO_2. Explored reserves by categories A + B + C_1 make up 18.9 Mt and the total resources 72 Mt (please note that the figures of reserves hereinafter are given in the Russian codes A–B–C unless otherwise specified).

Yuzhnonikopolske deposit. The Yuzhnonikopolske deposit (location 19 in Fig. 1; 19 in Table 1) includes bauxites that are confined to the upper section of the weathering crust that was formed from amphibolites, serpentinites and other rocks. Four accumulations (from 0.5 to 5.0 m in thickness) of high-ferruginous bauxites of nodular structure and hydrargillite–kaolinite composition are distinguished. Reserves by categories B + C_1 + C_2 total 535 kt.

In addition, small accumulations of bauxites in derived lateritic crusts are also known. Among the possible examples, the Smelyanske deposit in Cherkasy Oblast and some occurrences of bauxites in Vinnitsa Oblast should be noted but they have no practical importance.

Alunites are associated with secondary quartzites of Zakarpatska Oblast where some deposits, with reserves of alunite ores reaching more than 400 Mt, are known. These ores have a low alunite content (30–40%) but are suitable for complex use in the production of, for example, alumina, sulfuric acid and alkaline salts. The largest accumulations of alunite ores are associated with polymetallic deposits at Biganske and Beregivske.

Biganske deposit. The Biganske deposit (location 20 in Fig. 1; 20 in Table 1) formed as a result of the hydrothermal alteration of Miocene volcanogenic and sedimentary rocks. The alunite accumulations are confined to secondary quartzites with thickness up to 70–120 m. At depth, quartz–alunite ores pass into baryte–alunite and further into baryte–polymetallic and polymetallic varieties. Explored reserves of alunite ores make up 290 Mt with an average alunite content of 33.4% and alumina content of 15%.

Beregivske deposit. The Beregivske deposit (location 20 in Fig. 1; 20 in Table 1) possesses explored reserves of alunite ores reaching 50 Mt and has mineralization characteristics that are similar to the Biganske deposit. Alunite accumulations occur in simple mining and geological conditions.

Nepheline high-aluminous associations of metamorphic–magmatic genesis are developed within Proterozoic alkaline complexes where nepheline syenites, foyaites and alkaline pegmatites may be of interest. These rocks include 19–20% alumina, 53–56% silicon dioxide, 10–14% alkalis and 3–5% iron oxides. They might be of interest only as complex alumina–rare-metal objects. Among possible examples of such deposits are the Mazurivske mariupolite deposit (22.45% Al_2O_3 with reserves of more than 1 Bt) and the Kalinino–Shevchenkivske mariupolite and foyaite deposit (330 Mt reserves of nepheline ores), which are confined to the Oktiabrsky massif.

High-aluminous quartzites are developed within Sushchany–Perga zone where the Sushchanske kyanite deposit is known. The mineralization is associated with secondary quartzites that form layer- and lens-shaped accumulations with a thickness of 37 m and an average kyanite content of 20%. Garnet–sillimanite ores, which have inferred resources estimated at 60–70 Mt, are associated with Precambrian metamorphic rocks of the Near Azov area. The State Commission on Mineral Reserves of Ukraine takes into account two deposits of high-aluminous raw materials: Vovchanske and Malyshevske in Dnipropetrovsk Oblast. The total reserves of kyanite and sillimanite are about 3 Mt.

Thus, Ukraine has quite good prospects to expand the mineral resource base of aluminium raw materials, provided the development of new highly effective processing technologies of alunite ores in Zakarpatska Oblast and nephelines in Near Azov go ahead. However, the perspectives of commercial development of these deposits are not clear.

Lead

Lead bismuthate, lead sulfide (PbS) and iodide of lead are applied as the cathode material in lithium batteries; lead chloride ($PbCl_2$) is used as the cathode in emergency current generator cells; lead telluride ($PbTe_2$) is used as a thermoelectric material (thermoelectric power 350 $\mu V\ K^{-1}$), and as the most widely applied material in the production of thermoelectric generators and thermoelectric refrigerators; lead dioxide (PbO_2) is used in lead accumulators and also as the basis for production of chemical sources of electrical energy (e.g. lead-chlorine element, lead and fluoric element); and lead sulfate ($PbSO_4$) is used in accumulators. Moreover, lead is used as the heat-transfer agent in perspective fast-fission reactors. Lead alloys are also widely used. In addition, welding alloys containing 67% Pb and 33% Sn are applied in electrical equipment. Lead alloys with antimony are usually used for cable sheaths and accumulator plates. Lead–acid accumulators are used as starter batteries in vehicles, emergency and reserve power supplies.

The largest reserves of lead are concentrated in Australia, China, Russia, Peru, Mexico and the USA, which are, at the same time, also the largest producers of this metal.

There are a number of lead deposits known in Ukraine; however, their small size does not cover the domestic demands for these metals. As a result, Ukraine needs to import lead and zinc from Kazakhstan, Russia, Uzbekistan, Bulgaria, Czech Republic and Poland.

Polymetals

The following geological and commercial types of deposits of polymetals are known in Ukraine: (1) vein and veinlet-impregnated mineralization in extrusive rocks (the Beregove–Bigansky ore district of the Trans-Carpathians); (2) veins in terrigenous folded rocks (Nagolno-Tarasivske and Nagolchanske in the Donbas); (3) stratiform mineralization in terrigenous and carbonaceous rocks (Markivske on the slope of the Voronezh massif and Truskavetske in the Fore-Carpathians);and (4) salt-dome structures (Belyaevske in the Dnipro–Donetsk Rift).

Beregivske gold and polymetallic deposit. The Beregivske gold and polymetallic deposit (location 20 in Fig. 1; 20 in Table 1) is confined to the southern closure of the sub-meridional brachyanticlinal uplift. Ore bodies are localized mainly in Neogene tuffaceous rocks. The main ore-bearing horizon is composed of rhyolitic tuffs in the column middle part. Partially, the mineralization occurs in the lower part of the sedimentary pile. Rocks are cut by two systems of cracks of different direction and age. The first system with which gold and polymetallic mineralization is associated has a west to NW strike. The second system of north to NE strike cuts polymetallic veins, and its formation is associated with the deposition of kaolin and alunite accumulations (Fig. 8).

Gold and polymetallic mineralization is represented by four morphological groups of ores: (1) complex ore veins and vein zones in faults of a NW and NE direction; (2) veinlet-impregnated mineralization in zones of extensive fracturing; (3) subtabular bodies in layered volcanogenic and sedimentary sequences; and (4) ore stockworks in sites of extensive fracturing. Veins are 3–5 m thick, 350–450 m long and can be traced to a depth of 350 m. The main ore minerals are represented by sphalerite, pyrite, galena, marcasite and chalcopyrite. Minor minerals include hematite, tetrahedrite, gold, silver, electrum, wurtzite and melnikovite.

The content of lead in the ore zone averages 2.09% and zinc 5.08%. High cadmium, low antimony and arsenic are determined. The deposit belongs to a gold and polymetallic ore formation, with the main components being represented by lead, zinc, gold and silver. The following mineral types of ores are distinguished: gold–pyrite–galena–sphalerite, gold–quartz–hematite, gold–adularia–quartz and gold–silver–baryte–hydromica. The deposit belongs to volcanogenic hydrothermal genetic type. The lead reserves by category C_1 make up 5.41 kt, zinc makes up 14.4 kt; lead resources by categories $P_1 + P_2$ are estimated at 3428 kt and zinc at 832.8 kt (Gursky 2008).

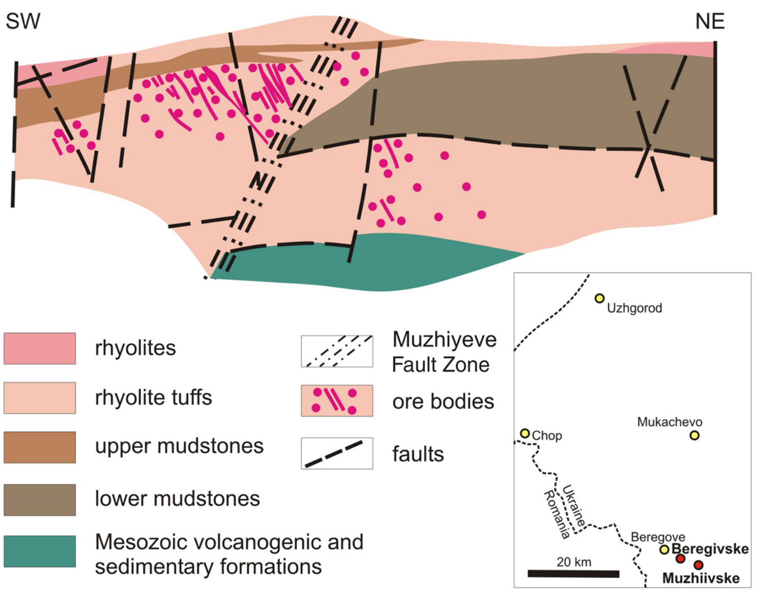

Fig. 8. Sketch of the geological cross-section of the Beregivske deposit. See Figure 1 for the location of this figure.

Biganske deposit. The Biganske deposit (location 20 in Fig. 1; 20 in Table 1) includes complex alunite–baryte–polymetallic ores and has a similar structure. Alunite ores comprise the upper part of the deposit and their reserves make 196 Mt. Below, baryte ores occur with reserves that reach 4.2 Mt. The bottom part of the deposit includes baryte–polymetallic ores with associated mineralization of copper, cadmium, silver and gold. The main ore minerals are represented by pyrite, marcasite, sphalerite, galena, chalcopyrite, grey copper ores, chalcosine, covellite, pyrargyrite, proustite and argentite. Reserves of lead are equal to 120.2 kt (average content of 1.22%) with 381.1 kt of zinc (3.83%) (Gursky 2008).

Muzhiivske gold–polymetallic deposit. The Muzhiivske gold–polymetallic deposit (location 20 in Fig. 1; 20 in Table 1) is characterized by a zonal structure. The upper part comprises stockwork zones with gold bodies. The lower part includes sulfide, quartz–sulfide, quartz–baryte, and quartz veins and veinlets, which are 0.5–50 m thick and up to 600–1300 m long. Here, veinlet-impregnated-sulfide mineralization occurs (Fig. 9). The main ore minerals are represented by sphalerite, galena, pyrite, chalcopyrite and sulfosalts. The average lead content is 1.62% and zinc content is 2.01%. Lead reserves by categories $C_1 + C_2$ make up 295 kt and 621.6 kt of zinc. Inferred resources are, following category C_2, 480 kt of lead and 960 kt of zinc (Gursky 2008).

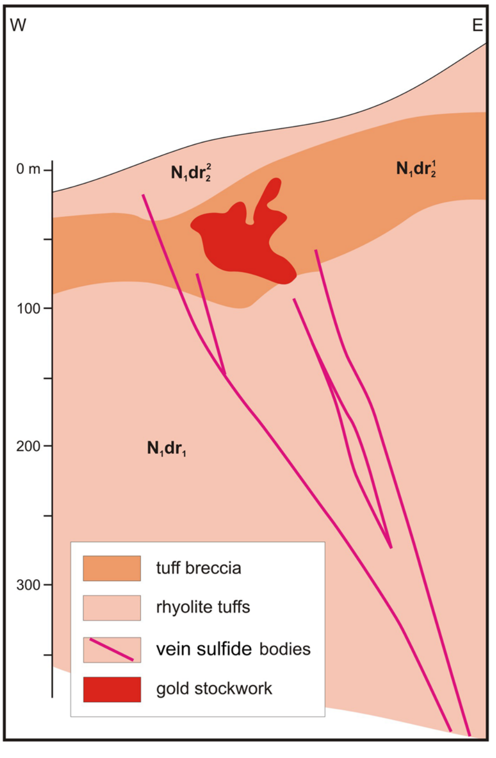

Fig. 9. Sketch of the geological cross-section of the Muzhyivske deposit. See Figure 8 for the location of this figure.

As a whole, the ore capacity of the Beregivske ore district is as follows: lead resources 822.8 kt and lead reserves 420.6 kt; zinc resources 1792.8 kt and zinc reserves 1017.1 kt.

Small deposits of polymetallic (Nagolno-Tarasivske and Nagolchanske), gold–polymetallic (Bobrikivske) and silver–polymetallic ores (Zhuravske) are known in the Nagolny Ridge of the Donbas. Most of these are of practical importance having a connection with gold and silver present in ores, and with lead and zinc only being processed as by-product components. Another area with zinc–lead sulfide mineralization is the Beliaevske deposit, which occurs in the salt-dome structures of the Dnipro–Donets Rift.

Beliaevske zinc–lead deposit. The Beliaevske zinc–lead deposit (location 21 in Fig. 1; 21 in Table 1) is located in the NW part of the Donbas, within the Bakhmutska Depression where salt-dome structures and brachyanticlinal folds are widespread. Polymetallic ores of the deposit are concentrated in the SE part of the salt-dome structure of the same name and occur in rocks on two structural levels. The upper level comprises sandstones of the Lower Triassic; the lower level occurs in the salt tectonic breccia represented by Devonian–Lower Triassic fragments of sandstones, limestones, argillites, aleurolites, anhydrites, and effusive rocks of mafic composition cemented by argillaceous and carbonaceous material. The breccia in places is saturated with bitumens. Mineralization is veinlet-impregnated, impregnated and sometimes massive. The thickness of the ore accumulations ranges from 2.7 to 90.7 m. The depth of mineralization is 200–1000 m.

The mineral composition of ores is rather simple. Ore minerals include galena, sphalerite, pyrite, marcasite, melnicovite, rarely chalcopyrite, pyrrhotite and pentlandite. Non-metallic minerals are represented by calcite, dolomite, manganese siderite, baryte, anhydrite, kaolin, jarosite and bitumen. Massive impregnated pyrite–marcasite–galena–sphalerite ores occurs in the upper part of the ore zone. The distribution of the lead and zinc is extremely irregular. The average ratio of zinc to lead is 3:1. The average lead content is 0.84% in sandstones, and zinc content is 2.36%. The ore breccia contains 3.04% of zinc and 1.1% of lead. Among the by-product components, cadmium (95 g t^{-1}) and thallium (7.4 g t^{-1}) are found.

The deposit is treated as being related to amagmatic hydrothermal salt-dome genetic type. Ore formation is polymetallic. Mineralogical type is galena–sphalerite. Deposit reserves by category C_2 give 265 kt of lead and 618 kt of zinc. Inferred resources include 556 kt of zinc and 142 kt of lead (Gursky 2008). Technological testing of ores with the production of saleable lead and zinc concentrates was carried out. By-product components include silver, gold and cadmium.

Availability and accessibility of 'Green Age' mineral data of Ukraine

The current policy of Ukraine is to make the country more and more open to western investors and research communities (Malyuk 2016). Thus, access to geological information is important, especially with regard to the potential to supply 'Green Age' minerals. National geological data are available at the English-language digital portal 'Mineral Resources of Ukraine' (https://eng.minerals-ua.info), developed in 2017 by SRDE 'Geoinform of Ukraine' together with NGU, the Geological Survey of Norway, in the joint project EIMIDA (European Integration of MIneral DAta), funded by the MFA, the Ministry of Foreign Affairs of Norway.

Furthermore, Ukraine is going to provide standardized and harmonized, INSPIRE-compliant mineral data to the pan-European digital platforms on the whole range of minerals, with a special emphasis on 'Green Age' minerals. This will be achieved by permanent participation of SRDE 'Geoinform of Ukraine' in various pan-European research projects initiated by EuroGeoSurveys, the Geological Surveys of Europe. These products already include pan-European digital portals developed in the context of several EU-funded projects such as Minerals4EU (2015: http://minerals4eu.brgm-rec.fr), ProSUM (2017: http://www.prosumproject.eu), GeoERA (2021: https://geoera.eu) and a forthcoming CSA-GSE project (2022–27) devoted to establishing the Geological Service for Europe, which will manage the common digital portal EGDI (European Geological Data Infrastructure: http://www.europe-geology.eu) under the FAIR (Findable, Accessible, Interoperable, Reusable) principles.

The European integration and 'Green Age' geological data management will be accelerated through the recently established EU–UA Strategic Partnership on Critical Raw Materials and Batteries, in a follow-up of Action 9 of the Critical Raw Materials action plan (European Commission 2020), that was initiated by the Memorandum of Understanding (MoU) signed by the Vice-President of the European Commission, Maroš Šefčovič, and the Prime Minister of Ukraine, Denys Shmyhal, at the high-level event held in Kyiv, Ukraine on 13 July 2021 (https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3633).

Conclusions

This analysis of Ukraine's mineral resources of critical value for development of a 'green' power industry in Europe identifies four groups of elements that can be classified in terms of geological certainty, reserves, stages of commercial development and/or perspectives for commercial exploitation. These are: (1) Iron, manganese and graphite – large-scale deposits that have been mined for a long period time in Ukraine and have almost unlimited resources/perspectives for further production. (2) Lithium and rare earth elements (REEs) – deposits that are mostly explored and possess considerable reserves; these deposits are not under exploitation but can be brought into commercial production pending appropriate geological and economic evaluation. (3) Cobalt and nickel – deposits that are discovered but their reserves are rather small and some technological problems of ore beneficiation exist; these deposits can only be developed with additional confirmation of their economic feasibility by objective economic–geological evaluation. (4) Aluminium and lead – small deposits and manifestations that are known but their reserves and ore grades are rather low; as a result, their exploitation is doubtful and possibilities for commercial output are not clear.

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Author contributions **VAM**: conceptualization (equal), formal analysis (equal), methodology (lead), writing – original draft (equal); **OVH**: data curation (lead), formal analysis (equal), investigation (equal), writing – original draft (equal); **BIM**: conceptualization (equal), formal analysis (equal), validation (lead), visualization (lead), writing – review & editing (lead).

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