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**Monitoring of graphite production in Ukraine**

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**SUMMARY**

The demand for many resources in world is increasing significantly due to their growing importance for industrial and technological development. Graphite, especially, high quality graphite can be used in many industrial applications including refractory, batteries, fuel cells, metallurgy ect. Innovation techniques will cause an increasing of graphite demand and the global market value of graphite is expected to growth. Ukraine has one of the largest reserves of natural graphite in the world. Main graphite deposits of Ukraine are related to Precambrian meta-morphic rocks of the Ukrainian Shield. According to the State balance of Ukraine, there are six graphite deposits one of them currently under development by Ltd. Zavallia graphite. The mining profitability is ensured by graphite quality, location, lithological and mineralogical characteristics of deposits. The graphite mining, ore processing, geological situation and total resources of the most important deposits as well as general analysis of Ukrainian graphite province and global market overview are given in the paper.



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**Introduction.** Graphite is a form of carbon with a wide industrial application. Natural graphite is an important industrial mineral which finds applications in almost every aspects of manufacturing. Graphite's inert behavior, high melting point (3 927°C) and other physical properties make it an ideal material for using in chemical and nuclear industry, electronics, hot metal processing, friction, coatings, aerospace, powder metallurgy, lubricants, refractory, paint and pencil production etc. (Mykhailov et al. 2008; Mykhailov, Hrinchenko, 2018). Graphite is a main strategic material for the green technologies because of advances in energy storage, electric vehicles and electronics. Graphite is considered to be critical raw materials in view of the economic importance and supply risk (European Commission..., 2020).

The total reserves of natural graphite in the world amounted to 320 million metric tons in 2020 (table 1). Turkey has the largest reserves. World graphite production has slightly decreased since 2015. In 2020 the total worldwide production of graphite amounted to 1.02 million metric tons. China has consistently been the leading global graphite producer, producing 62% of total world output (Mineral Commodity..., 2021). Innovation techniques will cause an increasing of graphite demand and the global market value of graphite is expected to increase to more than 27 billion U.S. dollars by 2025 comparing to 17.6 billion U.S. dollars in 2018 (Garside, 2019). High-technology applications of graphite such as lithium-ion batteries for electric motor vehicles, large – scale electric energy storage devices and numerous graphite derivatives like expanded graphite, graphite foils, spherical graphite and graphene are representing a part of market with the fastest expected growth (Garside, 2019).

**Table 1** World mine production and reserves (Mineral Commodity..., 2016-2021)

Country	Reserves, thousand metric ton	Production, thousand metric tons					
		2015	2016	2017	2018	2019	2020
Turkey	90 000	32	4	2,3	2	2	1,5
China	73 000	780	780	625	693	700	650
Brazil	70 000	80	95	90	95	96	95
Madagascar	26 000	5	8	9	47	48	47
Mozambique	25 000	-	-	0,3	104	107	120
Ukraine	18 000	5	15	20	20	20	19
Tanzania	17 000	-	-	-	0,1	0,1	0,1
India	8 000	170	149	35	35	35	34
Uzbekistan	7 600	-	-	-	-	0,1	0,1
Vietnam	7 600	-	5	5	5	5	4,5
Mexico	3 100	22	4	9	9	9	8
North Korea	2 000	30	6	5,5	6	6	5
Sri Lanka	1 500	4	4	3,5	4	4	3,5
Norway	600	8	8	15,5	16	16	15
Canada	-*	30	30	40	40	11	10
Russia	-*	15	19	17	25	25	24
Other	-*	50	23	20,4	31,9	15,8	1,3
<b>World total</b>	<b>349 400</b>	<b>1 190</b>	<b>1 150</b>	<b>897</b>	<b>1 120</b>	<b>1 100</b>	<b>1 020</b>

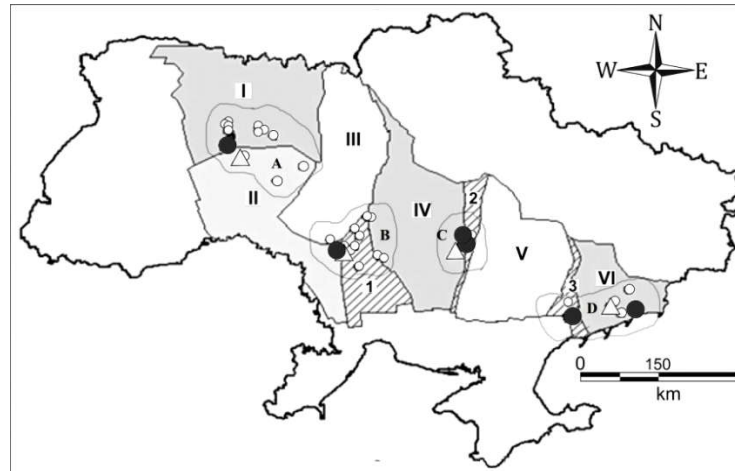
-\* - included with World total

The present research is aimed at analyzing the Ukrainian graphite province in terms of reserves, geological conditions, graphite quality, mining, ore processing and graphite production. The literary review and study of State Balance and Geological Survey materials were conducted during this research.

**Ukrainian graphite province: geological conditions, reserves, ore processing and graphite production.** Ukraine has one of the largest reserves of natural graphite related to Precambrian metamorphic rocks of the Ukrainian Shield (USh) which are metamorphosed to upper amphibolite and granulite facies (Fig. 1, 2). There are 6 well studied graphite deposits and one of them is currently under development. The total balance reserves were estimated to 306 million tons of ore for (A+B+C<sub>1</sub>+C<sub>2</sub>) categories and it is equal to 17.9 million tons of graphite (table 2). The most important

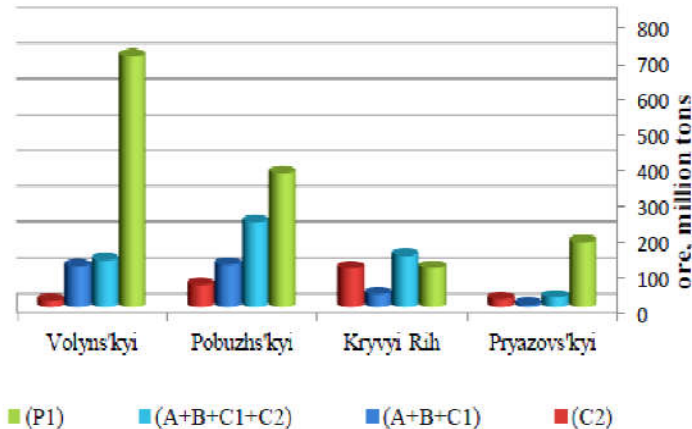


factors in economic evaluation of graphite deposits are size and tonnage of ore bodies, natural type, size and distribution of graphite (Zagnitko, Lyzhachenko, 2012). All Ukrainian deposits are large. Graphite is fine to coarse-grained and belongs to flake natural type. In addition to deposits, numerous graphite occurrences are also promising for further exploration works (Lyzhachenko, 2021). Graphite province within the USH consist of four following districts: Volyns'kyi, Pobuzhs'kyi, Kryvyi Rig, Pryazovs'kyi (Fig.1, A, B, C, D). The thick of overburden at the graphite deposits and occurrences is from 10 to 80 m.



**Figure 1** Regional setting of graphite deposits and occurrences of the Ukrainian shield.

Graphite deposits are marked by dark circles (left to right: Burtyns'ke, Zavalivs'ke, Balahivs'ke, Petrivs'ke, Troits'ke, Mariupols'ke), occurrences promising for further exploration — light triangles (left to right: Maharynetskyi, Dubynivs'kyi, Varvarivs'kyi, Sachkyns'kyi), small light circles — other occurrences); graphite districts: A — Volyns'kyi, B — Pobuzhs'kyi, C — Kryvyi Rig, D — Pryasovs'kyi; megablocks: I — Volyns'kyi, II — Dnisters'ko-Buz'kyi, III — Rosyns'ko-Tikyts'kyi, IV — Inguls'kyi, V — Middle-Prydniprov's'kyi, VI — Pryazovs'kyi; suture zones: 1 — Holovanivs'ka; 2 — Kryvyi Rih-Kremenchug, 3 — Horikhovo-Pavlograds'ka.



**Figure 2** Reserves of Ukrainian graphite province according to categories (A+B+C), (C), (P).

The following deposits and occurrences are taken into account: Zavalivs'ke, Burtyns'ke, Mariupol'ske, Troits'ke, Petrivs'ke, Balahivs'ke, Kosharo-Oleksandrivskyi, Demoviars'kyi, Rohivs'kyi, Kapitanivs'kyi, Lypovenkivs'kyi, Lashevats'kyi, Haschuvats'kyi, Dubynivs'kyi, Babenkivs'kyi, Vodians'kyi, Zelenivs'kyi, Varvarivs'kyi, Zamorochens'ko-Horodniavs'kyi, Maharynets'kyi, Yablunivs'kyi.

The Volyns'kyi graphite district situated in the north-western part of the USH (Fig. 1, A). The graphite content in ores of the Volyns'kyi district is elevated from 3.0 to 7.0 vol.%. The largest and most investigated reserve are concentrated at the Burtyns'ke deposit. A few graphite occurrences with total geological reserves of approximately 700 million tons were identified by prospecting works.



The Burtyns'ke natural graphite deposit is one of the most economically valuable on the USH. Significant graphite content has been identified in Proterozoic graphite-biotite gneisses and migmatites. The thickness of ore body varies from few meters to over 400 meters. The ore body is more than 18 km long, trend SE-NW. The thickness of overburden ranges from 2.5 to 20 m. The ore is processed by flotation method. Both chemical features of ores and graphite quality are similar to ore at Zavalivs'ke deposit. Average graphite content is 6.7%. The Burtyns'ke deposit is completely prepared for an industrial development and suitable for mining in open pit. The graphite concentrates are fit for use in domestic industries (metallurgy, batteries, thermal materials and refractories) as well as for exports.

The Kryvyi Rig graphite district situated in central part of the USH in the Kirovohrad administrative region of Ukraine. During XX century few deposits and occurrences were being discovered within this region during preliminary study (*Lyzhachenko, 2021*). Nowadays, Balahivs'ke and Petrivs'ke deposits are industrially significant. The total estimated reserves are 31.5 million tons of graphite ore. Except Balahivs'ke deposit, reserves of the Kryvyi Rig district were estimated only to 50–100 m depth and may increase after further prospecting and exploration works.

The graphite-bearing rocks of Petrivs'ke deposit occur as layers and elongated lenses following contact of Archean to Proterozoic crystalline limestone and metamorphic gneisses. Paragneisses are intruded by granite dikes of Ingulets complex. Graphite is mainly fine-grained (from 0,001 to 2–5 mm in size). The graphite content in ore of Petrivs'ke deposit varies in a range of 4.9 to 7.5%, locally up to 60% in small lens-shaped bodies. The thickness of layers is 7 to 50 m. Since 1915 deposit has been under developing during few years. It was the first period of commercial mining. At that time 2 700 tons of high quality graphite ores with graphite content up to 67% were extracted (*Shapiro, 1928*). The Petrivs'ke deposit was reinvestigated in 1953 and 1957. The calculated resources are given in table 2. The cut-off grade is 3% of graphitic carbon (C<sub>g</sub>).

**Table 2** Graphite reserves at main deposits, thousand tons (Mineral reserves..., 2020)

Deposit	A+B+C <sub>1</sub>		C <sub>2</sub>	
	ore	graphite	ore	Graphite
Zavalivs'ke	80 026.8	5 036.0	14 613.0	744.2
Petrivs'ke	7 523.0	540.0	1 696.0	115.0
Balahivs'ke	23 936.0	1 302.0	18 469.0	820.0
Burtyns'ke	113 390.9	6 584.7	39 429.7	2 405.9
Troits'ke	2 027.0	163.0	252.0	14.0
Mariupol'ske	34 40.0	135.0	1 347.0	41.0
<b>Total</b>	<b>230 343.7</b>	<b>13 760.7</b>	<b>75 806.7</b>	<b>4 140.1</b>

The Balahivs'ke deposit is the most economically significant in district. Deposit consist of four layered bodies of graphite-bearing gneisses deformed by faulting. Ore bodies are from 10 to 300 m thick, from 400 to 2 890 m long. Bodies lie in concordance to host rocks. Primary minerals in graphitic ores are mostly destroyed by weathering. The special permission to develop the Balahivs'ke deposit is acquired by Development of Pobuzhia Ltd. Mining is

suggested to be in open pit. Measured and indicated resources at the Balahivka are estimated to total of 42 405 thousand tons grading 5.6% graphitic carbon. The cut-off grade is 2.5% graphitic carbon. According to feasibility study a project lifetime is predicted to be 44 years long by production capacity of 714 500 tons of graphite ores per year.

The Pryazovs'kyi graphite district is located 40 km north of the Azov Sea, northwest of Mariupol', in the Zaporizhia and Donetsk administrative regions. Mariupol'ske and Troits'ke deposits and few occurrences are situated on the territory of the Pryazovia (*Lyzhachenko, 2021*). All graphite ores related to gneisses in the western and eastern wings of the Central Azov syncline. The graphite content varies from 1.0 to 30%. Mariupol'ske and Troits'ke deposits are presented by layered bodies of graphitic gneisses up to 3.5 km long intruded by granitoids and syenites. Pinching and swelling of beds are common. Both deposits are investigated by drilling, geophysical and structural study. Although none of this deposits are currently in production due to relatively small reserves. At the beginning of XX century Starokryms'ke occurrence was mined by underground method and in open pit. More than 360 000 pounds of ore were extracted in that period.

The Pobuzhs'kyi graphite district located in south-western part of the USH in the Kirovohrad region, partially capturing the northern districts of Odesa and Mykolaiv administrative regions of Ukraine.



The graphite district consist of number occurrences which are mostly located around one of the biggest in Europe currently exploited Zavalivs'ke deposit (*Lyzhachenko, 2021*). The graphite content in ore varies from 2.5 to 16.0%. The total proved reserves of district consist of above 110 million tons of graphite ore.

Nowadays the Zavalivs'ke graphite deposit is active. The total reserves of graphite ore are 946 398 thousand tons containing 57 802 thousand tons of graphite. Graphite content varies from 6 to 14% (average 6.5%). The commercial mining started in 1934. The Zavalivs'ke graphite deposit was an important source of graphite for Soviet Union industry for more than fifty years and still remains one of the main suppliers of graphite to the post-Soviet countries. Project lifetime was suspected to be 100 years long. Production capacity of plant is 800 thousand tons of graphite ore or 35 thousand tons of graphite concentrate. In the early 90's graphite production exceeded 40 thousand tons. Nowadays the Zavallia open pit is under development by Ltd. Zavalivs'kyi graphite. Mine capacity sufficiently reduced to 4-8 thousand tons per year (table 3). At present, Australian company Volt Resources Limited, based in Perth, Western Australia, has entered into binding Share Purchase Agreements to acquire a 70% interest in the Zavalivs'kyi Graphite business (according to official company announcements).

**Table 3** Dynamics of graphite production in Ukraine in 2010–2019, thousand tons

Years	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

The Zavalivs'ke graphite deposit presented by six mine section such us Zarichna, Pravoberezhna, Pivdena, Hutir Andriivka, Promizhna, Pivdenno-Shidna. The last one is currently under development and almost depleted. The graphite ores presented by Archean graphite, biotite-graphite, amphibole-biotite, biotite-chlorite, chlorite-sericite, chlorite-talc, chlorite and garnet-graphite-biotite gneisses. Deposit consist of more than 40 ore bodies from 200 m to 1 200 m long and from 3.5 m to 80 m thick. Graphite in ores is coarse-grained (2-4 mm) and shows evenly distribution.

Graphite ore is processed at the Zavallia graphite plant. Processing includes the crushing of the host rocks, grinding and chemical treating of ore to liberate the flake graphite. Gravity separation and flotation techniques are using at plant at present. The group of specialists from the Zavallia graphite plant are developed and implemented a method of oxidized graphite ores processing and producing high-quality graphite material which does not require significant investment (*Lyzhachenko at al, 2013*).

The Zavallia graphite plant produces a different products according to technical requirements and state standards. Graphite material has excellent physical and chemical properties, as well as the ideal structure of the crystal lattice. For example, graphite material which is used in the production of batteries characterized by an ash content – up to 2%, humidity – 1%, a residue on a sieve of 0.15 mm – not more than 15%, on a sieve of 0.063 mm – 30–50%, impurities are not allowed. Products such as buttery graphite, dry colloidal graphite, pencil graphite, crucible graphite and many others are exporting to various countries.

**Conclusions.** Graphite demand in world is progressively growth. The Ukrainian graphite province is characterized by following key features: large proven and predicted reserves, high graphite quality, favorable geological conditions and geographic location (close to European market and with good access to other markets in the USA and Middle East, ect.). Ukrainian graphite can be used in many industrial sectors including high technology and green energy. Graphite mining can increase after additional investments. A huge part of graphite reserves in Ukraine is still remaining undeveloped despite all favorable characteristics. It can be considered as an additional advantage for foreign investors.

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