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Economic assessment of the Northern Copper Belt deposits – a future resource base of copper and silver ores in SW Poland

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Seven undeveloped sediment-hosted stratiform Cu-Ag deposits constitute a future resource base of copper and silver ores in the Fore-Sudetic Monocline in SW Poland. Among these, four have only recently been discovered and documented: Nowa Sól, Sulmierzyce North, Mozów (forming a part of the Northern Copper Belt) and Żary. The three remaining deposits – Bytom Odrzański, Głogów and Retków – surround the currently mined New Copper District to the north-west, north and north-east. Polish Cu-Ag deposits are polymetallic: copper, silver, lead, nickel as well as subordinate rhenium and gold are currently extracted. However, they show high reporting of other by-product metals, such as cobalt, molybdenum, vanadium, zinc and rare earth elements.

Unit ore values expressed in US dollars per metric ton of ore have been calculated for deposits in the Northern Copper Belt to compare them with other undeveloped and mined Polish sediment-hosted stratiform Cu-Ag deposits. The calculated unit ore values for the deposits studied are primarily influenced by copper, with a significant contribution (up to 29%) from silver. In terms of base metals other than copper, their contribution to the unit ore values is here relatively low, accounting for only 1–11% of the total value. The proportions of silver and lead in the unit ore value show a trend: they tend to be lower in the vicinity of oxidized fields and gradually increase with distance from these oxidized areas. The share of nickel in the unit ore value, on the other hand, is not influenced by distance from the oxidized fields. Instead, it is dependent on factors such as the thickness and organic content of the shale ore, which affect the accumulation of non-ferrous, redox-sensitive by-product metals, including nickel. Furthermore, we provide a comparative analysis of the total unit ore value among Polish sediment-hosted stratiform Cu-Ag deposits. Particular emphasis is placed on the deposits that constitute the future resource base of copper and silver ores in southwest Poland. A market perspective is drawn to highlight the influence of metal price fluctuations on the unit ore values of the various deposits. By examining the dynamic nature of metal prices, the study offers insights into how changes in market conditions can impact the economic viability of deposits located in different parts of the Fore-Sudetic Monocline. The deposits that constitute the future resource base of copper and silver in Poland show remarkably high copper and silver grades, resulting in significantly higher unit ore values compared to other world-class deposits of different types such as porphyry, epithermal, and IOCG (iron oxide copper gold) deposits.

Key words: copper, silver, critical metals, resource base, economic assessment; sediment-hosted deposits.

INTRODUCTION

In the era of energy transformation and decarbonization, access to many raw materials has become critically important. The European Commission has assessed some raw materials as essential for the development of strategic sectors, e.g., renewable energy, electric mobility, defense, aerospace and digital technologies (European Commission, 2023). Consumption of metallic raw materials by these strategic sectors will increase in the coming years. For instance, it is thought that an estimated 40 Mt of copper will be necessary by 2050 to fulfill the EU Green Deal requirements. Additionally, the COVID-19 crisis exposed the European Union's vulnerability to critical raw materials along supply chains. World mining production is focused on Asia today (almost 60% of total mining production combined; Lewicka et al., 2021) while numerous critical raw materials crucial for the European economy are imported from Africa. For example, it is estimated that between 54 and 61% of mined cobalt production originates from the Democratic Republic of Congo and almost half of refined cobalt production comes from China (Gulley et al., 2016). Russia, Indonesia, Philippines and New Caledonia combined account for >50% of global nickel mining production (Mudd, 2010; Mudd and Jowitt, 2022) and ~80% of global vanadium production originates from China and Russia. China is also a dominant rare earth elements producer (Simandl, 2014; Weng et al., 2015; Dushyantha et al., 2020) and an important supplier of lithium produced from hard-rock minerals (spodumene sources). European mining accounts for only 8.5% of global mining production (Lewicka et al., 2021; European Commission, 2023).

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The Southern European Permian Basin, hosting world-class sediment-hosted stratiform Cu-Ag deposits, is the most important copper and silver producing region in Europe (Zientek et al., 2015). Apart from copper and silver, nickel, lead, gold and rhenium are extracted from these mineral deposits. This Cu-Ag ore is currently mined in Poland and, in the past, mining also took place in Germany (e.g., Speczik, 1995; Rentzsch and Franzke, 1997; Zientek et al., 2015). Poland is the largest Cu producer in Europe and the second largest producer of Ag globally (Flanegan, 2022; Anderson, 2022). Polish sediment-hosted stratiform Cu-Ag deposits can be assessed as polymetallic: apart from copper and silver, they contain variable amounts of lead, zinc, cobalt, nickel, molybdenum, vanadium, rhenium, gold and rare earth elements. Among the metals which are hosted by the Cu-Ag ores in Poland, copper, rare earth elements, cobalt, vanadium and nickel are on the latest version of the European Union list of critical raw materials (European Commission, 2023).

In this paper we provide an economic assessment of mined and undeveloped Polish Cu-Ag deposits. Special attention is given to undeveloped, recently discovered deposits in the Northern Copper Belt of SW Poland, which we believe constitute a future resource base for Europe. Assessment is based on unit ore value [US$/metric ton of ore], which enables comparison between deposits of distinct types. Undeveloped deposits of the Northern Copper Belt and the deposits surrounding the New Copper District (identified resources) are compared with mined Polish deposits (economic reserves) and selected examples of deposits of different types: porphyry, epithermal, IOCG and VMS. A historical market perspective is provided to show the effect of price volatility on the economic values of Polish sediment-hosted Cu-Ag deposits. Finally, we discuss the necessity of reporting by-product metals in geological documentations of sediment-hosted stratiform deposits.

CATEGORIZATION OF THE POLISH SEDIMENT-HOSTED STRATIFORM Cu-Ag DEPOSITS – COMPARISON TO INTERNATIONAL CLASSIFICATIONS

Deposits located on the Fore-Sudetic Monocline in SW Poland can be divided into two groups – undeveloped and mined. In order to facilitate a comprehensive understanding of the contrast between developed and undeveloped Cu-Ag deposits in southwest Poland, a prerequisite is to understand Polish reporting standards pertaining to mineral resources and ore reserves. Mineral resources/ore reserves reporting is based on the estimation certainty and geological assurance (Nieć and Sobczyk, 2017). Standardization is required by international financial institutions in order to compare the economic value of publicly reported resources and reserves and to assess the value of the company on the stock exchange. For this reason, mining and exploration companies use internationally recognized reporting standards such as the JORC Code (2012), National Instrument 43-101, PERC Standard or SAMREC Code to report exploration results. Classification of resources and reserves in accordance with Polish Geological and Mining Law takes into consideration estimation certainty and geological assurance, albeit with some variations from the international standards. Despite these slight differences, it is generally possible to draw comparisons between the Polish and international reporting codes (Szamałek and Wierchowiec, 2015; Nieć and Sobczyk, 2017). In this contribution the JORC Code (2012) is utilized to show certainty of resources estimation in comparison to Polish estimation criteria.

The category of undeveloped deposits encompasses all deposits found in the Northern Copper Belt (Nowa Sól, Sulmierzyce North and Mozów), the Żary deposit, as well as the deposits surrounding actively mined deposits within the New Copper District, namely Bytom Odrzański, Głogów and Retków. Conversely, the Rudna, Sieroszowice, Polkowice, Lubin–Małomice, Głogów Deep and Radwanice–Gaworzyce deposits belong to the mined deposits group and are collectively referred to as the New Copper District (Fig. 1). Deposits constituting future resource base of Poland (the Northern Copper Belt deposits as well as the Żary, Retków, Bytom Odrzański and Głogów deposits) are currently documented in either the C_2+D, C_2 or C_2+C_1 categories and no mining activity is carried out within their boundaries. Deposits of the New Copper District, which are mined, exhibit a higher certainty of resource estimation (categories C_1, B, A and economic reserves; Table 1).

Polish sediment-hosted stratiform Cu-Ag deposits of the Fore-Sudetic Monocline show outstanding continuity on a mining district scale. As a result, geological recognition in the C_1 category (indicated resources) is enough to apply for a mining licence. Drilling aiming to increase geological recognition (e.g. methane hazard identification) or short- and mid-term extraction planning, is usually carried out from the mined level, which is cheaper than drilling from the surface. A generally consistent geological pattern is clearly visible in the Nowa Sól deposit. However it is documented in the C_2 (inferred) category, and its calculated relative estimation error of resource estimation is <30 % (Speczik et al., 2021), which means that the deposit can already be documented in the C_1 (indicated) category. Notwithstanding existing knowledge, additional drilling is essential to validate the continuity of the deposit and to accurately estimate its resources. Subsequently, this data will facilitate the determination of reserves with greater precision.

POLISH SEDIMENT-HOSTED STRATIFORM DEPOSITS – GENERAL INFORMATION

Mined sediment-hosted stratiform deposits in Poland constituting the New Copper District are located ~65 km north-west of Wrocław, between the cities of Lubin in the east and Głogów in the west. The deposits of the newly discovered Northern Copper Belt are situated north-west (Nowa Sól and Mozów deposits) and north-east (Sulmierzyce North deposit) of the New Copper District. The Żary deposit is located farther west, some 20 km from the Polish-German border (Fig. 1).

Polish sediment-hosted Cu-Ag deposits occur in the Fore-Sudetic Monocline (New Copper District and Northern Copper Belt), North Sudetic Trough (the “Old Copper District” – Niecka Grodziecka, Nowy Kościół and Wartowice deposits) and the Żary Perycline (Żary deposit). The North Sudetic Trough deposits are historically important, but currently only the Wartowice deposit contains remaining copper resources of potential economic interest (>1 Mt copper) and therefore this region will not be discussed in this contribution (Szuflicki et al., 2022). Cu-Ag ores in Poland are hosted by sedimentary rocks: the mineralized intervals form a continuous unit of variable thickness (from <1 m to >40 m), which spans across the lower Permian terrestrial red-bed sandstones and the upper Permian marine rocks grading from organic-rich shales (*Kupferschiefer*) and organic-rich limestones/marls to dolomites (e.g., Wodzicki and Piestrzyński, 1994; Piestrzyński et al., 2002). The Cu-Ag mineralization occurs along the rims of hematite-bearing oxidized fields called the Rote Fäule (Oszczepalski and Rydzewski, 1997; Oszczepalski, 1999). Copper and silver grades are variable across the deposits and depend on host

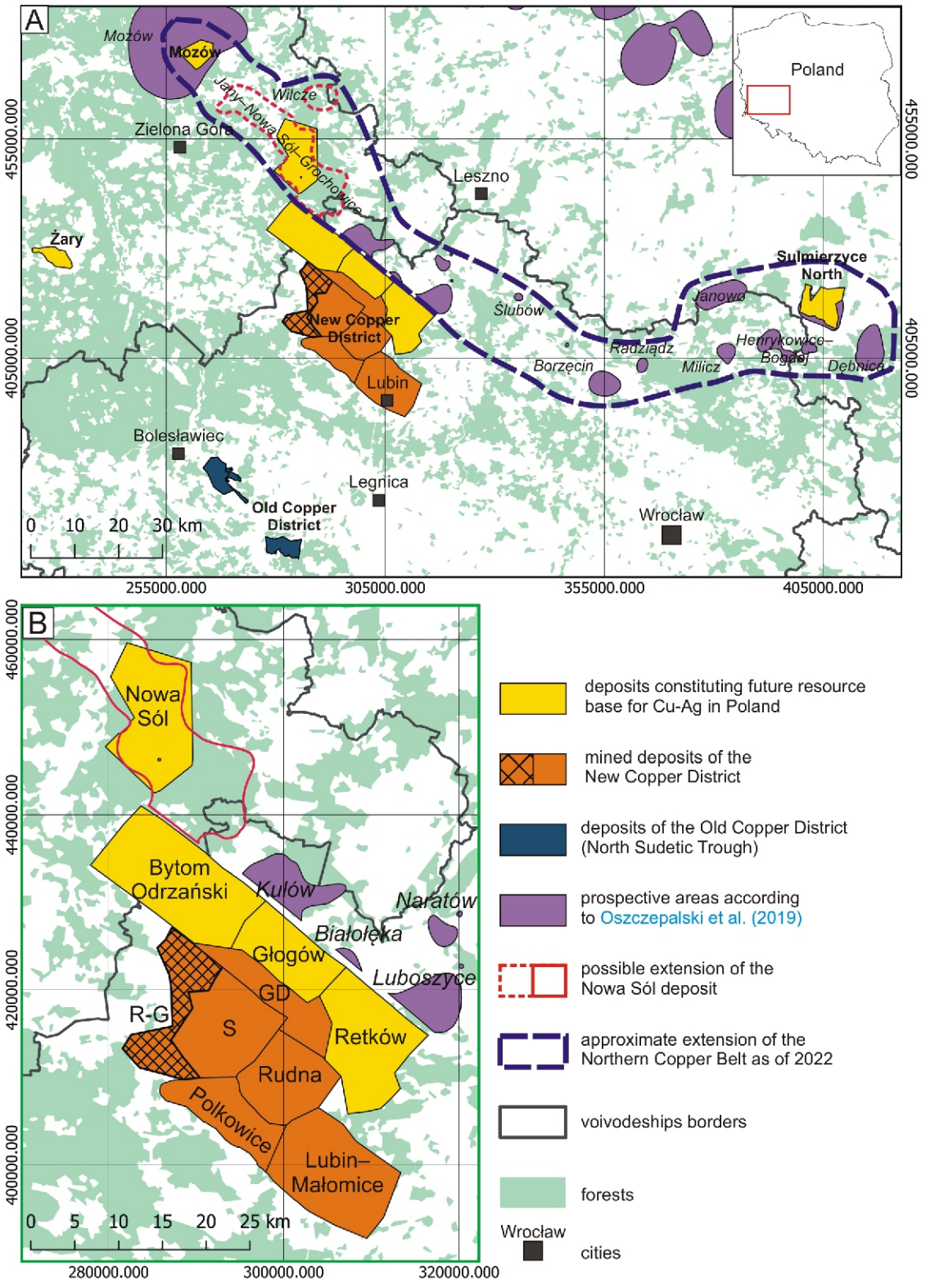


Fig. 1A – location of sediment-hosted stratiform Cu-Ag deposits in SW Poland; B –detail of the New Copper District and the Nowa Sól deposit

R-G – Radwanice–Gaworzyce, S – Sieroszowice, GD – Głogów Deep

Table 1

Resource/reserve classification of the deposits studied according to JORC and Polish Low

Deposit name		Reporting category (JORC Code/Polish equivalent)					
		Identified resources increasing certainty of resource estimation					Ore reserves
		Inferred		Indicated	Measured		Economic reserves (mining areas)
		D	C_2	C_1	B	A	
Undeveloped deposits	Nowa Sól						
	Sulmierzyce North						
	Mozów						
	Żary						
	Retków						
	Bytom Odrzański						
	Głogów						
Mined deposits	Rudna						
	Sieroszowice						
	Polkowice						
	Lubin-Małomice						
	Głogów Deep						
	Radwanice-Gaworzyce						
	Sieroszowice-Lubin (as of 1959)[1]						

The darker the colour, the greater the certainty of the reported resource or reserve estimation; [1] – for the purpose of comparison, the Sieroszowice-Lubin deposit as of 1959 is shown. In the initial geological documentation of this deposit, the reporting category assigned was C_2 (Oszczepalski, 2017)

lithological unit. The highest copper and silver grades are normally encountered in the Kupferschiefer *sensu stricto* – up to 20 wt.% and some 1000 g/t, respectively (Salamon, 1979; Mikulski et al., 2020). The sandstone and carbonate ores are generally less endowed in metals; however, these ores combined host the vast majority of copper and silver in the Polish deposits. The average copper grade in currently mined ore from the New Copper District in SW Poland is 1.49 wt.%, whereas the silver grade ranges between 48 and 52 g/t (Szuflicki et al., 2022). Current depths of mining operations range between 500 m b.g.l. (metres below ground level) in the Polkowice deposit to >1200 m b.g.l. in the Rudna deposit. According to Polish Geological Law, mineralization occurring deeper than 1500 m b.g.l. is assessed as sub-economic unless customized threshold parameters are provided. In Poland, identified mineral resources occur at depths of up to 2500 m b.g.l. (Mozów deposit).

The Fore-Sudetic Monocline mineral system is one of the largest sediment-hosted stratiform deposits in the world (Speczik, 1994; Hitzman et al., 2005; Fig. 2) with identified mineral resources of >3 billion metric tons of ore containing ~52 Mt of Cu and 148 kt of Ag, including >1.5 billion metric tons of ore containing ~28.11 Mt of Cu and ~82.05 kt of Ag in currently mined deposits (Szuflicki et al., 2022). Additionally, >1 billion metric tons of ore containing ~21.5 Mt of Cu and ~65 kt of Ag are assessed as economic ore reserves. With annual production in the range between 450 and 550 kt of Cu and 1300–1500 t of Ag, economic reserves of Polish sediment-hosted Cu-Ag deposits are estimated to last another 50 years.

According to the USGS (Flanegan, 2022), global copper reserves and identified resources account for 880 Mt and 2.1 billion tons, respectively, whereas silver reserves are estimated to be 530 kt. Annual global copper and silver mine production as of 2021 was 21 Mt and 24 kt, respectively (Anderson, 2022). This means that Polish (Fore-Sudetic Monocline) economic ore reserves and identified resources combined account for ~2.5% of global copper reserves and resources and Poland is responsible for 2.4% of global copper mine production. In the case of silver, 12.3% of global reserves are hosted in Polish sediment-hosted Cu-Ag deposits and 6.3% of global silver production takes place in Polish mines.

Deposits are located in 3 voivodeships – Lower Silesian (New Copper District, Old Copper District), Lubuskie (Nowa Sól, Mozów, Żary and Part of Bytom Odrzański) and Greater Poland (Sulmierzyce North). The Radwanice–Gaworzyce deposit is currently explored and its eastern part is mined in the Sieroszowice area.

NEW COPPER DISTRICT – MINED AREAS AND NEIGHBORING DEPOSITS

The New Copper District is located on the southern margin of the Fore-Sudetic Monocline, forming the south-eastern portion of the European Permian Basin (Oszczepalski and Rydzewski, 1997). It is situated on the southern flank of the Odra River, between Głogów and Lubin in SW Poland, covering an area of ~600 km^2. In total, there are 6 Cu-Ag deposits in the New Copper District: Głogów Deep, Lubin–Małomice, Polkowice, Radwanice–Gaworzyce, Rudna and Sieroszowice. Within these deposits, there are 3 operating mines: Polkowice–Sieroszowice, Rudna and Lubin. Additionally, 3 deposits encompass mining areas to the north-west (Bytom Odrzański), north (Głogów) and north-east (Retków). The Bytom Odrzański, Głogów and Retków deposits constitute an immediate resource base for the New Copper District mines. The identification of the New Copper District occurred in 1957 through the efforts of ge-

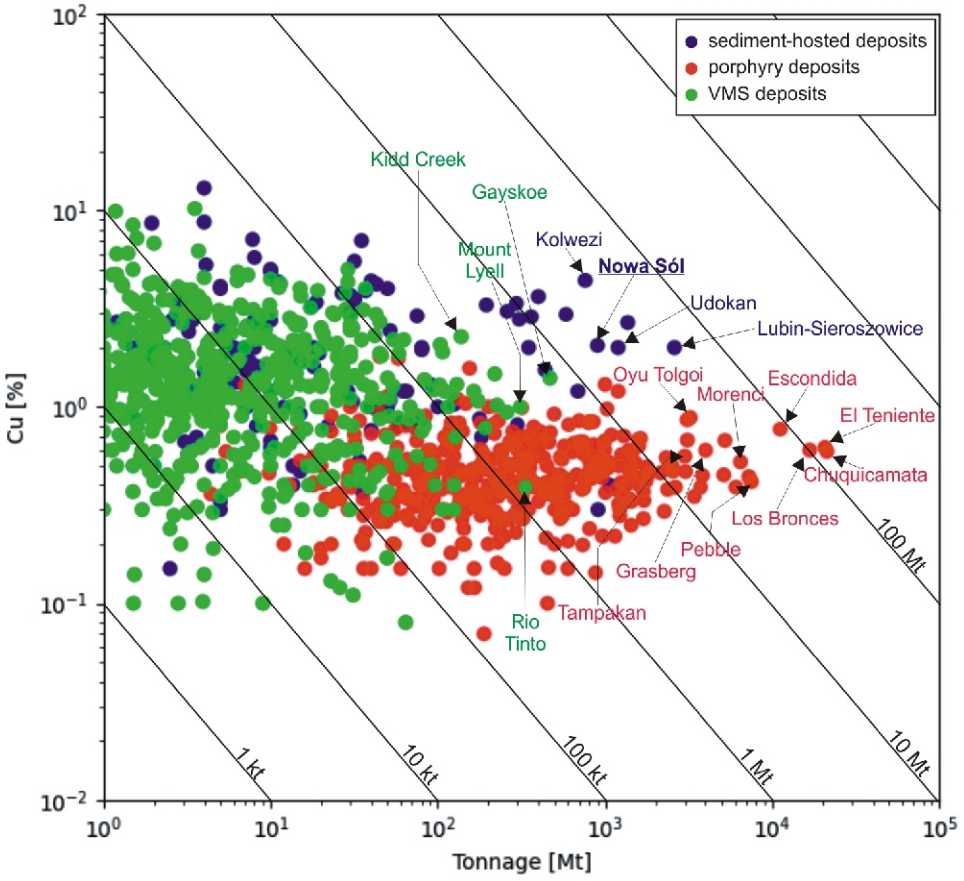


Fig. 2. Tonnage and copper grade characteristics of sediment-hosted, porphyry and VMS deposits worldwide (data from USGS) and geological documentation of Polish sediment-hosted stratiform Cu-Ag deposits (described in detail by Speczik et al., 2021)

ologists from the Polish Geological Institute. This significant finding emerged as a result of the Sieroszowice IG 1 borehole, which intersected a 1.96 m-thick interval at depths ranging from 656.30 to 658.26 metres b.g.l., revealing a copper content of 1.5 wt.%. Mining started in 1963 in Lubin and since then >1 billion metric tons of ore have been mined in the New Copper District by the state-owned KGHM Polish Copper S.A. (Oszczepalski, 2017). In total, the New Copper District identified resources (excluding sub-economic resources) accounting for 1 689.566 Mt of ore containing 30.262 Mt of Cu and 110 kt of Ag. Among known geological (identified) resources, 2% are assessed as inferred (Polish D and C_2 categories), 59% as indicated (Polish C_1 category) and 38% as measured (Polish A and B categories; Szuflicki et al., 2022).

Mined deposits of the New Copper District as well as adjacent areas have been minutely studied in terms of genesis and evolution, mineralogy, petrology, metal distribution, geochemistry, tectonics, hydrogeology, ore processing and resource estimation, collectively described by Piestrzyński (2007).

THE NORTHERN COPPER BELT

The Northern Copper Belt consists of 3 deposits located north-west (Mozów and Nowa Sól) and north-east (Sulmierzyce North) of the New Mining District, in areas where, until recently, mining was believed to be economically unjustified. Deposits of the Northern Copper Belt were discovered and documented between 2011 and 2021 by the Miedzi Copper Corporation owned by the Canadian Lumina Capital Group (Speczik et al., 2021). Depths of mineralized intervals are between 1635 and 2060 m b.g.l. in Sulmierzyce North, between 1780 and 2160 m b.g.l. in Nowa Sól and between 2370 and 2540 m b.g.l. in Mozów. Average copper equivalent (Cu wt.% + $\frac{1}{100}$ Ag g/t) grades are between 2.34 wt.% in Sulmierzyce North and 2.96 wt.% in Nowa Sól. In total, identified mineral resources of the Northern Copper Belt account for 1 339.241 Mt of ore containing 20.285 Mt of Cu and 49 kt of Ag in the inferred category. At present, the deposits are documented in the C_2 and D Polish categories. Infill boreholes aiming to increase the certainty of reported resources are currently carried out only on the Nowa Sól deposit.

Before 2011, according to Polish Geological and Mining Law and Regulations of the Minister of the Environment, the maximum depth of a sediment-hosted stratiform Cu-Ag deposit was 1500 m b.g.l. In 2011 the Ministry of the Environment passed regulation allowing introduction of customized threshold parameters defining mineral deposits and their boundaries in cases of *exceptional geological conditions*. This enabled the documention of Cu-Ag deposits north of the New Copper District, at depths exceeding 1500 m b.g.l.. The successful exploration campaign was based on reinterpretation of archival data – geophysical, palaeothermal and mineralogical – and was described in detail by Speczik et al. (2020a). Reevaluation of more than 200 archival oil and gas boreholes was crucial to delineating potential areas with rich Cu-Ag mineralization in deeper parts of the Fore-Sudetic Monocline. Two out of three (Mozów and Sulmierzyce North) deposits of the Northern Copper Belt were identified in areas previously described as perspective by the Polish Geological Institute.

Due to their recent discovery, Northern Copper Belt deposits and prospects have been studied in less detail than the deposits of the New Copper District. However, some studies regarding exploration strategy (Speczik et al., 2020a, b), mineralogy (Bieńko and Pietrzela, 2022), geochemistry and metal distribution (Oszczepalski et al., 2019; Bieńko and Pietrzela, 2022; Pietrzela and Bieńko, 2023), resource policy (Zieliński et al., 2021), implementation of legal regulations (Speczik et al., 2020b) and future directions of exploration (Oszczepalski et al., 2019; Speczik et al., 2022) have been published.

The Northern Copper Belt consists also of several prospective areas, beyond already-identified deposits and constituting their natural extension (Fig. 2). Prospective areas of the Northern Copper Belt have been categorized based on the criteria proposed by Oszczepalski et al. (2019). Areas close to the identified deposits have been described as having hypothetical resources. Areas distant from the identified deposits and designated by more than one historical borehole have speculative resources of high potential, and those designated by a single borehole have speculative resources of low potential. Apart from 3 deposits (Nowa Sól, Mozów and Sulmierzyce North), the Northern Copper Belt consists of 15 prospective areas. Their surface area ranges from 0.16 km^2 to almost 50 km^2, while their estimated copper resources are from 5 kt to 6.2 Mt. The mineralized interval within prospective areas of the Northern Copper Belt occurs at variable depths, from 1400 to >2500 m b.g.l. It has been estimated that prospective areas located close to recently identified deposits of the Northern Copper Belt (namely Jany–Nowa Sól–Grochowice, Sulmierzyce and Mozów) contain not less than 52.5 Mt of Cu and 186 kt of Ag (Table 3). Additionally, an estimated 20 Mt of Cu and 65 kt of Ag may be discovered within prospective areas possessing hypothetical and speculative resources (Oszczepalski et al., 2019; Table 2).

Table 2

Prospective areas of the Northern Copper Belt, as shown in Figure 1 (Oszczepalski et al., 2019; Speczik et al., 2022)

Resource category	Area name	Area size [km^2]	Depth range [m b.g.l.]	Average thickness [m]	Average Cu content [%]	Cu resources [Mt]	Average Ag content [ppm]	Ag resources [kt]
Speculative of high potential	Janowo	42.98	1700–1800	1.11	1.64	1.956	36	4.294
	Henrykowice	28.9	1400–1700	1.08	1.73	1.35	34	2.653
	Dębnica	50.4	1500–1800	0.51	6.21	3.99	167	10.731
Speculative of low potential	Wilcze	35.58	2400–2500	0.23	8.12	1.661	920	18.882
	Naratów	8.15	1400–1500	0.52	2.07	0.219	86	0.911
	Lipowiec1	0.16	1400–1500	0.6	2.06	0.005	64	0.015
	Ślubów	2.51	1300–1400	0.2	9.08	0.114	164	0.206
	Bartków1	0.47	1300–1400	0.32	4.18	0.016	71	0.027
	Borzęcin	32.15	1400–1600	0.51	4.91	2.013	n.i.	n.i.
	Radziądz	6.44	1600–1800	1.65	0.93	0.247	7	0.186
	Milicz	13.93	1600–1700	1.86	0.89	0.576	26	1.684
	Bogdaj	2.08	1400–1500	1.58	1.52	0.125	34	0.279
Hypothetical	Kulów	49.68	1500–1800	1.59	3.14	6.201	86	16.983
	Białołęka	6.81	1500–1600	1.8	1.08	0.331	51	1.563
	Luboszyce	38.43	1400–1600	1.42	0.89	1.214	53	7.231
					Total Cu:	20.018	Total Ag:	65.645

[1] – Bartków and Lipowiec prospective areas are located in the vicinity of the Naratów and Luboszyce prospective areas

Table 3

Prospective areas in the extension of the Northern Copper Belt ore deposits (after Speczik et al., 2022)

Identified ore deposits			Prospective areas close to the identified deposits		
Name	Cu resources [Mt]	Ag resources [kt]	Name	Cu resources [Mt]	Ag resources [kt]
Nowa Sól	10.583	36.410	Jany–Nowa Sól–Grochowice	34.748	148.256
Sulmierzyce North	5.652	6.868	Sulmierzyce	7.767	17.793
Mozów	4.586	6.487	Mozów	10	20
Total	20.821	49.765	Total	52.515	186.049

METHODS

The economic values of Polish sediment-hosted Cu-Ag deposits, given in US$ per metric ton of ore, were calculated in order to assess the contribution from copper, silver and the accompanying metals. The calculation of total unit ore value of the deposit is based on data provided by the PGI-NRI in the Balance of Mineral Resources of Poland (e.g., Szuflicki et al., 2022). In this approach, metal resources (in Mt or kt) are divided by total amount of ore (in Mt) to get the average amount of given metal contained in every metric ton of ore. This value is than multiplied by the price of this metal. For example, in the Nowa Sól deposit, an average metric ton of ore contains 0.043 kg (~1.38 troy oz) of silver (as the inferred and indicated resources of the Nowa Sól deposit amount to 848 Mt of ore containing 36.6 kt of silver). The price of silver in December 2022 was 23.33 US$/troy oz (The World Bank Commodity Price Data), therefore the value of silver in an average ton of the Nowa Sól deposit ore was ~32.20 US$. The total unit ore value can be calculated by summing the unit ore values of each individual metal present in the ore. The same calculation approach can be applied to any other type of deposit, of which total ore and metal resources are known.

In this study, values of metals extracted from Polish Cu-Ag mines – copper, silver, nickel and lead – are considered. Zinc is considered in the total unit ore value even though it is not recovered from Polish ores, because it is hosted in amounts similar to lead. Also, its share in net metal endowment rises as mining activities move outwards from the closest vicinity of the oxidized areas, as in the case of the Lubin–Sieroszowice mining district.

Recently, a dynamic model of polymetallic Zechstein mineralization was developed in order to assess the polymetallic grade of sediment-hosted deposits in Poland, and to trace changes in this grade as metal prices fluctuate (Zieliński et al., 2019). This model proved to be very useful as an improvement over the regulations concerning this type of deposit in Poland; however, it is based on productivity [kg/m^2], which, as a grade indicator, is applicable to a very specific type of sediment-hosted stratiform/strata-bound deposit, and thus excludes comparison with other types of copper deposit, e.g., porphyry, VMS or magmatic sulfide. In the present study, unit ore values [US$/metric ton of ore] of metals hosted by Polish Cu-Ag deposits were calculated for the metal prices as of December 2022.

Such comparisons should always be treated with caution, as metal prices fluctuate. In the present contribution, we apply metal prices as of 31st December 2022. Copper, silver, nickel, lead, zinc and gold prices in period 2000–2022 are used to discuss the effect of price volatility on the economic values of Polish sediment-hosted Cu-Ag deposits. Metal prices come from World Bank Commodities Price Data. Numerical data regarding economic reserves, identified resources and metal production of Polish Cu-Ag deposits come from the Balance of Mineral Resources of Poland as of 31st December 2021 (Szuflicki et al., 2022) and historical editions of the Balance of Mineral Resources of Poland (2000–2021). Data regarding economic reserves and identified mineral resources of deposits compared to Polish Cu-Ag deposits were sourced from mining company reports and USGS open access databases.

ECONOMIC ASSESSMENT OF THE FORE-SUDETIC MONOCLINE DEPOSITS

NEW COPPER DISTRICT MINED DEPOSITS

Mined deposits consist of both identified resources and economic reserves. The latter show a substantially higher estimation certainty of reported metals, updated every year with regard to volume of extracted ore. In the context of this contribution, the term “mined deposits” specifically refers to economic reserves (Table 3). According to the Balance of Mineral Resources of Poland (Szuflicki et al., 2022), the economic reserves reported are limited to copper and silver, despite an annual decrease in identified resources of lead, zinc, and nickel due to mining activities. Therefore, in the calculation of unit ore value for mined deposits, only copper and silver were considered.

Out of the six sediment-hosted stratiform Cu-Ag deposits currently being mined in Poland, four of them (Sieroszowice, Polkowice, Głogów Deep, and Radwanice–Gaworzyce) demonstrate unit ore values exceeding US$200 per metric ton of ore (Table 4) as of December 2022. The Rudna and Lubin–Małomice deposits have unit ore values below US$200 per metric ton of ore. The distribution of reported metals in terms of unit ore value varies within the New Copper District. For copper, the share ranges from 72% in the Lubin–Małomice deposit to 86% in the Radwanice–Gaworzyce deposit. As for silver, its share in the unit ore value ranges from 14% in the Radwanice–Gaworzyce deposit to 28% in the Lubin–Małomice deposit (Table 4). The average total unit ore value of mined deposits is US$225.33/metric ton ore.

UNDEVELOPED DEPOSITS SURROUNDING THE NEW COPPER DISTRICT

While certain sections of the mined deposits, such as the northern-east part of the Lubin–Małomice deposit and the western part of the Radwanice–Gaworzyce deposit, remain undeveloped, the term “undeveloped deposits” in this context specifically pertains to the deposits surrounding the active mining areas (Fig. 1). These are Bytom Odrzański, Głogów and Retków. All of these deposits are considered sub-economic in the Balance of Mineral Resources of Poland as of 31st December 2021 (Szuflicki et al., 2022), due to their depths, which are >1250 m b.g.l. in the case of the Bytom Odrzański deposit and 1500 m b.g.l. in the Głogów and Retków deposits. In geological documentation of the Bytom Odrzański, Głogów and Retków deposits surrounding the New Copper District mines, not only copper and silver, but also other valuable by-product metals were reported: cobalt, nickel, lead, zinc, molybdenum and vanadium. Among these, lead, zinc and nickel are included in the unit ore value calculation.

The unit ore value of New Copper District undeveloped deposit ranges between US$163.98/metric ton ore (Retków) to US$206.17/metric ton ore (Głogów). The average total unit ore value of these deposits is US$183.30/metric ton ore. The share of metals in the total unit ore value ranges from 70% to 84 % in the case of copper, from 15% to 26% for silver and from 1 to 4% for non-ferrous base metals other than copper (Table 4).

Table 4

Unit ore values of Polish sediment-hosted stratiform Cu-Ag deposits with the metal value split. Only deposits located in the Fore-Sudetic Monocline and the Żary Perycline are considered. Commodity prices are as of December 2022 (The World Bank Commodity Price Data)

Deposit name		Unit ore value (US$/metric ton ore)						Share of metals in total unit ore value [%]		
		Copper	Silver	Nickel	Lead	Zinc	Total	Copper	Precious	Other base excluding copper[2]
Undeveloped deposits (identified resources)	Nowa Sól	104.46	32.18	0.53	4.34	1.50	143.02	73	23	4
	Sulmierzyce North	170.28	19.28	2.05	5.94	13.26	210.81	81	9	10
	Mozów	160.28	19.20	1.20	0.29	0.21	181.18	88	11	1
	Żary	139.36	56.72	–	6.47	–	202.55	69	28	3
	Retków[1]	123.72	34.04	–	6.22	–	163.98	75	21	4
	Bytom Odrzański[1]	161.57	28.83	1.04	<0.01	0.31	191.76	84	15	1
	Głogów1	144.55	52.94	2.33	3.32	3.02	206.17	70	26	4
Mined deposits[2] (economic reserves)	Rudna	136.64	33.50	–	–	–	170.13	80	20	n.i.
	Sieroszowice	235.03	50.04	–	–	–	285.07	82	18	n.i.
	Polkowice	193.56	33.72	–	–	–	227.28	85	15	n.i.
	Lubin–Małomice	104.76	39.82	–	–	–	144.58	72	28	n.i.
	Głogów Deep	205.73	64.77	–	–	–	270.50	76	24	n.i.
	Radwanice–Gaworzyce	218.16	36.28	–	–	–	254.44	86	14	n.i.
Lubin–Sieroszowice (as of 1959)		118.70	19.78	–	–	–	138.48	86	14	n.i.

[1] – sub-economic (if the mineralized horizon occurs at depths > 1500 m b.g.l., according to Polish Geological Law, a deposit is categorized as sub-economic) resources according to Szuflicki et al. (2022); [2] – by-product metals not reported as economic reserves in geological documentation of currently mined deposits; n.i. – no information

NORTHERN COPPER BELT DEPOSITS AND THE ŻARY DEPOSIT

Three deposits of the Northern Copper Belt and Żary deposit are the newest discoveries constituting the future resource base of Poland. All these deposits have been added to subsequent releases of the Balance of Mineral Resource of Poland in the years 2020–2022. They were discovered in areas where the lower/upper Permian boundary was previously intersected only by single, rather irregularly spaced, oil and gas boreholes (Speczik et al., 2020a, 2021, 2022). The biggest undeveloped Cu-Ag deposit in Poland – Nowa Sól – was a greenfield discovery. Before 2011 in this area that covers some 120 km^2, no boreholes intersected the base of the Zechstein. Two approaches to reporting by-product metals were implemented by geologists documenting new deposits in the Fore-Sudetic Monocline and Żary Pericline. In case of the Northern Copper Belt deposit, a holistic approach was used: apart from copper, silver, lead, zinc and nickel (which are mined in New Copper District), cobalt, molybdenum, vanadium, rhenium and rare earth elements resources were identified. In the Żary deposit, copper, silver and lead resources are reported in the geological documentation.

The Northern Copper Belt deposits and the Żary deposit show strongly variable unit ore values, from US$143.02/metric ton ore (Nowa Sól) to US$210.81/metric ton ore (Sulmierzyce North; Table 4). The average value for the Northern Copper Belt deposits is US$178.34/metric ton ore. The share of particular metals in the unit ore value changes over a wide range as well. In the case of copper it is from 69% (Żary) to 88% (Mozów). The silver share in unit ore value ranges between 9% (Sulmierzyce North) and 28% (Żary), whereas the share of other non-ferrous base metals other than copper is between 1% (Mozów) and 10% (Sulmierzyce North).

DISCUSSION

COMPARISON BETWEEN MINED AND UNDEVELOPED DEPOSITS AND THE ECONOMIC SIGNIFICANCE OF THE NORTHERN COPPER BELT

Based on the information provided in the Balance of Mineral Resources of Poland (Szuflicki et al., 2022) as of December 31st 2021, and the metal prices as of December 31st 2022 (The World Bank Commodity Price Data), the unit ore values for the Cu-Ag deposits studied in Poland range from US$143.02 per metric ton of ore to US$285.07 per metric ton of ore. The average unit ore value for the deposits of the Fore-Sudetic Monocline and the Żary Perycline is calculated to be US$198.38 per metric ton of ore. The unit ore value of the deposits is dominated by copper (from 69% in the Lubin-Małomice deposit to 88% in the Mozów deposit; arithmetic mean 78%). Silver is the second most important metal in all the deposits investigated. Its share in the value of one metric ton of ore ranges from 9% (Sulmierzyce North deposit) to 28% (Żary and Lubin–Małomice deposits; Table 4). The average share of other metals in the unit ore value varies greatly, but in terms of the metal prices as of December 2022 it is only 4% (note that this value corresponds only to undeveloped deposits).

On average, mined deposits of the New Copper District show significantly higher unit ore value than do adjacent undeveloped deposits constituting their resource base (US$225.33/metric ton ore compared to US$187.30/metric ton ore; Fig. 3). At this moment the Sieroszowice and Głogów Deep deposits are the richest areas within the New Mining District due to their exceptionally high copper and silver grades. The Rudna and Lubin deposits show relatively low unit ore values probably because most copper, silver and accompanying metals are hosted by the sandstone ore, which generally has slightly lower

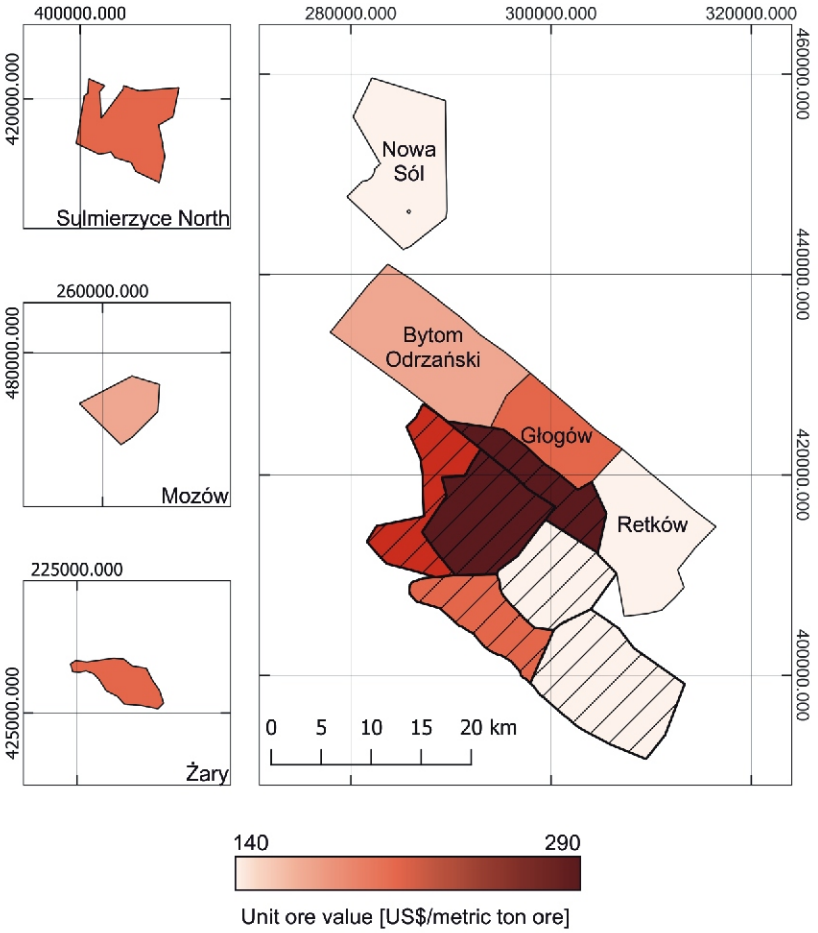


Fig. 3. Unit ore values of the deposits studied

Mined deposits (economic reserves) are hatched. Names of deposits mined are shown in Figure 1

metal grades. The Radwanice–Gaworzyce and Polkowice deposits are located close to the oxidized field, which makes them more irregular with regard to both the thickness of the mineralized interval and the copper and silver grades (Oszczepalski and Rydzewski, 1997). Furthermore, within these deposits, very rich copper-bearing zones co-occur with barren areas and the share of silver in their unit ore value is relatively low compared to other New Copper District deposits (e.g., Piestrzyński, 2007). As a result, the Ag-poor deposits located adjacent to the Rote Fäule areas show slightly lower unit ore values than do the Ag-rich deposits of the New Copper District situated farther north.

The difference in unit ore values between mined and undeveloped deposits should reflect the much better geological recognition of mined deposits and selection of only the richest (and shallowest) parts of mineralized areas for mining operations in the 1960s. The economic reserves to which we refer here, while describing mined deposits, are identified resources made smaller by mining shaft pillars, which are often located in barren or less endowed (economically less profitable) parts of the deposit. In the Fore-Sudetic Monocline, lower Zechstein rocks plunge northwards at 2–3° and so do the mineralized intervals. The richest parts of the New Copper District (Polkowice, Sieroszowice and the western part of the Lubin deposits) are located close to the Fore-Sudetic Block, in areas where the copper-bearing rocks are buried at shallow depths (<500 m b.g.l.). The depth of the ore-bearing interval increases gradually northwards; in the Rudna area it reaches 1000 m b.g.l. and in the Głogów Deep it locally exceeds 1400 m b.g.l. (Oszczepalski et al., 2019). Historically, deeper parts of the New Copper District were considered sub-economic due to this depth range and for this reason mineral exploration in areas surrounding active mines were not prioritized. In effect, the Bytom Odrzański, Głogów and Retków areas are penetrated by fewer boreholes and their reported resources fall into the C_2+C_1 categories (inferred/indicated resources; Table 1). This in turn results in less precise geological recognition, which translates to slightly lower unit ore values.

Undeveloped deposits surrounding the New Copper District show comparable unit ore values to the Northern Copper Belt and Żary deposits: US$187.30/metric ton ore, US$178.34/metric ton ore and US$202.55/metric ton ore, respectively. The share of metals in the unit ore values is between 69 and 88% in the case of copper, similar to mined deposits of the New Copper District. The share of silver in undeveloped deposits' unit ore values is slightly lower than in mined deposits, at 19% compared to almost 20%, due to a relatively low share of silver in the Mozów and Sulmierzyce North deposits. If these two deposits were excluded, the average share of silver in the unit ore value for the remaining undeveloped deposits would be 23%. It is im-

possible to compare the share of non-ferrous metals other than copper in the unit ore value, because the mined deposits lack these metals in sufficient reporting category (Table 4).

The differences shown in unit ore values between mined and undeveloped deposits provoke the question about the future mining profitability of Fore-Sudetic deposits constituting a resource base for the New Copper District. To answer this question, it is necessary to look at the historical development of the Lubin–Sieroszowice deposit, discovered in 1959 on the southern part of the Fore-Sudetic Monocline (Oszczepalski, 2017) and mined since the 1960s until now. Initially, 23 boreholes were drilled in the area of the Lubin–Sieroszowice deposit, among which 6 were negative or sub-economic. This enabled identification of 1 364.65 Mt of ore containing an estimated 16.49 Mt of copper and 36 kt of silver. Immediately following its discovery, in 1960–1962, the Lubin–Sieroszowice deposit was subject to an intensive infill drilling campaign that resulted in significant increase in geological recognition of the area and higher certainty of resource estimation. In order to facilitate geological analysis, the deposit was subdivided into three smaller areas: Lubin (east), Polkowice (central) and Sieroszowice (west). Soon, copper and silver identified resources increased by 15 and 100%, respectively, with a slight decrease in ore volume and virtually no change in the deposit area (Oszczepalski, 2017; Speczik et al., 2020b). As a result, the average unit ore value for the whole deposit increased by almost 100% (from US$138.38/metric ton ore to the average of US$273.50/metric ton ore; Table 5). By analogy, future exploration of the Bytom Odrzański, Głogów and Retków deposits may result in a similar rise in their unit ore value. As of today, the cumulative mine production from 6 deposits of the New Copper District (formerly a single Lubin–Sieroszowice deposit) has exceeded 1 billion tons of ore containing >18 Mt of copper, with remaining ore reserves and mineral resources close to the mining district exceeding 1 billion tons of ore (Szuflicki et al., 2022).

The other question concerns the feasibility of future exploration and development of the Northern Copper Belt deposits. These deposits do not neighbour the New Copper District. Instead, they constitute greenfield discoveries in areas previously poorly explored or totally unexplored. Undoubtedly, they are part of the same mineral system, albeit occupying its less recognized parts.

The Nowa Sól deposit, although located ~30 km from the mined deposits of the New Copper District, strongly resembles deposits of this area in terms of mineralogy, distribution of metals, relation to the Zielona Góra oxidized field and position of ore-bearing rocks in the lower Permian stratigraphic profile (e.g., Bieńko and Pietrzela, 2022). In particular it can be compared to the Rudna deposit. With regard to metal endowment, it shows a slightly elevated share of silver in the total unit ore value, comparable to the Głogów, Głogów Deep, Retków and Lubin–Małomice deposits, located in the northern and eastern parts of the New Copper District. The Nowa Sól deposit has a slightly elevated share of accompanying metals in unit ore value compared to the deposits of the New Copper District (Table 4), due to its relatively high lead resources.

The unit ore value of the Nowa Sól deposit is US$143.02/metric ton of ore as of December 2022 (The World Bank Commodity Price Data), being one of the lowest among the deposits investigated. However, its cumulative metal value is significantly higher than any other Cu-Ag deposit in Poland due to its size (848.5 Mt ore containing 10.5 Mt of Cu and 36.5 kt of Ag; Table 5). The Nowa Sól deposit covers an area of ~120 km^2, and it is still open towards the and north (Jany–Nowa Sól–Grochowice and Wilcze prospective areas; Fig. 1). In addition, when it enters the mature phase of exploration (preparation for a mining license), it is highly probable that additional infill drilling will lead to an increase in the mineral resources and ore reserves of copper, silver and by-product metals. The history of the Lubin–Sieroszowice deposit shows a continuous rise in mineral resources and ore reserves over time, resulting from exploration drilling from the surface and from the underground mine level (Oszczepalski, 2017). The same scenario may be applicable to the Nowa Sól deposit, which in fact might be a cluster of 2 or 3 smaller deposits, each showing a higher unit ore value. Finally, the Nowa Sól deposit is open towards the west, into the Jany area, towards the north, into the Wilcze area, and towards the east, into the Grochowice area; combined, containing an estimated 34 Mt of Cu and 148 kt of Ag. Exploration and development of other types of deposit show that an upgrade of mineral resources to ore reserves significantly increases their unit ore values (Table 5), especially when the high-grade core of the deposit is developed first, which is usually the case in many mineral projects.

By contrast, the Sulmierzyce North deposit, located in the eastern part of the Fore-Sudetic Monocline, close to the eastern rim of the Wolsztyn High (see Kiersnowski et al., 2010; cf. Fig. 1), shows very high unit ore value at the primary phase of exploration (US$210.81/mt ore). To date, 5 new boreholes have been drilled in an area previously penetrated only by oil and gas boreholes, enough to identify 267.17 Mt of ore containing an estimated 5.43 Mt of copper and 6.9 kt of silver in a relatively small area of 61.1 km^2. At this phase of exploration, the Sulmierzyce North deposit seem to be exceptionally rich, however it is difficult to compare it with the Lubin–Sieroszowice deposit due to considerable differences in lithology, position of oxidized facies in the stratigraphic profile, relation to adjacent oxidized fields, depth range, tectonics and distribution of metals (Speczik et al., 2020a; Pietrzela and Bieńko, 2023). The Sulmierzyce North deposit sits on anomalously thick mineralized Kupferschiefer *sensu stricto*, which resembles copper-bearing marl from the North Sudetic Trough rather than typical organic-rich copper-bearing shale of the Fore-Sudetic Monocline (Speczik et al., 2020a, 2021). Such thick shale is the reason for the very high share of non-ferrous metals other than copper in the unit ore value of the Sulmierzyce North deposit – 11%, the highest value among all the deposits studied. Additionally, the deposit is wedged between two large (Krotoszyn and Ostrzeszów) and a few smaller oxidized fields. It is suggested that metalliferous brines in the Sulmierzyce North region carried less silver than fluids that transported metals to the New Copper District and Nowa Sól deposits. Interestingly, Sulmierzyce North hosts much zinc in relation to lead, which is another distinguishable feature of this deposit. The Sulmierzyce North deposit can be extended towards the west and north. In these directions an estimated 7.8 Mt of Cu and 17.8 kt of Ag can still be discovered, according to Oszczepalski et al. (2019).

The Mozów deposit is situated in the western part of the Fore-Sudetic Monocline, where the depth of the mineralized interval reaches 2500 m b.g.l. Because of this, the drilling campaign in the Mozów region focused solely on the richest parts of prospective area delineated earlier by the Polish Geological Institute. By drilling two new boreholes and re-examining 4 historical boreholes drilled by the oil and gas industry, the Miedzi Copper Corporation delineated the Mozów deposit, covering 31.5 km^2 with identified resources of 223.589 Mt ore containing an estimated 4.3 Mt of copper and 5.7 kt of silver. This translates to a relatively high unit ore value of US$181.18 /metric ton ore. Unlike the Nowa Sól deposit, the position of the oxidized facies within the lower Zechstein profile of the Mozów deposit is virtually constant in all the boreholes drilled. The Mozów deposit stands out among the deposits studied because of its low share

Table 5

Historical development of the Lubin–Sieroszowice Cu-Ag deposit (today's New Copper District) from inferred to indicated category compared to the current status of the Northern Copper Belt deposits. Nominal metal prices as of December 2022 (The World Bank Commodity Price Data)

Deposit name (year)	Category [JORC]	Area [km^2]	No. of boreholes	Identified resources	Total average unit ore value [US$/mt ore]
Lubin–Sieroszowice (1959)	C_2 (inferred)	170.0	23	1 364.650 Mt ore 16.492 Mt Cu 36 kt Ag	138.48
Lubin (1959)	C_1+C_2 (inferred/indicated)	55.9	30	354.977 Mt ore 6.677 Mt Cu 54 kt Ag	280.84
Polkowice (1961)	C_1+C_2 (inferred/indicated)	58.8	41	330.545 Mt ore 8.312 Mt Cu 17.5 kt Ag	250.79
Sieroszowice (1962)	C_1 (indicated)	53.9	41	126.588 Mt ore 3.818 Mt Cu 6 kt Ag	288.91
Nowa Sól (2019)	C_2 (inferred)	119.0	18	848.481 Mt ore 10.583 Mt Cu 36.4 kt Ag	143.02
Sulmierzyce North (2020)	C_2+D (inferred)	61.1	8	267.171 Mt ore 5.432 Mt Cu 6.9 kt Ag	210.81
Mozów (2020)	C_2 (inferred)	31.5	6	223.589 Mt ore 4.270 Mt Cu 5.7 kt Ag	181.18
Sulmierzyce North (2020)[1]	C_2 (inferred)	28.6	4	147.173 Mt ore 3.728 Mt Cu 4.4 kt Ag	244.98

[1] – part of the Sulmierzyce North deposit documented in the C_2 category (higher certainty of resource estimation)

of silver (11%) and by-product metals (1%) in the unit ore value. The very low share of metals other than copper may result from the low Kupferschiefer thickness and the near proximity to the oxidized field. Firstly, the thin, on average 0.31 m thick mineralized Kupferschiefer, has insufficient volume to host large amounts of by-product metals. Secondly, the deposit is located between the Zielona Góra and Radoszyn oxidized fields, whose interaction precludes formation of Ag and Pb-Zn bearing zones within the current boundaries of the Mozów deposit (such a zone is clearly visible in the Nowa Sól deposit). With regard to metal distribution and geochemical zonation, the Mozów deposit can be, in some sense, compared to the Radwanice-Gaworzyce and Polkowice deposits, which are also located close to the edge of the oxidized field.

MARKET PERSPECTIVE ON NORTHERN COPPER BELT DEPOSITS

Metal price volatility has a significant impact on all mining projects, as it affects their economic profitability and technical feasibility. It is especially critical for deep mining operations, which require very high initial infrastructure investments and may be characterized by potential geological instability (Ranjith et al., 2017; Peng and Mei-feng, 2021). Additionally, resource estimation is much more challenging in deeper-seated deposits than in those located near to the surface (e.g., Schodde, 2014; Wood and Hedenquist, 2019). From the market perspective, metal price changes may influence investment decisions, as their fluctuation can alter the expected returns from investments, which are usually huge (Schodde, 2014, 2020). For this reason, market volatility can make it more difficult for mining companies to secure financing for new projects, as investors may be more hesitant to invest in an industry that is subject to significant price changes. Finally, if metal prices fall below the break-even point for a project, it can become unprofitable, and the mining company would be forced to halt or suspend operations, which is risky in the case of deep mining.

On the other hand, long-term and continuous large-scale exploitation has largely exhausted shallow metal mineral resources, and deeper mining has become inevitable (Peng and Mei-feng, 2021). Indeed, the exploration of deep mineral resources is a necessary choice under the assumption of continuous economic development. Despite the exhaustion of shallow deposits, it was shown that rising global copper mine production is matched by growth in estimated copper ore reserves and mineral resources (Mudd and Jowitt, 2018). This happens because deeper and previously unavailable parts of known, especially mature, mineral systems are explored (Jowitt et al., 2013; Schodde, 2014) and new, more effective and cheaper, exploration technologies emerge (e.g., Okada, 2022). Among many others, there is the case of the world largest deposits, such as Grasberg, Chuquicamata, Palabora, Kiruna and Ernest Henry. The Fore-Sudetic Monocline mining history is a perfect example of such progressive transition from shallow underground operations to much deeper mining and proof that giant deposits are economic in nearly all settings (Oszczepalski, 2017).

It is believed that global macroeconomic shocks are the main source of commodity price volatility. These factors are demand, supply and shocks specific to particular commodity markets. Between 2000 and 2022 nominal and indexed real prices of metals have shown massive, to some extent synchronized, fluctuations (Fig. 4). In this period 6 major macroeconomic events contributed to volatilities in the metal market: (1) The

2005–2007 unprecedented economic growth in China and India; (2) the 2008/2009 financial crisis; (3) the 2010/2011 post-crisis price rebound; (4) the 2014–2017 slowdown in Chinese economy; (5) the 2018–2020 China–USA trade war; (6) the 2020–2021 COVID-19 pandemic and (7) the 2022 Russian invasion of Ukraine (Fig. 5). Among the metals studied, silver and nickel exhibited highest volatility in period under review (2000–2022). Copper, lead and zinc price fluctuations were slightly milder (Fig. 4).

To show how market factors affect identified resources over time, metal price volatility can be translated into ore values of the Northern Copper Belt deposits studied (Figs. 6–8). It is shown that the higher the total unit value of the deposit, the larger is the difference between the highest and lowest unit ore value in the period studied. For Sulmierzyce North, Mozów and Nowa Sól, the range of unit ore values in the period investigated were US$217.94, US$188.32 and US$159.60, respectively (Table 6). These deposits reached their highest nominal annual median unit ore values in 2011. This was US$232.69 in the case of Sulmierzyce North, US$205.60 for Mozów and US$169.21 for the Nowa Sól deposit. In 2001, the deposits studied had the lowest nominal annual median unit ore value. When monthly prices are taken into account, each deposit shows minimum/maximum unit ore values in different periods. The Nowa Sól highest and lowest nominal monthly unit ore values were in April 2011 and October 2001, respectively, whereas for Sulmierzyce North and Mozów these were March 2022 and October 2001, respectively. This difference results from the varying share of by-product metals in the deposits' unit ore values; in case of the Nowa Sól deposit, the share of silver reached its maximum (32%) in April 2011, leading to a significant increase in unit ore value at that time. By contrast, the Sulmierzyce North and Mozów deposits, with their relatively low share of silver (9 and 11%, respectively as of December 2022), had the highest nominal unit ore values in March 2022, when the copper price was at its all-time maximum. Similar fluctuations were observed in mined Cu-Ag deposits of the New Copper District.

The example of the Sulmierzyce North deposit shows how metal price volatility shapes the share of by-product metals other than copper and silver in unit ore value. Between December 2006 and February 2007, due to the very high zinc price, the share of by-product metals other than copper and silver reached levels of >15% (Fig. 7). A similarly high share of these metals in unit ore value took place between January 2000 and April 2002 (13% due to low copper and silver prices), between October 2006 and November 2007 (12–16% amid subsequently high zinc, nickel and lead prices) and between August 2016 and June 2018 (12–13% amid increases in lead and zinc prices in relation to a stagnant silver price). This means that, for long periods (up to 2 years) zinc, lead and nickel would have played an important role in the unit ore value of Sulmierzyce North deposit, if it were developed at that time. This also emphasizes the purpose of documenting by-product metals, which in some deposits are present in elevated amounts (Banaś et al., 2007). Similar long-term rises in the share of unit ore value are attributed to silver in the Nowa Sól deposit. The median share of silver in the unit ore value of the Nowa Sól deposit in the period investigated was 22%; however, between November 2010 and May 2013 this value exceeded 25%, reaching up to 32% in the spring of 2011. The same happened between January and November 2016 as well as between July 2020 and February 2021. The Mozów deposit has a very low silver and other-by product metals share in unit ore value (12% cumulative), and therefore price fluctuations do not affect its unit ore value on the levels of the Nowa Sól or Sulmierzyce North deposits (Figs. 5–7). Different metals control the economic values of the deposits studied; silver and copper have the biggest impact on unit ore value of the Nowa Sól deposit, copper, zinc, lead and nickel in the Sulmierzyce North deposit and copper with minor silver in the Mozów deposit.

SHARE OF BY-PRODUCT METALS IN THE UNIT ORE VALUE ON THE FORE-SUDETIC MONOCLINE

The economic assessment of Polish sediment-hosted stratiform deposits provided can facilitate inter-comparison of the deposits and show how commodity prices affect the values of the resources identified. It also poses a question about the spatial distribution of metals across the mineral system and leads to inferences about the share of different metals in ore that will be mined in the future.

As noted earlier, silver is the second most important metal extracted in the Polish Cu-Ag mines. In general, deposits located close to oxidized fields (Rote Fäule) have lower shares of silver in the ore value than deposits located away from the Rote Fäule areas (Table 4 and Fig. 1). The deposits studied (developed and undeveloped combined) show strongly variable shares of silver, from 9 to 28%, with an arithmetic mean of 19.38%. New Cu-Ag deposits documented in Poland, e.g., Nowa Sól and Żary, have relatively high shares of silver in the unit ore value, compared to the already mined deposits (Fig. 9B). This is in line with the geological and geochemical studies of deposits from the Fore-Sudetic Monocline (e.g., Oszczepalski and Rydzewski, 1995; Pieczonka et al., 2007; Pieczonka, 2011, and Bieńko and Pietrzela, 2022). Even within a single deposit, the share of silver in the unit ore value may differ significantly. For example, in the Nowa Sól deposit, the central part is strongly enriched in silver and other by-product metals relative to the southern part (Bieńko and Pietrzela, 2022). As the mining goes deeper in the New Copper District, particularly in the Głogów and Głogów Deep deposits, it is very likely that silver production will rise in the near future. However, according to geochemical and mineralogical studies, this rise in the share of silver will not be infinite: the rise in share of silver will slow as the mining approaches the Pb-bearing zone developed around most of the Cu-Ag deposits on the Fore-Sudetic Monocline (Oszczepalski, 1999; Oszczepalski and Chmielewski, 2015).

The results provided here differ from the assumptions made by Mudd and Jowitt (2018), who indicated that the share of precious metals in the unit ore value in sediment-hosted stratiform/strata-bound Cu deposits averages only 5.8%. The group of precious metals described by Mudd and Jowitt (2018) consisted of: gold, silver and platinum group elements (PGE). Nonetheless, gold is extracted from the ores as a precious by-product, gold production in 2021 reaching 768 kg (Szuflicki et al., 2022); however, only silver is included in the mineral resource and ore reserve reporting of Cu-Ag deposits in Poland, and is thus considered as the only precious metal. Therefore, the relatively high share of precious metals in the unit ore value of the deposits studied is slightly underestimated, but in general it should be attributed solely to silver (in 2021 1,332 tons of silver were produced in comparison to 768 kg of gold). The share of precious metals indicated by Mudd and Jowitt (2018) is significantly lower than is described in this contribution, probably because those authors included in their calculations some sediment-hosted stratiform/strata bound Cu deposits which do not host silver as a primary product. These are for example the African Cu-Co deposits, with low silver and gold grades (Rentzsch, 1974; Kelepile et al., 2020).

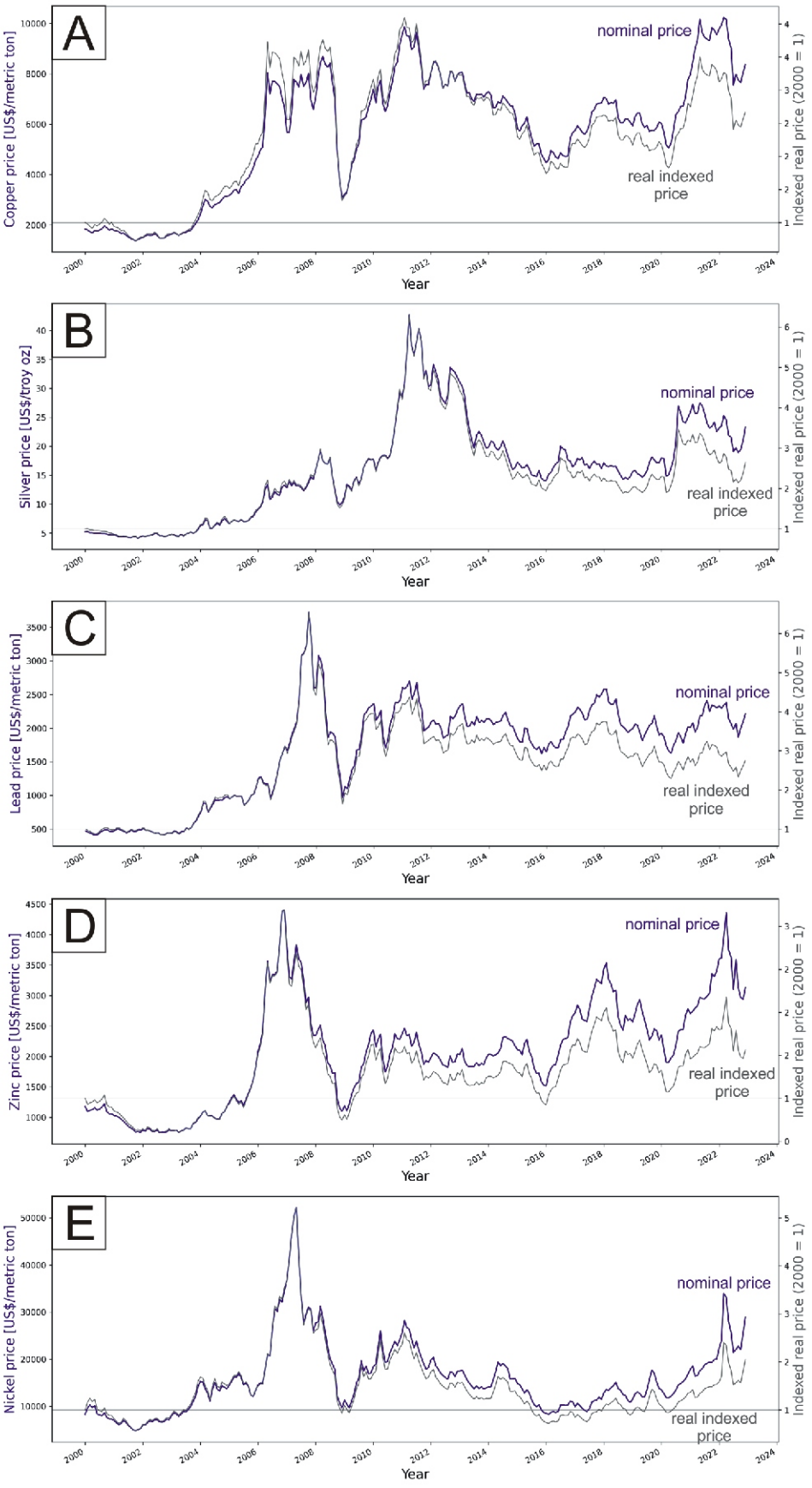


Fig. 4. Nominal and indexed real prices of selected metals between 2000 and 2022

Source: World Bank Commodity Prices; **A** – copper, **B** – silver, **C** – lead, **D** – zinc, **E** – nickel. The nominal value is the current value, without taking inflation or other market factors into account. The real value is the nominal value after it has been adjusted for inflation. Here, the real price is indexed to the year 2000 (which is a base date)

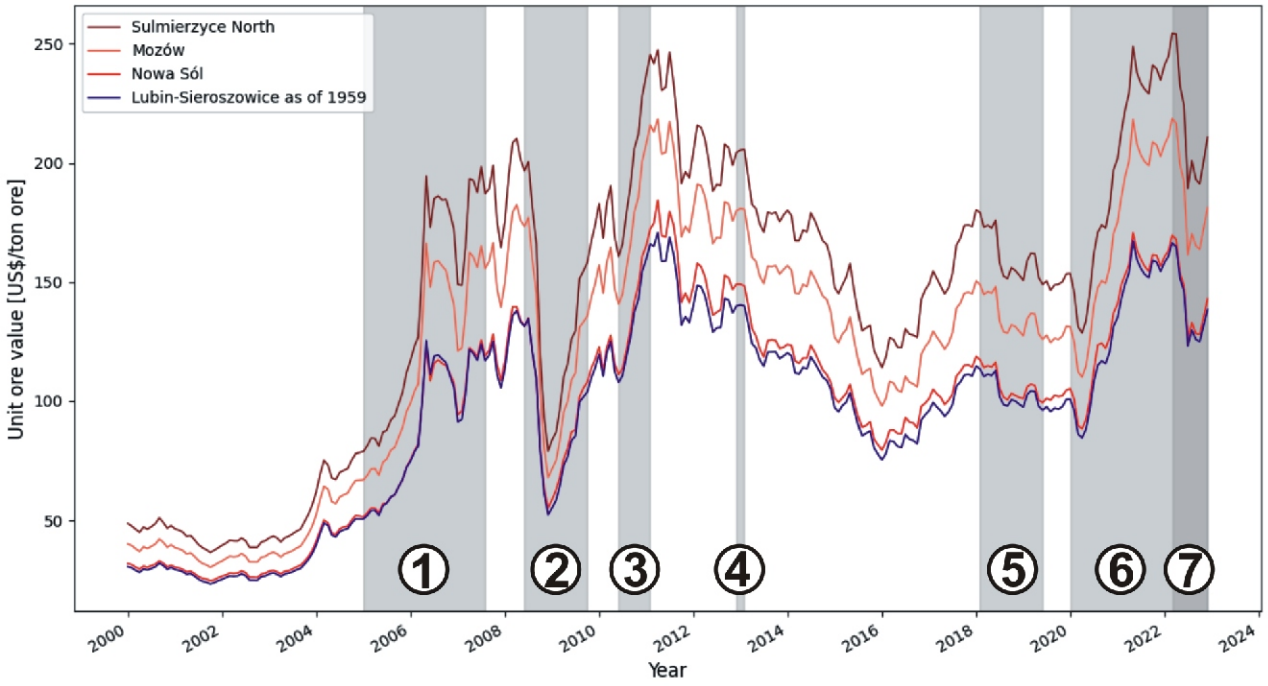


Fig. 5. Unit ore values of the Northern Copper Belt deposits in the years 2000–2022 compared to the Lubin–Sieroszowice deposit as of 1959

Shaded areas indicate the most important periods influencing unit ore values of these sediment-hosted stratiform Cu-Ag deposits. 1 – the 2005–2007 unprecedented economic growth in China and India; 2 – the 2008/2009 financial crisis; 3 – the 2010/2011 post-crisis price rebound; 4 – the 2014–2017 slowdown in the Chinese economy; 5 – the 2018–2020 China–USA trade war; 6 – the 2020–2021 COVID-19 pandemic; 7 – the 2022 Russian invasion of Ukraine

Table 6

Unit ore values of undeveloped sediment-hosted stratiform Cu-Ag deposits of the Fore-Sudetic Monocline in the years 2000–2022 according to nominal metal prices

Deposit name	Unit ore value (US$/metric ton ore)				
	Min	Max	Mean	Median	Range
Nowa Sól	24.62	184.22	97.66	104.89	159.60
Sulmierzyce North	36.46	254.40	143.49	155.43	217.94
Mozów	30.29	218.61	123.24	132.60	188.32
Retków	28.08	210.11	112.18	120.26	182.03
Bytom Odrzański	32.26	237.09	130.46	139.53	204.83
Głogów	35.59	269.20	140.35	150.43	233.61
Lubin–Sieroszowice[1] (as of 1959)	23.25	170.75	94.31	100.97	147.50

[1] – Lubin–Sieroszowice deposit, documented for the first time in 1959, was added in comparison purposes

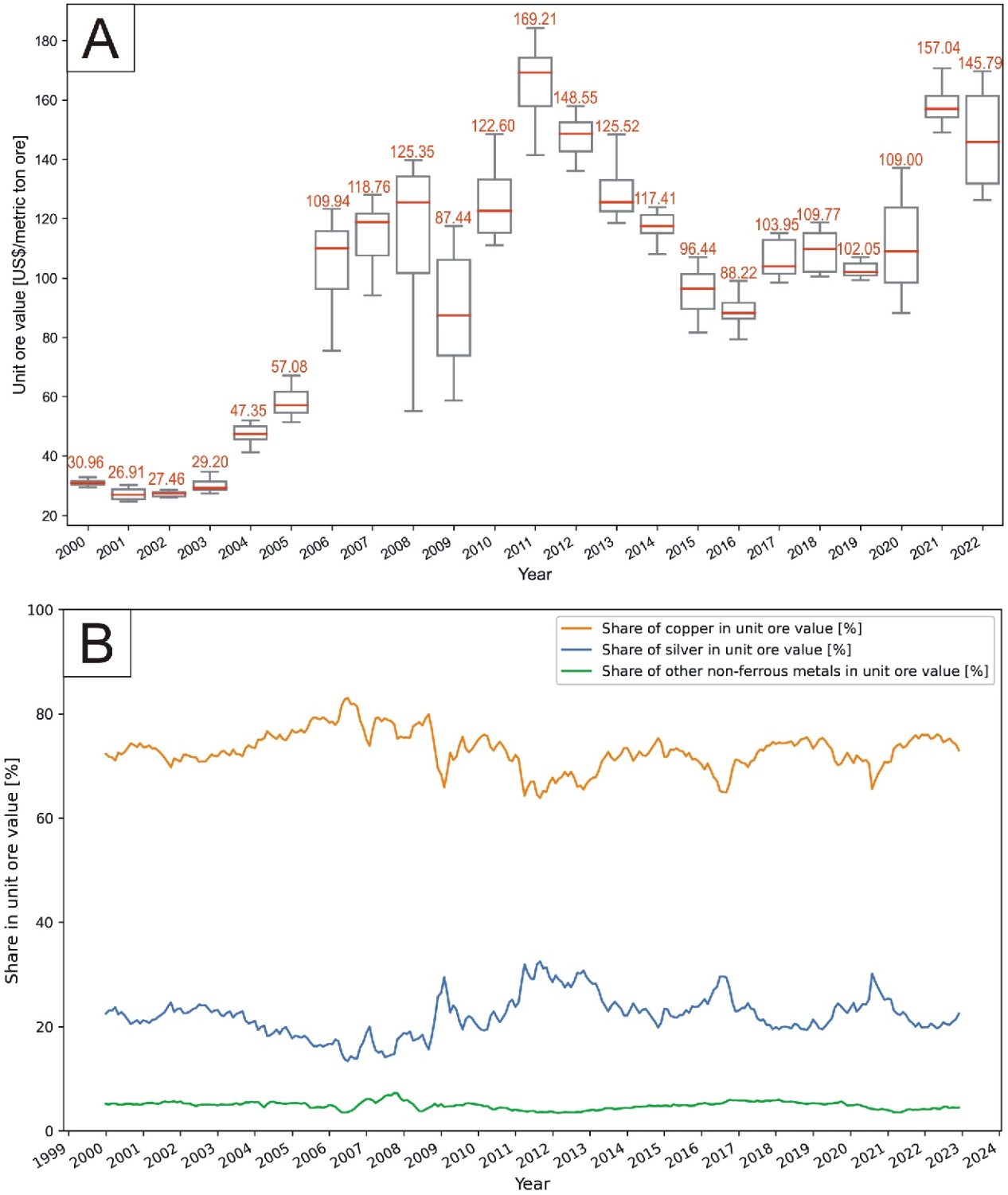
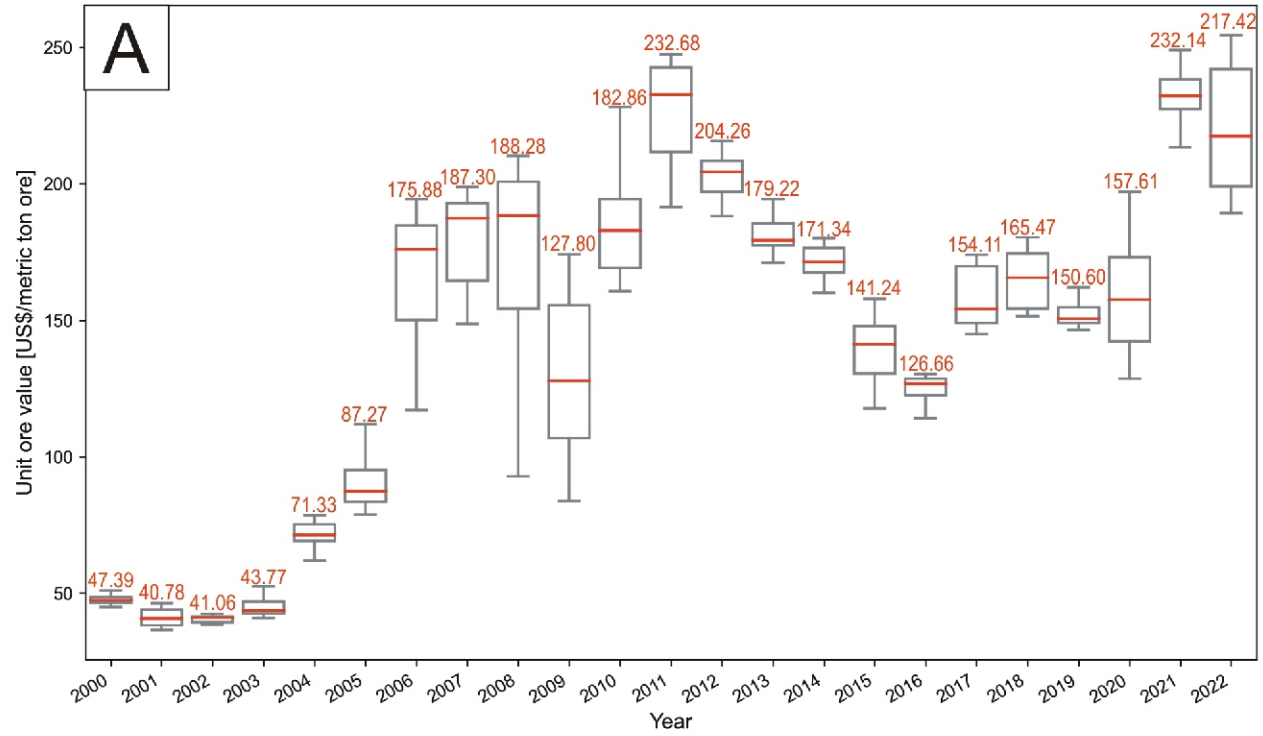
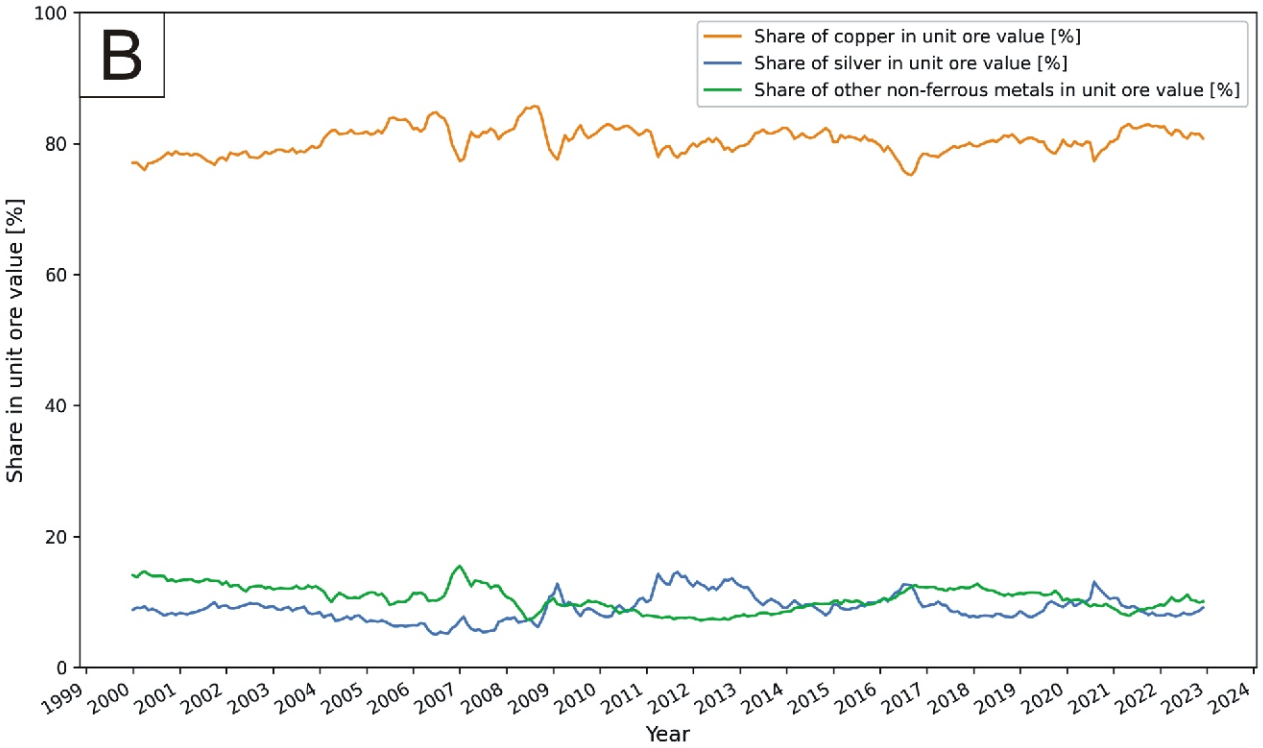


Fig. 6. Change in unit ore value of the Nowa Sól deposit in the years 2000–2022 (A) the annual median of the nominal unit ore value is shown in red; (B) the share of copper, silver and non-ferrous metals other than copper in the unit ore value of the Nowa Sól deposit in 2000–2022


A
Unit ore value [US$/metric ton ore]
Year
47.39
40.78
41.06
43.77
71.33
87.27
175.88
187.30
188.28
127.80
182.86
232.68
204.26
179.22
171.34
141.24
126.66
154.11
165.47
150.60
157.61
232.14
217.42


B
Share of copper in unit ore value [%]
Share of silver in unit ore value [%]
Share of other non-ferrous metals in unit ore value [%]
Share in unit ore value [%]
Year

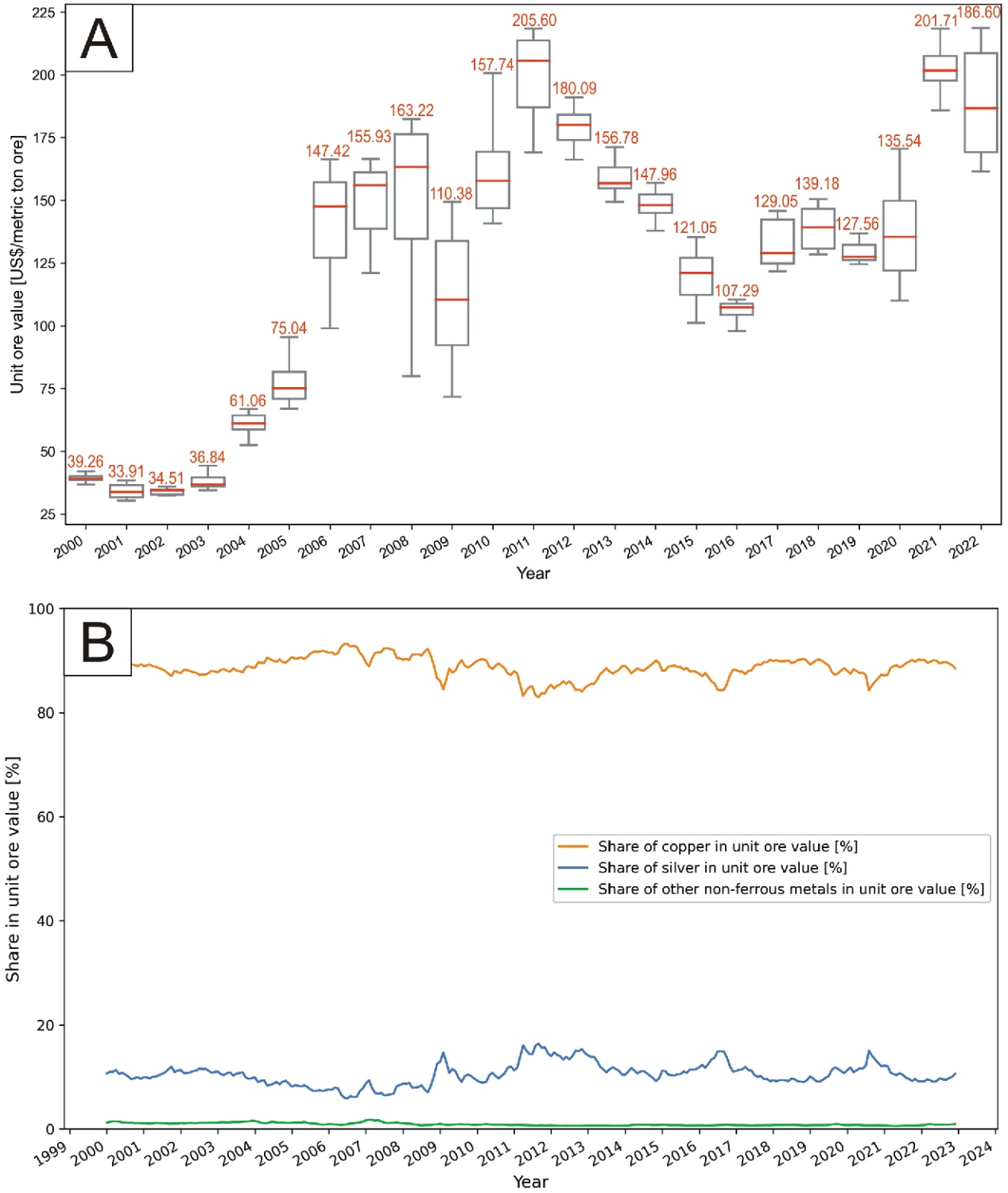


Fig. 8. Change in unit ore value of the Mozów North deposit in the years 2000–2022 (A) the annual median of the nominal unit ore value is shown in red; (B) the share of copper, silver and non-ferrous metals other than copper in the unit ore value of the Mozów deposit in 2000–2022

The majority of the Cu-Ag deposits analyzed, excluding Sulmierzyce North, have an insignificant shares of metals other than copper in the unit ore value (Fig. 9C). In the past, these metals accounted for as much as 3% of produced unit ore value (in 2007 and 2015; Fig. 10). However low, these shares are likely to rise, as the price of nickel is expected to grow in the next few decades due to supply shortages and a jump in demand (Sverdrup et al., 2017; Fu et al., 2020). In some geological documentation, the accompanying metals were omitted in the estimation of mineral resources and none of these metals are included in the estimation of economic reserves of mined deposits. This causes a minor underestimation of the average value of one metric ton of ore in these deposits. In general, it is assumed that the two most important by-product metals other than silver – nickel and lead – behave quite differently in the mineralized lower Permian intervals. Lead tends to be concentrated around and above the copper-bearing succession, forming galena-dominated areas north of the mined deposits (Oszczepalski and Rydzewski, 1997), whereas nickel generally concentrates in organic-rich intervals, being less dependent on the oxidized zone (e.g., Banaś et al., 2007). Therefore, it is possible to forecast a slightly increasing share of lead in the mined ore, but impossible to easily assess future nickel grades in mine feed.

Polish Cu-Ag deposits show significantly lower shares of non-ferrous metals other than copper, compared to other sediment-hosted stratiform/strata-bound Cu deposits (Mudd and Jowitt, 2018). This should be attributed to the fact that other world-class sediment-hosted stratiform/strata-bound deposits, e.g., the African Cu-Co deposits, contain much more cobalt per metric ton of ore than these Polish deposits. In comparison to other types of deposit, the share of non-ferrous metals other than copper in the Polish Cu-Ag deposits studied falls in-between the porphyry deposits (an average of 2.5% as of 2018) and the IOCG deposits (an average of 7.5% as of 2018; Mudd and Jowitt, 2018). Sulmierzyce North stands out among the deposits studied, as it shows particularly high shares of non-ferrous metals other than copper in unit ore value (11% as of 2022). If cobalt, molybdenum and vanadium (present in slightly elevated amounts in the organic-rich Kupferschefer of the deposits studied) were included in the unit ore value, the share of non-ferrous base metals, other than copper, would rise to 14% in the case of Sulmierzyce North and to 6% in the Nowa Sól deposit (Table 7). However, in the present study, these metals do not contribute to unit ore values because they show low grades and no feasible extraction method is available to date (Gibas et al., 2015). Despite that, identification of critical by-product metals resources is a need, especially in deposits located at greater depths, where extraction of all valuable elements would be desirable due to resource policy reasons.

RELATIVE VALUE OF THE NORTHERN COPPER BELT SEDIMENT-HOSTED STRATIFORM Cu-Ag DEPOSITS

As pointed out by Mudd and Jowitt (2018), porphyry copper deposits, despite being the most widely mined, show rather low average unit ore values among the various types of deposits (US$40.4/metric ton of ore as of 2018). In comparison, the unit ore values of mined Polish sediment-hosted stratiform deposits are very high: on average US$225.33/metric ton ore, with a maximum of US$285.07/metric ton ore in the case of the Sieroszowice deposit as of December 2022. Unit ore values of the sediment-hosted stratiform Cu-Ag deposits located on the Fore-Sudetic Monocline and the Żary Pericline significantly exceed the average values for this type of deposit, which back in 2018 were on average US$109.9/metric ton of ore (Mudd and Jowitt, 2018). Even after taking into consideration the upsurge of metal prices and inflation, Polish deposits remain significantly "richer" than most porphyry, epithermal, IOCG and other sediment-hosted base metal deposits in the world (Table 8).

Despite very high average unit ore values, sediment-hosted deposits are currently not the most important exploration targets worldwide. Although Polish sediment-hosted deposits are either large (>5 Mt Cu; Sulmierzyce North) or giant (>10 Mt Cu; New Copper District deposits combined and Nowa Sól), and thus their mining scale and mine lifespan (life of mine, LOM) are very favorable, similarly to porphyries, their prevalence is much lower. Furthermore, they are located at greater depths, demanding much higher investments at the beginning of the LOM and higher operational costs, increased by ventilation and ore hauling. Nonetheless, given the mining and economic trends emerging in the 21st century (such as a decline in grades, the deposits becoming larger, enabling larger project scales, the growing demand and uses of copper and other metals, the location of deposits of critical metals in unfavourable jurisdictions), large and giant high-grade projects in the European Union's jurisdiction should become desirable for investors as well as for the banking and mining businesses. World-class examples of giant sediment-hosted deposits, such as Kamoa-Kakula in the DRC (Broughton and Rogers, 2010; Schmandt et al., 2013), Udokan in Russia (Zientek et al., 2014) and the Polish Permian deposits that are the subject of this paper, show that successful exploration and development of this type of deposit is profitable in the long run.

CONCLUSIONS

Combined, 7 undeveloped deposits account for >60% of copper and silver resources identified in Poland. Among these, Retków, Bytom Odrzański and Głogów are evident areas of future mining, as they neighbour actively mined deposits of the KGHM Polska Miedź. These deposits constitute a relatively well-investigated part of the Polish copper and silver resource base. To date, they are documented in the $C_2 + C_1$ category or inferred/indicated according to the JORC Code, and require only additional infill drilling before mining operations commence. Today, their estimated average unit ore values are lower than those of mined deposits: US$187.30/metric ton ore compared to US$225.33/metric ton ore. However, they show a slightly higher share of silver in the ore value.

Collectively, the deposits of the Northern Copper Belt host twice as much copper and silver resources as all the undeveloped deposits adjacent to the New Copper District. The Northern Copper Belt deposits are less well recognized and therefore are documented in the C_2 and $C_2 + D$ categories or inferred resources according to the JORC Code. Each deposit of the Northern Copper Belt shows a distinctive share of by-product metals. The share of silver in the Nowa Sól deposit ore value is very high, being similar to that of deposits surrounding the New Copper District to the north (Retków and Głogów), whereas the Sulmierzyce North and Mozów deposit silver/copper ratio is comparable to those of the Bytom Odrzański and Radwaniace–Gaworzyce deposits located close to the oxidized

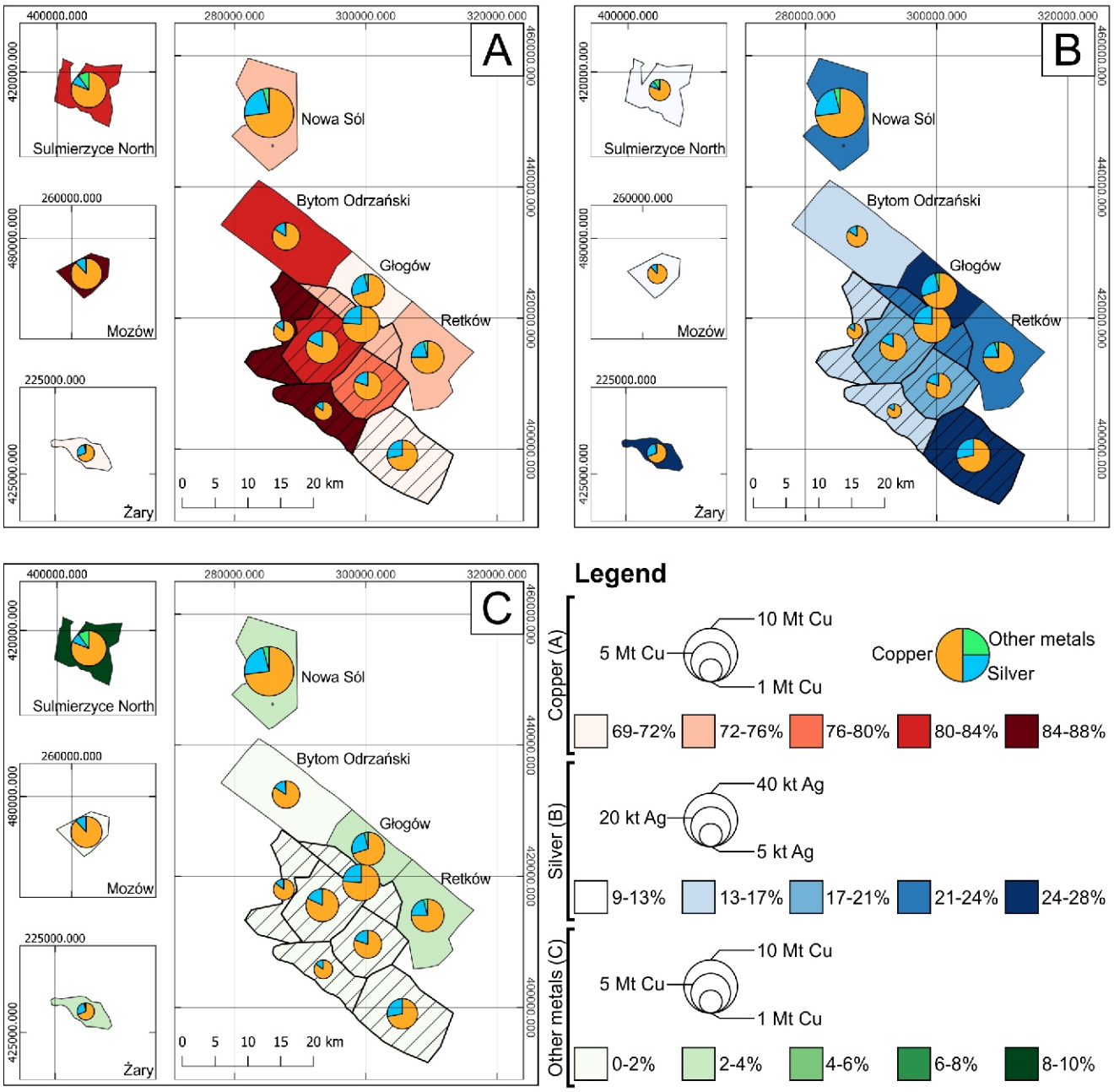


Fig 9. Share of copper (A), silver (B) and non-ferrous metals other than copper (C) in the unit ore value of the Polish Cu-Ag deposits. Mined deposits (economic reserves) are hatched

The names of the mined deposits are shown in Figure 1. All maps have the same scale

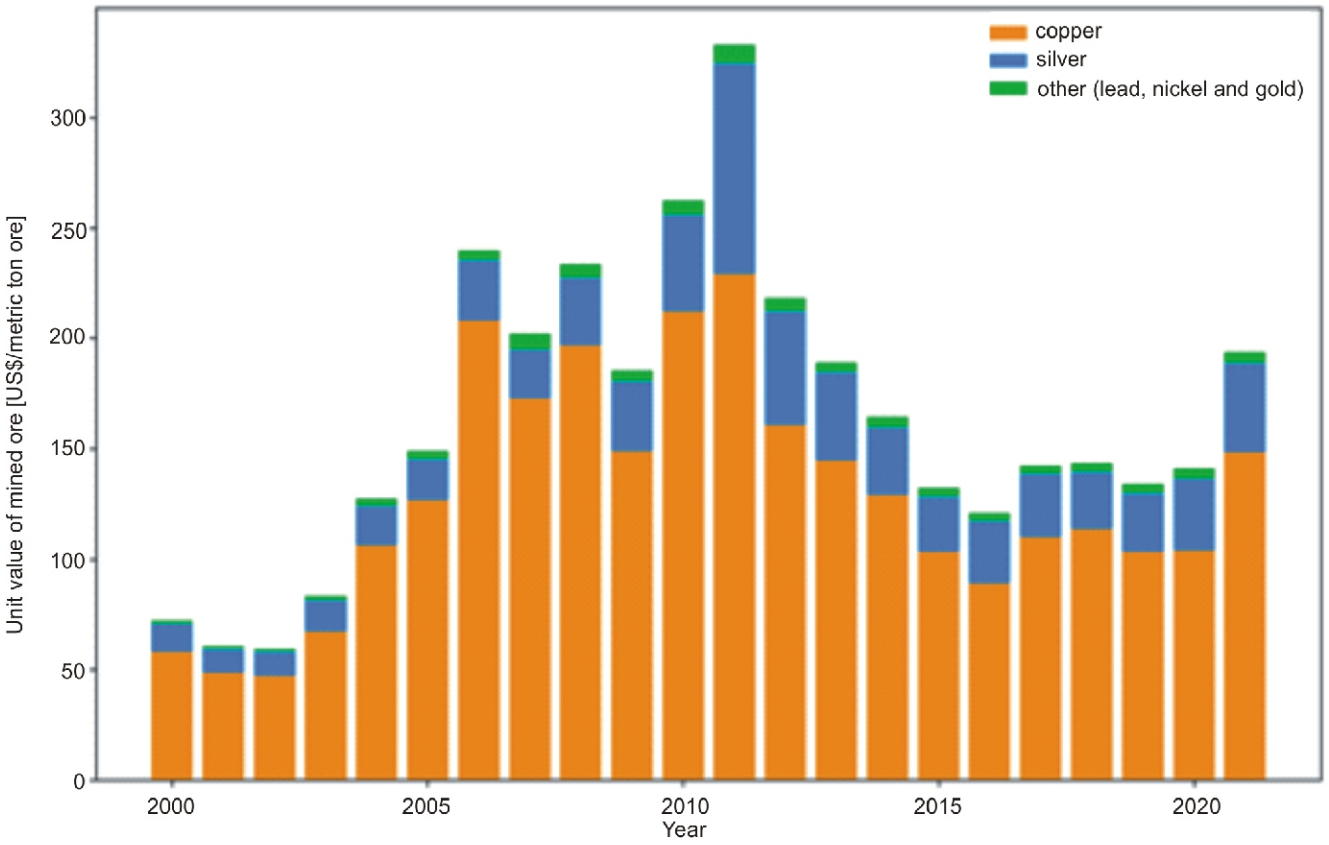


Fig. 10. An estimated unit value of ore mined in New Copper District mines (data from subsequent editions of the Balance of Mineral Resources of Poland from 2000–2021), calculated according to indexed real prices

Table 7

Metal endowment of Northern Copper Belt deposits including identified resources of all documented metals (Szuflicki et al., 2022)

	Metal	Deposit name		
		Nowa Sól	Sulmierzyce North	Mozów
Unit ore value (US$/metric ton ore)[1]	Copper	104.47	170.29	160.29
	Silver	32.18	19.28	19.20
	Lead	4.34	5.94	0.29
	Nickel	0.53	2.05	1.20
	Zinc	1.45	12.81	0.20
	Cobalt	1.12	4.37	0.61
	Molybdenum	0.92	3.60	0.51
	Vanadium	0.45	2.80	2.35
	Total	145.46	221.14	202.55
Share of metals in total unit ore value (%)	Copper	72	77	87
	Silver	22	9	10
	Other base metals excluding copper	6	14	3

[1] – all metal prices are as of December 2022 (The World Bank Commodity Price Data); zinc, cobalt, molybdenum and vanadium are shown in italics, because these metals are not recovered from active Polish mines. Please note that, in this contribution, zinc is included in the calculation of total unit ore value due to its elevated concentrations in the ores

Table 8

Comparison of unit ore values of new sediment-hosted stratiform deposits in Poland and selected world-class deposits of other types

Deposit name (deposit type)	Tonnage [kt ore]	Mean copper concentration [%]	Unit ore value (US$/metric ton ore)			
			Copper	Precious (Au + Ag + PGEs)	Other non-ferrous excluding copper	Total
Nowa Sól (SSC)	848 481	2.03	104.46	32.18	6.38	143.02
Sulmierzyce North (SSC)	296 043	2.06	170.28	19.28	21.25	210.81
Mozów (SSC)	233 176	2.40	160.28	19.20	1.70	181.18
Żary (SSC)	78 688	n.d.	139.36	56.72	6.47	202.55
Kamoa-Kakula[1] Ore Reserves (SSC)	235 000	4.47	374.90	0.00	0.00	374.90
Kamoa-Kakula[1] Indicated Mineral Resources (SSC)	1 387 000	2.74	229.46	0.00	0.00	229.46
Kamoa-Kakula[1] Inferred Mineral Resources (SSC)	339 000	1.68	140.58	0.00	0.00	140.58
Udokan Indicated Mineral Resources (SSC)	1 483 000	1.01	84.15	8.39	0.00	92.54
Udokan Inferred Mineral Resources (SSC)	932 000	0.89	74.59	10.68	0.00	85.27
Alpala Indicated and Measured Mineral Resources (porphyry)	2 663 000	0.37	31.14	15.52	0.00	46.66
Alpala Inferred Mineral Resources (porphyry)	544 000	0.24	20.02	6.72	0.00	26.74
Filo del Sol Ore Reserves (epithermal, porphyry)	259 100	0.39	29.05	26.06	0.00	55.11
Quellaveco[2] Measured and Indicated Mineral Resources (porphyry)	789 900	0.42	27.31	0.00	4.90	32.21
Quellaveco[2] Ore Reserves (porphyry)	1 333 400	0.57	47.49	0.00	8.14	55.63
Carrapateena Mineral Resources (IOCG)	950 000	0.57	47.46	14.51	0.00	61.97
Carrapateena Ore Reserves (IOCG)	220 000	1.10	88.16	25.53	0.00	113.70

Metal prices as of December 2022 (The World Bank Commodity Price Data); SSC – sediment-hosted stratiform copper deposits, IOCG – iron oxide copper-gold deposits; [1] – Kamoa-Kakula resource statement does not include by-product metals such as silver and cobalt; [2] – molybdenum is the single by-product metal reported in the ore reserve/mineral resources statement of the Quellaveco deposit
References: Kamoa-Kakula (Peters et al., 2020), Udokan (Simpson et al., 2016), Alpala (Artica, 2020), Filo del Sol (https://filocorp.com/operations/resource-estimate/), Quellaveco (AngloAmerican, 2021), Carapateena (OZ Minerals, 2022)

field. Sulmierzyce North stands out among all the deposits studied due to its high share of by-product metals, particularly lead, zinc and nickel, which results from the anomalously thick Kupferschiefer hosting most of the ore in the deposit.

Commodity price fluctuations strongly affected the unit ore values of these Cu-Ag deposits between 2000 and 2022. All undeveloped deposits showed above-average unit ore values in three periods: between April 2006 and September 2008 (the pre-crisis boom); between August 2009 and May 2015 (post-crisis rebound); and between November 2016 and now (the US-China trade wars followed by the COVID-19 crisis and the Russian invasion of Ukraine). The share of different metals, particularly silver, strongly influenced the unit ore values in this period. In the phase of the highest commodity prices (April 2011 for silver-enriched deposits and March 2022 for copper-dominated deposits) Polish Cu-Ag deposits were valued at levels 20–25% higher than those calculated as of December 2022 (The World Bank Commodity Price Data).

As of December 2022, the unit ore values of the Northern Copper Belt deposits are slightly lower compared to undeveloped deposits of the New Copper District. However, the 60-years praxis of documenting sediment-hosted stratiform Cu-Ag deposits in Poland demonstrated that increasing geological recognition results in increasing resources and, later, reserves. It is suggested that new infill drilling within previously delineated deposits would result in a sharp increase of their unit ore values, as was the case for the Lubin–Sieroszowice deposit.

In general, unit ore values of mined and undeveloped Polish sediment-hosted stratiform Cu-Ag deposits are significantly higher than those of most porphyry, epithermal and IOCG world-class deposits. This is because the Polish sediment-hosted stratiform Cu-Ag deposits show higher copper and silver grades compared to porphyry, epithermal and some IOCG deposits. Unit ore values of the sediment-hosted stratiform deposits studied are dominated by copper; however, their most distinctive feature is a relatively high share of silver in the ore value, of up to 28%. The average share of other metals in the unit ore value is only 3.9%.

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