

Research Paper**CRITICAL AND STRATEGIC METAL RESOURCES OF GREECE****Ananias Tsirambides* and Anestis Filippidis****Aristotle University of Thessaloniki, School of Geology, Department of Mineralogy-Petrology-Economic Geology, 54124 Thessaloniki, Greece*****ananias@geo.auth.gr anestis@geo.auth.gr****Correspondence to:**
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Abstract

Greece has a large number of critical and strategic metal resources. The proven and indicated reserves of aluminum amount to 2.5 mt and their gross value €5.075 b. Those of chromium amount to 1.2 mt with gross value €4.320 b, while of cobalt are 129 th. t with gross value €3.348 b. The proven and indicated reserves of copper from Chalkidiki and Kilikis areas are approximately 3.04 mt and their gross value €24.776 b, while those of manganese are 2.25 mt with gross value €5.400 b. Molybdenum has been located in Pigi Kilikis with indicated reserves of about 7.7 th. t and gross value €326 m. Under mining are the vein type magnesite deposits of Gerakini Chalkidiki and North Evia. The total reserves (proven + indicated) of magnesite are 280 mt and their gross value €9.800 b. The most important lateritic Fe-Ni-bearing ores are those of Evia Island, Agios Ioannis Viotia, Lokrida Fthiotida, Mesopotamia and Ieropigi Kastoria. The proven and indicated reserves of nickel are 1.39 mt and their gross value €22.240 b. The Rizana/Lachanas porphyry-epithermal antimony deposit is considered the most important stibnite ore. The proven and indicated reserves of stibnite are at least 100 th. t with an average Sb content of 0.3 wt%. Copper, chromium, and cobalt present good prospects for mining. Platinum group metals (PGMs), with economic interest, are contained in the porphyry Cu deposits of Skouries Chalkidiki. Strymonikos Gulf, together with the neighboring coastal and submarine sands, is the most probable area for locating exploitable rare earth metals (REMs). There are excellent investment opportunities in the exploration and mining of Bi, Te, Ga, Ge, and In metals. The deposits of other critical and strategic metals of Greece should be adequately assessed.

Keywords: *Reserves, metal concentrations, gross value, production.*

ΠΕΡΙΛΗΨΗ

Στην Ελλάδα υπάρχει μεγάλος αριθμός κρίσιμων και στρατηγικών μεταλλικών πόρων. Τα βεβαιωμένα και ενδεικτικά αποθέματα του αλουμινίου ανέρχονται σε 2,5 εκατ. τόνους με ακαθάριστη αξία 5,075 δισ. ευρώ. Εκείνα του χρωμίου ανέρχονται σε 1,2 εκατ. τόνους με ακαθάριστη αξία 4,320 δισ. ευρώ, ενώ του κοβαλτίου είναι 129 χιλ. τόνοι με ακαθάριστη αξία 3,348 δισ. ευρώ. Τα βεβαιωμένα και ενδεικτικά αποθέματα του χαλκού από τις περιοχές της Χαλκιδικής και του Κιλκίς είναι περίπου 3,04 εκατ. τόνοι με ακαθάριστη αξία 24,776 δισ. ευρώ, ενώ του μαγγανίου 2,25 εκατ. τόνοι με ακαθάριστη αξία 5,400 δισ. ευρώ. Μολυβδαίνιο έχει εντοπιστεί στην Πηγή Κιλκίς με ενδεικτικά αποθέματα περίπου 7,7 χιλ. τόνων και ακαθάριστη αξία 326 εκατ. ευρώ. Υπό εκμετάλλευση βρίσκονται τα φλεβικού τύπου μεταλλεύματα μαγνησίτη της Γερακινής Χαλκιδικής και της Βόρειας Εύβοιας. Τα συνολικά αποθέματα (βεβαιωμένα + ενδεικτικά) μαγνησίτη είναι 280 εκατ. τόνοι και η ακαθάριστη αξία τους 9,800 δισ. ευρώ. Τα σημαντικότερα Fe-Ni-ούχα λατεριτικά μεταλλεύματα είναι της Εύβοιας, του Αγίου Ιωάννη Βοιωτίας, της Λοκρίδας Φθιώτιδας, της Μεσοποταμίας και της Ιεροπηγής Καστοριάς. Τα βεβαιωμένα και ενδεικτικά αποθέματα νικελίου είναι 1,390 εκατ. τόνοι και η ακαθάριστη αξία τους 22,240 δισ. ευρώ. Το κοίτασμα πορφυριτικού-επιθερμικού αντιμονίου των Ριζανών/Λαχανά θεωρείται το σημαντικότερο μετάλλευμα στιβνίτη. Τα βεβαιωμένα και ενδεικτικά αποθέματα στιβνίτη είναι τουλάχιστον 100 χιλ. τόνοι με μέση περιεκτικότητα σε Sb 0,3% κ.β. Ο χαλκός, το χρώμιο και το κοβάλτιο παρουσιάζουν καλές προοπτικές εξόρυξης. Πλατινοειδή μέταλλα (PGMs), με οικονομικό ενδιαφέρον, περιέχονται στα πορφυριτικά κοιτάσματα χαλκού των Σκουριών Χαλκιδικής. Ο Στρυμονικός Κόλπος, μαζί με τη γειτονική παράκτια και υποθαλάσσια άμμο, είναι η πιο πιθανή περιοχή για τον εντοπισμό εκμεταλλεύσιμων μετάλλων σπάνιων γαιών (REMs). Υπάρχουν εξαιρετικές ευκαιρίες επένδυσης για έρευνα και εξόρυξη των μετάλλων Bi, Te, Ga, Ge και In. Τα κοιτάσματα άλλων κρίσιμων και στρατηγικών μετάλλων της Ελλάδας θα πρέπει να αξιολογηθούν επαρκώς.

Λέξεις - Κλειδιά: Αποθέματα, συγκεντρώσεις μετάλλων, ακαθάριστη αξία, παραγωγή.

1. Introduction

Some metals are considered critical because of their economic value, their scarcity, and the high supply risks affected by unpredictable market conditions. In 2023 the European Commission upgraded its initial list from 14 to 34 critical raw materials (CRMs) for the European Union (EU). They are considered crucial to the development of Europe's

economy, especially to modern technologies. Some of these critical metals present low concentrations in earth's crust and some others are produced as by-products through the processing of basic metal ores (<https://single-market-economy.ec.europa.eu>). Demand for CRMs will increase greatly in the coming years. According to the International Energy Agency, the reduction of pollutants to zero by 2050 would require six times more such minerals in 2040 than today. It is estimated that demand for lithium would increase globally 42-fold by 2040 than today, cobalt 21-fold, and nickel 19-fold (Ragonnaud, 2023). Climate goals can't be met without critical raw materials. Europe's opportunity to become self-sufficient in mineral raw materials supply from own sources, is urgent today. Production of critical and strategic metals from European primary and secondary resources was put in priority by the European Commission. For the EU the development of critical mineral supplies, less dependent on China, must be a dominant target (Arvanitidis, 2024). Some countries have significant mineral resources beneath their sea bottoms at depths up to 200 m. Three main types of deposits contain the most minerals: 1. Ferromanganese crusts which hold Mn, Fe, Co, Cu, Ni, and PGMs. 2. Polymetallic nodules, which are rich in Mn, Ni, Cu, Co, Mo, and REMs. 3. Sulfide deposits, which contain Cu, Au, Zn, Pb, Ba, and Ag. In the exclusive economic zones of some countries (i.e. Japan, Norway) several exploration projects are carried out. However, there are strong environmental hurdles (Ragonnaud, 2023).

The total number of state mining areas (i.e. areas of Greece where the mineral rights belong to the state) exceeds 200. Most of these areas are not currently leased to mining companies. Therefore, a significant opportunity to develop new projects for exploration, mining and processing of critical and strategic metals exists. More than 20 mineral raw materials, included in the list of EU of critical and strategic raw materials, have been identified in the Greek territory (i.e. aluminum, antimony, chromium, cobalt, copper, gallium, germanium, indium, magnesium, manganese, molybdenum, nickel, silicon, tellurium, tungsten, light rare earths, platinum group metals, baryte, feldspar, graphite and phosphorite) (Zafeiratos, 2023). Greece is the only country in the EU with large reserves of aluminum, chromium, manganese, and nickel. It is the leading producing country for aluminum (from bauxite) and nickel (from laterite) and a significant producing country for magnesium (from magnesite) in the EU. Some important sites with critical and strategic metals referred to in this manuscript are shown in Figure 1. Greece has a comparative advantage in relation to other European countries since it presents a great potential for supplying some of the critical and strategic metals, since it hosts promising ore deposits of them. Antimony-bismuth alloys and Ag-, Cu-, Pb-, Sb-, Bi- sulfosalts have been discovered in some metal assemblages in the Serbomacedonian Rhodope Metallogenic Belt (SRMB). The epithermal- and porphyry-

type deposits of this metallogenic province in northeastern Greece are the main targets for exploration of Sb, Bi, Te, Mo, REMs, and PGMs. REMs are found in high contents at the coastal sediments of Strymonikos Gulf and elevated PGM concentrations have been located in the porphyry deposits of Cu at Skouries Chalkidiki. Therefore, the mineral wealth of Greece can contribute significantly to a sustainable and competitive economy of Europe (Melfos and Voudouris, 2012; Tsirambides and Filippidis, 2019).

In northern Greece (Regions of Macedonia and Thrace), there is a large number of occurrences and ores of basic metals, which are often accompanied by Mo, Sb, Bi, Te, W, Ag, Au, and other rare metals. Usually these deposits are porphyry-epithermal, sheeted veins, carbonate replacements, or shear-zone hosted deposits. Some of these ores are economically very significant (Kalogeropoulos et al., 1989; Tsirambides and Filippidis, 2012, 2016; Voudouris et al., 2009, 2011, 2013a, 2013b; Stergiou et al., 2021a, 2022, 2023a). Metal assemblages of Sb-Bi alloys and Ag-Cu-Pb-Sb-Bi sulfosalts have been located in the SRMB. The most important ores of Sb contain stibnite, while those of Bi contain bismuthinite and bismite. The Bi-sulfosalts and precious/critical/strategic metal tellurides can be considered as pathfinder minerals for Au and are usually associated with Au-bearing ores (Voudouris et al., 2018). These Bi-minerals may provide suitable physicochemical environment for the formation of precious metals (Cook, 1997; Ciobanu and Cook, 2000; Ciobanu et al., 2005; Cook et al., 2009). The Vertiskos Unit of the Serbomacedonian Massif hosts several Oligocene-Miocene ore deposits and occurrences. Some of these contain significant amounts of metals such as Sb, Bi, Te, Co, REMs, and PGMs (Stergiou et al., 2021b). PGMs, gold, tellurium, and arsenic have been identified in porphyry copper occurrences in Chalkidiki (Eliopoulos and Economou-Eliopoulos, 1991) and in Kilkis (Economou-Eliopoulos and Eliopoulos, 1993). Ilmenite, rare earths, and placer gold have been detected in the seafront sands of Nea Peramos-Loutra Eleftheron Kavala (Pergamalis et al., 2001).

Greece is expected to remain a major supplier of bauxite, ferronickel, and magnesite. After the completion of the investment at Skouries Chalkidiki, Greece will establish itself in the 3rd place of gold production in Europe. The pending production of copper, chromium, and cobalt in the near future will strengthen the country's mining industry and hence Greece's economy. The outlook of the critical and strategic metal resources of Greece is the focus of this paper.

2. ALUMINUM (Al)

Aluminum in small amounts to certain metals improves their properties for specific uses, as in aluminum bronzes. The metal and its alloys are used extensively for aircraft construction, building materials, consumer goods (refrigerators, air conditioners, cooking utensils), electrical conductors, and chemical equipment. The karst bauxites of Greece are among the world's most important sources of non-metallurgical bauxite. These deposits are interbedded in the form of lenses, veins, pockets or irregular masses in limestone formations. Exploitable deposits of bauxites exist in the regions of Parnassos Mt, Giona Mt, and Helikon Mt. Economically insignificant occurrences of bauxites are found at Kallidromo Mt, Iti Mt, Othrys Mt, Evia, Skopelos, and Elefsina. In general, these deposits are brown-red in color, because of the contained iron oxides.

In addition, there are white colored bauxites, which are richer in aluminum and poor in iron. The bauxites of the Parnassos-Giona Zone are mainly characterized by oolitic texture. Diaspore, boehmite, and hematite are the major mineral constituents. Kaolinite, rutile, and anatase are present in minor phases. Ilmenite, rutile, chromite, and zircon, are common detrital minerals. Some authigenic minerals with low content are REE-phosphates, barite, and gypsum (Mondillo et al., 2022). The mineralogical composition of the bauxites of this zone is (in wt%): 20-50 diaspore, 10-30 boehmite, 20-25 haematite, 1-5 calcite, 1-2 quartz, 1-5 kaolinite, and 0.5-2 anatase (Tsirambides and Filippidis, 2012). In addition, in these bauxites the overall REE concentration varies from 192 ppm to 1109 ppm (av. 463 ppm). The most abundant REE is Ce (av. 193 ppm). Scandium is another critical element (av. 47 ppm) (Table 1). The concentration of REEs is much higher in Fe-rich (red) bauxite, compared to Fe-depleted (white) bauxite (av. REEs 569 ppm and 268 ppm, respectively) (Gamaletsos et al., 2019).

The total production of all three companies operating in the above zone in 2022 was 1.173 mt of bauxite and 197 th. t of aluminum (Ministry of Environment and Energy, 2024). In 2023 the acquisition and the merger process of Imerys Bauxites to Mytilineos was completed. This company became the largest bauxite producer in Europe, significantly increasing its production capacity. The acquisition concerned all bauxite mining activities in the Fokida area and boosted the annual production capacity of the new enterprise to 1.2 mt, the largest production in Europe and among the largest globally (<https://www.mytilineos.com>). The proven and indicated reserves of aluminum are approximately 2.5 mt and their gross value €5.075 b (<https://www.lme.com>) (Table 2).

3. ANTIMONY (Sb)

Antimony is used in the electronics industry to make specific semiconductor devices, such as infrared detectors and diodes. It is alloyed with lead or other metals to improve their hardness and strength. Antimony compounds are used in batteries, paints, ceramics, plastics, rubber, textiles, adhesives, glass and pottery, as well as in flame retardants. The antimony deposits of Greece are mainly related to hydrothermal processes and are usually associated with Cenozoic magmatism. They are simple Sb-deposits, where stibnite is the predominant mineral, or polymetallic deposits with varying contents of antimony minerals (Kanellopoulos et al., 2024). Antimony has been found in veins of the mineral antimonite mainly in Rizana Kilkis, Filadelfio and Lachanas Thessaloniki, Neo Kallyntirio Rhodope, Chios and Samos with contents from 1% to 2.5% of Sb and common presence of critical, strategic and precious metals such as Pb, Zn, Cu, Mo, As, Te, Ag, Au, and in some cases of W (Melfos and Voudouris, 2012). The most important porphyry-epithermal ore occurrences in the Regional Unit of Kilkis are those of Rizana, Pontokerasia, Vathi and Gerakario (Stergiou et al., 2021a, 2022, 2023b). The Rizana/Lachanas porphyry-epithermal deposit is related to sheeted quartz veins, usually of small dimensions, that crosscut Paleozoic metamorphic rocks such as gneisses and amphibolites. Many occurrences of minerals of Sb and some of W exist in the broader area. The mineral paragenesis of the ore is mainly: quartz, pyrite, calcite, dolomite, sericite, chlorite, stibnite, and wolframite. In the period of 1930-50 about 9,000 t of stibnite ore and some tons of wolframite ore have been extracted from rough tunnels of 350 m total length. The Sb concentration reached 40% for half of the total production. The mineralization is spread over an area of 50 km long and 30 km wide. The proven reserves of stibnite are 5,000 t (av. Sb=0.3 wt%) and its indicated reserves 50,000-100,000 t of the same Sb concentration. The proven reserves of wolframite are 1000 t (Tsirambides and Filippidis, 2012, 2016, 2019; Stergiou et al., 2022, 2023b).

At the Pontokerasia porphyry-epithermal deposit Sb-bearing minerals (e.g. bournonite, boulangerite, jamesonite, etc.) have been detected inside a complex of small veins. Usually rounded tiny crystals of bournonite occur inside larger euhedral galena crystals. These Sb-minerals were formed under hydrothermal processes. Bournonite was formed under hypothermal (500-300°C) conditions, boulangerite under mesothermal (300-200°C) conditions and jamesonite under epithermal (200-50°C) low depth (1000 m) conditions (Melidonis, 1973). The Pontokerasia Cu-Mo-Au deposit contains up to 0.3 wt% Cu and up to 0.16 ppm Au (Table 1) (Tsirambides and Filippidis, 2016). The Vathi Cu-Au-U±Mo deposit is associated with a high-K calc-alkaline monzonite intrusion.

The probable and indicated reserves are 0.15 mt ore with up to 0.3 wt% Cu and up to 0.8 ppm Au. Other constituents of this deposit are: 0-341 ppm Mo, 0.4-239 ppm Bi, 0.1-11 ppm Sb, 0.1-4.6 ppm Ag (Table 1) (Tsirambides and Filippidis, 2016). The Gerakario Cu-Au deposit is hosted in a calc-alkaline syenite and granodiorite intrusion. The probable and indicated reserves are 0.13 mt ore with up to 0.3 wt% Cu and up to 1.4 ppm Au (Table 1) (Tsirambides and Filippidis, 2016). Further investigations are needed to determine the grade and the proven reserves of the critical metals Sb and W in the Regional Unit of Kilkis. The Neo Kallyntirio porphyry-epithermal deposit is a Sb-Pb-Zn-Ag-Au-Te occurrence (Table 1). It is hosted within silicified marbles and schists and occurs in the form of dissemination, in quartz-barite-carbonate veins and breccias. The ore developed from early pyrite, followed by low-iron sphalerite, galena, chalcopyrite, and bournonite group minerals and then by antimonite, arsenopyrite, and realgar. The deposit presents features similar with the detachment related sedimentary rock-hosted low-sulfidation mineralization in Bulgaria. For both sites, the magmatic contribution is supported because of the presence of tellurides in both systems (Kanellopoulos et al., 2014, 2024). The proven and indicated reserves of antimony are approximately 30 th. t and their gross value €369 m (<https://www.argusmedia.com>) (Table 2).

4. BISMUTH (Bi) and TELLURIUM (Te)

Bismuth alloys with tin or cadmium present low melting points and are used in fire detectors and extinguishers, electric fuses, and solders. Bismuth compounds are used in cosmetics, pigments, pharmaceuticals, atomic fire alarms, and sprinkler systems. The primary use of tellurium is the production of CdTe solar panels and thermoelectric devices. In addition, it is used in alloys, mostly with copper, lead, and stainless steel, to improve their machinability and strength. Tellurium can be doped with silver, gold, copper or tin in semiconductor applications. Globally most of the tellurium produced is obtained as a by-product of copper processing. Bismuth is contained in many Bi-sulfosalts and Bi-tellurides which are common in porphyry-, epithermal-, and intrusion-related ores at the Serbomacedonian and Rhodope Massifs, such as in Skouries and Stanos Chalkidiki, Vathi Kilkis, Kimmeria Xanthi, Rhodope (Sapes, Perama Hill, Maronia), and Evros (Konos Hill, Pagoni Rachi, Esymi-Leptokarya) (Michailidis et al., 1989; Vavelidis et al., 1989; Voudouris et al., 2006; Melfos and Voudouris, 2012). The Skouries porphyry intrusion and the surrounding rocks are strongly fractured and intensely altered by hydrothermal fluids. Mineralization mainly includes chalcopyrite, pyrite, bornite, chalcocite, and magnetite in the form of veins, stockworks, and

disseminations. Native gold and electrum are commonly present as small inclusions in chalcopyrite. The deposit exhibits high levels of Cu, Au, Ag, Bi, Co, Se, and Te (Eliopoulos and Economou-Eliopoulos, 1991). The indicated reserves of this deposit are 246 mt of ore grading by average at 0.49% Cu (~1205 th. t Cu) and 0.7 g/t Au (~166 t Au) (Tsirambides and Filippidis, 2016). The Stanos area hosts several Cu-Bi-As-Au ore bodies, which are polymetallic including native Bi, bismuthinite, cosalite, and emplectite associated with native Au, galena, and chalcopyrite (Voudouris et al., 2013b; Bristol et al., 2015). The Sapes ore represents a multi-centered, porphyry-epithermal system developed at a calc-alkaline to a high-K calc-alkaline suite of volcanic rocks. The ore mineralization includes hessite, altaite, stützite, and tetradymite in close relation to a high-sulfidation assemblage of enargite, chalcopyrite, goldfieldite, and native Au. The ore consists of Au, Ag, Te, Bi, and Mo (Table 1), which suggests a magmatic contribution to the mineralizing fluids. Ore-forming constituents were derived from the porphyritic rocks (Voudouris et al., 2006). The indicated reserves are 1.32 mt of ore at an average grade of 15.1 g/t Au (~16 t Au), 8.2 g/t Ag (~8 t Ag), and 0.3% Cu (~3000 th. t Cu) (Tsirambides and Filippidis, 2016).

The Perama Hill deposit is a high-sulfidation Au-Ag-Bi-Te-Se epithermal system (Table 1) hosted at its deeper levels in silicic- and argillic-altered andesitic rocks and in sandstones. The deposit covers an area of approximately 700 m in length to 300 m in width and is oxidized. Eighty percent of the gold is hosted by sandstones (oxidized upper part of the deposit) and the rest is associated with base metal sulphides and tellurides hosted within andesitic breccias and conglomerates. The presence of tellurides and Bi- and Sn-bearing minerals in the ore means direct deposition of metals from the vapor phase of a degassing magmatic body (Voudouris et al., 2011). The indicated reserves of this deposit are ~11.7 mt of ore at an average grade of 3.1-3.5 g/t Au (~74 t Au) and 2.8-4.2 g/t Ag (~62 t Ag) (Tsirambides and Filippidis, 2016). Several polymetallic mineralizations, hosted in quartz veins and metamorphic rocks in the Vertiskos unit of the Serbomacedonian Massif, are enriched in Cu-As-Pb-Bi-Ag-Au-Te-Sb-W. The highest content in critical metals was found at Kolchiko with Bi (995 ppm), W (844 ppm), and Co (320 ppm) (Stergiou et al., 2023b). In northeastern Greece tellurium is a common constituent of Cu-Au epithermal mineralizations. Spatially tellurium is associated with porphyry Cu-Mo or with intrusion-related Au-Bi-Te systems. The richest in Te deposits contain up to 40 ppm in Pagoni Rachi, up to 41 ppm in Vathi, up to 43 ppm in St Philippos, up to 45 ppm in Perama Hill, up to 60 ppm in Pangeon Mt, and up to 1000 ppm in Pefka Evros. The last area is the most promising prospect for future Te exploration and mining (Voudouris, 2006; Melfos and Voudouris, 2012).

5. CHROMIUM (Cr)

Metal alloys account for 85% of the available chromium. The remainder is used in the chemical, refractory, and foundry industries. Chromium is primarily used to harden steel. In addition, chromium compounds are used as industrial catalysts and pigments. More than 200 chromite ores of all four textural types (podiform, disseminated, nodular, massive) are known in Greece. The ores are found within dunitic bodies of the Pindus Mt, Vourinos Mt, Othrys Mt, and in other ophiolitic complexes. The most important chromite ores of metallurgical type are in Kozani (Vourinos, Xerolivado, and Rodiani), Veria, Edessa, and Chalkidiki (Gerakini, Ormylia). The most important chromite ores of refractory type are in Eretria Larissa and Domokos Fthiotida (Michailidis, 1990; Michalidis and Sklavounos 1996; Filippidis, 1997; Filippidis et al., 2000; Melfos and Voudouris, 2022). Both types are economically significant. The largest deposits of chromite are those of Vourinos Mt, which were under mining until 1991. Among critical metals, PGMs predominate at the ophiolites from Vourinos, Xerolivado, and Milia. In addition, PGMs have been detected in the ophiolites of Gerakini and Vavdos Chalkidiki, Triadi Thessaloniki, and Vermio Mt (Melfos and Voudouris, 2012). Chromite ores at Othrys Mt are of high Al refractory type with Cr/Fe=2.5. In Domokos the mine operated from 1918 to 1960 and 455,000 t were mined. The ore contained 38-40% Cr₂O₃ and 18-20% Al₂O₃. In Eretria the mine operated from 1880 until 1993 and its ore contained by average 45% Cr₂O₃. The total chromite reserves at Othrys Mt are estimated to be at least 3 mt (Melfos and Voudouris, 2022). The metallurgical company “Almyros Magnisia” produced ferrochromium during the period 1983-1991. The reasons for closure of the chromite mines and the ferrochrome metallurgical plant in 1991 were the crisis in the price of chromium, the inability to produce fine grained ore material for the production of Cr₂O₃ concentrate and the high number of personnel.

Today the reopening of the chromite mines is favored because of the high demand for chromium, its significant reserves and the existence of the metallurgical plant. In 2018 the Hellenic Mining company started the mining of chromite in Vari Grevena on an area of 200,000 acres of northern Vourinos Mt. Crushed material was exported for a few years to China for beneficiation; however, both high production and freight costs made the export unprofitable. Because the chromite reserves are sufficient for at least 30 years, the company has planned an investment to create a vertically integrated unit, which will include the construction of beneficiation and metallurgical plants, so that the final metal is produced in the area. According to the Environmental Impact Study, the unit after the completion of the investment (2027) is expected to employ approximately 400 people and produce 27,000 t of ferrochrome per year. Thus, Greece could become

the fourth ferrochrome producing country in the EU (<https://www.metaliakozanis.gr> ; <https://www.capital.gr>). The proven and indicated reserves of chromium from Vourinos Kozani are 1.2 mt (Gkikas and Georgakakis, 1997) and their gross value €4.32 b (<https://www.plutus.co.jp>) (Table 2).

6. COBALT (Co)

Cobalt is mainly mined as a by-product of copper and nickel deposits. It is useful in numerous metallurgical and chemical applications. Except for the superalloys for the production of jet engines and gas turbines, nowadays its largest application is for rechargeable lithium-ion batteries (Harper et al., 2012). Based on published information 509 cobalt-bearing deposits and occurrences have been identified in 25 countries in Europe. In the Balkans and Turkey cobalt presence is known in 27 nickel laterite deposits. Some of them contain more than 10,000 t of Co metal the recovery of which is pending through new processing technologies such as high-pressure acid leaching (Horn et al., 2021). The Fe-Ni laterite deposits of Greece which contain cobalt are associated with ophiolites and are intercalated in limestones. The reserves reported for lateritic nickel deposits include almost 50,000 t of cobalt and mineral resources comprise an additional 79,000 t of this critical metal. The main laterite deposits are located at Kastoria, which has a resource of 8.7 mt at 0.16 wt% cobalt; Agios Ioannis Viotia, with a resource of 43.6 mt at 0.15 wt% cobalt; and Lokrida Fthiotida, with a resource of 228.3 mt at 0.22 wt% cobalt (Apostolikas et al., 2000; Eliopoulos and Economou-Eliopoulos, 2000). All are currently being operated by troubled Larco. The company, one of the world's biggest nickel producers, was liquidated in 2020 following a decision by a European court, which said Greece had failed to recover €135.8 m of illegal state aid to the company. Although a special administrator was appointed at the same year to sell Larco's assets in separate tenders the sale is not yet completed (<https://investingnews.com>). Some non-economic sulfide ores hosted in the ophiolite complexes in Greece, include those of Cyprus-type and Fe-Cu-Ni-Co type, at Pindos Mt and Othrys Mt which contain up to 2,300 ppm cobalt (Economou-Eliopoulos et al., 2008). The probable and indicated reserves of cobalt in Greece are approximately 129 th. t and their gross value €3.348 b (<https://www.lme.com>) (Table 2).

7. COPPER (Cu)

There are many products around us that are made of copper or copper-based alloys. Most of these alloys have different colors and shades depending on their composition.

Such products are: kitchen sinks, jewelry, railings, musical instruments, tools, wires, pipes, gutters etc. The major portion of copper produced in the world is used by the electrical industries. The copper deposits of Greece are divided into the following ore deposit types (Karmis and Zagouroglou, 1987; Filippidis et al., 1990; Melfos et al., 2002; Kioussis and Papavassiliou, 2005): (a) Porphyry-type: they are the most abundant; they are associated with granitic to dioritic magma intrusions and are low in Cu content. They are found in large reserves and usually contain small amounts of Au and Mo. (b) Epithermal high-sulfidation Cu-Au: of such type are the deposits of Pefka Evros and Sapes Rhodes. (c) Volcanic-hosted massive sulfides: they are genetically connected with submarine exhalations of basic magmas. The copper deposits of Ermioni Argolida belong to this type. (d) Skarn-type: the deposit of Kimmeria Xanthi belongs to this class.

The most important and economically significant ore is the porphyry-type deposit of Skouries Chalkidiki with proven and indicated reserves of copper 1,940 th. t. In 2011 Eldorado Gold granted the right to exploit this ore (Tsirambides and Filippidis, 2012). The annual production of 7 t to 9 t of copper from Skouries Chalkidiki by Eldorado Gold is pending from 2025 onwards (<https://www.hellas-gold.com> ; <https://www.miningweekly.com>). The probable and indicated reserves of copper from Skouries Chalkidiki are approximately 1.940 mt and their gross value €15.811 b. Of the same type are the deposits of Kilgis (Gerakario/Vathi and Pontokerasia). The probable reserves of the first area are 28 mt of ore with 0.4 wt% Cu and 0.9 g/t Au. Their gross metal value is €1.88 b. The indicated reserves of the same area are 180 mt with approximately the same metal concentrations and gross metal value €11.75 b. The indicated reserves of Pontokerasia are 50 mt of ore with 300 th. t copper and 50 t gold and gross metal value €4.12 b (Arvanitidis, 2012). The probable and indicated reserves of copper from Kilgis are approximately 1.100 mt and their gross value €8.965 b. The probable and indicated reserves of copper from both areas of Chalkidiki and Kilgis are approximately 3.040 mt and their gross value €24.776 b (<https://www.lme.com>) (Table 2).

8. GALLIUM (Ga), GERMANIUM (Ge), INDIUM (In)

Gallium is most commonly found in bauxite. It can be extracted as a by-product from the processing of bauxite to alumina. However, the largest reserves of gallium are associated with phosphate ores. Germanium is primarily mined from sphalerite; in addition it is recovered from silver, lead, and copper ores. Some of the most common uses of gallium include thermometers, semiconductors for electronics, and light-

emitting diodes. Germanium is used in the manufacture of plastics, mobile phones, electronics, solar panels, camera lenses, satellites, computer screens, medical diagnostics, global positioning systems (GPS), as well as of advanced driver assistance systems. In addition, germanium is used in the manufacture of some military accessories (i.e. weapon-sighters). Seventy percent of global indium is used to make indium tin oxide, which is an important part of touch screens and solar panels. Other indium compounds are used in transistors and microchips. Indium metal sticks to glass and can give a mirror finish to windows of tall buildings. European Union imports from China 71% gallium, 45% germanium, and 43% indium for the needs of its industry in the last years. There are only a handful of companies outside of China capable of producing these high-purity metals. European Union in 2023 agreed with Mytilineos Energy & Metals, a Greek aluminum producer, to explore producing the critical metal gallium as a byproduct at its metallurgy plant at Agios Nikolaos Viotia that turns bauxite into alumina. Mytilineos undertook a pilot project to assess the most efficient method for the production 40-45 t of gallium metal, annually (<https://www.mytilineos.com>).

In the last decade two mineralization assemblages, rich in critical elements have been studied in detail in Evros Prefecture Unit. The Pefka Cu-Au-Te-In-Se vein-type deposit is hosted in andesitic lavas and consists of two crosscutting vein systems with high and intermediate sulfidation mineral assemblages. It is enriched in Te (<1,400 ppm), In (<675 ppm), Se (<100 ppm), and Cu (<1 wt%) (Table 1). The St Philippos Pb-Zn-Bi-Sn-Ge-Ga-In breccia-type deposit is hosted in sandstones and quartz-feldspar porphyry dikes. It is enriched in Bi (<2,000 ppm), Ga (<466 ppm), In (<222 ppm), Ge (<100 ppm), Sn (<100 ppm), Pb (>1 wt%), and Zn (>1 wt%) (Table 1). The element association of both areas, Pefka and St Philippos, is very rare. It has been previously reported only in a few other regions in the world (e.g. Capillitas deposit, Argentina and Kawazu deposit, Japan). Thrace presents a great potential region for the mining of some critical and strategic metals (Melfos and Voudouris, 2012; Voudouris et al., 2022). Relatively high gallium contents were also identified in the sphalerite concentrates from Stratoni of Chalkidiki reaching up to 25 g/t (Tzamos et al., 2019) and in the phosphate rocks of Vegora Florina with values up to 16 g/t (Stamatakis, 2004). The Molaoi Zn-Pb-Ag-Ge ore is reportedly a volcanogenic massive sulphide deposit in the Laconia Prefecture Unit. It consists mainly of subaerial andesites, felsic pyroclastics and renowned sill lithologies such as the ‘Krokeatis Lithos’, a plagioclase-phyric andesite widely used in the past for the construction of Roman baths. Probable ore reserves are reported to be 2.9 mt of Zn (7 wt%), Pb (3 wt%), and Ag (up to 1.5 g/t). Between 1980 and 1988 about 150 exploration drill-holes were drilled, but Molaoi never developed into a mining area (Kevrekidis et al., 2017). In 2023 the exploration company Rockfire

Resources confirmed the existence of the critical metals Ge and Ga at the Molaoi ore. Germanium is expected to be recovered as part of the zinc concentrate. The germanium metal price is currently at €1,270 per kg whereas gallium is trading at €687 per kg (<https://www.statista.com>). Germanium grades between 9.0 g/t and 40.0 g/t and gallium between 9.7 g/t and 19.0 g/t (<https://www.hellenicminerals.com> ; <https://greekreporter.com>).

9. MAGNESIUM (Mg)

The magnesite ores of Greece are of vein or sedimentary type. The first are exclusively associated with ophiolites and they have been developed in serpentinites, frequently schisted, where magnesite zones are very thick and several kilometers long. The major vein type magnesite ores (stockwork) are in Chalkidiki and have been under mining since 1960. Similar ores exist in North Evia; their mining restarted in 2015. In addition, there are occurrences of magnesite in Gomati and Nea Roda Chalkidiki, Kozani, Atalanti, and Lesvos. The ophiolite complex of Chalkidiki is about 70 km long and its average thickness is at least 2 km; the average depth of the exploitable ore is 50-60 m. The presence of vast magnesite reserves has been confirmed, which is enough to meet the needs of the European Union for at least the next 200 years. The sedimentary ores of magnesite, which currently are not exploited, are located in the Serbia-Eani basin and Varvara Chalkidiki where they are hosted in clay-marly sediments (Dabitzias, 1980; Dabitzias and Vacondios, 1994). “Grecian Magnesite” is the largest export company of magnesia in the EU and the largest in sales of caustic magnesia in the world. Most reserves, along with the processing unit, stand in Gerakini Chalkidiki. Currently, the company exports magnesite, caustic and burned magnesia and refractory masses. In 2022 the annual production of magnesite was 393,000 t and of final products (caustic and burned magnesia, refractory masses) 148,000 t, 90% of which were exported mainly to EU, but also to the USA, other European countries, Middle East, and Australia (Ministry of Environment and Energy, 2024). Since 2015, “GEK TERNA” operates in the Gerorema area in Evia. The Company offers a wide range of Dead Burned Magnesia (DBM) products, under the brand name NOVAPYR, serving the demanding and growing needs of refractory industry and other industrial applications, such as welding fluxes, leather tanning, heating elements, etc. A new production line was set in 2019. The new rotary kiln has a capacity of 60,000 t annually of sintered/calcined product (www.gekterna.com). The proven and indicated reserves of magnesite ore are 280 mt (170 mt in Chalkidiki, 70 mt in Servia Kozani, and 40 mt in Evia) and their gross value €9.8 b (Table 2).

10. MANGANESE (Mn)

Pure manganese produced electrolytically is used mostly in the preparation of alloys of copper, aluminum, magnesium, and nickel and in the production of high-purity chemicals. The largest use of manganese is the production of manganese steel (contains about 13% Mn). This is extremely strong and is used for railway tracks, safes, rifle barrels, and prison bars. In addition, manganese is used in the production of a variety of batteries and of certain types of resistors. Manganese (II) oxide is used to make fertilisers and ceramics. The western Rhodope massif in NE Greece contains a significant number of “battery grade” Mn-oxide deposits. These are best developed in the areas of Drama (Nevrokopi, Granitis, and Perithorio) and Chalkidiki (Varvara and Stratoniki). The underground of NE Chalkidiki hosts significant ores of base metals (Zn, Pb, Cu) associated with remarkable quantities of Mn (Arvanitidis et al., 1994). The mineralization was formed by weathering of hydrothermal veins that are genetically related to Oligocene magmatism. The economically significant ore of Granitis Drama has a maximum thickness of 40 m, 70-90 m length, and 22-29% content in Mn (Nimfopoulos and Patrick, 1991). The Palea Kavala ore system consists of about 150 minor Fe-Mn (Pb±Zn±Ag), Fe-Mn-Au, Fe-As-Au, Fe-Cu-Au, and Bi-Te-Au occurrences that are primarily contained in quartz-calcite-sulfide veins. The sulfide mineralization forms <5% of these veins (Melfos et al., 2008; Fornadel et al., 2011). The ore reserves are estimated at about 1.5 mt with 15-50% Fe, 1-42% Mn, 1.5-13% (Zn+Pb), 1-8% As, up to 34.5 ppm Au, and up to 190 ppm Ag (Chatzipanagis and Dimitroula, 1996). Sub-marine manganese deposits in the form of nodules have been reported in Greece (Varnavas and Papatheodorou, 1987; Robertson and Degnan, 1998). Manganese nodules, spheroid or columnar in shape, up to 7 cm, have been found in pelagic limestones in Panormos Fokida. These nodules are characterized by a high ratio of Mn/Fe and low concentrations of trace elements (e.g. Ni, Co, Pb, and Zn) (Varnavas and Panagos, 1981).

In the Gulf of Corinth, a deposit rich in Fe-Ti-Cr-Ni metals has been formed in a low-energy environment by the discharge of bauxitic red mud tailings. The average discharge rate was 500,000 t/y for a period of 10 years from the adjacent aluminum processing plant. The deposit covers an area of about 28 km² and occurs between the 80 m and 120 m isobaths. In 1986 the deposit was estimated at 2.2 mt with significant metal concentrations such as (in tons): 632,200 Fe, 129,400 Al, 64,400 Ti, 3,500 Cr, 1,800 Ni, 1,500 Mn, 280 Pb, 150 Co, 130 Zn, 110 Cu (Varnavas and Papatheodorou, 1987). Additional critical metals, such as Cd, Hg, Ag, and V were found at a later stage (Iatrou et al., 2010). In 2012 the free discharge of the tailings in the Gulf ended bringing

however the total amount of the man-made metallic deposit at least to 7 mt. On the basis of the current metal prices the gross value of the deposit is approximately €2.5 b. Greece's sole natural "Manganese Mining Co" exploited the ore in Granitis Drama until the mid-90s. The material produced was in two grades, Scalma 74 (min. 72% MnO₂) and Scalma 72 (min. 70% MnO₂). Both grades were chiefly supplied for dry electrical cells. In addition, the Japanese Company Tosoh-Hellas produces 12,000 tpa (tonnes per annum) of electrolytic manganese dioxide (EMD) from its plant in Thessaloniki for use in alkaline batteries (Harries-Rees, 1993; <http://www.tosoh-hellas.gr>). The mining of manganese ores in Greece was interrupted in the mid-90s, although it is the only country in the EU that has natural reserves of this metal. The proven and indicated reserves of manganese are 2.25 mt and their gross value €5.4 b (<https://www.argusmedia.com>) (Table 2).

11. MOLYBDENUM (Mo)

Most molybdenum is used to make alloys, especially steel alloys, to increase strength, hardness, electrical conductivity and resistance to corrosion. Such alloys are used in engines, heating elements, drills, and saw blades. Other uses of molybdenum are catalysts for the petroleum industry, inks for circuit boards, pigments, and electrodes. Molybdenite occurs in three mineralization types in Greece: (a) porphyry Mo-Cu- (\pm Te-Ag-Au), (b) reduced intrusion-related Mo-W systems, and (c) shear zone-related Cu-Au-Bi-Mo. In the porphyry prospects molybdenite and pyrite are the main ore constituents in quartz stockworks crosscutting porphyry rocks as: at dacite at Pagoni Rachi/Kirki and Konos/Sapes; microgranite at Ktismata/Maronia; monzonite at Skouries/Chalkidiki. Reduced intrusion-related systems are characterized by the presence of molybdenite, pyrite, and wolframite (i.e. granodiorite at Kimmeria/Xanthi and leucogranite at Pigi/Kilkis). In the shear-zone Stanos prospect molybdenite accompanies chalcopyrite, native Bi, Bi-tellurides, and sulfosalts (Voudouris et al., 2010). The Pigi Mo-deposit is composed of high silica leucogranites that intrude the ophiolites of the Axios Zone. Molybdenite is found within the leucogranites as disseminations and filling veinlets. Associated minerals are wolframite, pyrite, galena, quartz, sericite, chlorite, fluorite, and kaolinite (Michailidis et al., 1993; Voudouris et al., 2010). A small molybdenite production was operated in Pigi Kilkis in 1940-1944 with variable Mo content (0.3 wt% to 1.3 wt%) (Maben and Zigdis, 1947). Four groups of molybdenites are distinguished on the basis of their rhenium content: (a) Re-free molybdenites (i.e. Stanos), (b) very low-Re molybdenites (Re-content from 10 ppm to 1,300 ppm) in the intrusion related systems (i.e. Pigi and Kimmeria) (c) intermediate-

to high-Re molybdenites (Re-content from 300 ppm to 10,600 ppm) in the porphyry systems (i.e. Skouries) and (d) ultrahigh-Re molybdenites (Re-content from 380 ppm to 46,900 ppm) in the porphyry rocks (i.e. Pagoni Rachi, Konos/Sapes, Maronia) (Voudouris et al., 2010). The Stanos Chalkidiki ore assemblage is characterized by a Fe-bearing sulphide introduction and by a Cu-bearing association with minor amounts of molybdenite and Bi-Au-Te minerals (Table 1). The metallic minerals of Cu, Bi, Au, and Te occur as disseminated or massive aggregates along foliation planes (Voudouris et al., 2013b). The Vathi Kilkis porphyry Cu-Au \pm Mo is mainly hosted in latite and is genetically associated with the intrusion of quartz monzonite. The deposit is enriched in Cu (av. 2313 ppm), Mo (av. 152 ppm), Au (av. 0.46 ppm), and U (av. 31 ppm). A local enrichment in some REMs (up to 894 ppm Ce, 613 ppm La, 211 ppm Nd, and 79 ppm Pr) is attributed to the phreatic breccia and to secondary supergene mineralization (Stergiou et al., 2021b).

The Kimmeria Xanthi (Table 1) Mo-Cu-W-Bi-Au deposit is mainly associated with an Oligocene granodiorite and two different ore types genetically related to the magmatic intrusion: a) Massive Au-bearing skarn-type mineralization and b) Mo-Cu-Bi-W quartz vein mineralization. Bi-sulfosalts bearing up to 6.65 wt% Se are included in pyrite and Se-bearing galena (up to 3.2 wt% Se and 1.5 wt% Bi). Bulk chemical analyses of vein-type mineralization have revealed that contains \sim 1 wt% Cu, \sim 0.2 wt% Mo, up to 2.7 g/t Au, up to 80 g/t W, up to 457 g/t Bi, and up to 4 g/t Te (Table 1) (Theodoridou et al., 2016). The Maronia Rhodope Cu-Mo \pm Re porphyry-epithermal deposit (Table 1) is hosted by microgranite porphyry that intruded an Oligocene monzonite. Chalcopyrite-pyrite-molybdenite mineralization, containing up to 7,600 ppm Mo, occurs as disseminations, veinlets, and segregations (Melfos et al., 2002). The high-oxidation state of the magmas and the hydrothermal fluid circulation were responsible for the metal and sulfur enrichments of the aqueous fluid phase, the breakdown of the magmatic silicates and the extensive potassic and sodic-calcic alterations (Melfos et al., 2020). The Konos Hill Rhodope is a Mo-Cu-Re-Au porphyry occurrence, which contains the ore minerals pyrite, molybdenite, chalcopyrite, and rheniite. Bulk ore analyses showed a relative enrichment in Se, Mo, and Bi (Mavrogonatos et al., 2018). The Pagoni Rachi Evros Mo-Cu-Te-Ag-Au- porphyry-epithermal system hosted by dacite and porphyry dikes, contains in quartz veins molybdenite (with Re-content up to 4.7 wt%), Fe-Cu sulphides, Pb- Sn- and Cl-bearing oxides, hematite, ilmenite, and Bi-tellurides (Table 1) (Voudouris et al., 2009). Four paragenetic stages have been detected: (1) sodic/potassic-calcic alteration with quartz- and magnetite-bearing veins (A- and M-type), (2) sodic/potassic alteration with quartz-pyrite-chalcopyrite-molybdenite veins (B-type), (3) sericitic alteration with “transitional” porphyry to epithermal pyrite-

chalcopyrite-molybdenite veins (D-type) and (4) argillic alteration with quartz-calcite base metal and precious metal-rich veins (E-type) with epithermal affinity. The D-type veins contain Ag- Bi- Te- and Se-bearing minerals. The Pagoni Rachi Evros system was deposited at 360-510°C and pressures up to 690 bars (<2 km depth) in A-veins and up to 360 bars (<1.5 km depth) in B-veins (Voudouris et al., 2013a, 2013b). The Esymi-Leptokarya Evros is a Mo- porphyry-epithermal occurrence hosted in an Oligocene felsic dyke complex, which intrudes Upper Eocene sandstones, marls and a monzodiorite. The main ore minerals are pyrite, molybdenite, magnetite, bismuthinite, galena, and sphalerite. Bulk ore analysis in the quartz veins, showed Mo (up to 215 ppm), Se (up to 29 ppm), Sn (up to 14 ppm), and Bi (up to 8 ppm) (Table 1). The Mo ore has affinities to the “arc-related” class of porphyry Mo-deposits (Galanopoulos et al., 2018). The indicated reserves of molybdenum from Pigi Kilkis are 7,700 t and their gross value €326 m (<https://www.dailymetalprice.com>) (Table 2).

12. NICKEL (Ni)

Nickel is mainly used in making alloys resistant to corrosion such as stainless steel. Nichrome is an alloy of nickel and chromium with small amounts of silicon, manganese, and iron. A copper-nickel alloy is commonly used in desalination plants, which convert seawater into fresh water. Other alloys of nickel are used in boat propeller shafts and turbine blades. More than 12% of global nickel production is used for major home appliances, mostly in the form of stainless steel. In addition, it is used in batteries, coins, and as a catalyst for hydrogenating vegetable oils. More than 110 sites with ores and occurrences of Fe-Ni-bearing deposits, which come from lateritic weathering of ophiolites and contain extra Cr and Co, have been identified in Greece. The most important lateritic Fe-Ni-bearing ores are those of Evia Island, Agios Ioannis Viotia, Lokrida Fthiotida, Mesopotamia and Ieropigi Kastoria (Skarpelis et al., 1993; Alevizos, 1997). Occurrences of such mineral assemblages are referred in Kozani, Pella, Parnitha Mt, Skyros and Mytilini (Michailidis, 1982; Skarpelis, 2006). The Ni-bearing lateritic iron ores from Larymna and Evia are characterized by similar Ni concentrations (ca. 0.6-0.7 wt%), crystalline hematite, and chlorite group minerals in the <2 µm fraction. The Larymna ore contains double quantities of Co and it is enriched in rare earths compared to Evia (total REE = 774 ppm and 76 ppm respectively), while Sc concentrations are comparable in both mining areas (64 ppm and 42 ppm respectively) (Samouhos et al., 2019).

Since 2017, Greece has fallen to 2nd place in European nickel production, behind Finland (Benardos et al., 2021). “Larco” represents the sole Ni miner and producer in the country. It operates in five regional units of the country. From the mines of Evia, Viotia, and Kastoria in 2022 a total of 193 th. t of nickel-iron ore was extracted and ferronickel production was 6,880 t. The large (~80%) reduction in nickel-iron ore production, compared to 2020, is a result of the special management regime in operation that Larco has put (law 4660/2020) (Ministry of Environment and Energy, 2024). The total production of the company is exported in the form of ferronickel alloy in stainless steel European industries. A pre-feasibility assessment was found technically sound for the underground mining of Greek Fe-Ni ores (Benardos et al., 2021). The metallurgical plant is located in Larymna Fthiotida. Because of the recent deep recession of the Greek economy the State decided to sell this company. Currently, the shareholder structure of the company is: 36% Greek State, 35% National Bank of Greece (NBG), and 29% Public Power Corporation (PPC). In 2020 the Greek State allocated for sale all of the shares it holds (<http://investingnews.com>). The proven and indicated reserves of nickel metal in Greece are 1.39 mt and their gross value €22.24 b (<https://www.dailymetalprice.com>) (Table 2).

13. PLATINUM GROUP METALS (PGMs)

The platinum group metals (PGMs), due to their unique physical and chemical properties, make them critical to many emerging technologies and industries. Apart from their application in jewelry, they are used in anticancer drugs, dentistry, electronics, vehicle exhaust catalysts, as well as in chemical, petroleum, high-tech, electrical and aerospace industries. In Greece the main sources of PGMs are the stratiform Cr deposits and the Ni-Cu sulphide deposits (Melfos and Voudouris, 2022). Platinoid metal concentrations with economic interest are the porphyry deposits of Cu of the metallogenic arc in NW direction from the Skouries-Fissoka Chalkidiki to Pontokerasia-Gerakario Kilkis. Specifically, in the exploitable ore of Skouries economic concentrations of palladium (Pd) of 0.5 g/t have been identified, widening further the already rich mineral potential and the value of the ore. In some other cases, elevated levels of platinoids have been also identified in Fe-Ni-bearing laterite deposits (e.g. Vermio Mt) (Kiouisis and Papavasiliou, 2005; Bristol et al., 2015). The Pd content in the Skouries deposit is up to 490 ppb and in chalcopyrite concentrates up to 3,300 ppb. Since the investment in Skouries focuses on Au and Cu mining and metallurgy, the recovery of Pd and Pt has a positive economic potential for future sustainable development (Economou-Eliopoulos and Eliopoulos, 2000; Kiouisis et al., 2005).

Another significant petrographic system is associated with the ophiolites of Vermio Mt and Pindus Mt. High PGM concentrations (Os = 7,400, Ir = 6,020, Ru = 9,700, Rh = 310, Pt = 760, Pd = 750, all in ppb), reaching 25 ppm in total, were determined in chromites hosted in the Vermio Mt ophiolites (Economou-Eliopoulos, 1996; Tsoupas and Economou-Eliopoulos, 2008). In Pindus Mt the PGM-mineralization is associated with several PGM grains (Pd-Cu alloys, sperrylite, Pt-Fe-Ni alloys, and native Au). The total PGM content in the chromites is 28 ppm (Pt = 17,100, Pd = 7,860, Ru = 2,100, Rh = 1,140, all in ppb), among the highest ever measured in ophiolitic chromitites worldwide and the highest ever mentioned for chromitites from Greece (Kapsiotis et al., 2010).

14. RARE EARTH METALS (REMs)

The rare earth metals (REMs) are used in a wide range of consumer products such as automobile catalytic converters, photovoltaic systems, wind turbines, panel displays, magnets, hybrid and electric vehicles, as well as in jet fighter engines, space-based satellites, and communication systems. The presence of some REMs has been confirmed from many research works that have been carried out during the last decades in petrographic formations of Greece. REMs with contents >100 ppm have been found in rocks of many regions of the country, but without being of economic interest. Cerium (Ce) was found in the granitic and volcanic rocks of Samothrace (100-114 ppm), in the granites of Kerkini Mt (103 ppm), as well as in the plutonic (112 ppm) and metamorphic rocks (104 ppm) of Varnountas Mt Florina (Christofides et al., 1998, 1999; Vlahou et al., 2006). In the meta-sediments of Pigi and Karathodoros Kilkis the total rare earths are 14-577 ppm (Zachariadou et al., 2004). Total rare earths in the granite of Fanos Kilkis are 92-249 ppm (Soldatos et al., 1993). Very important is the Cu-Au porphyritic system in Vathi Kilkis, with total content of rare earths up to 0.19 wt% (Stergiou et al., 2021a). The bauxites and bauxitic laterites of Central Greece with contents ranging from 3,275 g/t to 6,378 g/t in rare earths are of significant interest for systematic deposit exploration. The emerging economic interest even includes red mud from aluminum metallurgy (Bristol et al., 2015; Gamaletsos et al., 2019). The Fe-Ni-bearing lateritic ores of karst type from Evia and Lokrida contain La 299 ppm, Nd 163 ppm and the lateritic bauxites of the same areas La 223 ppm (Rosenberg, 1984; Economou-Eliopoulos et al., 1997). A similar ore from Marmeiko Viotia contains La 294-573 ppm, Ce 156-246 ppm, Nd 123-327 ppm, Y 468-890 ppm, and total rare earths 1288-2452

ppm (Skarpelis et al., 1989). The bauxites of Iti Mt contain La 272-385 ppm and Ce 644-800 ppm (Papastavrou and Perdikatsis, 1987).

In 2001, IGME completed the assessment of the submarine uranium-thorium bearing rare earths ore in the sediments of Strymonikos Gulf. Their mineral components are (wt%): quartz 41, feldspars 26, goethite 11.7, magnetite 7.1, carbonate minerals 2.5, amphiboles 1.9, garnets 1.5, micas 1.4, chlorite 0.5, as well as allanite 2.4, epidote 1.8 and titanium minerals 1 which are rich in rare earths, Y, U, and Th. Of the total rare earths (11,000 ppm) 93.5% belongs to the light ones. The elements Ce, La, Nd, and Pr are present in higher concentrations and in proportions above their world average content. The indicated total reserves (coastal and submarine) of rare earths, titanium, gold, thorium, and uranium amount to 490 mt with an average content of 1.17% in rare earths. The gross value of the final products (metals) exceeds €230 b. Today, Strymonikos Gulf, together with the neighboring coastal and submarine sands, is the most probable area for locating exploitable rare earth metals. In a trial production of uranium concentrate from Paranesti Drama participation of seven rare earths was found (Pergamalis et al., 1998, 2001). Furthermore, the European competitive project EURARE (Development of a sustainable mining scheme for Europe's Rare Earth ore deposits) is in progress, targeting their identification in various European countries, such as the Scandinavian, Austria, Greece, for the determination of optimal enrichment methods and for new uses in "green" technologies. Engineering schools, geological institutes, mining companies, and end product industries such as Nokia, Neorem Magnets, Renault, and others, participate. Mineral experts in Greece and Nordic countries agree that the European Union could do more to exploit rare earth reserves in their countries (Kosmides and O'Dwyer, 2012; Papadopoulos et al., 2019).

15. CONCLUSIONS

The Greek territory hosts various mineral raw materials including critical and strategic metals (Al, Co, Cr, Mg, Mn, Mo, Ni, Sb, PGMs, REEs, Bi, Te, Ga, Ge, and In); therefore, there are excellent opportunities for investment in their research and mining. Greece is expected to remain a major supplier of bauxite, ferronickel, and magnesia products. The probable exploitation of some critical and strategic metals will strengthen the country's mining industry and hence Greece's economy.

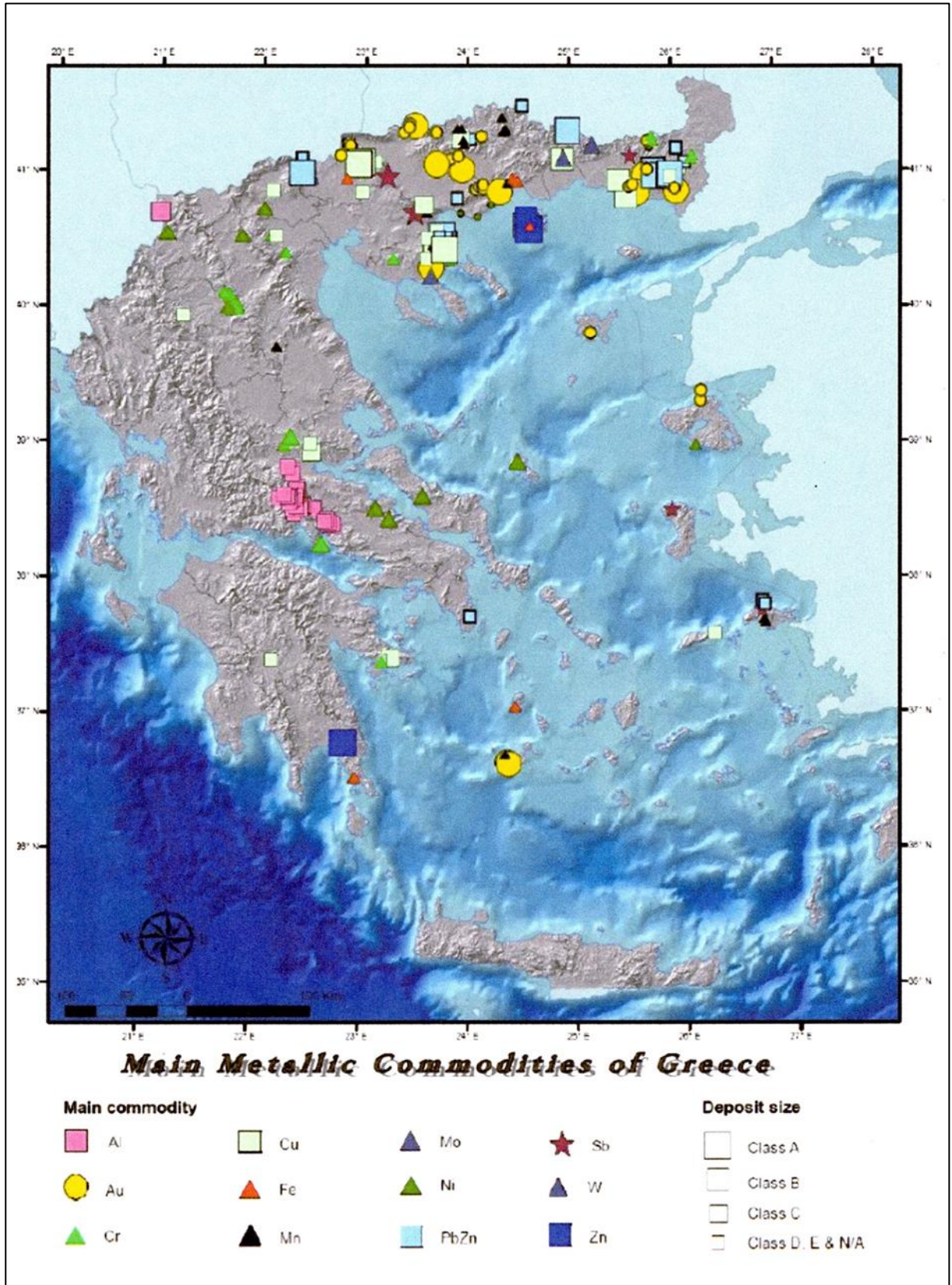


Fig. 1. Important sites with critical and strategic metals of Greece (HAGMR, <https://gaia.igme.gr/portal/apps/webappviewer/index.html?id=d460bca9d1aa4418ba3caff7fd84729f>, 2017).

Table 1. Characteristics of critical, strategic and precious metals of Greece¹.

Region/site	Type	Metals, concentrations
Macedonia/Olympiada-Stratoni	R-C	Pb (av. 4 wt%), Zn (av. 4 wt%), Au (7.4 g/t), Ag (124 g/t), PGMs, Ga (up to 25 g/t), Ge, In, Te, As
Macedonia/Skouries	P-E	Cu (av. 0.5 wt%), Au (8.3 g/t), Ag, Mo, Co, Bi, Se, Te, As, Pd (up to 0.5 g/t), Pt, Ru
Macedonia/Stanos	S-R	Pb, Zn, Cu, Au, Ag, Mo, Bi, Te
Macedonia/Kolchiko	Vein	Cu, Pb, Au, Ag, Bi (up to 995 g/t), W (up to 844 g/t), Co (up to 320 g/t)
Macedonia/Laodikino	Vein	Cu, Pb, Ag (up to 2,430 g/t), Au (up to 3 g/t), W (up to 844 g/t), Co (up to 166 g/t), Te, Bi (up to 83 g/t), Se (up to 58 g/t), Ga (up to 10 g/t), REEs (av. 26 g/t)
Macedonia/Rizana-Lachanas	P-E	Sb (av. 0.3 wt%), W, Mo, Bi, Te
Macedonia/Pontokerasia	P-E	Pb, Zn, Cu (<0.3 wt%), Au (up to 0.16 g/t), Mo, Sb
Macedonia/Vathi	P-E	Pb (20-977 g/t), Zn (9-156 g/t), Cu (<0.3 wt%), Mo (up to 341 g/t), Sb (up to 11 g/t), Au (up to 0.8 g/t), Ag (up to 4.6 g/t), Bi (up to 239 g/t), W, Se, Te, REEs (up to 0.2 wt%), U (up to 328 g/t)
Macedonia/Gerakario	P-E	Cu (<0.3 wt%), Au (up to 1.4 g/t), Sb
Macedonia/Palea Kavala	I-R	Pb, Zn, Cu, Fe, Mn (up to 42 wt%), Au (up to 34.5 g/t), Ag (up to 190 g/t), Bi, Sb, Te, W, As
Macedonia/Pigi	I-R	Mo (up to 1.3 wt%), W, REEs (up to 577 g/t)
Thrace/Kimmeria	I-R	Pb (<290 g/t), Zn (<0.7 wt%), Cu (<1 wt%), Mo (<0.2 wt%), Bi (<457 g/t), Sb (<332 g/t), W (<80 g/t), Au (<2.7 g/t), Te (<4 g/t), As (<76 g/t), Sn (<50 g/t)
Thrace/Neo Kallyntirio	P-E	Pb, Zn, Cu, Sb, Ag, Au, Te, As
Thrace/Sapes	P-E	Cu (0.3 wt%), Au (av. 15.1 g/t), Ag (av. 8.2 g/t), Mo, Re, Bi, Te
Thrace/Perama Hill	HSE	Au (3.1-3.5 g/t), Ag (2.8-4.2 g/t), Bi, Sn, Te (<45 g/t), Se
Thrace/Maronia	P-E	Cu (up to 2 wt%), Zn (up to 1800 g/t), Pb (up to 2640 g/t), Mo (7,600 g/t), Au (up to 12 g/t), Ag (up to 17 g/t), Re
Thrace/Konos Hill	P-E	Cu, Au, Mo, Re, Te, Se, Bi
Thrace/Pagoni Rachi	P-E	Cu (up to 1 wt%), Mo (up to 0.2 wt%), Sn, Au (up to 5.1 g/t), Ag, Re (up to 20 g/t), Te (up to 40 g/t), Se, Bi
Thrace/Esymi-Leptokarya	P-E	Cu, Au, Mo (<215 g/t), Se (<29 g/t), Sn (<14 g/t), Bi (<8 g/t)
Thrace/Pefka	V-E	Cu (<1 wt%), Mo (<24 g/t), Ag (<100 g/t), Au (<10 g/t), Te (<1000 g/t), Bi (105 g/t), In (<675 g/t), Se (<100 g/t)
Thrace/St Philippos	V-E	Pb (>1 wt%), Zn (>1 wt%), Sn (<100 g/t), Mo (<62 g/t), Bi (<2,000 g/t), Ga (<466 g/t), In (<222 g/t), Ge (<100 g/t)
Peloponnese/Molaoi	P-E	Zn (7 wt%), Pb (3 wt%), Ag (up to 1.5 g/t), Ga (9.7 g/t to 19.0 g/t), Ge (9.0 g/t to 40.0 g/t)
Macedonia/Pindus Mt-Vermio Mt-Chalkidiki	Magmatic	Cr, PGMs (total up to 28 g/t) (Os up to 0.14 g/t, Ir up to 0.24 g/t, Ru up to 0.15 g/t)
Thessaly/Othrys Mt (Eretria)	Magmatic	Cr, Al, Co (up to 2,300 g/t)
Stereia Ellada/Othrys Mt (Domokos)	Magmatic	Cr, Al, Co (up to 2,300 g/t)
Evia Island	Magmatic	Cr, PGMs
Macedonia/Gerakini	Vein	Mg, Ca, Al, Si, Fe, Ti, Cr, Ni, Co, Ba, Sr, PGMs
Evia Island/Gerorema	Vein	Mg, Ca, Al, Si, Fe, Ti, Ni, Co
Macedonia/Vermio-Kastoria-Grevena	Ni-Fe laterites	Ni, Fe, Co (<0.16 wt%), PGMs
Stereia Ellada/Lokrida-Evia Island	Ni-Fe laterites	Ni (0.6-0.7 wt%), Fe, Co (<0.22 wt%), Sc, REEs
Stereia Ellada/Parnassos Mt-Giona Mt-Helikon Mt	Karst-bauxites	Al, Fe, Ti, Cr, Ga, Sc (av. 47 g/t), REEs (av. 463 g/t)

¹references are presented in the text; R-C: Replacement Carbonate; P-E: Porphyry-Epithermal; S-R: Shear-zone Related; I-R: Intrusion-Related; HSE: High Sulfidation Epithermal; V-E: Vein Epithermal.

Table 2. Reserves (proven + indicated) and gross value of the critical and strategic metal resources of Greece.			
Metal resource	Reserves (th. t)	Price (€/t)¹	Gross value (m. €)
Aluminum	2,500	2,030	5,075
Antimony	30	12,300	369
² Chromium	1,200	3,600	4,320
² Cobalt	129	25,950	3,348
³ Copper	3,040	8,150	24,776
Magnesite (ore)	280,000	35	9,800
² Manganese	2,250	2,400	5,400
Molybdenum	7.700	42,400	326
Nickel (metal)	1,390	16,000	22,240

¹accessed from relevant websites on 26 and 27 March, 2024; websites are presented in the text,
²good prospect of mining,
³production is pending in 2025, €1=\$1.1 (March 26, 2024).

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