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Perspectives for copper-silver deposits in Poland: current resources and future exploration opportunities

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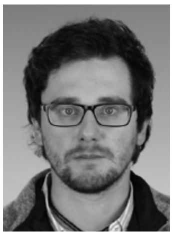

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A b s t r a c t. Poland is well-known for its significant sediment-hosted stratiform, Kupferschiefer-type copper-silver deposits in the Lubin-Sieroszowice Copper District hosted in the lowermost Zechstein rocks of SW Poland. These deposits have been extensively studied since their discovery in 1957. They are of great importance to the Polish economy, as the country is the largest producer of copper and silver in Europe. The Zechstein ore series in southwestern Poland contains numerous Cu-Ag deposits, prospects and occurreneces. However, the future of the copper-silver mining industry in Poland depends on the ability to access deeper deposits and improve existing extraction technologies. Exploration for new prospective areas will require advanced geological analysis to identify new ore bodies for evaluation and mining. This need for continuous exploration and development underscores the importance of continuing research and the utilization of innovative mining technologies to ensure the long-term sustainability of copper-silver resources. Almost all Cu-Ag prospective areas identified have been covered by exploration concessions in recent years, whether active or abandoned. The greatest potential for documenting Cu-Ag ore deposits exists in the copper-bearing belt which forms the northwestern extension of the Lubin–Sieroszowice deposit, as well as in the Ostrzeszów region, the Żary Pericline and the North Sudetic Synclinorium. Drilling exploration is currently ongoing in all areas with active concessions. Nevertheless, alongside these ongoing efforts, there is an increasing necessity for new brownfield and greenfield exploration, to investigate unexplored areas that have yet to be developed. Such exploration will be crucial for identifying new copper-silver deposits and securing the long-term future of Poland's mining industry.

Keywords: *Kupferschiefer, Rote Fäule, Cu-Ag deposits, resource base, prospective areas, SW Poland*

COPPER-SILVER RESOURCE DEVELOPMENT IN POLAND

The Kupferschiefer mineralization, a type of sediment-hosted stratiform copper deposits (SSC-type deposit), is associated with sedimentary sequences that are typically thin but exhibit significant lateral extent (Gustafson, Williams, 1981; Kirkham, 1989; Hitzman *et al*., 2005; Cox *et al*., 2007; Taylor *et al*., 2013; Zientek *et al*., 2015). The Kupferschiefer mineralization is located between the Rotliegend red bed sediments and the lowermost Zechstein (Fig. 1) and are hosted within the Zechstein copper-bearing series, which include the Weissliegend sandstones (Ws), the Kupferschiefer shales (T1) and the Zechstein Limestone (Ca1) carbonates (Fig. 1). Occasionally, mineralization reach the lowermost parts of the Lower Anhydrite (A1d) (Oszczepalski, Chmielewski, 2018). This sequence is also known as the Kupferschiefer-series and it serves as the host for the significant Cu-Ag ore deposits making it a key focus of geological and mining investigations.

The history of copper and silver mining in Poland is intimately linked to the Lower Silesia region. Systematic exploration as well as development of Cu-Ag deposits gained momentum in the 20th century. German geologists began exploration in the North Sudetic Synclinorium near Złotoryja in 1914 and in Grodziec in 1936. That same year, construction of the Lena mine started, followed by the development of the Konrad and Lubichów mines. These efforts laid the foundation for the region's growth into a key copper mining centre, later known as the Old Copper District. On the other hand, early geological research within the Fore-Sudetic Monocline near Wrocław was limited, with only a few boreholes drilled. Berger (1932) and Eisentraut (1939) studied the region's geology, but no copper-silver deposits were identified. The post-war period saw a major focus on recognizing the precise boundaries of the Fore-Sudetic Block to aid exploration efforts. This understanding was fundamental for the commencement of significant prospecting activities. For this purpose, in 1952–1953 the Bolesławiec-Głogów seismic profile was recorded. In a research project led by Jan Wyżykowski, the Polish Geological Institute (PGI) drilled 3 boreholes along this profile in 1955–1956, but the deposit was not reached for technical reasons. The first deep borehole drilled by the oil and gas industry (PPN in Piła) in the central part of the Fore-Sudetic Monocline in 1956 was subsequently examined by the Polish Geological Institute (Wyżykowski, 1958). The results obtained provided important support for further drilling activities. This culminated in the implementation of a copper ore exploration project by the Polish Geological Institute, which finally led to the discovery of the Lubin-Sieroszowice deposit in 1957 following the drilling of the Sieroszowice S-1 borehole. The first geological documentation of the deposit was completed in 1959, laying the foundation for understanding the structure of the Fore-Sudetic Monocline (Wyżykowski, 1958). Economic development following the successful exploration of the Lubin-Sieroszowice deposit was a turning point in the domestic copper industry, and modern mining techniques enabled deeper excavations and more efficient mining. Moreover, this discovery initiated a period of intensive exploration and allowed for the initial determination of prospects for further exploration of Cu-Ag ore deposits associated with the Zechstein copper-bearing series (Rydzewski, 1964, 1969). Early studies identified regional patterns

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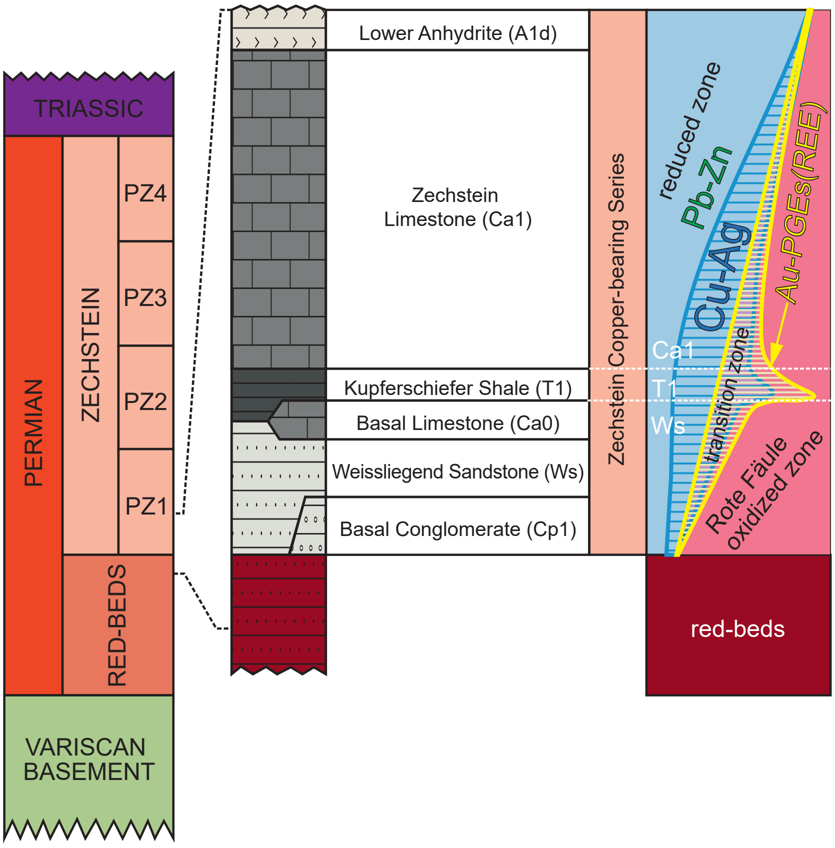

Fig. 1. The stratigraphic position of the Zechstein copper-bearing series and the distribution chart of geochemical zones that cross the strata (modified after Oszczepalski *et al.*, 2019)

of mineralization across Lower Silesia and Poland (Rydzewski, 1969; Wyżykowski, 1971b).

By 1968, Polish mining companies began exploiting deposits in the area, later known as the New Copper District or the Lubin-Sieroszowice Copper District (LSCD). By the late 20th century, mining in the Old Copper District began to decline, a process that started in the 1970s and peaked in the late 1990s with the closure of mines. The depletion of easily accessible ores and the development of advanced mining technologies led to a shift from the Old Copper District to the New Copper District, generating large-scale exploration. Additionally, political and economic changes, that took place in 1989, contributed to this decline. Despite the closure of the Lena (1973), Nowy Kościół (1967) and Konrad (1989) mines, these deposits remain listed as undeveloped due to economic downturns, not resource depletion (Malon *et al.*, 2024).

In parallel with further assessment of the LSCD, the Polish Geological Institute (PGI) continued exploration in its northern and eastern parts, following Wyżykowski's "General Exploration Project for Copper Ore Deposits, 1964". New boreholes, including Głogów IG 1, Gawrony IG 1, Dłużyce IG 1 and Zaborów IG 1, helped explore the previously unknown surrounding area (Wyżykowski, 1971b). In 1974, the PGI launched the "Exploration Project for Zechstein Copper Ores in the Western Fore-Sudetic Monocline, Żary Pericline and North Sudetic Synclinorium". This exploration demonstrated the potential to extend the Lubin-Sieroszowice deposits northwards at depths exceeding 1000 m (Gospodarczyk, 1976, 1978). The key finding was that the copper-silver ore bodies occurred in the close vicinity of oxidized zones (Rote Fäule) and the lateral contact between oxidized and reduced zones became an exploration guide for the regional prospection strategy (Oszczepalski, Rydzewski, 1983). The political transformation in Poland led to the discontinuation of exploration drilling for copper-silver ores by the PGI in 1992. However, research on archived core samples from PGI and the oil and gas industry increased to gather new data, supporting further survey efforts (Oszczepalski, Rydzewski, 1989, 1993, 1995). The findings were compiled into the "Metallogenic Atlas of the Zechstein Copper-Bearing Series in Poland" (Oszczepalski, Rydzewski, 1997) and additional studies identified regional mineralization in the LSCD (Oszczepalski, Rydzewski, 1998). Later evaluations refined resource estimates (Speczik *et al.*, 2007; Wirth *et al.*, 2007; Bachowski *et al.*, 2007, 2011). The new assessment identified numerous promising areas (Oszczepalski, Speczik, 2011a).

By the 1990s, the Polish copper-silver mining industry had integrated into the global market, benefiting from modern technologies and infrastructure, with the New Copper District cementing Lower Silesia's role as a major copper and silver producer in Europe. Research funded by the Ministry of Environment, PGI and KGHM Polska Miedź S.A. (KGHM PM) identified new Cu-Ag mineralization zones (Oszczepalski *et al.*, 2010, 2012a). In the following years, the cooperation with Miedzi Copper Corporation (MCC) was initiated to assess the possibility of documenting deposits in several areas of the Fore-Sudetic Monocline within previously designated prospective areas (Speczik *et al.*, 2011a, b; Oszczepalski *et al.*, 2012b; Chmielewski, Oszczepalski 2013). All of these recent findings contributed to the preparation of a new compilation map that illustrates the distribution of the Rote Fäule oxidation areas, which formed the basis for the most current evaluation (Oszczepalski, Chmielewski, 2015; Mikulski *et al.*, 2016; Oszczepalski *et al.*, 2016b). A new assessment of Cu-Ag resources in Poland (Zientek *et al.*, 2015) synthesizes available data on permissive tracks and estimates the location and quantity of undiscovered copper-silver resources associated with the Kupferschiefer series. In recent years, the expanded database has enabled a new summary assessment to be made to delineate prospective areas with prognostic, prospective and hypothetical resources based on information gathered from over 1600 boreholes (Oszczepalski *et al.*, 2020). Subsequent assessment of prospective areas and resource estimates resulted in changes in delineation criteria (Oszczepalski *et al.*, 2019). On this basis, search targets were set and several companies have lately drilled on their granted concessions. The exploration drilling program of MCC has resulted in the discovery of the Nowa Sól deposit, as well as in the recognition of the Mozów and Sulmierzyce North deposits.

This article provides a comprehensive review of the current state of copper-silver resources in Poland, highlighting the latest research results, exploration activities and uncovering new opportunities. Furthermore, strategic recommendations are outlined to enhance Polish exploration capabilities. These include continued investment in cutting-edge exploration activities, a more targeted approach to resource evaluation, and the adoption of sustainable mining practices. The work ultimately underscores the ongoing importance of these resources to the Polish economic future and their role in the broader context of global mineral production.

Cu-Ag DEPOSITS: STATUS AND GROWTH POTENTIAL

Currently, the only economically significant Cu-Ag deposits in Poland are located in the Fore-Sudetic Monocline (New Copper District), the North Sudetic Synclinorium (Old Copper District) and the Żary Pericline. Following the cessation of mining in the North Sudetic Synclinorium, the Polish copper industry now relies entirely on ores from the New Copper District. Cu-Ag ore extraction within the LSCD has been ongoing there for several decades (Malon *et al.*, 2024). In Polish geological and mining law, C1-classified Cu-Ag deposits are considered indicated resources with a moderate level of geological certainty. This category is defined by a medium density of exploration data, such as drilling results, geophysical and geochemical surveys, and petrographic analysis, along with limited insight into the structure of the ore bodies. Enhancing resource assessment requires more intensive drilling, advanced analytical studies, and evaluation of the economic viability of potential mining operations.

There are ten documented Cu-Ag deposits within Lubin-Sieroszowice Copper District within the Fore-Sudetic Monocline, six of which are currently being exploited: (1) Głogów Głęboki Przemysłowy, (2) Lubin-Małomice, (3) Polkowice, (4) Radwanice-Gaworzyce, (5) Rudna and (6) Sieroszowice (Table 1 and Figs. 2–4). KGHM PM holds the mining concessions for all of these deposits, with active operations at the Lubin, Polkowice-Sieroszowice and Rudna mines. There are four additional documented undeveloped Cu-Ag deposits: (1) Bytom Odrzański, (2) Głogów, (3) Retków and (4) Retków-Grodziszcze. Additionally, three more documented undeveloped Cu-Ag deposits are located in the North Sudetic Synclinorium: (1) Niecka Grodziecka, (2) Nowy Kościół, and (3) Wartowice.

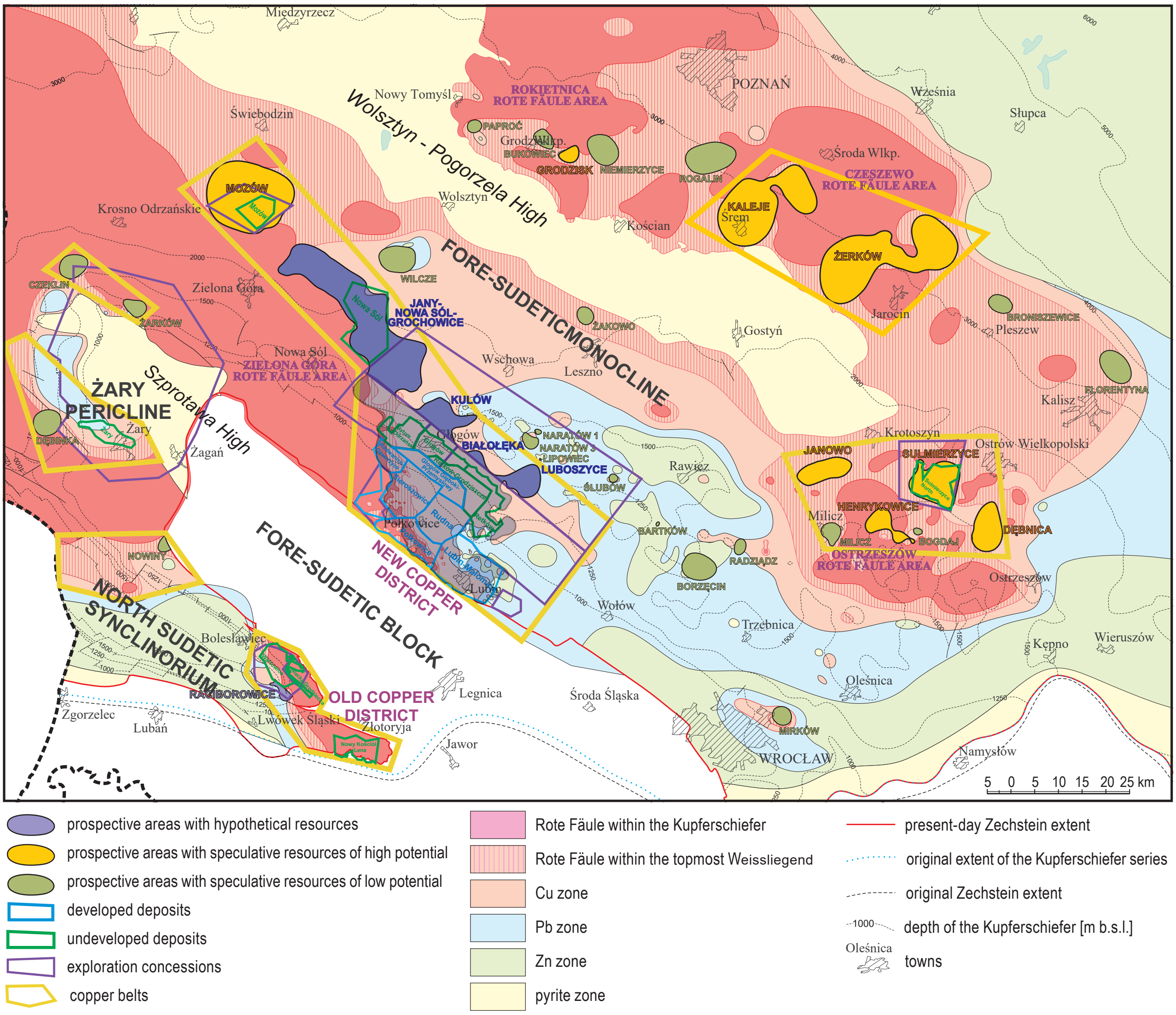

Fig. 2. Prospective areas, their association with the Rote Fäule, and metal zonation (modified after Oszczepalski *et al.*, 2019)

Recent years have seen a significant expansion of the copper-silver resource base in Poland through the documentation of new Cu-Ag deposits (Malon *et al.*, 2024). In 2019, the Żary deposit in the North Sudetic Synclinorium, located in the Lubusz Voivodeship, was documented and included in the national balance of resources. The total estimated resources for this deposit were classified as 76.69 Mt of ore in category D (probable resources). The documentation of new Cu-Ag deposits within the Fore-Sudetic Monocline continued in 2018–2020, with the official approval of another two significant Cu-Ag deposits: Nowa Sól (Speczik, 2019) in the Lubusz Voivodeship (preceded by preliminary documentation (Szamałek *et al.*, 2018) and Sulmierzyce North in the Greater Poland Voivodeship (Speczik, 2020a). These approvals led to a significant increase in the Polish documented Cu-Ag resources, with the Nowa Sól deposit contributing 848.48 Mt of ore in category C1 (indicated resources), while Sulmierzyce North added 267.17 Mt (147.17 Mt in category C2 (inferred resources) and 120 Mt in category D (probable resources). The documentation of these Cu-Ag deposits involved the application of modified threshold parameters for Cu-Ag ore deposits, differing from the legal regulations outlined by the Ministry of the Environment. One of the key changes was an increase in the maximum deposit depth, which ultimately reached 2160.53 m (average 1975.12 m) for the Nowa Sól deposit and 2059.59 m (average 1824.92 m) for the Sulmierzyce North deposit (Speczik *et al.*, 2020b; Zieliński, Speczik, 2023). Another major update in 2021 was the approval of the Mozów deposit in the Lubusz Voivodeship (Speczik, 2020b). This Cu-Ag deposit contributed 223.59 Mt of ore in category C2 (inferred resources) to the national resource balance. Ultimately, the maximum depth of the Mozów deposit is 2537.00 m (average 2471.51 m). Further expansion of the resource base continued in 2022 with the approval of the Retków-Grodziszcze deposit in the LSCD in accordance with the mining concession granted to KGHM PM. This deposit was delineated from the best-documented parts (category C1 – indicated resources) of the existing Głogów and Retków deposits, adding 416.02 Mt of ore in category C1 (indicated resourecs). These recently measured resources highlight the constant determinations to upgrade and expand the understanding of Cu-Ag depo-sits in Poland, further securing the country's position as a major producer in the global market.

Based on the latest edition of the "Bilans zasobów złóż kopalin w Polsce" (The balance of mineral resources deposits in Poland – in Polish), the total geological identified resources of copper and silver ores in the regions of the Fore-Sudetic Monocline, Żary Pericline and the North Sudetic Synclinorium amounted to a total of 3542.39 Mt of ore, containing 56.92 Mt of copper and 164.73 kt of silver (Malon *et al.*, 2024). The geological identified resources of Cu-Ag ores in developed deposits accessible in active mines within the LSCD amounted to 1487.46 Mt of ore, containing 27.05 Mt of copper and 78.06 kt of silver. Therefore, 41.99% of the total amount of geological identified resources were found in the developed deposits. The geological identified resources of undeveloped Cu-Ag deposits are primarily found in the depth range of 1,000 to 1250 m and even up to 1450 m (previously considered off-balance due to the depth of the ore bodies).

All undeveloped copper deposits adjacent to the northern margin of the LSCD are considered to be the most prospective resource base for Cu-Ag ore mining (Bytom Odrzański, Głogów, Retków and Retków-Grodziszcze). The identified economic resources in undeveloped deposits for the LSCD include a total of 535.891 Mt of ore, containing 6.420 Mt of copper and 27.618 kt of silver (Table 2). On the other hand for the North Sudetic Synclinorium, the total identified economic resources for undeveloped deposits consist of 103.085 Mt of ore, containing 1.422 Mt of copper and 5.344 kt of silver (Table 2). As noted above, the geological identified resour-ces of the North Sudetic Synclinorium are included in "Bilans zasobów złóż kopalin w Polsce" (The balance of mineral resources deposits in Poland – in Polish) because the discontinuation of production at the Lena, Nowy Kościół and Konrad mines happened as a result of an economic downturn and not due to the depletion of resources. In this case, the total geologically identified resources of all undeveloped LSCD deposits and those in the North Sudetic Synclinorium amount to ~638.976 million tonnes (Mt) of ore, containing 7.842 Mt of copper and 32.962 thousand tonnes (kt) of silver. The total inferred resources for the Fore-Sudetic Monocline (Mozów, Nowa Sól and Sulmierzyce North deposits) as well as the Żary Pericline (Żary deposit) are estimated at 1,293.712 Mt of ore, with 20.234 Mt of copper and 51.224 kt of silver (Table 3).

The mining and processing plants in KGHM PM have maintained a stable production level for many years. The documented Cu-Ag ore resources are gradually being depleted and the degree of consumption of Cu-Ag resources is very high (Szamałek, 2011). Over half a century of operation, KGHM PM has mined 1.278 bilion tonnes of ore and produced almost 23 Mt of copper (Table 4). Moreover, in order to sustain the current level of production from the industrial re-

Table 1. Identified resources and production in 2023 in developed deposits in the Fore-Sudetic Monocline (modified after Malon *et al.*, 2024)

Developed deposits	Identified resources			Economic reserves			Production	
	Ore [Mt]	Cu [Mt]	Ag [kt]	Ore [Mt]	Cu [Mt]	Ag [kt]	Cu [kt]	Silver [t]
Głogów Głęboki Przemysłowy	256.098	6.315	22.029	234.056	5.820	20.204	92	413
Lubin-Małomice	367.200	4.703	19.791	319.100	3.956	16.852	71	313
Polkowice	79.489	1.912	3.899	62.868	1.464	2.887	16	20
Radwanice-Gaworzyce	331.284	4.560	8.803	71.354	1.872	3.487	4	11
Rudna	296.255	4.750	13.041	194.115	3.136	8.458	75	264
Sieroszowice	157.134	4.809	10.494	140.193	4.301	9.353	185	511
Total	1,487.460	27.049	78.057	1,021.686	20.549	61.241	443	1532

Table 2. Identified resources in 2023 in undeveloped deposits adjacent to mining areas within the Fore-Sudetic Monocline and in undeveloped deposits of North Sudetic Synclinorium (modified after Malon *et al.*, 2024)

Undeveloped deposits	**Identified economic resources**			**Inferred marginal resources**		
Fore-Sudetic Monocline	Ore [Mt]	Copper [Mt]	Silver [kt]	Ore [Mt]	Copper [Mt]	Silver [kt]
Bytom Odrzański	2.247	0.930	54	169.551	3.271	6.517
Głogów	—	—	—	211.224	3.611	15.200
Retków	119.875	1.856	9.800	167.168	2.528	7.600
Retków-Grodziszcze	416.016	4.564	17.764	—	—	—
Total	535.891	6.420	27.618	547.943	9.410	29.317
North Sudetic Synclinorium	Ore [Mt]	Copper [Mt]	Silver [kt]	Ore [Mt]	Copper [Mt]	Silver [kt]
Niecka Grodziecka	10.291	0.141	0.501	2.205	0.030	0.070
Wartowice	79.316	1.165	4.260	17.286	0.201	0.582
Nowy Kościół	13.478	0.116	0.583	15.878	0.102	0.608
Total	103.085	1.422	5.344	35.369	0.333	1.260

Table 3. Inferred resources in 2023 in undeveloped deposits within the Fore-Sudetic Monocline and Żary Pericline (modified after Malon *et al.*, 2024)

Undeveloped deposits	**Inferred (i) and probable (p) resources**		
Fore-Sudetic Monocline and Żary Pericline	Ore [Mt]	Copper [Mt]	Silver [kt]
Mozów	223.589 (i)	4.270 (i)	5.724 (i)
Nowa Sól	846.262 (i)	10.960 (i)	35.320 (i)
Sulmierzyce North	147.173 (i)	3.728 (i)	4.380 (i)
Żary	76.688 (p)	1.276 (p)	5.800 (i)
Total	1,293.712 (i+p)	20.234 (i+p)	51.224 (i+p)

Table 4. Historical mine production in the New Copper District

Year	**Production of ore [Mt]**	**Cu metal [kt]**	**Year**	**Production of ore [Mt]**	**Cu metal [kt]**
1968	0.844	13.3	1996	25.988	473
1969	2.194	35.4	1997	24.741	463
1970	4.298	72.8	1998	26.087	488
1971	6.544	110.3	1999	26.925	520
1972	8.674	148.9	2000	27.142	513
1973	9.835	175.6	2001	28.785	536
1974	11.265	217.2	2002	28.48	572
1975	14.537	268,7	2003	25.67	612
1976	16.883	301.1	2004	26.124	626
1977	18.463	331.1	2005	25.443	586
1978	18.914	359	2006	25.903	553
1979	20.504	377	2007	23.686	408
1980	22.212	396	2008	22.75	474
1981	18.45	340	2009	23.161	491
1982	22.427	419	2010	22.448	472

Year	**Production of ore [Mt]**	**Cu metal [kt]**	**Year**	**Production of ore [Mt]**	**Cu metal [kt]**
1983	24.301	464	2011	22.985	459
1984	24.507	457	2012	**30.182**	**479**
1985	24.681	457	2013	**30.647**	**482**
1986	25.08	451	2014	**31.023**	**473**
1987	25.183	457	2015	**31.568**	**479**
1988	25.216	453	2016	**31.984**	**480**
1989	26.219	398	2017	**31.185**	**467**
1990	20.23	359	2018	**30.252**	**452**
1991	19.403	350	2019	**29.991**	**449**
1992	21.595	373	2020	**29.660**	**442**
1993	24.629	428	2021	**30.000**	**443**
1994	23.743	423	2022	**30.452**	**443**
1995	24.113	433	2023	**30.372**	**445**
				1,278.578	**22848.4**

sources of the Fore-Sudetic Monocline, KGHM PM supplements its own feedstock by purchasing concentrates and is also involved in the extraction of raw materials located outside the country. According to the published production and sales report of the KGHM PM in 2023, electrolytic copper production amounted to 592.40 kt in total with 443.00 kt coming from internal feedstock and 149.40 kt from external feedstock (Malon *et al.*, 2024). The smelting production of Ag in the same year amounted to 1532 t (silver at KGHM PM comes exclusively from its own feedstock).

Over the past 12 years the average annual ore extraction rate has been 30.600 kt. The average annual production of metallic copper and silver during this period amounts to 461 kt and 1453 t respectively (Table 5). Estimating the static sufficiency of geological identified resources in developed deposits at 1487.46 Mt of Cu-Ag ore (containing 27.05 Mt of copper and 78.06 kt of silver), it can be assumed that at the average annual ore extraction rate (Table 5), these resources will ensure production sustainability for a long but limited period of 49 years, and approximately an additional 66 years when including geological identified resources in undeveloped deposits amounting to 2031.16 Mt of Cu-Ag ore (29.62 Mt of copper and 85.59 kt of silver).

The resource timeframe may be extended by optimizing extraction to stabilize production at a slightly lower level or by mining deeper reserves and prospective deposits. To maintain current Cu-Ag output, it will also be necessary to develop the northern sections of the deposits down to and <1500 m.

Table 5. The extraction of Cu-Ag ore and the production of metallic copper and silver over the past 12 years (since the time when ore extraction by KGHM PM has exceeded an average of over 30.000 Mt)

Year	Extraction of Cu-Ag ore [Mt]	Cu metal production [kt]	Ag metal production [t]
2012	30.182	479	1342
2013	30.647	482	1393
2014	31.023	473	1384
2015	31.568	479	1407
2016	31.984	480	1482
2017	31.185	467	1490
2018	30.252	452	1471
2019	29.881	449	1455
2020	29.660	442	1423
2021	30.000	443	1522
2022	30.452	443	1533
2023	30.372	445	1532
average	30.600	461	1453

KUPFERSCHIEFER-HOSTED Cu-Ag STRATIFORM SYSTEM – A REVIEW OF CURRENT RESEARCH

Over the past 25 years, numerous studies have improved the understanding of the Kupferschiefer-type Cu-Ag mineralization within and around the LSCD, and several criteria were considered when assessing the potential for predicted deposits. These efforts refined the boundaries of known prospective areas and Rote Fäule zones, identified new targets and prompted reassessment of exploration potential. They also encouraged discussion regarding metal enrichment processes, underlining the need to critically review existing mineralization models to support future exploration.

Ores. Recently, many detailed investigations have been conducted on the ore minerals found in the ore bodies of the Fore-Sudetic Monocline encompassing both the LSCD and its surroundings. More than 140 ore minerals have been identified in Polish copper ore deposits (Pieczonka, Piestrzyński, 2006). The following six primary types of mineralization have been recognized: disseminated, nest, vein, lenticular, laminated and massive (Piestrzyński, 2007a). Cu sulphides form a large number of composites displaying mutual intergrowths and overgrowths and replacements of carbonate cements, feldspar and lithic grains. Extensive copper sulphide replacement of pre-existing framboidal pyrite clearly indicate a post-syndiagenetic origin of ore-stage copper assemblages (Oszczepalski, 1999).

The characteristics and composition of the Lubin-Sieroszowice ore bodies were described by Kucha (2003, 2007), Piestrzyński (2007a) and Pieczonka (2011) based on comprehensive mineralogical and geochemical studies. They thoroughly discussed the minerals of the Cu-S system (chalcocite, digenite, djurleite, anilite, covellite), the Cu-Fe-S system (bornite, chalcopyrite, idaite), the Cu-As-Sb-S system (tennantite, tetrahedrite, enargite), Pb and Zn minerals (galena, sphalerite), selenides (clausthalite, naumannite), silver minerals (native silver, stromeyerite, jalpaite, mackinstryite, melnikovite, silver amalgams), Au minerals (native gold, electrum, platinum gold, palladium arsenides), as well as nickel and cobalt minerals (cobaltite, gersdorffite, rammelsbergite, niccolite), molybdenum minerals (castaingite, molybdenite), uranium minerals (thucholite, uraninite), and iron minerals (pyrite, marcasite, thiosalts). The main copper minerals are chalcocite, bornite and chalcopyrite, accompanied by digenite, djurleite, covellite and tennantite. In the newly recognized Mozów and Nowa Sól deposits, chalcocite-bornite mineralization is present, accompanied by digenite, covellite and silver minerals, while the Sulmierzyce North deposit is characterized by chalcopyrite and bornite, associated with minerals from the tennantite-tetrahedrite group, as well as galena and sphalerite (Pietrzela, Bieńko, 2023, 2024). The use of scanning electron microscopy and electron microprobe analysis revealed the presence of new phases from the Cu_2S-CuS series: spionkopite, geerite, yarrowite, roxbyite, and anilite (Large *et al.*, 1995; Piestrzyński, Pieczonka, 1998; Kucha, 2007; Piestrzyński, 2007a; Chmielewski, Oszczepalski, 2017a; Chmielewski *et al.*, 2019; Mikulski *et al.*, 2020 and references therein) and among copper-iron sulphides bornite and chalcopyrite dominate with scant idaite, mooihoekite and haycockite (Kucha, 2003, 2007). An interesting initiative was the more detailed study (compared to the first geological documentation of the Lubin-Sieroszowice deposit compiled in 1959) of the ore mineralization in the discovery borehole Sieroszowice S-1, where chalcopyrite-bornite mineralization predominates accompanied by digenite and covellite (Oszczepalski, Chmielewski, 2017).

Second-stage (veinlet) mineralization is represented by both bedding-plane and diagonal veinlets, formed after lithification through natural hydrofracturing (Jowett *et al.*, 1987 with references therein)) and fracture fillings, representing the youngest tectonic deformation event (Salski, 1977; Kucha, 2003; Piestrzyński, 2007b). The deposits mainly contain chalcocite, bornite, and chalcopyrite veinlets. Furthermore, Kucha and Przybyłowicz (1999) distinguished gypsum-hematite-calcite-silver amalgams infilling fractures that cut through all earlier stages of mineralization. According to Chmielewski (2012) and Chmielewski *et al*. (2019), secondary sulphide mineralization occurs near tectonic deformation structures including faults, superimposed on primary ore mineralization and hematitized rocks.

Silver. Silver associated with copper is an equivalent component, jointly determining the economic value of specific deposit areas (Banaś *et al*., 2007; Kucha Mayer, 2007; Piestrzyński, 2007a). It has been found that silver occurs as isomorphic substitutions in copper sulphides, which are the most valuable forms of occurrence, with the highest concentrations observed in chalcocite and bornite and lower concentrations in digenite, chalcopyrite, covellite and tennantite (Kucha, 2003, 2007; Kozub-Budzyń, Piestrzyński, 2017). While silver does not form enrichments in the oxidezed zone, it is a crucial constituent in reduced rocks. Additionally, silver is observed in the form of its own minerals, such as native silver, electrum, stromeyerite, mckinstryite, jalpaite, naumannite and silver amalgams (Kucha, 2007; Kozub-Budzyń, Piestrzyński, 2017; Chmielewski *et al*., 2021a; Bieńko *et al*., 2023a; Pietrzela, Bieńko, 2023, 2024; Speczik *et al*., 2024).

Recent electron microprobe (EPMA) determinations revealed strong enrichments of Ag in geerite, chalcocite, and bornite, with lower concentrations in djurleite, yarrowite and digenite (Mikulski *et al*., 2020). Both the vertical and horizontal distributions show a distinct positive correlation silver with copper. The silver content in the copper ores ranges from 10 to 5780 ppm, with an average of 77 ppm, while the highest average content of 134 ppm Ag is typical of shale ores (Banaś *et al*., 2007 and references therein).

Associated elements. Copper-silver ores in Poland yield not only copper and silver but also gold, lead, nickel, selenium and rhenium, with sulphuric acid as by-products. KGHM Polska Miedź S.A. reported that in 2023, 442 kg of gold, 29.51 kt of lead, 2.13 kt of nickel sulphate, 73.86 t of selenium, and 9.38 t of rhenium were produced from the Cu-Ag ore (Malon *et al*., 2024). For these reasons, research is being conducted on the carriers of not only recovered elements (Bieńko, Pietrzela, 2022; Foltyn *et al*., 2022; Kijewski, Kaczmarek, 2024) but also other associated elements (Banaś *et al*., 2007; Spalińska *et al*., 2007; Mikulski *et al*., 2018, 2020; Bieńko, Pietrzela, 2022). A number of trace elements, classified as critical for the economy of the European Union, including Co, V (in reduced rocks) and REE, Se (in oxidized rocks) may eventually be recovered in the future from these deposits if proper ore-processing circuits and increasing demand are favorable. Cobalt is recognized as a strategic metal which is crucial for the world's development and transition to a low-carbon economy. Among Co minerals, sulphosalts dominate (cobaltite-gersdorffite series), arsenides (skutterudite and safflorite) are also common and sulphides from the siegenite group are rare (Piestrzyński *et al*., 1998; Bieńko *et al*., 2023a).

EPMA analyses confirmed high admixtures of Co in the transient pyrite phases up to 5000 ppm (Mikulski *et al*., 2020). The average content in the Kupferschiefer deposit is 50–80 ppm, with the highest concentration in the Lubin area (140 ppm). In the Nowa Sól deposit, a thin stratigraphic horizon, ranging from 0.06 to 0.59 m, shows notable concentrations of critical metals, including on average 318 ppm Co and 345 ppm Ni (Pietrzela, Bieńko, 2023; Bieńko *et al*., 2023a). Co and Re correlate with Ag (Bieńko, Pietrzela, 2022). However, to extract Co the application of modern hydrometallurgy techniques should be considered as a complementary process in processing. REEs are also gaining attention, as they, like Co, are recognized as critical raw materials for the EU. The highest ΣREE and ΣMREE concentrations are found to be associated with oxidised shales (Bechtel *et al*., 2001a; Sawłowicz, 2013; Oszczepalski *et al*., 2016a; Mikulski *et al*., 2020; Bieńko, Pietrzela, 2022).

Au and PGEs. Since the discovery of native gold in the Kupferschiefer shale (Piestrzyński *et al*., 1996), extensive studies have been conducted on the occurrence of gold and platinum-group elements (PGEs) in the copper-bearing Zechstein series within the LSCD deposits. These studies have examined both mine profiles and drill cores from archival boreholes (e.g., Oszczepalski *et al*., 1997; Piestrzyński *et al*., 1997; Oszczepalski, Rydzewski, 1998). In the following years, detailed studies were conducted on Au-Pt-Pd mineralization associated with the oxidized zone (Piestrzyński *et al*., 1996, 1997, 2002; Speczik *et al*., 1996, 1997; Oszczepalski, Rydzewski, 1998; Pieczonka *et al*., 2008; Kucha, Przybyłowicz, 1999; Piestrzyński, Sawłowicz, 1999; Piestrzyński, Wodzicki, 2000; Bechtel *et al*., 2001a; Oszczepalski *et al*., 2002; Oszczepalski, 2007). Gold is recovered from Cu-Ag ore during technological processes, despite the fact that reduced rocks are poor in these metals (typically <50 ppb). Only locally have high concentrations of Au, Pt and Pd been found in black shales (including thucholite shales) west of Lubin (Kucha, 2007 with references therein). The latest studies demonstrate that the highest gold and PGE concentrations occur in oxidized rocks, especially in the transition zone, with the Polkowice and Sieroszowice being key areas. Comprehensive analyses of the mineral composition in those areas have confirmed the presence of gold and PGE in multiple parageneses, featuring main minerals such as hematite, native gold, electrum, clausthalite, tetra-auricupride, palladium arsenides, sobolevskite and silver amalgams (Kucha, Przybyłowicz, 1999; Piestrzyński, Wodzicki, 2000; Piestrzyński, 2007a; Pieczonka *et al*., 2008, 2019). Intergrowths and inclusions of native gold in hematite and Cu sulphides have been demonstrated (Piestrzyński, 2007a). This paragenesis is accompanied by low concentrations of Cu sulphides, with chalcopyrite dominating, along with bornite, pyrite, and Cu-S type sulphides. In the Polkowice-Sieroszowice mine area there was documented up to 95 ppm Au with a 0.23 m-thick horizon yielding 2.37 ppm Au, 0.138 ppm Pt and 0.082 ppm Pd (Piestrzyński *et al*., 2002; Pieczonka *et al*., 2008). Other mining parcels found in the Radwanice and Gaworzyce areas are also appropriate for selective exploitation in underground workings through the oxidized rocks (Oszczepalski, 2007; Chmielewski *et al*., 2021b). Oxidized rocks are characterized by an increased content of gold and PGE, with palladium seemingly dominating in the central parts of the oxidized areas, while gold and platinum are more prevalent on their outskirts (Oszczepalski, Chmielewski, 2015). Since the Au-Pt-Pd mineralization is present in oxidized rocks, nearly all oxidized areas can be considered prospective (Oszczepalski, 2007; Mikulski *et al*., 2011; Oszczepalski, Chmielewski, 2015; Mikulski, Oszczepalski, 2020), although the currently identified concentrations do not form a deposit that meets the conditions for independent mining exploitation.

Rote Fäule. Although red-stained rocks within the Zechstein copper-bearing series were known in the past, it was only after in-depth petrographic research that it was confirmed these are secondarily oxidized, hematized rocks, called Rote Fäule in Germany (Rydzewski, 1969, 1978). These rocks are barren of sulphide mineralization and red because pyrite and iron-bearing sulphides have been replaced by hematite (Rydzewski, 1978; Oszczepalski, 1989). It turned out later that the distribution of hematitic alteration zones can be a valuable exploration guide (Oszczepalski, Rydzewski, 1983, 1991, 1993).

In the central parts of the oxidized zone, the oxidative alteration is remarkably voluminous and may locally reach even the lowermost portions of overlying Lower Anhydrite horizon (Oszczepalski, Rydzewski, 1991; Oszczepalski, Chmielewski, 2018). Outwards, the redox front cuts across the strata, moving from anhydrites to the lowermost part of the Weissliegend as it moves farther from the Rote Fäule. In oxidized rocks, iron oxides (hematite, goethite) are dispersed throughout the strata or concentrated to form red spots, bands or earthy masses. They occur principally as submicroscopic red pigment and aggregates. Common hematite spherules have a shape, size and mode of occurrence strongly suggesting that they are pseudomorphs after pyrite framboids (Oszczepalski, 1989, 1999; Oszczepalski, Rydzewski, 1991). Oxidized rocks locally contain small amounts of sparsely dispersed sulphides (mostly pyrite, marcasite, chalcopyrite and covellite) with aureoles of red pigment or surrounded by replacement iron oxides (Oszczepalski, 1999; Chmielewski, Oszczepalski, 2017b; Oszczepalski *et al*., 2017a, b). Relict mineralization indicates that the hematitic alteration overlapped deposition of the earliest sulphides indicating the progressively advancing range of the Rote Fäule formation. Superposition of authigenic illite and calcic alteration is the next rule within the oxidized rocks (Bechtel *et al*., 1999; Oszczepalski, 1999). Based on earlier studies (Speczik, Püttmann, 1987; Püttmann *et al*., 1989, 1991) and a summary of the characteristics of these rocks (Oszczepalski, Rydzewski, 2007 with references therein), it is evident that these rocks contain minimal organic material (<0.5% TOC) with bitumens showing a low presence of hydrocarbons, isoprenoids and porphyrins, but a high proportion of aromatic hydrocarbons, asphaltenes, and phenanthrenes (e.g., Bechtel *et al*., 2000, 2001b, 2002; Sawłowicz *et al*., 2000; Oszczepalski *et al*., 2002; Speczik *et al*., 2003; Kotarba *et al*., 2007). The Rock-Eval method was used to determine the maturity of organic matter (Bechtel *et al*., 2002; Oszczepalski *et al*., 2002; Więcław *et al*., 2007; Pieczonka *et al*., 2008, 2017; Oszczepalski, Speczik, 2009), similar to earlier studies by Püttmann *et al.* (1991) for the Grodziec Synclinorium. It was shown that oxidized shales are characterized by low HI values (<50) and high OI and T_{max}. A characteristic feature is also the presence of relic vitrinite and vitrinite-like macerals (secondary bituminite) with high reflectivity of up to 1.33% R_o (Nowak *et al*., 2001; Oszczepalski *et al*., 2002; Speczik *et al*., 2003, 2007), indicating maximum palaeotemperatures for the Kupferschiefer shale up to 135°C. Maturation parameters suggest the presence of degraded hydrogen-poor and aromatic-rich kerogen of III type and maximum palaeotemperatures between 100 and 130°C (Bechtel *et al*., 2001b; Speczik *et al*., 2005; Więcław *et al*., 2007). The alteration scale of organic material proved to be an excellent additional tool in exploration for the Kupferschiefer-type Cu-Ag deposits.

The new distribution map of oxidized areas (Oszczepalski, Rydzewski, 1997) was continuously updated in the following years as more detailed investigations were carried out (Oszczepalski, Rydzewski, 2007; Oszczepalski, Speczik, 2011a; Oszczepalski, Chmielewski, 2015; Oszczepalski *et al*., 2016b). Currently, at least 33 such areas of varying sizes are distinguished in southwestern Poland (Oszczepalski *et al*., 2019, 2020). The distribution of red-spot zones in the Polkowice-Sieroszowice area was described by Pieczonka (2000) and Piestrzyński *et al.* (2002). Basing upon macro- and microscopic observations, two types of red spots have been distinguished, formed during two different oxidation stages (Pieczonka, 2000; Piestrzyński *et al*., 2002; Pieczonka *et al*., 2008). According to Kucha (2003), secondary hematite occurs in four different assemblages and may suggest four epigenetic mineralization stages.

Transition zone. Following the identification and definition of the transition zone between oxidized Rote Fäule and reduced rocks (Rydzewski, 1978; Oszczepalski, Rydzewski, 1991), many studies have been conducted to provide a complete characterization of this zone (e.g., Oszczepalski, 1989, 1994, 1999; Bechtel *et al*., 2002; Oszczepalski *et al*., 2002; Piestrzyński *et al*., 2002). The transition zone exhibits intermediate characteristics between oxidized and reduced rocks (Fig. 3) featuring hematite (often as hematitic framboids), sparse infrequent sulphide grains, and a slight increase in copper content compared to the oxidized area (Oszczepalski, Rydzewski, 2007). A characteristic feature of this zone is the presence of sparsely disseminated relics of sulphides with hematite pigment halos, as well as partial replacements of chalcocite, covellite, and chalcopyrite by hematite and goethite, indicating that sulphidation preceded oxidation (Oszczepalski, 1999). This means that hematite emplacement overprinted early copper minerals. Organic matter alteration follows a pattern closely associated with metal zonation. In particular, the dominance of aromatic hydrocarbons is diagnostic of the transition zone and may serve as an additional tool for exploration (Bechtel *et al*., 2001b; Oszczepalski *et al*., 2002).

Research on this zone accelerated following the discovery and subsequent identification of Au-Pt-Pd mineralization in the oxidized rocks (e.g., Piestrzyński *et al*., 1996, 2002; Kucha, Przybyłowicz, 1999; Piestrzyński, Wodzicki, 2000; Bechtel *et al*., 2001a; Oszczepalski *et al*., 2002; Oszczepalski, 2007; Pieczonka *et al*., 2008), as the highest concentrations of Au and PGE were found in the transition zone. Detailed investigations by Piestrzyński *et al.* (2002) and Pieczonka *et al.* (2008) uncovered three forms of gold at the interface between oxidized and reduced zones: native gold associated with hematite and covellite, electrum associated with chalcocite, digenite, bornite and minor clausthalite, galena, tetra-auricupride, spionkopite, yarrowite and tiemannite, as well as invisible gold dispersed in coarse-grained hematite and Cu sulphides.

Recent studies involving detailed microscopic observations and microprobe analyses in the transition zone at the Polkowice and Radwanice deposits, and in the north-west extension of the Lubin-Sieroszowice deposit, have identified remnants of Cu sulphides, which have been partially replaced by iron oxides and a unique assemblage consisting of these iron oxides and relict copper sulphides (Chmielewski, 2011, 2014; Chmielewski *et al.*, 2015; Oszczepalski *et al.*, 2017b, 2019). In this zone, remnant covellite predominates, with minor amounts of chalcocite, bornite, digenite, chalcopyrite, galena, pyrite, tetrahedrite, tennantite, native gold, electrum, domeykite, loellingite, saflorite, and hauerite. Phases of the Cu-S system identified include chalcocite, djurleite, anilite, geerite, spionkopite, yarrowite, and covellite. Silver is present as Cu and Fe isomorphic substitutions in the crystal lattice of copper sulphides of the Cu-S and Cu-Fe-S groups and in As and Sb sulphosalts and occurs also as electrum, stromeyerite, silver amalgams and substitutions in remnant copper sulphides, mainly in covellite, chalcocite and tetra-auricupride (Chmielewski *et al.*, 2021a, b). A thin interval of the transition zone in the Mozów deposit contains relicts of chalcocite, digenite, anilite, geerite and covellite along with native copper, silver, gold, and bismuth, as well as silver amalgams, auricupride, nickeline and a group of copper selenide-sulphides (Krzemiński, Speczik, 2013; Krzemiński, 2015b). Relic mineralization indicates that originally reduced strata underwent far-reaching degradation, due to intense oxidative alteration that converted copper sulphide-bearing rocks into red-coloured lithologies.

In the newly documented deposits adjacent to the Rote Fäule zones, ore bodies are dominated by chalcocite, digenite, djurleite, covellite, bornite, chalcopyrite and the tennantite-tetrahedrite group, along with native silver, silver amalgams, stromeyerite, the cobaltite-gersdorffite series, galena, sphalerite, pyrite, and native bismuth (Oszczepalski *et al.*, 2019; Bieńko, Pietrzela, 2022; Pietrzela, Bieńko, 2023, 2024). In the Nowa Sól and Mozów deposits, Cu-S-type minerals dominate, while in the Sulmierzyce North deposit, apart from the Cu-S-type minerals, the ore mineral assemblage is predominated by chalcopyrite, accompanied by bornite and the tennantite-tetrahedrite group minerals (Speczik *et al.*, 2022, 2024).

Metal and mineral zonation. It is generally accepted that copper minerals are vertically zoned, with chalcocite group sulphides predominating at the lower levels, followed by bornite, chalcopyrite, galena, sphalerite and pyrite towards the topmost parts of the copper-bearing series. Similarly, in the lateral distribution, there is mineral zonation oriented outwards from the Rote Fäule in the following order: hematite – chalcocite – bornite – chalcopyrite – galena – sphalerite – pyrite. Although ore textures are complex, replacement paragenesis indicate that base-metal sulphides postdated pyrite, Cu-S sulphides sequentially replaced Cu-Fe-S sulphides (bornite, chalcopyrite), and that hematite replaced both pyrite and Cu sulphides. Metals are consistently distributed in a sequence of Fe^{3+}(Au, PGE) – Cu(Ag) – Pb-Zn-Fe^{2+} in distinct solubility- and redox-controlled large-scale zones surrounding the hematitic Rote Fäule altered areas (Oszczepalski, Rydzewski, 1991, 1997; Kijewski, 1998).

Even though Wodzicki, Piestrzyński (1994) holded the opposite opinion, stating that "the supposed horizontal zonal pattern of Cu-Pb-Zn may not be helpful in regional prospecting", the zonal regularity is commonly used in exploration.

Extremely valuable and comprehensive information on the patterns in the distribution of ore minerals in the copper-silver ore deposit of the Fore-Sudetic Monocline was provided by Piestrzyński (2007a), Pieczonka *et al.* (2007) and Pieczonka (2011). Based on many profiles, cross-sections and maps, a zonation of ore occurrences in vertical profiles and horizontal distribution was observed, where chalcocite dominates the centre of the deposit, and towards the east,

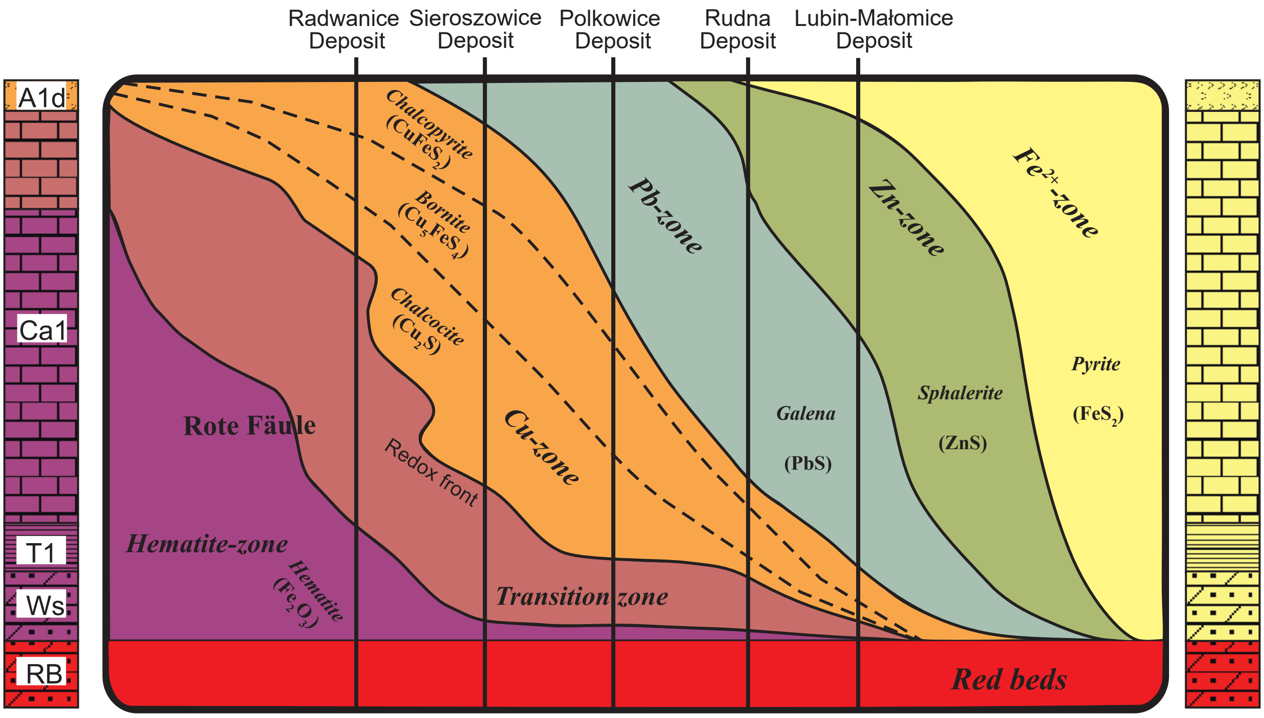

Fig. 3. Schematic section of the Kupferschiefer-series showing the spatial relationship between ore mineralization and the oxidized Rote Fäule front position (modified after Oszczepalski, Chmielewski, 2019). Explanations: **A1d** – Lower Anhydrite, **Ca1** – Zechstein Limestone, **T1** – Kupferschiefer Shale, **Ws** – Weissliegend Sandstone, **RB** – red beds

bornite, chalcopyrite (locally tennantite), galena, and sphalerite appear sequentially. According to Piestrzyński (2007a), no horizontal zonation was observed on the scale of the deposit as, in two small areas at the southwestern end of the deposit, chalcopyrite predominates, which slightly disrupts the well-documented regional zonation (cf. Pieczonka, 2011). Since the mineralization is solubility- and redox-controlled, it can be assumed that the dominance of chalcopyrite in these areas, where oxidized rocks lie beneath the ore bodies, is a result of the leaching of pre-existing Cu-S series sulphides by mineralizing solutions.

In areas adjacent to the oxidized zones, a distinct zonation is observed, transitioning from oxidized rocks with relic copper mineralization and gold and PGE enrichments, through Cu-Ag ore bodies dominated by Cu-S type sulphides at the reduced side of the Rote Fäule front, to Cu-Fe-S-type mineralization along with galena and sphalerite (Oszczepalski, Rydzewski, 1997; Pieczonka *et al.*, 2007; Chmielewski, 2011, 2014; Pieczonka, 2011; Oszczepalski *et al.*, 2017b, 2019). Metal zonation of the Nowa Sól deposit can be drawn in the following order outwards from the Rote Fäule: Au-REE-bearing transition zone, REE-enriched Cu-bearing reduced zone, Ag-Re-Co-enriched Cu-bearing reduced zone, Pb-Ag-Co-enriched Cu-bearing reduced zone, and Pb-bearing reduced zone (Bieńko, Pietrzela, 2022). Progressive enrichment in REE content (including Y and Sc) outwards from the rocks with pyritic and Pb-Zn mineralization, across the Cu zone towards the oxidized (Rote Fäule) areas was registered (Sawłowicz, 2013; Oszczepalski *et al.*, 2016a). It is commonly accepted that the main causes of broad metal and mineral zoning is a result of the oxidative alteration of reduced rocks and large-scale lateral fluid passage from the feeder area to peripheral parts of the ore system. This is seen not only by the metal zonation and the distribution of mineral associations relative to the Rote Fäule, but also by the corresponding regional variability in organic matter maturity (Bechtel *et al.*, 2000, 2002; Oszczepalski *et al.*, 2002; Speczik *et al.*, 2005, 2007; Kosakowski *et al.*, 2007; Więcław *et al.*, 2007) as well as in the systematic spatial zonation in Cu isotope composition (Asael *et al.*, 2009).

Mineralization ages. There is no doubt that Cu-Ag ore deposits formed during the post-sedimentary process, but the various dating methods applied to different rock materials have yielded inconsistent results. It seems plausible that the processes leading to the formation of the Kupferschiefer ore patterns were possibly long-lasting, continuing for tens of million years after the deposition of the Kupferschiefer dated at 258 Ma (mid-Wuchiapingian; Peryt *et al.*, 2012). The dating results obtained so far can be categorized into six main periods: Permian-Triassic (Nawrocki, 2000, 2017), Triassic (Jowett *et al.*, 1987; Pašava *et al.*, 2007), Late Triassic (Mikulski, Stein, 2017), Triassic-Jurassic (Bechtel *et al.*, 1999), Early Jurassic (Kucha, 2007), Jurassic and Cretaceous (Alderton *et al.*, 2016), and Late Jurassic-Cretaceous (Symons *et al.*, 2011). The mineralization was dated using palaeomagnetic, K-Ar and Re-Os methods.

Jowett *et al.* (1987) obtained a Triassic paleomagnetic age of hematite (250–220 Ma) for hematitic Rote Fäule rocks of the Kupferschiefer series using samples from the Konrad, Lena and Nowy Kościół copper mines. Using a more recent apparent polar wander path, this age was corrected by Nawrocki (2000) to a range of 255–245 Ma (Upper Permian-Lower Triassic) and recalculated by Symons *et al.* (2011) to give an age of 254 ±6 Ma. Palaeomagnetic data for the rocks from the North Sudetic Synclinorium suggested an age of the Rote Fäule between 258 and 250 Ma (Nawrocki, 2017). Palaeomagnetic ages determined for 14 sites with reduced rocks at Sangerhausen (Symons *et al.*, 2011) have given an age 149 ±3 Ma (Upper Jurassic) of pyrrhotite and magnetite mineralization from reduced samples to provide data for the age of the Kupferschiefer mineralization and the possibility of a 53 ±3 Ma (Paleogene) mineralization age was also considered; however, the authors themselves made this data debatable. They came to the conclusion that, regardless of whether the 149 ±3 Ma age or the 53 ±3 Ma age is correct, the Kupferschiefer at Sangerhausen underwent a thorough chemical reorganization and remagnetization long after the Rote Fäule formation (cf. Jowett *et al.*, 1987). Thus, the Kupferschiefer ores and Rote Fäule in their view were not formed in coeval events.

The ages estimated by Bechtel *et al.* (1999) for the diagenetic illite present in the oxidized and ore-containing Kupferschiefer at many localities around the Fore-Sudectic Block derived from K-Ar dating are in the range of 216 to 190 Ma (Upper Triassic-Lower Jurassic). This age of neogenic illite provide indirect evidence for a diagenetic event coeval with the ore formation. Within limits of the uncertainties (±20 Ma), the ages obtained are in agreement with the date of the Kupferschiefer mineralization proposed by Jowett *et al.* (1987) from palaeomagnetic measurements and with the Re-Os dates obtained by Pašava *et al.* (2007) and Mikulski and Stein (2017). Maturity analysis revealed that the increased maturity occurred successively during the Triassic after rapid burial signifying ore formation in the 1–2 km range (Kosakowski *et al.*, 2007). Michalik (2001) reported K-Ar ages of authigenic illite in the Weissliegend sandstone from the Fore-Sudetic Monocline ranging from 186.2 ±4.2 to 158.8 ±3.6 Ma (Lower-Middle Jurassic). This age is attributed to fluid flow reflecting the timing of hydrocarbons migration.

Pašava *et al.* (2007) reported a Re-Os age of 240 ±3.8 (Middle Triassic) from Cu-rich Kupferschiefer whole-rock samples from the Lubin mine. Re-Os model ages of the bornite and chalcopyrite veinlets (Mikulski, Stein, 2017) are in the range between 268–256 Ma and for one of the chalcopyrite veinlets was 217 ±2 Ma. A Re-Os isochron age indicates a crystallization event in the Late Triassic (Norian), ~212 ±7 Ma. Therefore, they concluded that the Re-Os ages may suggest at least two stages of Cu-Ag ore mineralization in the Late Permian and Late Triassic. Subsequent Re-Os age determinations (Alderton *et al.*, 2016) on ore-bearing samples from the Rudna, Polkowice and Lubin mines have generated two age ranges: 264.7 ±1.8–245.2 ±1.6 Ma (Late Permian-Middle Triassic) and 184.3 ±2.2–162.3 ±0.8 Ma (Early-Middle Jurassic), with the oldest ages revealed for single specimens being 252 ±1.7 Ma (Late Permian) for bornite and 245.2 ±1.6 Ma (Middle Triassic) for chalcopyrite. The age of thucholite calculated from the U/Pb ratio is 180–175 Ma (Early/Middle Jurassic) coinciding probably with Jurassic extension tectonism (Kucha, 2003).

In summary, the collection of such a large range of diverse ages, from shortly after the Kupferschiefer shale deposition up to the Paleogene, is understandably surprising and not helpful in creating a fully reliable genetic model. Although most researchers claim that the obtained age data indicate the main phase of the ore formation process, they rather indicate the final phase of the mineralization study, with older ages erased. Importantly, the youngest ages do not contradict an earlier occurrence of mineralization. A striking example is the Late Triassic age of an ore veinlet (Mikulski, Stein, 2017), which implies that the disseminated ores (main form of mineralization) formed earlier or at latest contemporaneously.

The diversity of ages may be due to many reasons, such as different methods, research material and locations. Particularly embarrassing are the different dates obtained for materials collected from the same locations (e.g., Pašava *et al.*, 2007; Alderton *et al.*, 2016). Therefore, it is necessary to conduct future research jointly by a team of experts, using most of methods on the same material and from the same locations.

Genesis. Application of the correct genetic model is crucial for copper deposit exploration. In recent years, there is general agreement that Cu-Ag Kupferschiefer-type deposits formed due to the ascent of oxidising, metal-bearing basinal chloride-rich fluids up-dip the flanks of palaeohighs through reduced Zechstein rocks sealed by evaporites, as well as lateral flow outwards from the feeder area (Fig. 4). Flow was driven by fluid overpressure during burial produced by rift-related compaction supported by convection. The prevailing hypothesis suggests a dual metal source: primary – metamorphic and magmatic rocks of the Carboniferous basement; and secondary – red bed formations of the footwall Rotliegend. The metals-transporting solutions were heated brines, as indicated by the palaeotemperatures of indigenous vitrinite (<35°C) and other thermal maturity indicators. Sulphur isotopic ratios of disseminated Cu sulphides (generally from –2 to –44‰) suggest bacterial sulphate reduction as a main source of sulphur. Other potential sour-ces are: pyrite, organically-bound reduced sulphur and extrinsic sulphur. Additional reduced sulphur would have also been provided by subsequent thermochemical sulphate reduction; however, strongly negative $\delta^{34}S$ values are not consistent with an abiogenic model.

The precise timing of the ore bodies' formation remains controversial. Over recent years, four main genetic models have been formulated: early-to-late diagenetic (Oszczepalski, 1989, 1994, 1999; Oszczepalski, Rydzewski, 1991; Cathles *et al.*, 1993; Speczik, 1995), late diagenetic (Jowett *et al.*, 1987; Bechtel *et al.*, 1999, 2000, 2001b; Blundell *et al.*, 2003), multistage (Vaughan *et al.*, 1989; Wodzicki, Piestrzyński, 1994, 2007b; Alderton *et al.*, 2016), and late diagenetic-epigenetic (Kucha, Pawlikowski, 1986, 2010; Borg *et al.*, 2012).

The early-to-late diagenetic model evolved from an early diagenetic model after the discovery of Cu sulphide pseudomorphs after framboidal pyrite in reduced rocks and hematite pseudomorphic after pyrite framboids in oxidized rocks, which became evidence of the post-syndiagenetic formation of Cu-Ag mineralization (Rydzewski, 1978; Oszczepalski, 1989; Oszczepalski, Rydzewski, 1991). Currently, proponents of this model (Oszczepalski, 1999; Oszczepalski *et al.*, 2002; Oszczepalski, Chmielewski, 2019) maintain that the Cu-Ag ore deposits were formed through a process extending from early to late diagenesis, more likely in brine pulses rather than in a continuous process, as indicated by the wide and variable range of fluid-rock interaction manifested by complex replacement paragenesis of sulfides and hematite. This is also supported by cross-cutting relationships, the transgressive nature of the transition zone and metal/mineral zonation patterns relative to the redoxcline, reflecting the telescoped character of the mineralizing system. The presence of organic-rich reduced rocks with syngenetic pyrite created a geochemical barrier, enabling the extraction of metals from mineralizing fluids via the destabilization of chloride complexes. During the mineralization processes, the transition zone acted as a dynamic redox interface in which extensive destruction of the primary components led to the replacement of pyrite and copper sulphides by hydrothermal hematite with the redistribution of metals. Metal and mineral zonation, along with the distribution of copper and silver *versus* gold and platinum-group elements on opposite sides of the redox interface, resulted from the directional transport of metals by fluids spreading outwards from the centres of ascent, which were the Rote Fäule areas. The final outcome of the ore-forming process was the formation of Au-Pt-Pd mineralization on the oxidized side of the redox boundary and copper-silver ore deposits surrounding the oxidized areas. A joint action of fluid flows related to compaction of the Permian Basin, and brine recirculation caused by the geothermal field, was possible (Speczik, Berendsen, 1985; Cathles *et al.*, 1993).

The Triassic palaeomagnetic age of the Rote Fäule supports the proposed contemporaneous late diagenetic origin of the associated ore bodies and their formation immediately after continental rifting, that initiated convective flow of ore fluids considered to have been generated due to renewed extensional rifting during the Triassic (Jowett *et al.*, 1987). The results from K-Ar dating of illite (Late Triassic-Early Jurassic) suggest that the formation of neogenic illite was induced by the processes of ore formation during infiltration of the oxidizing brines into the reduced Kupferschiefer (Bechtel *et al.*, 1999, 2001b). Blundell *et al.* (2003) suggested that mineralization may have resulted from a large number of brief pulses of fluids, and cross-stratal flow was triggered by coseismic strain associated with normal faulting in relation to Permian-Triassic rift basin.

The multistage mineralization model proposed by Vaughan *et al.* (1989) was significantly expanded by Wodzicki, Piestrzyński (1994), who identified four types of mineralization: early diagenetic, peneconcordant late diagenetic, discordant late diagenetic and veining (polymetallic veinlets). They developed the concept of Kucha, Pawlikowski (1986) suggesting that formation of the ores lasted from the early diagenetic stage until Alpine tectonism. Mineralization of the peneconcordant main ore-forming stage took place as a result of mixing of a reducing fluid descending from hangingwall anhydrites with the ascending oxidizing fluids. However, this proposition by Piestrzyński (2007b) offered no viable data supporting a role of descending fluids and, indeed, downward fluid passage seems to be unlikely under lithostatic pressure during basin compaction. Michalik, Sawłowicz (2001) proposed a two-stage mechanism: syn-early diagenetic origin of the dispersed mineralization and later stages of mineralization of massive deposits in the Weissliegend, which lasted at least until the Late Jurassic. Alderton *et al.* (2016), while accepting the possibility of mineralization occurring in the Permian and Triassic, argue for subsequent mineralization processes in the Late Triassic and Jurassic generated by episodic fluid release, concluding that the mineralization

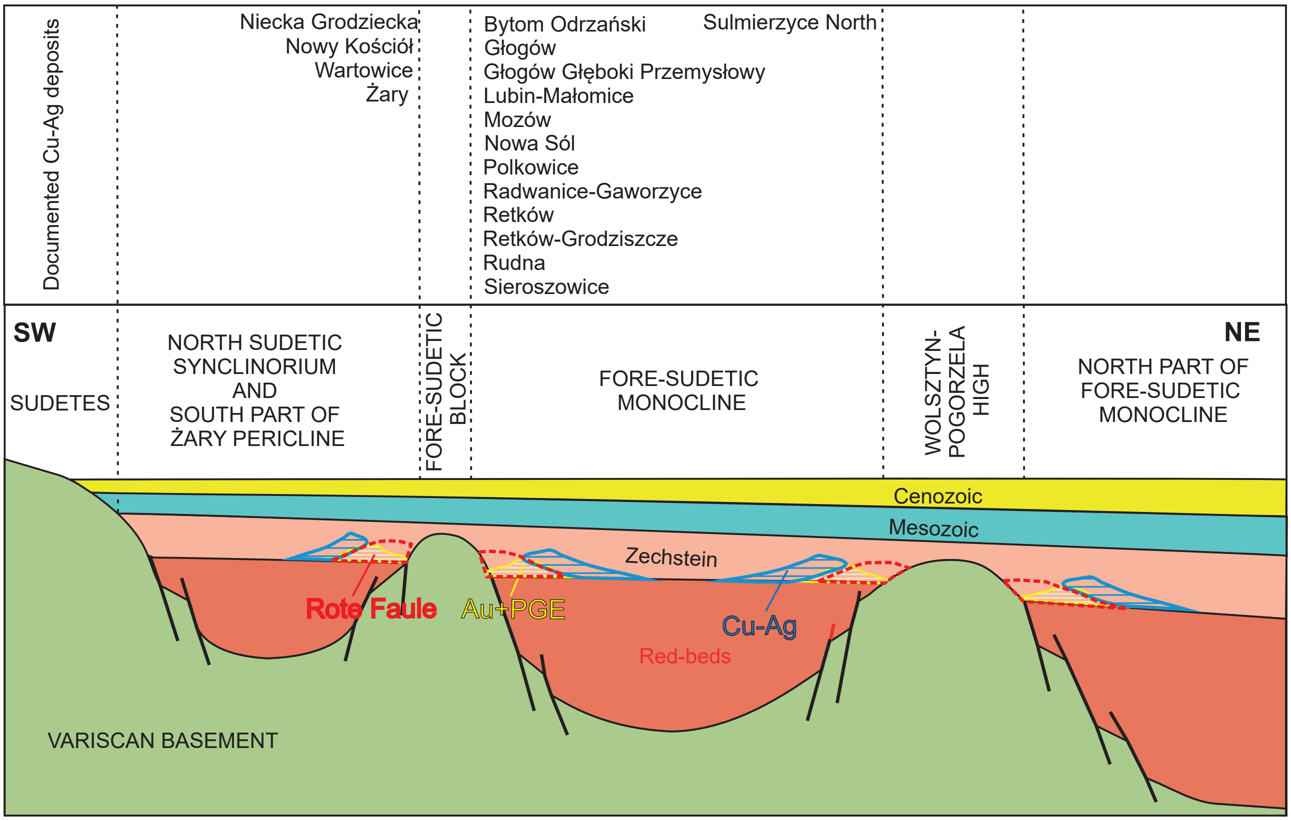

Fig. 4. Schematic geological cross-section through the areas of Cu-Ag ore deposits (modified after Oszczepalski, Rydzewski, 1997)

process may have taken place over a period of at least 100 Ma, in the least three main stages: Late Permian-Early Triassic, Late Triassic-Early Jurassic and Early-to-Middle Jurassic. According to Kucha, Pawlikowski (1986, 2010), the mineralization formed as a result of the mixing of two brines. The lower hot brine originated in the depocentre of the Polish Permian Basin and was then halotectonically expelled southwards to the Zechstein subcrops over a distance of ~300 km. This model, however, is hard to accept, since it would be difficult to allow the flow of large volumes of fluids over the Wolsztyn-Pogorzela elevation without the main aquifer, the Rotliegend strata. Despite the dating evidence for the formation of mineralization during the diagenesis of the Lower Zechstein formations (e.g., Jowett *et al.*, 1987; Bechtel *et al.*, 1999; Symons *et al.*, 2011), Borg *et al.* (2012) put forward a hypothesis of a late diagenetic-epigenetic origin for the main-stage mineralization. They argued that the major Kupferschiefer mineralization was formed within a time span from the Late Jurassic to the Mid-Cretaceous, as a result of major crustal rearrangement during the break-up of Pangea based on the recent paleomagnetic dating of mineralization age in the Sangerhausen region (Symons *et al.*, 2011) giving ages of 149 and/or 53 Ma.

Three main genetic models have been proposed for the Rote Fäule-related Au-Pt-Pd mineralization: (1) an epigenetic model: precious metals deposited in the Early Jurassic, 40–60 million years after the formation of copper deposits, as well as in the Early Cretaceous based on the age of lead amalgams and the vein association (Kucha, Przybyłowicz, 1999); (2) an epigenetic mixing model: from the mixing of gold-bearing descending solutions containing polysulphide Au complexes with gold-bearing oxidising ascending solutions, transporting Au in thiosulphate complexes (Pieczonka, Piestrzyński, 2000; Piestrzyński, Wodzicki, 2000; Pieczonka *et al.*, 2008), or as a result of gold deposition from oxidized gold-bearing solution at the redox interface, with Paleogene/Neogene alluvial gold not being excluded as a potential gold source, suggesting a very late timing for Au mineralization (Piestrzyński *et al.*, 2002). According to Pieczonka *et al.* (2008), the Au accumulations were formed after formation of Cu deposit when the oxidation processes started; (3) early-to-late diagenetic model: similar to Cu-Ag mineralization, Au enrichments formed due to the ascending migration of oxidizing solutions with gold in the form of chloride complexes as a result of interaction with a reducing environment; inclusions of gold in hematite and Cu sulphides indicate Au formation prior to the hematitization and Cu-Ag mineralization; the distribution of Cu-Ag mineralization zones and Rote Fäule-related Au-Pt-Pd mineralization indicates their mutual relationship within an integral mineralizing system; the spatial separation of Cu-Ag and Au-Pt-Pd mineralization is a result of the redistribution of metals caused by successive pulses of mineralizing solutions, leaching base metals from the oxidized rocks (Oszczepalski *et al.*, 1997, 2002; Oszczepalski, Rydzewski, 1998; Oszczepalski, 1999, 2007; Bechtel *et al.*, 2001a).

In summary, it should be noted that the proposed models, suggesting various ages and protracted timings, are mostly different and often mutually exclusive. The most objectionable are the long-term polyphase models. If we accept different mineralization datings and long-lived multi-stage formation mechanisms, we would have to accept the fact that the Rote Fäule, Cu-Ag, and accompanying Pb-Zn and Au-Pt-Pd mineralization, formed in a polycyclic manner over an extremely long interval. Hence this would require the assumption that the mineralization system was stable during a very long period of about 200 Ma or even longer, despite the multi-stage development of the Permian and Mesozoic basins, characterized by periods of increased extension and subsidence, separated by periods of tectonic compression.

The above analyses argue strongly for the early-to-late model that best interprets the principal characteristics of the Rote Fäule ore system by clearly indicating the role of ascending and lateral flows of mineralizing solutions. Remarkably, practical application of the model has allowed identification of successive prospective areas (cf. Oszczepalski, Rydzewski, 1997; Oszczepalski *et al.*, 1999, 2002, 2016b; Speczik *et al.*, 2005, 2014; Oszczepalski, Speczik, 2011a, 2014; Oszczepalski, Chmielewski, 2015). Within these areas, exploration targets were set, which, as a result of drilling projects, led to the identification and documentation of new Cu-Ag ore deposits (Szamałek *et al.*, 2018; Speczik, 2019, 2020a, b). Many papers have summarized the current (Oszczepalski *et al.*, 2017a, b, 2019, 2020; Zieliński *et al.*, 2017; Zieliński, Speczik, 2019) and final exploration results (Speczik *et al.*, 2020b, 2021, 2022, 2024).

REVISED ASSESSMENT OF PROSPECTIVE Cu-Ag RESOURCES

Prospective areas

The classification of prospective areas within the Fore-Sudetic Monocline, Żary Pericline and North Sudetic Synclinorium has changed over time, driven by updated geological data and exploration findings. This process considers factors such as proximity to known deposits, exploration efforts and criteria such as depth range and thickness of copper-bearing series. Ongoing enhancement is key to improving resource estimation, optimizing exploration and deepening our understanding of the region's geological potential. New technologies and analytical techniques will improve the identification of overlooked prospects. Multidisciplinary data, including geophysics and advanced drill core logging, will develop Cu-Ag mineralization modelling. Maceral analysis and Rock-Eval pyrolysis will aid in understanding the Kupferschiefer shale's thermal maturity. The application of machine learning techniques may further optimize resource identification and exploration planning.

Previous assessments

The need to identify and evaluate copper-bearing series intensified after 1971 when Poland's copper resources could not balance offset losses. Research into Zechstein copper-silver ores, the only resource base for the industry, became crucial. PGI also performed exploratory drilling in all prospective regions, even at depths surpassing 1000 m (Wyżykowski, 1971a)

Exploration programmes were supported by systematic research of oil and gas borehole cores, significantly increasing data on ore mineralization distribution (Gospodarczyk, 1978). The main exploration guide, the close spatial association of copper-silver orebodies with Rote Fäule oxidized rocks, formed the basis for the exploration strategy (Rydzewski, 1969, 1978; Oszczepalski, Rydzewski, 1983). Chemical studies led to the creation of the "Cu-Pb-Zn" database for 700 boreholes, the first digital metallogenic maps (Oszczepalski, Rydzewski, 1989), the identification of metal distribution patterns and the assessment of genetic implications (Oszczepalski, 1989; Oszczepalski, Rydzewski, 1991).

The continuation of long-term studies on borehole core samples conducted around the LSCD led to the development of subsequent assessments of the prospects for the occurrence of copper ores in Poland (Gospodarczyk, 1976, 1978; Gospodarczyk, Metlerski, 1986; Oszczepalski, Rydzewski, 1993, 1997; Oszczepalski, Speczik, 2011a; Oszczepalski, Chmielewski, 2015; Oszczepalski *et al.*, 2016b, 2019, 2020). The discussion on the prospective copper ore resource base in Poland has been further developed in complementary publications (Rydzewski *et al.*, 1996; Wirth *et al.*, 2007; Speczik, Oszczepalski, 2011; Oszczepalski, Speczik, 2014).

Initial evaluations (Gospodarczyk, 1976; Gospodarczyk, Metlerski, 1986) identified prospective areas located north and east of the Lubin-Sieroszowice deposit, down to depths of 2000 metres. The resource assessment included in the collective report "Prospective Resources of Mineral Deposits in Poland" as of December 31, 1990 (Oszczepalski, Rydzewski, 1993) estimated prognostic copper ore resources across six areas within the Fore-Sudetic Monocline, the Żary Pericline and the North Sudetic Synclinorium. The areas with the most significant deposit potential were identified in three zones of the Fore-Sudetic Monocline: Grochowice-Sława (to the north of the Lubin-Sieroszowice deposit), Borzęcin-Sulmierzyce (in the eastern Fore-Sudetic Monocline), and Mirków (east of Wrocław), in addition to two locations within the Żary Pericline (Żarków, Czeklin) and regions near the Old Copper District deposits in the North Sudetic Synclinorium.

The ongoing drilling efforts by PGI and the petroleum industry allowed for a considerable expansion of the database, which now includes 774 boreholes, paving the way for the publication of the "Metallogenic Atlas of the Zechstein Copper-Bearing Series in Poland" (Oszczepalski, Rydzewski, 1997). This atlas illustrates the distribution of oxidized Rote Fäule areas, with a specific focus on the boundaries of the Zielona Góra oxidized zone, a critical region where rich ore bodies were expected to occur. Besides the previously identified prospective areas, the Grochowice-Luboszyce area was marked, and to the north-east of the oxidized zone, based on the Jany 1, Kije 2, 9, and 10 as well as Mozów 1 boreholes, the Jany and Mozów prospective areas were determined. Only four boreholes from the oil industry were examined between the Grochowice-Luboszyce area and the Jany and Mozów areas: Bojadła 1, Dąbrowa 2, Zabór 1, and Zabór 2, which revealed moderate copper mineralization. Subsequently, the main element of the exploration strategy implemented by PGI has always been, and remains, to conduct exploration in areas adjacent to oxidised zones. It was already anticipated at that time that the Bytom Odrzański deposit and the Grochowice-Luboszyce area may be connected to the Jany and Mozów areas.

"Bilans perspektywicznych zasobów kopalin Polski" (Balance of prospective mineral resources – in Polish), published in 2011 and reflecting data as of December 31, 2009, resulted in the division of the Grochowice-Luboszyce area into the Kulów and Luboszyce areas after further drilling. Given that no drilling was performed by the petroleum industry north of the Grochowice M 9 borehole, it was concluded that, along the boundary of the Zielona Góra oxidized zone, the Bytom Odrzański and Kulów prospective areas were expected to extend in a northwestern direction (Oszczepalski, Speczik, 2009, 2011a; Oszczepalski *et al.*, 2010; Speczik, Oszczepalski, 2011).

The identification of the new Wilcze prospective area has enhanced the likelihood of discovering significant mineralization along the eastern boundary of the Zielona Góra oxidized zone. Moreover, on the Fore-Sudetic Monocline, 15 prospective areas were delineated (S-16, Kożuchów, Ślubów, Borzęcin, Mirków, Janowo, Milicz, Henrykowice, Sulmierzyce, Mozów, Wilcze, Paproć, Kaleje, Żerków, Florentyna), along with areas located on the Żar Pericline (Żarków, Czeklin) and within the North-Sudetic Synclinorium (Nowiny, Wartowice West). Beyond the Kulów and Luboszyce areas, significant focus was directed towards the prospective areas in the eastern Fore-Sudetic Monocline. These areas have been thoroughly investigated and identified as having high potential for major discoveries since the 1960s, based on promising boreholes (with Sulmierzyce 1 being the richest) and oxidative alteration (Oszczepalski, Rydzewski 1997; Speczik *et al.*, 1997). CUPRUM commissioned an assessment of mineralization in the Ostrzeszów region, resulting in the identification of three prognostic regions: Chruszczyn-Henrykowice-Dębnica, Szklarka and Brzostowo-Międzybórz (Rydzewski *et al.*, 1999).

As the flow of information increased, the ranges of prospective areas and resource estimates were made more precise in subsequent assessments (Oszczepalski, Rydzewski 1997; Speczik *et al.*, 2007, 2013; Oszczepalski, Speczik, 2009, 2011a, b; Oszczepalski *et al.*, 2012a). After carefully study of the previous research conducted by PGI and MCC, a large exploration programme was initiated focused on the predicted Cu-Ag deposits of the Fore-Sudetic Monocline within the granted exploration licenses. The first phase of work in 2011–2012 was carried out in the core repositories of the National Geological Archive and PGNiG. It involved handheld XRF analysis and further extensive laboratory examinations, including petrographic and chemical analyses

Following a commission from MCC group companies, studies were conducted to refine the identification and verification of prospective areas outlined in PGI's works. The reports included profiling and sampling cores from archival boreholes in the central Fore-Sudetic Monocline, mainly from the petroleum industry, which had not been examined by others. Samples were analysed mineralogically, petrographically, and chemically to determine element contents (Speczik *et al.*, 2011a, b; Oszczepalski *et al.*, 2012b). Successive studies of borehole cores from the northern part of the Fore-Sudetic Monocline allowed for the refinement of the boundaries of three regions with high concentrations of copper and silver (Kaleje, Żerków, Florentyna) and the identification of five new regions (Paproć, Bukowiec, Grodzisk, Niemierzyce, Rogalin). Additionally, these investigations enabled the delineation of the pyrite zone, which corresponds to the Wolsztyn-Pogorzela palaeohigh, separating the prospective areas of Greater Poland and Lower Silesia (Oszczepalski, Speczik, 2014; Oszczepalski, Chmielewski, 2015). A total of 411 archival boreholes were profiled, of which 216 underwent petrographic, mineralogical and chemical analyses, as well as field studies using an XRF spectrometer. For chemical analyses, 2,559 core samples and 147 point samples were collected, while 1,081 samples were gathered for petrographic and mineralogical studies.

Based on this, PGI in collaboration with MCC systematically carried out a series of resource assessments for the designated prospective areas in the entire southwestern part of Poland, focusing on the region to the north and northeast of the Lubin-Sieroszowice deposit (Oszczepalski, Speczik, 2014; Oszczepalski, Chmielewski, 2015; Speczik *et al.*, 2015; Mikulski *et al.*, 2016; Oszczepalski *et al.*, 2016b; Oszczepalski, 2017). As a result, the previous prospective areas were divided into four new prognostic areas: Grochowice I, Kulów, Białołęka, and Luboszyce, and five smaller areas were delineated: Sława, Grochowice II, Lipowiec, and Naratów I and II. Predicted regional trends for undiscovered deposits were identified (Zientek *et al.*, 2015).

Continuing along this path, MCC considered the most promising areas and selected targets for the drilling programme in the Mozów, Nowa Sól, and Sulmierzyce regions. Starting in 2013, MCC began drilling within the exploration concessions acquired (Krzemiński, Speczik, 2013; Oszczepalski, Chmielewski, 2015; Speczik, 2015; Zieliński *et al.*, 2017). The first boreholes in the Nowa Sól area turned out to be pioneering, displaying high copper and silver contents. This allowed for additional verification of the limits of the Zielona Góra oxidised zone and indicated the possibility of the Bytom Odrzański deposit continuing in a northwestern direction (Oszczepalski *et al.*, 2017a, b).

Given ongoing Cu-Ag exploitation in the LSCD, further research must focus on undeveloped deposits and unexplored areas. The feasibility of extraction from deep-seated ore bodies emphasizes the need to investigate new potential mineralization zones. Due to the sparse and irregular borehole network, the boundaries and metal quantities remain approximate and estimates of Cu-Ag resources carry uncertainty. As exploration advances and more detailed drilling data is obtained, these estimates may change. Continued prospection is necessary to refine the boundaries and parameters of copper mineralization.

Current evaluations

A new version of the "Polish Mineral Resources Balance" (Oszczepalski *et al.*, 2020), based on the data as of 2018, provides a comprehensive overview of the criteria and methods used for classifying and defining these prospective areas. The classification of resources into specific categories was based on the location of prospective areas in relation to the recognized deposits, as well as the maximum depths at which ores with Cu or Cu equivalent content of at least 35 kg/m² were found (Table 6). Following

Table 6. Criteria for classification of prospective resources within prospective areas (after Oszczepalski *et al.*, 2020)

Category of Cu-Ag resources	Location of the prospective area in relation to	Maximum depth of the copper-bearing series	Number of boreholes with Cu_e
Prognostic	proximal area	<1800	≥1
Prospective	distal area	<2000	>1
			1
Hypothetical		>2000	≥1

the methodology from the prior report (Oszczepalski, Speczik, 2011a), it is assumed that the 35 kg/m² Cu contour lines (or Cu when Ag data is missing) mark the boundary of the potential deposits aligning with the minimum ore resource content. These Cu-Ag resources were also adjusted according to the number of boreholes analyzed. This assessment process assembled the resources in line with accepted principles (Smakowski, Szamałek, 2011) into three main categories (Table 6):

- Prognostic resources, which were located directly adjacent to recognized deposits;
- Prospective resources, located in areas distant from recognized deposits at depths of up to 2000 m;
- Hypothetical resources, which were found at depths greater than 2000 m and those defined based on a single borehole (regardless of depth).

The process of evaluation led to the identification of 38 prospective areas (Table 7), each considered a potential site for further exploration and evaluation at the time (Oszczepalski *et al.*, 2020). This assessment identified 26 prospective areas at depths reaching up to 2000 m, including 6 areas with prognostic resources (Białołęka, Grochowice I, Krępa, Kulów, Luboszyce and Raciborowice), 4 areas with prospective resources (Dębnica, Henrykowice, Janowo and Sulmierzyce), and 16 areas with hypothetical resources (<2000 m) (Bartków, Bogdaj, Borzęcin, Czeklin, Dębinka, Grochowice II, Lipowiec, Milicz, Mirków, Naratów I, Naratów II, Nowiny, Radziądz, Sława, Ślubów, Żarków; Table 7). Beyond the prospective areas identified at depths of up to 2000 m, another 12 areas with hypothetical resources located deeper than 2000 m have also been delineated (Bukowiec, Florentyna, Grodzisk, Jany, Kaleje, Mozów, Niemierzyce, Paproć, Rogalin, Wilcze, Żakowo, and Żerków; Table 7).

According to the current assessment of Cu-Ag resources (Oszczepalski *et al.*, 2019), these were also classified into three groups based on their proximity to documented Cu deposits and the number of boreholes meeting the criteria of Cu equivalent productivity ≥35 kg/m², corrected by the number of boreholes analysed but ignoring the maximum depth (Table 8). As a result of this process, the following resource categories were identified:

- Hypothetical resources, these include resources that are directly adjacent to identified Cu-Ag deposits. Due to their proximity to existing deposits, they are considered to have a relatively high likelihood of being economically viable, but their potential still needs to be confirmed through advanced geological and drilling investigations;

Table 7. Prognostic, prospective and hypothetical resources of Cu-Ag ores in prospective areas (after Oszczepalski *et al.*, 2020, modified)

Resource cathegory	Prospective area	Area [km^2]	Depth range (MBGL)	Average thickness [m]	Average Cu grade [%]	Resources Cu [Mt]	Average Ag grade [ppm]	Recource Ag [kt]
Prognostic	Białołęka	13.8	1500–1600	2.11	1.07	0.779	44	3.203
	Grochowice I	15.8	1600–1800	1.1	2.59	1.125	170	7.386
	Krępa	9.61	400–500	3.32	0.72	0.574	16	1.276
	Kulów	48.64	1500–1700	1.59	3.14	6.071	86	16.628
	Luboszyce	36.19	1500–1600	1.34	0.97	1.176	57	6.910
	Raciborowice	7.78	900–1500	3.75	0.79	0.576	24	1.937
Total		131.82	400–1700	(N/A)	(N/A)	10.301	(N/A)	37.340
Perspective	Dębnica	49.8	1600–1800	0.51	6.21	3.943	167	10.604
	Henrykowice	28.4	1400–1700	1.08	1.73	1.327	34	2.396
	Janowo	50.7	1600–1900	1.11	1.64	2.307	36	5.065
	Sulmierzyce	69.75	1600–1900	2.13	2.18	8.097	26	9.657
Total		198.65	1400–1900	(N/A)	(N/A)	15.674	(N/A)	27.722
Hypothetical <2000 m	Bartków	0.52	1300–1400	0.32	4.18	0.017	71	0.029
	Bogdaj	7.5	1400–1600	1.58	1.52	0.45	34	1.007
	Borzęcin	31.7	1400–1600	0.51	4.91	1.984	–	–
	Czeklin	23.75	1600–1800	0.23	10.54	1.439	–	–
	Dębinka	25.64	1400–1600	2.3	0.69	1.017	44	6.487
	Grochowice II	2.35	1600–1700	1.52	1.6	0.143	23	0.205
	Lipowiec	0.12	1400–1500	0.6	2.06	0.004	64	0.011
	Milicz	13.6	1500–1700	1.86	0.89	0.563	26	1.644
	Mirków	12.84	1100–1300	1.17	1.56	0.586	–	–
	Naratów I	0.25	1500–1600	0.52	2.07	0.007	86	0.028
	Naratów II	7.88	1400–1500	0.55	3.99	0.432	319	3.456
	Nowiny	5.7	400–600	0.47	2.64	0.177	100	0.670
	Radziądz	6.25	1600–1800	1.65	0.93	0.24	7	0.180

Tab. 7. cont.

Resource cathegory	Prospective area	Area [km^2]	Depth range (MBGL)	Average thickness [m]	Average Cu grade [%]	Resources Cu [Mt]	Average Ag grade [ppm]	Recource Ag [kt]
Hypothetical <2000 m	Sława	9.48	1900–2000	0.45	1.92	0.205	161	1.717
	Ślubów	2.5	1300–1400	0.2	9.08	0.113	164	0.205
	Żarków	13.76	1000–1500	3.01	1.34	1.387	22	2.278
Total		163.84	400–2000	(N/A)	(N/A)	8.764	(N/A)	17.917
Hypothetical >2000 m	Bukowiec	12.17	2700–2800	0.6	2.87	0.524	89	1.625
	Florentyna	88.58	3200–4200	1	2.66	5.891	33	7.308
	Grodzisk	10.35	2700–2800	1.07	3.54	0.98	94	2.603
	Jany	11.51	2000–2200	1.34	2.13	0.821	–	–
	Kaleje	195.4	2700–3400	2.3	2.75	30.904	26	29.218
	Mozów	370.03	2100–2700	2.33	2.73	58.843	51	43.971
	Niemierzyce	32.74	2700–2900	1	4.16	3.405	21	1.719
	Paproć	6.39	2500–2700	0.1	17.27	0.276	421	0.673
	Rogalin	53.84	2900–3200	1.9	1.42	3.631	7	1.790
	Wilcze	162.21	2000–2500	0.49	5.15	10.29	537	106.706
	Żakowo	10.29	2100–2300	0.4	3.36	0.346	45	0.463
	Żerków	263.8	2600–3700	1.75	2.29	26.38	58	66.939
Total		1217.31	2000–4200	(N/A)	(N/A)	142.231	(N/A)	263.008
Total of prognostic. perspective and hypothetical		1711.62	400–4200	(N/A)	(N/A)	176.97	(N/A)	345.987

(N/A) – not applicable

Table 8. Criteria for classification of prospective resources within prospective areas (after Oszczepalski *et al.*, 2019)

Category of prospective resources	Location of the area in relation to documented Cu-Ag deposits	Number of boreholes with Cu productivity ≥35 kg/m²
Hypothetical	proximal area	>1
Speculative of high potential	distal area	>1
Speculative of low potential	distal area	1

- Speculative resources with high potential, these are resources located in areas distant from known Cu-Ag deposits but identified by more than one borehole. The high potential of these resources arises from the fact that multiple drilling points indicate the presence of Cu-Ag mineralization, suggesting that the area could be worth further prospecting. However, full certainty regarding their economic viability requires additional examination;
- Speculative resources with low potential, these resources have been identified based on only a single borehole. This limited data leads to a higher degree of uncertainty regarding their actual potential. While these resources may still hold value, they are considered less promising due to the lack of sufficient exploration and data.

The recent changes in the assessment of Cu-Ag prospective resources (Oszczepalski *et al.*, 2019) are the result of the gathering of additional archival and new exploration data as well as the exclusion of the depth parameter for copper-bearing series. This assessment takes into account, to a greater extent than the "Bilans perspektywicznych zasobów kopalin Polski" (Balance of prospective mineral resources – in Polish) (Oszczepalski *et al.*, 2020), the current results of MCC's drilling exploration (cf. Zieliński, Speczik, 2017, 2019; Zieliński *et al.*, 2017).

The outcome of this process was the designation of 36 prospective areas, each regarded as having potential for forthcoming exploration and detailed evaluation (Table 9 and Fig. 2). These revisions were made to enhance the classification process and provide a more accurate representation of the prospective areas. The updated assessment offers a stronger understanding of the Cu-Ag mineralization distribution, taking into account progress in drilling exploration at that time. As a result, some areas have been reclassified leading to a more precise identification of regions with high potential for Cu-Ag resource discovery and future development.

The current classification of Cu-Ag prospective resources has evolved between the assessments made by Oszczepalski *et al.* (2019, 2020) with some categories roughly corresponding to one another. The prognostic, prospective and hypothetical resource categories taken from the "Bilans perspektywicznych zasobów kopalin Polski" (Balance of prospective mineral resources – in Polish) (Oszczepalski *et al.*, 2020) classification align approximately with the hypothetical, speculative of high potential and speculative of low potential, categories from current assessment of Cu-Ag resources (Oszczepalski *et al.*, 2019). A key change in the previous assessment (Oszczepalski *et al.*, 2020) was the removal of the depth parameter to focus instead on proximity to documented Cu-Ag deposits and the number of boreholes meeting the Cu productivity threshold. This adjustment allowed for a more flexible approach to defining prospective areas, emphasizing geological potential rather than fixed depth limits. Additionally, the reclassification led to a clearer distinction between high- and low-potential speculative resources based on the number of boreholes confirming the presence of Cu-Ag ore mineralization. These changes contribute to a more precise identification of areas with higher potential for Cu-Ag discoveries refining exploration priorities.

Overall, this classification is a critical part of assessing prospective resources for Cu-Ag mineralization in Poland facilitating the prioritization of regions for further explora-

Table 9. Prospective Cu-Ag resources in the copper-bearing series of SW Poland (after Oszczepalski *et al.*, 2019)

Resource cathegory	Prospective area	Area [km^2]	Depth range (MBGL)	Average thickness [m]	Average Cu grade [%]	Resources Cu [Mt]	Average Ag grade [ppm]	Recource Ag [kt]
Hypothetical	Białołęka	6.81	1500–1600	1.80	1.08	0.331	51	1.563
	Jany-Nowa Sól-Grochowice	320.07	1600–2200	1.93	2.25	34.748	96	148.256
	Kulów	49.68	1500–1800	1.59	3.14	6.201	86	16.983
	Luboszyce	38.43	1400–1600	1.42	0.89	1.214	53	7.231
	Raciborowice	7.57	900–1500	3.75	0.79	0.561	24	1.703
Total		422.56	900–2200	(N/A)	(N/A)	43.055	(N/A)	175.736
Speculative of high potential	Dębnica	50.40	1500–1800	0.51	6.21	3.990	167	10.731
	Grodzisk	10.70	2700–2800	1.07	3.54	1.013	94	2.690
	Henrykowice	28.90	1400–1700	1.08	1.73	1.350	34	2.653
	Janowo	42.98	1700–1800	1.11	1.64	1.956	36	4.294
	Kaleje	196.68	2700–3400	2.30	2.75	31.100	26	29.404
	Mozów	213.99	2300–2600	2.09	2.71	30.300	50	55.905
	Sulmierzyce	75.82	1600–2100	1.49	2.75	7.767	63	17.793
	Zerków	263.70	2600–3600	1.51	2.40	23.891	55	54.751
Total		883.17	1400–3600	(N/A)	(N/A)	101.367	(N/A)	178.221
Speculative of Low Potential	Bartków	0.47	1300–1400	0.32	4.18	0.016	71	0.027
	Bogdaj	2.08	1400–1500	1.58	1.52	0.125	34	0.279
	Borzęcin	32.15	1400–1600	0.51	4.91	2.013	—	—
	Broniszewice	15.10	2100–2200	0.46	5.97	1.037	142	2.466
	Bukowiec	12.23	2700–2800	0.60	2.87	0.526	89	1.633
	Czeklin	23.48	1700–1800	0.23	10.54	1.423	—	—
	Dębinka	25.39	1400–1600	2.30	0.69	1.007	44	6.424
	Florentyna	33.68	3700–4000	1.00	2.66	2.240	33	2.779
	Lipowiec	0.16	1400–1500	0.60	2.06	0.005	64	0.015
	Milicz	13.93	1600–1700	1.86	0.89	0.576	26	1.684
	Mirków	12.69	1100–1300	1.17	1.56	0.579	—	—
	Naratów 1	1.80	1500–1600	0.55	3.99	0.009	319	0.789
	Naratów 3	8.15	1400–1500	0.52	2.07	0.219	86	0.911
	Niemierzyce	32.35	2700–2900	1.00	4.16	3.364	21	1.698
	Nowiny	5.72	400–600	0.47	2.64	0.177	100	0.672

Tab. 9. cont.

Resource cathegory	Prospective area	Area [km^2]	Depth range (MBGL)	Average thickness [m]	Average Cu grade [%]	Resources Cu [Mt]	Average Ag grade [ppm]	Recource Ag [kt]
Speculative of low potential	Paproć	6.41	2500–2700	0.10	17.27	0.277	421	0.675
	Radziądź	6.44	1600–1800	1.65	0.93	0.247	7	0.186
	Rogalin	54.36	2900–3200	1.90	1.42	3.667	7	1.807
	Ślubów	2.51	1300–1400	0.20	9.08	0.114	164	0.206
	Wilcze	35.58	2400–2500	0.23	8.12	1.661	920	18.882
	Zakowo	10.33	2100–2300	0.40	3.36	0.347	45	0.465
	Zarków	13.19	1200–1500	3.01	1.34	1.330	22	2.184
Total		348.20	400–4000	(N/A)	(N/A)	20.959	(N/A)	43.782
Total hypothetical and speculative resources		1653.9	400–4000			165.381		397.739

(N/A) – not applicable

tion. It is important to note that hypothetical and speculative resources (with high and low potential), despite varying levels of certainty, still require systematic investigation to evaluate their feasibility for exploitation. Compared to the previous assessment carried out by Oszczepalski (Oszczepalski *et al.*, 2020), these changes allow for a more precise identification of areas with higher potential for Cu-Ag deposit discoveries.

Hypothetical resources

The Fore-Sudetic Monocline contains four prospective areas with hypothetical resources: Białołęka, Jany-Nowa Sól-Grochowice, Kulów and Luboszyce, adjacent to the LSCD (Table 9 and Fig. 2) and represent the most significant prospects, as they may become an important reserve resource base for the copper-silver mining industry, though more detailed exploration is still required. The total area of these prospective areas within the Fore-Sudetic Monocline covers 414.99 km², with a potential of 42.494 Mt of Cu and 174 kt of Ag, and an average thickness between 1.4 and 2.0 m. The average grades range from 0.8 to 3.1% Cu and 50 to 100 ppm Ag at depths of 1400 to 2200 m (Table 9). Another potential target, known as Raciborowice, is adjacent to undeveloped deposits: Niecka Grodziecka and Wartowice (Fig. 2).

The greatest resource potential among the hypothetical resources has been attributed to the Jany-Nowa Sól-Grochowice prospective area located to the north-west of the Bytom Odrzański deposit, extending along the eastern boundary of the Zielona Góra oxidized zone. This area was formed by the merging of the prospective areas of Grochowice I and II, Jany and Sława, which were identified in the previous assessment (Oszczepalski *et al.*, 2020). These changes were made as a result of ongoing drilling exploration by MCC. The resources of the entire area have been calculated taking into account the results from drilling conducted within the Nowa Sól deposit.

Other acknowledged prospective areas in the immediate vicinity of the LSCD, such as Białołęka, Kulów and Luboszyce, also represent a direct and natural extension of the well-known Cu-Ag deposits. For this reason, they can be considered among the most important prospective areas warranting further in-depth exploration.

The Białołęka prospective area has undergone a significant reduction in size, decreasing from 13.80 to 6.81 km² in the latest evaluation. Additionally, the depth range stayed at the same level (1500–1700 m) but the average thickness of copper-bearing series has been revised from 2.11 to 1.80 m. Copper resources have been adjusted downwards from 0.779 to 0.331 Mt, while silver resources have also decreased from 3.203 to 1.563 kt.

The Luboszyce prospective area has undergone some changes in the most recent evaluation. Its area has expanded from 36.19 to 38.43 km², the depth range has expanded from 1500–1600 to 1400–1600 m and the average thickness of copper-bearing series has slightly increased from 1.34 to 1.42 m. Copper resources have also grown from 1.176 to 1.214 Mt, while silver resources have risen from 6.91 to 7.231 kt. These revisions are based on the influx of updated data, providing a more refined and accurate assessment of this area potential.

The Kulów prospective area has experienced minor adjustments. Its area has slightly increased from 48.64 to 49.68 km² and the depth range has expanded from 1500–1700 m to 1500–1800 m. While the average thickness of copper-bearing series and the average copper content have remained the same at 1.59 m and 3.14%, respectively, copper resources have grown from 6.071 to 6.201 Mt. Silver resources have also seen a slight decrease from 16.628 to 16.983 kt. These updates result from the incorporation of new data, offering a more precise and accurate evaluation of the Kulów area.

The North Sudetic Synclinorium features Raciborowice as its exclusive prospective area. Its surface has been reduced from 7.78 to 7.57 km², but the depth range and average thickness of copper-bearing series remain the same at 900–1500 and 3.75 m respectively. Copper resources have slightly decreased from 0.576 to 0.561 Mt and silver resources dropped from 1.937 to 1.703 kt. These changes are attributed to the addition of new data resulting in a more detailed evaluation of the resource potential.

Speculative resources with high potential

The prospective areas for speculative resources with high potential lie farther from the LSCD, presenting challenges in access and infrastructure development (Table 9 and Fig. 2). These greenfield prospects remain relatively unexplored and are not fully integrated into the mining infrastructure. Despite their distance, they hold significant Cu-Ag resources, indicating strong exploration potential. However, their depth poses a challenge, as extracting copper-bearing series could be complex and costly. The total extent of these prospective areas is 883.17 km², with a depth range spanning from 1400 to 3600 m. The average Cu grade ranges from 1.64 to 6.21% and for silver spans from 26 to 167 ppm. The estimated copper resources amount to 101.367 Mt, while silver resources stand at 178.221 kt. Current prospective drilling is insufficient to fully assess the scale and quality of resources, with most data coming from a few boreholes. Extensive exploration is needed to refine geological models and confirm a significant copper-silver deposit.

This category encompasses four prospective areas (Dębnica, Henrykowice, Janowo and Sulmierzyce) located at depths between 1400 and 2100 m, as well as an additional four areas identified at depths ranging from 2300 to 3600 m (Grodzisk, Żerków, Kaleje and Mozów). The prospects from the first group (Dębnica, Henrykowice, Janowo and Sulmierzyce) are located in the eastern region of the Fore-Sudetic Monocline, ~15 km east of the Lubin-Sieroszowice Cu-Ag deposit. The rich copper-silver mineralization in this region is associated with the large Ostrzeszów Rote Fäule area and several smaller scattered oxidised zones around it (Fig. 2).

The most recent assessment of the Dębnica prospective area reveals a slight decline in its size, from 50.40 to 49.80 km², indicating a minor adjustment to the region under evaluation. The depth range of the ore-bearing horizon has changed from 1600–1800 to 1500–800 m, while the average thickness of the copper-bearing series remains unchanged at 0.51 m. However, there have been slight adjustments in the estimated resources, which have been slightly reduced from 3.990 to 3.943 Mt, reflecting a minor decrease in the potential for copper extraction. By contrast, silver resources show a slight increase, growing from 10.604 to 10.731 kt. These minor revisions offer a more accurate understanding of the mineral potential in the Dębnica area, particularly by linking it to the Cu-rich Sulmierzyce area.

The most current estimation of the Henrykowice prospective area reveals several important changes when compared to previous data (cf. Oszczepalski *et al.*, 2020). The area has seen a slight increase from 28.40 to 28.90 km² indicating that the scope of the evaluation has been expanded slightly to encompass a broader region. The depth range of the copper-bearing series varies between 1400 and 1700 m and remains unchanged, as does its average thickness, which continues to be 1.08 m. However, there has been a small adjustment in the estimated copper resources. The previous estimate of 1.327 Mt of copper has been slightly revised upwards to 1.350 Mt, reflecting a more optimistic outlook on the copper potential of the area. The average copper content of 1.73% and the silver content of 34 ppm remain unchanged, indicating that the mineralization in terms of both copper and silver has not been reassessed. The silver resources have increased from 2396 to 2653 kt, reflecting a slight change in the estimated amount of silver in the area. The recent evaluation of the Henrykowice prospective area includes a slight expansion and a small increase in copper resources, while depth, thickness and silver resources remain unchanged.

The most recent appraisal of the Janowo prospective area shows several modifications based on updated data. The area has decreased moderately from 50.70 to 42.98 km² and the depth range has been revised to 1700–1800 from 1600–1900 m. The average thickness of the copper-bearing series and the average copper content remain unchanged at 1.11 m and 1.64% respectively. However, estimated copper resources have decreased from 2.307 to 1.956 Mt and silver average content dropped from 36 to 34 ppm, with silver resources revised down from 5.065 to 4.294 kt. These changes reflect a more refined understanding of the area's mineral potential.

The latest evaluation of the Sulmierzyce prospective area displays several minor changes. The total area has increased from 69.75 to 75.82 km², suggesting a broader space for exploration. The depth range has been extended from 1600–1900 to 1600–2100 m, allowing for the exploration of deeper copper-bearing levels. The average thickness of the copper-bearing series has decreased somewhat from 2.13 to 1.49 m, reflecting a thinner mineralized layer. The average copper content has increased from 2.18 to 2.75%, while estimated copper resources have been adjusted slightly downwards from 8.097 to 7.767 Mt. The average silver content has increased from 26 to 63 ppm and estimated silver resources have increased significantly from 9.657 to 17.793 kt. These changes provided a more refined picture of the mineral potential in the area, with some resources being revised upwards while others have decreased. The most significant resource changes resulted from MCC's drilling exploration, leading to the documentation of the Sulmierzyce North deposit (Speczik, 2020a).

The four areas from the second group (Grodzisk, Kaleje, Zerków and Mozów) are located farther from the LSCD. Three of them (Grodzisk, Kaleje and Zerków) are found 60–70 km to the north of the LSCD, beyond the Wolsztyn-Pogorzela High, while Mozów is about 50 km to the northwest of the LSCD, situated south of the Wolsztyn-Pogorzela High. All of these areas were initially classified as hypothetical resources >2000 m due to their depth (Oszczepalski *et al.*, 2020). Following the recent assessment (Oszczepalski *et al.*, 2019) which eliminated the depth criterion for the copper-bearing series, a reevaluation was initiated. As a result, these areas were reclassified as speculative resources of high potential, highlighting their mineral potential even at greater depths.

The recent evaluation of the Grodzisk prospective area shows a few insignificant changes. The total area has slightly increased from 10.35 to 10.70 km², indicating a marginally larger region for exploration. The depth spans from 2700 to 2800 m. The mineralized layer has an average thickness of 1.07 m with copper content of 3.54% and silver content of 94 ppm, all of these remaining unchanged. Estimated copper resources have been revised to 0.980 Mt, reflecting a slight decrease from the previous figure of 1.013 Mt. Meanwhile, estimated silver resources have slightly increased from 2.603 to 2.690 kt.

The latest assessment of the Kaleje prospective area highlights several updates. The total area has been enlarged slightly from 195.40 to 196.68 km², indicating a marginally larger region for potential exploration. The depth range remains consistent, spanning from 2700 to 3400 m, reflecting the unaffected vertical extent of the mineralized horizon. The copper-bearing series has an average thickness of 2.30 m, with copper content averaging 2.75% and average silver content at 26 ppm, both of which have remained steady. The revised estimate for copper resources is now 31.100 Mt, showing a modest increase from the earlier value of 30.904 Mt. At the same time, the estimated silver resources have risen from 29.218 to 29.404 kt.

The newest review of the Żerków prospective area introduces several updates to the dataset. The total area has marginally decreased from 263.80 to 263.70 km², indicating a slightly reduced possible exploration zone. The depth range has been narrowed from 2600–3700 to 2600–3600 m, reflecting a thinner mineralized horizon. The average thickness of copper-bearing series has decreased slightly from 1.75 to 1.51 m, suggesting a thinner layer of mineralization. The average copper content has remained stable, with a slight increase from 2.29 to 2.40%. The copper resources have fallen by ~2.5 Mt, from 26.377 to 23.891 Mt, and silver resources have also dropped from 66.932 to 54.751 kt.

The current estimation of the Mozów prospective area shows several substantial changes when comparing data from prior assessments (Oszczepalski *et al.*, 2020). In the latest evaluation (Oszczepalski *et al.*, 2019), the total area of Mozów has decreased from 370.03 to 213.99 km², indicating an large diminution of the exploration area. The depth range has been adjusted from 2100–2700 to 2300–2600 m, demonstrating that the mineralized horizon is now found at slightly shallower depths. The average thickness of the copper-bearing series has decreased a little from 2.33 to 2.09 m, indicating a thinner mineralized layer in the updated assessment. The average copper content has remained relatively stable, decreasing marginally from 2.73 to 2.71%, while the average silver content has also declined slightly from 51 to 50 ppm, demonstrating a marginal reduction. The copper resources have decreased by 28.543 Mt, dropping from 58.843 to 30.300 Mt. Silver resources have risen sharply from 43.971 to 55.905 kt, marking an increase of 11.934 kt. These changes reflect a shift in the Mozów prospective area's mineral potential, with a reduced exploration area, slightly shallower depths, lower estimated Cu resources and higher Ag resources than previously assessed. Note that these evaluations do not include the latest data, which has been incorporated into the Mozów deposit documentation (Speczik, 2020b).

Speculative resources of low potential

The recent evaluation of prospective areas with speculative resources of low potential has led to the identification of 22 areas with varying degrees of recognition and potential for Cu-Ag deposits (Table 9 and Fig. 2). The boundaries of these areas are defined by only a single borehole with productivity over 35 kg/m². The total area with speculative resources of low potential spans 348.20 km², with a depth range of 400 to 4000 m, where the copper-bearing series has an average thickness ranging from 0.10 to 3.10 m. The average Cu grade ranges from 0.94 to 17.27% and for silver the average grade ranges from 7 to 920 ppm. Copper resources are estimated at 20.959 Mt, while silver resources are approximately 43.782 kt.

The speculative resources of low potential are most promising in areas rimming oxidized fields and at shallower depths, such as Nowiny, Żarków, Mirków and Milicz (Table 9). Furthermore, regions at slightly greater depths, but not deeper than 2000 m, such as Bogdaj, Czeklin and Dębinka, deserve distinctive consideration. Additionally, areas potentially associated with other high-potential regions, such as Naratów 3 and Milicz, should also be given particular attention.

Another interesting region for Cu-Ag mineralization is the surrounding Wolsztyn-Pogorzela palaeo-high, which constitutes the central part of the mineralization system in the Fore-Sudetic Monocline. The most Cu-Ag mineralized areas are located around the oxidized zones along both slopes of this palaeo-high (Fig. 2). Six prospective areas (Paproć, Bukowiec, Niemierzyce, Rogalin, Broniszewice, Florentyna) are situated north of the Wolsztyn-Pogorzela High, whereas the remaining two (Wilcze i Żakowo) are found to the south. Despite the mineralized rocks being located at significant depths (<2100 m), their areas have been evaluated (Table 9). The remaining prospective areas hold limited significance due to their small size (Bartków, Lipowiec, Naratów 1 and Ślubów), while two other areas (Borzęcin and Radziądz) contain polymetallic (Cu-Pb-Zn) mineralization. These areas are located farther from the redox boundary, which reduces the potential for discovering rich Cu-Ag ore bodies. As can be seen from the above assessments, all prospective areas with low-potential speculative resources have been thoroughly reevaluated. PGI, in cooperation with MCC, updated area sizes, depth ranges and Cu-Ag contents based on refined geological data. Copper and silver resource estimates were recalculated for greater accuracy. These revisions provide a clearer, more reliable assessment of the areas' resource potential, highlighting both opportunities and challenges. Several key trends have emerged across the areas examined from the updated data that contribute to a better understanding of the mineral potential in these regions.

Considering all prospective areas with speculative resources of low potential, it is clear that the areas of Wilcze, Florentyna, Bogdaj and Naratów 1 have seen the most substantial modifications in terms of area size. The area of Wilcze has been sharply reduced from 162.21 to 35.58 km², representing an ~78% decrease. This reduction occurred due to the emergence of a new Jany-Nowa Sól-Grochowice prospective area, situated south of the Wilcze area. The latest drilling campaign in this region has enabled a more precise assessment of Cu-Ag resources. Similarly, the Florentyna prospective area has decreased from 88.58 to 33.68 km² (62% reduction), as a portion of its extent was designated to form the new Broniszewice prospective area, located to the west. New drilling data has also driven modifications to the Bogdaj prospective area, reducing its size from 7.5 to 2.08 km² (72% decrease) while expanding the neighbouring prospective area such as

Sulmierzyce and Henrykowice. Meanwhile, Naratów 1 has grown substantially, from 0.25 to 1.80 km², indicating a 620% increase. This enlargement is attributed to updated calculations of deposit parameters in the Naratów region.

As a result of the changes in the areas of Wilcze, Florentyna, Bogdaj and Naratów 1, there have been significant modifications to the estimated Cu and Ag resources within these regions. The reduction in the size of the Wilcze area led to a decrease in Cu resources from 10.233 to 1.661 Mt and a decline in Ag resources from 106.706 to 18.882 kt. The decrease in the size of the Florentyna area resulted in a reduction of Cu resources from 5.891 to 2.240 Mt, and a fall in Ag resources from 7.308 to 2.779 kt. In the case of the Bogdaj area, the reduction in size led to a decrease in Cu resources from 0.45 to 0.125 Mt and a decline in Ag resources from 1.007 to 0.279 kt. The size reduction of the Bogdaj area resulted in a decrease in Cu resources from 0.45 to 0.125 Mt and a drop in Ag resources from 1.007 to 0.279 kt. In contrast, the Naratów 1 area saw a minor increase in Cu and Ag resources, from 0.007 to 0.009 Mt for Cu and from 0.028 to 0.789 kt for Ag; this modest expansion was not substantial due to the area's relatively small size.

Despite the changes in the areas of the various prospective zones, the average metal grades for copper and silver have remained relatively stable across most prospective areas. This stability suggests that, while the volume of the Cu-Ag resources has been reassessed in the light of the areal modifications, the basic quality of the Cu-Ag mineralization has not undergone significant fluctuations. For example, in the Bartków area, despite a decrease in area size from 0.52 to 0.47 km², the average copper grade of 4.18% and silver content of 71 ppm remained unchanged. Similarly, Bogdaj experienced a substantial reduction in area size, from 7.5 to 2.08 km², but the copper grade stayed constant at 1.52%, and silver content remained stable at 34 ppm. Even in the case of Florentyna, where the area decreased significantly from 88.58 to 33.68 km², copper content and silver contents remained at 2.66% and 33 ppm, respectively. These examples clearly show that the changes in area size and depth range did not cause notable fluctuations in metal grades. Thus, the overall value of the resources, though revised in terms of volume, still reflects a steady quality of mineralization. This implies that the changes to the areas were primarily spatial, with minimal impact on the fundamental parameters of the mineralization itself.

IMPLICATIONS OF REVISED Cu-Ag RESOURCE ASSESSMENT FOR FUTURE MINING

The recent evaluation of Cu-Ag resources for all type of prospective area reveals several noteworthy changes in relation to the previous assessment (Oszczepalski *et al.*, 2020). The total area of hypothetical and speculative resources (with high and low potential) has decreased from 1,711.62 to 1,653.9 km², reflecting noticeable reduction in the exploration area. The depth range has been marginally adjusted from 400–4200 to 400–4000 m. The copper resources have declined by 11.589 Mt, from 176.970 to 165.381 Mt (Table 10), amounting to a reduction of about 6.55%. Conversely, silver resources have shown a marked increase of 51.752 kt, growing from 345.987 to 397.739 kt (Table 10), representing an rise of approximately 14.96%. Overall, the revised evaluation points to a considerable shift in the geological potential of all prospective areas, with a minor reduction in the exploration area, a large decline in copper resources and a significant increase in silver resources relative to prior assessments (cf. Oszczepalski *et al.*, 2020). Furthermore, additional exploration could reveal valuable Cu-Ag resources highlighting the substantial mineral potential of all these prospective areas.

The Cu resources are predominantly distributed among speculative resources with high potential which account for 61.5% (43.055 Mt) of the total resources, followed by hypothetical resources at 25.8% (101.367 Mt) and speculative resources with low potential at 12.7% (20.959 Mt). On the other hand, silver resources are more equally divided, with hypothetical resources comprising 43.9% (175.736 kt), speculative resources with high potential making up 44.9% (178.221 kt) and speculative resources with low potential at 11.1% (43.782 kt) (Table 11). This distribution suggests that the speculative resources with high potential hold the majority of the copper resources. Silver resources are more evenly spread between hypothetical and speculative resources with high potential.

As mentioned above, ongoing drilling activities have been providing new data, allowing for the integration of previously identified prospective areas such as Grochowice I and II, Jany and Sława, leading to the creation of a new prospective area: Jany – Nowa Sól – Grochowice. At the same time, the exclusion of the depth parameter for copper-bearing series in the latest assessments (Oszczepalski *et al.*, 2019) has significantly upgraded many prospective areas to a higher category, further underlining the substantial potential for new deposit discoveries. This reassessment not only enhances the economic viability of these areas but also reinforces the strategic importance of continued exploration, making future projects both justified and increasingly attractive.

Hypothetical resources in areas that represent the continuation of documented Cu-Ag deposits are potentially exploitable in the future (potentially economic), while speculative resources with high potential are likely exploitable (intrinsically economic). Speculative resources with low potential determined based on single boreholes, may have economic potential only if confirmed by additional boreholes or connected to areas that are suitable for use. In practice, speculative resources with high potential, although not currently economically viable, may become profitable in

Table 10. Copper and silver resources by category (Oszczepalski *et al.*, 2019)

Metal	Total resources	Hypothetical resources	Speculative resources with high potential	Speculative resources with low potential
Cu [Mt]	165.381	43.055	101.367	20.959
Ag [kt]	397.739	175.736	178.221	43.782

Table 11. Percentage of copper and silver by particular resource category

Resource category	Copper [%]	Silver [%]
Hypothetical resources	25.8%	43.9%
Speculative resources – high potential	61.5%	44.9%
Speculative resources – low potential	12.7%	11.1%

the future due to technological advances or changes in commodity prices. Meanwhile, speculative resources with low potential require further geological studies and confirmation to assess their true economic value. One of the most important barriers is the risk of gas (hydrocarbons, nitrogen, helium) that is associated with the underlying Rotliegend and the hanging wall of Zechstein rocks in many parts of prospective areas. Highly innovative and cutting-edge solutions will need to de-gas ore bodies before predicted production. Another problem is related to the relatively high temperature within the ore horizon that varies in the range 45–65°C at depth 1400–2000 m (Speczik *et al.*, 2007; Oszczepalski, Chmielewski, 2015; Oszczepalski *et al.*, 2020). Nevertheless, modern air-conditioning systems and ventilation techniques are able to provide the appropriate conditions for mining and operating efficiency even in hot underground workings (Speczik *et al.*, 2013, 2015, Speczik, 2015; Zieliński, Speczik, 2017; Oszczepalski *et al.*, 2019, 2020).

In conclusion, ongoing exploration, coupled with advances in mining technologies, especially for deeper deposits, will likely lead to the discovery of new mineralized zones and the development of previously inaccessible Cu-Ag ore bodies. The integration of geological, geophysical and geochemical data has been crucial for improving resource assessments and enhancing the viability of these deposits (Speczik *et al.*, 2012, 2024; Zieliński, Wierchowiec, 2018; Zieliński, Speczik, 2019; Dziewińska *et al.*, 2020; Bieńko *et al.*, 2023b).

Continuous geological and economic studies are vital for accurately assessing the potential and long-term viability of these resources. Additionally, some prospects may extend existing Cu-Ag ore bodies, emphasizing the importance of persistent exploration and data collection.

FUTURE POTENTIAL OF Cu-Ag RESOURCES IN SW POLAND

Current approaches to copper belts

The Polish Geological Institute's mission has always been to investigate mineral deposits crucial for Poland's economic development. Post-WWII research led to the discovery of the Lubin-Sieroszowice deposit. Later efforts focused on gathering data from PGI and the oil and gas industries, which laid the foundation for further assessments of the prospects for Kupferschiefer-type Cu-Ag deposits. (Speczik *et al.*, 2015; Oszczepalski *et al.*, 2018; Oszczepalski, Chmielewski, 2019; Oszczepalski *et al.*, 2019). These tasks will also be important in the future for the metal resources security of the country and EU (Galos *et al.*, 2012a, b; Galos, Lewicka, 2016; Radwanek-Bąk, *et al.*, 2018; Wołkowicz *et al.*, 2020).

Extensive geological research over several decades across the Polish Zechstein Basin, particularly in the Fore-Sudetic Monocline, North Sudetic Synclinorium and Żary Pericline, has provided valuable insights into its base metal potential. Intra-basin uplifts, such as the Fore-Sudetic Block and Wolsztyn–Pogorzela High, are key geological units where slopes acted as pathways for mineralizing fluids. The Rote Fäule-ore systems closely correspond to these units. The most favorable areas for high-grade Cu-Ag ore discoveries are found near paleo-uplifts, where suitable conditions for ore body formation existed. The observed metal and mineral zonation trends point out the most promising copper-bearing areas that rim the oxidized zones. Understanding large-scale metal zonation patterns has been essential in refining exploration strategies (Oszczepalski *et al.*, 2016b, 2017b, 2019, 2020; Zieliński Speczik, 2017, 2019; Speczik *et al.*, 2021). The implementation of key principles and guidelines, along with the distribution of delineated prospective areas, has improved the accuracy and efficiency of Cu-Ag deposit recognition. Integrating structural, geochemical and petrographic data enables a more targeted approach, reducing exploration risks and enhancing resource estimation. Studies on organic matter and relic mineralization in oxidized areas have particularly helped in determining the oxidation front. Leveraging these insights, modern exploration strategies can optimize drilling locations, ensuring more sustainable and economically viable resource development in the Polish copper-silver mining sector.

Recent investigations of many borehole cores provide compelling evidence that the Kupferschiefer series in SW Poland holds substantial prospective Cu-Ag resources beyond the boundaries of the LSCD (Oszczepalski *et al.*, 2019, 2020). These findings suggest that previously underexplored regions could present significant economic potential, warranting further detailed exploration, assessment and documentation of new deposits. The presence of extensive mineralized zones at varying depths underscores the need for advanced geological modelling and innovative mining techniques to unlock Cu-Ag resources while ensuring economic and environmental sustainability. Advances in ventilation, rock pressure management and automated mining systems will be crucial for making deep-seated deposits economically resonable (Speczik *et al.*, 2007, 2013, 2015, 2020b, 2021; Speczik, 2015; Zieliński, Speczik, 2017, 2019; Oszczepalski *et al.*, 2019, 2020). As the industry continues to push technological boundaries, deeper ore bodies that were once considered inaccessible may become key contributors to future copper and silver production. Also, the excluding depth of copper-bearing series in latest assessments of Cu-Ag resources (Speczik *et al.*, 2013, 2015, 2020b; Speczik, 2015; Zieliński, Speczik, 2017; Oszczepalski *et al.*, 2019, 2020) caused a considerable increase in resources, therefore making future exploration justified and more appealing. It was also proposed to change the legal provisions regarding the balance sheet criteria for deep deposits (Zieliński, Wierchowiec, 2018; Zieliński *et al.*, 2021; Bieńko *et al.*, 2023b; Zieliński, Speczik, 2023).

The future security of Polish copper and silver resources depends on developing the northern sections of documented Cu-Ag deposits to depths beyond 1500 m. This strategy is necessary to retain the Polish market position amid increasing global demand. Deeper exploration is essential due to the decline in accessible resources, helping

Poland stay competitive in the European copper industry and reducing reliance on imports (Galos *et al.*, 2012a, b).

The prospective areas for Cu-Ag ore mineralization demarcated by the PGI located around oxidized areas were considered while determining the boundaries of exploration targets (Fig. 2). Since 2011, nearly all prospective areas for Cu-Ag mineralization (Oszczepalski, Speczik, 2011a, 2014; Oszczepalski, Chmielewski, 2015; Oszczepalski *et al.*, 2016b), have been covered by exploration concessions. However, given the depth of the Cu-Ag mineralization, which reduces the likelihood of economically viable extraction, areas with mineralization deeper than 2400 m and those with lower prospectivity were excluded from further exploration (Speczik *et al.*, 2022). These days, prospecting activities and exploration efforts are vigorously underway across several concessions located within previously chosen prospective areas. Numerous concessions are managed by different companies, with the goal of identifying and evaluating copper-silver resources. KGHM PM is leading in exploration efforts on the Bytom Odrzański, Głogów, Radwanice-Gaworzyce and Retków-Grodziszcze concessions, which directly border the LSCD mining areas. All of these areas are of strategic interest due to their proximity to existing mining operations and their potential for expanding the company's resource base. The company also obtained the Synklina Grodziecka and Konrad exploration concessions comprising the documented but undeveloped Niecka Grodziecka and Wartowice deposits (cf. Paulo, 2006; Kubiak *et al.*, 2007), further strengthening its exploration portfolio in these promising regions. Additionally, the company holds the Kulów-Luboszyce exploration concession, which, although situated farther from active mining areas, directly adjacent to the LSCD concessions.

Some of the prospecting targets currently being considered are also located far from the LSCD. Exploration efforts can be more accurately focused by integrating data from recognized prospective regions and established Cu-Ag mineralization trends. Therefore the companies within the MCC group (Zielona Góra Copper sp. z o.o., Ostrzeszów Copper sp. z o.o. and Mozów Copper sp. z o.o.) decided to obtain exploration concessions responsible for the Nowa Sól, Sulmierzyce North and Mozów deposits. Furthermore, Kompania Górnicza AMARANTE sp. z o.o. controls the Peryklina Żary concession (Amarante, 2019), while Viper Trading sp. z o.o. oversees the Niemstów-Redlice concession, which directly borders the Lubin-Małomice deposit. In this region drilling operations were previously carried out under the Niemstów-Wielowieś license by Balamara Resources Limited. Five boreholes revealed rich lead mineralization and poor Cu-Ag mineralization at shallow depths (500–600 m). The richest profile showed an 8.5 m-thick interval with an average content of 0.36% Cu and 12 ppm Ag (Balamara Resources Limited, 2013).

The documentation of new Cu-Ag ore deposits (Mozów, Nowa Sól and Sulmierzyce North) encouraged the MCC research team to connect all of these deposits as the Northern Copper Belt (Speczik *et al.*, 2021, 2022; Bieńko *et al.*, 2023b). Its delineation is at least controversial, as the central part of this belt lacks significant Cu-Ag prospective areas, except for a few isolated boreholes showing slight copper enrichment. By contrast, instead of Cu-Ag mineralization, this central region predominantly shows Zn-Pb mineralization. Therefore, this belt is not continuous in reality. This problem was noted by Pietrzela, Bieńko (2024) who drew the boundaries of this belt in such a way that it almost disappears in the central part of the Northern Copper Belt. Moreover, this belt crosses metal zones and runs independently of the Rote Fäule, which contradicts the widely accepted genetic models that emphasize the crucial role of Rote Fäule fronts in the formation of the Cu-Ag deposits.

In contrast to the above view and according to current knowledge presented in recent works (Oszczepalski *et al.*, 2019, 2020) there are two major copper belts in the southern part of the Fore-Sudetic Monocline: Lubin-Mozów and Sulmierzyce-Dębnica, as well as four smaller copper belts in the areas of the Żary Pericline and the North Sudetic Synclinorium: Czeklin-Żarków, Żary, Nowiny and Konrad-Lena (Fig. 2). In the northern part of the Fore-Sudetic Monocline, several prospective areas are associated with the northern slopes of the Wolsztyn-Pogorzela High, headed by the richest Kaleje-Żerków copper belt. Due to limited geological prospection and significant depths, the copper belts in the northern Fore-Sudetic Monocline cannot be precisely defined. These areas are considered to have lower potential for Cu-Ag deposits and will not be further discussed.

Lubin-Mozów copper belt. This 85-km-long belt is one of the most prominent and economically significant areas in the southern Fore-Sudetic Monocline adjacent to the Zielona Góra oxidized field. In addition to the well-documented Cu-Ag deposits of the LSCD, including the newly discovered Mozów and Nowa Sól deposits, this belt also represents a brownfield area with promising prospects, such as Kulów, Białołęka and Luboszyce. Including the New Copper District, the Lubin-Mozów belt holds substantial importance for future mining operations, with ongoing exploration likely to refine our understanding of its full potential and guide future resource extraction. Such research is an imperative for boosting resource extraction efficiency and minimizing environmental impact, making the Lubin-Mozów copper belt an attractive prospect for sustainable investment and long-term development.

Sulmierzyce-Dębnica copper belt. This belt is particularly notable for the presence of the documented Sulmierzyce North deposit. This deposit is an essential part of the copper-silver resources in the eastern part of Fore-Sudetic Monocline characterized by its rich bornite-chalcopyrite mineralization, which makes it a focal point for ongoing mining activities and further exploration. Despite vertical redox changes over short distances, high-grade mineralization may exist near all oxidized areas. In addition to the Sulmierzyce North deposit, this region encompasses several prospective areas (Dębnica, Henrykowice and Janowo) adjoining numerous oxidized fields, with the potential for significant mineralization, though they have not yet been fully explored. These areas are expected to be key exploration targets soon. Dębnica and Henrykowice are close to the Sulmierzyce North deposit and share similar geological features.

Czeklin-Żarków copper belt. This is a prospective area, meaning that although full geological surveys have not yet been completed, there is a high probability of discovering significant mineral deposits. This belt is located north of the Szprotawa High and forms embayments within the Zielona Góra Rote Fäule zone. Consequently, this region is gaining increasing interest from exploration companies.

Żary copper belt. This belt is home to the documented Żary deposit located between the oxidized field and the Szprotawa High. In addition to the Żary deposit, there are prospects for further discoveries near the redox interface, including Dębinka. Given its proximity to the Szprotawa High, there is potential for mineralization extending along this elevation.

Nowiny copper belt. This is located at the boundary between the North Sudetic Synclinorium and the Żary Pericline, adjacent to the oxidized field to the north and the Fore-Sudetic Block to the east. While the full extent of the Nowiny copper belt is yet to be fully explored, its location suggests that it could play an important role in the further development of the copper-silver resource base. This area presents the possibility of encountering an ore body at a favorable depth of 300–700 m, with a west-east orientation and a width ranging from 1–3 km, extending up to 10 km if the ore body continues southeastwards.

Konrad-Lena copper belt. This belt encompasses the documented Konrad, Wartowice and Nowy Kościół-Lena Cu-Ag deposits, all of which are part of the Old Copper District. Additionally, the area between these deposits holds potential for further exploration. Although extensively examined earlier, these areas remain an important part of the country's expanding resource base. The Raciborowice area, adjacent to the Wartowice deposit, is notable, with the gap between Wartowice and Nowy Kościół along the redoxcline offering potential for new discoveries. This region is becoming a focus for future investments, especially as advances in low-grade deposit extraction may uncover more Cu-Ag ore bodies. With its resource potential and existing infrastructure, the Konrad-Lena copper belt is also critical for the future growth of copper-silver mining and Au-Pt-Pd potential.

FURTHER OPPORTUNITIES AND RECOMMENDATIONS

Recent assessments of Cu-Ag deposits in Poland have underscored their economic significance and the need for advance exploration to accurately define their extent and resource potential. The newly identified Cu-Ag deposits have been evaluated in accordance with the regulations in force in Poland as in category C2 (inferred resources) – the Nowa Sól, Mozów and Sulmierzyce North deposits, and D (probable resources) – the Żary deposit. Further drilling activities are designed to upgrade those deposits to higher categories and expand their measured resources, which is objectively possible considering the existence of prospective areas encompassing these deposits. Currently, these regions represent the most favourable targets for continued exploration and should be prioritized in the next phase of drilling prospects. Additionally, obtaining a C1 (indicated resources) classification is a fundamental prerequisite for securing a mining license. A standard mining license in Poland lasts ~30 years with the option for renewal, making it highly feasible to develop a new Cu-Ag mine at the beginning of the 2030s.

Documenting Cu-Ag ore deposits in Poland shows that adding new boreholes to existing grids leads to a small but steady increase in resources due to the geological uniformity of these deposits (Speczik *et al.*, 2022). Research in the Fore-Sudetic Monocline confirms the predictability of the Cu-Ag deposits, despite local variability, a trend supported by evidence from active mines. In early exploration stages, a higher proportion of negative boreholes occur, as the extent of the deposit and its contact with oxidized Rote Fäule facies and basement uplifts remained undefined. Similar trends are seen globally in SSC deposits, where systematic drilling consistently leads to resource increase. For example, studies on the Central African Copperbelt (Hitzman *et al.*, 2005) and Kupferschiefer-type deposits in Germany (Kopp *et al.*, 2010; Borg *et al.*, 2012) highlight that the lateral continuity and stratiform nature of these Rote Fäule-related ore bodies facilitate predictable resource extensions with continued advanced exploration. Many prospective areas are near new Cu-Ag deposits, indicating that their resources may be extended through advanced research. Establishing a regular drilling grid around these areas is essential, particularly where expansion is possible, or to connect adjacent prospective areas or existing deposits. Most Cu-Ag areas were identified using boreholes from the oil and gas industry, which follow different drilling patterns. A systematic drilling approach is crucial for accurate spatial mapping, better resource forecasts and reducing uncertainties in mineralized zone continuity. Broad drilling grids are essential for recognizing disconnected resource areas, improving resource management and guiding future exploration phases. Furthermore, regular sampling of new oil and gas boreholes is essential for updating the extents of oxidized zones and identifying additional Cu-Ag targets near oxidized facies. This practice not only allows the discovery of overlooked prospective areas but also aids in developing new exploration forecasts. Incorporating data from both the oil and gas exploration and mining sectors provides a more comprehensive subsurface view, leading to more effective exploration strategies.

Extensive deep exploration drilling campaigns are currently being carried out by KGHM PM, MCC and Kompania Górnicza AMARANTE sp. z o.o. to comprehensively evaluate the resource potential of their respective research areas. These programs aim to gather more detailed geological data and better understand the extent and quality of the ore mineralization. The results from these efforts will play a crucial role in assessing the viability of future mining projects and in refining the resource calculations for Cu-Ag deposits. Areas near existing Cu-Ag deposits are high-priority exploration targets due to their strategic location and geological potential. Continued exploration could improve our understanding of mineralization patterns, developing efficiency and reducing mining costs. However, extracting deep ore deposits, which exceed current depths at the Lubin–Sieroszowice deposit, will require innovative technologies to address challenges such as pressure, temperature, and gas hazards. Studies commissioned by MCC assessing the potential for deep copper-silver ore development (Goodell *et al.*, 2017) indicate that, with the application of appropriate technologies, economically viable intelligent mining could be conducted at depths of up to 2400 m below ground level (Speczik *et al.*, 2022).

The greatest potential for increasing Cu-Ag resources lies in the area adjacent to the Lubin-Mozów copper belt (Fig. 2). This area offers considerable prospects for further geological exploration, given its abundant Cu-Ag mineralization and strategic setting. A significant redox front suggests that the Nowa Sól deposit, resembling those identified in the western sector of the LSCD, remains open in both eastern and northern directions, indicating continuity toward the Wilcze and Mozów areas. Targeted drilling campaigns should focus on the Wilcze and Mozów prospective areas, as well as to explore potential connections to the east for valuable geological insights.

The Sulmierzyce-Dębnica copper belt is a promising target for further prospecting due to its favorable Cu-Ag mineralization and geological conditions. The area near Sulmierzyce is particularly notable for its deposit parameters, which are similar to those in the western part of the LSCD, as well as its proximity to the Sulmierzyce North deposit. However, prospects in this belt will require overcoming gas hazards through the implementation of innovative technologies. Additional drilling is needed to define the boundaries of prospective areas like Dębnica, Henrykowice, Bogdaj and Janowo, to assess their potential extension of the Sulmierzyce North deposit and determine any geological connections. Confirming such links would enhance the resource base of Sulmierzyce North, making it a key exploration priority. However, the region's irregular mineralization pattern, with patchy oxidized areas, complicates ore body delineation, particularly in the Ostrzeszów oxidation field. Potential connections with the Milicz and Janowo areas could also help outline mineralization trends, though these regions should be of lower priority than areas near established deposits. If geological continuity is confirmed, resource estimates for the region could be significantly improved, requiring further drilling and geological assessment.

Technologically accessible prospective areas are also found within the Żary Pericline, where the existence of two copper belts has been documented (Czeklin-Zarków and Żary). The relatively shallow depth of the mineralized interval, ranging from 1200 to 1800 m below the surface, makes these areas particularly promising. The resource potential of this region has been partially confirmed through the exploration program being carried out by Kompania Górnicza AMARANTE sp. z o.o. on the Żary concession, which includes the Żarków prospective area and part of the Czeklin area. There is a high likelihood of the expansion of the Żary copper belt towards the south, reaching the boundary of the oxidized zone.

In the North Sudetic Synclinorium, where the Konrad-Lena copper belt is located, the most promising prospects for increasing Cu-Ag resources are associated with the Raciborowice prospect and the Nowy Kościół deposit. However, the lack of drilling in the northwest makes it unclear whether significant copper-silver mineralization extends in that direction. A substantial region between the Wartowice and Nowy Kościół deposits, situated along the predicted redox boundary, offers an optimistic target for ore bodies similar to those found in adjacent deposits. Conducting drilling operations to the south and west of Raciborowice would help assess the area's potential expansion and either confirm or disprove this hypothesis.The Nowy Kościół area remains a significant exploration target despite relatively low copper concentrations, due to its near-surface copper-silver mineralization. Notably, the copper-bearing series exhibits a geochemical profile where the lower section is poor in copper and silver, while the upper part hosts relatively rich copper-silver mineralization. Additionally, footwall rocks beneath the Cu-Ag ore bodies may contain elevated gold concentrations, and locally PGE, as observed in the nearby Niecka Grodziecka, Wartowice and Lena deposits (Speczik, Wojciechowski, 1997; Wojciechowski, 1999, 2001; Oszczepalski *et al.*, 2011). Moreover, archival borehole cores from the Nowy Kościół copper deposit are not preserved, hindering the assessment of Cu-Ag and Au-Pt-Pd mineralization potential to the north and west of the known deposit. A recent borehole, Lwówek-Pielgrzymka C8, encountered lead mineralization with minor copper presence (Krzemiński, Speczik, 2017), but this data is insufficient to evaluate the region's potential.

Besides conducting prospection strictly focused on discovering Cu-Ag deposits, it is also worth carrying out research activities aimed at filling knowledge gaps in areas lacking data from boreholes. This applies particularly to prospective areas that have not yet been granted exploration licenses, such as the Żakowo prospective area, as well as regions within abandoned concessions, like the Nowiny prospective area or the Krępa area directly adjacent to the west side of the Radwanice-Gaworzyce concession (Fig. 2).

The Żakowo prospective area remains unlicensed for exploration within the Fore-Sudetic Monocline. Identified after positive results from the Żakowo 4 borehole, preliminary estimates suggest ~0.347 Mt of copper and over 0.465 kt of silver at depths of 2100–2300 m. There is a possibility of encountering rich Cu-Ag mineralization along the redox boundary associated with the southern slope of the Wolsztyn-Pogorzela High. However, the absence of additional drilling data impedes the verification of these findings and hampers a comprehensive understanding of the area's mineralization potential.

Also some exploration activities in the Nowiny prospective area are vital for evaluating Cu-Ag mineralization and potential precious metal (Au-Pt-Pd) occurrences. Studies suggest mineralization may extend westwards towards the Weisswasser and Spremberg-Graustein deposits in Germany (Freund *et al.*, 2009; Kopp *et al.*, 2010; Kucha, Bil, 2017). Currently, the area westerly of the Nowiny prospect remains largely unexplored, with no additional boreholes available for study. Given its location along the Zielona Góra oxidation field, there is a strong likelihood of ore body occurrence along this geochemical corridor. Drilling is important to define the extent of mineralization and its potential continuation towards the German border. A systematic program will provide key geological data, while confirming mineralization trends could support cross-border cooperation in research and mining exploration.

The Krępa area marked by the S-16 borehole features an ore-bearing succession at a depth of 400–500 m, which occurs in the middle and upper parts of the Zechstein Limestone above oxidized rocks barren in Cu-Ag mineralization, though they may contain enrichments of gold and PGE. The primary goal of the proposed research is to analyze the spatial distribution of mineralization in this region, similar to that in the Radwanice and Gaworzyce deposits. The study should also aim to clearly outline the western and northwestern boundaries of economically viable Cu-Ag mineralization extending westwards outside the LSCD.

MULTI-METAL RECOVERY FOR SUSTAINABLE COPPER MINING IN POLAND

As global demand for metals continues to rise, the Polish copper mining industry faces increasing pressure to diversify and optimize the extraction of valuable by-products alongside copper and silver. The industry is tasked with increasing its operational efficiency while meeting the growing need for critical raw materials (CRMs) that are essential for technological advances and industrial applications. This shift towards a multi-metal recovery approach is not only necessary for boosting economic performance but also for reducing waste generation in mining operations. In response to growing market demand and the need for greater operational efficiency, the copper mining industry should place growing emphasis on increasing the extraction of valuable metals, which are partly recovered, such as lead, selenium, rhenium, nickel and PGE. Furthermore, efforts need to focus on extracting other significant metals, such as zinc, cobalt and cadmium, which are in alignment with the policy of rational resource exploitation, given their increasing industrial demand. Au-, PGE- and REE-enriched oxidized rocks should be selectively exploited and stored during current mining production, and this should also be included in the production plans for new deposits. Advanced hydrometallurgical and bioleaching technologies enable the efficient recovery of these metals, optimizing resource utilization and minimizing operational costs. The growing claim for critical metals, such as cobalt for battery production and PGEs used in automotive catalysts, makes their recovery a strategic priority. By adopting a multi-metal recovery strategy, copper mining operations can improve their economic performance while mitigating the risks of commodity price fluctuations. As mining operations advance into deeper and more polymetallic ores, it will become increasingly important to separate and improve multiple metal concentrates to maximize resource recovery and economic efficiency. Moreover, sustainable mining practices that highlight reducing environmental impact are essential for securing mining licenses and ensuring the long-term growth of the industry. This attitude allows for maximizing the value derived from copper-silver ores and improving overall resource utilization. Lastly, integrating artificial intelligence and big data analytics in mineral exploration could also improve the accuracy of resource assessments and improve decision-making processes for future mining projects.

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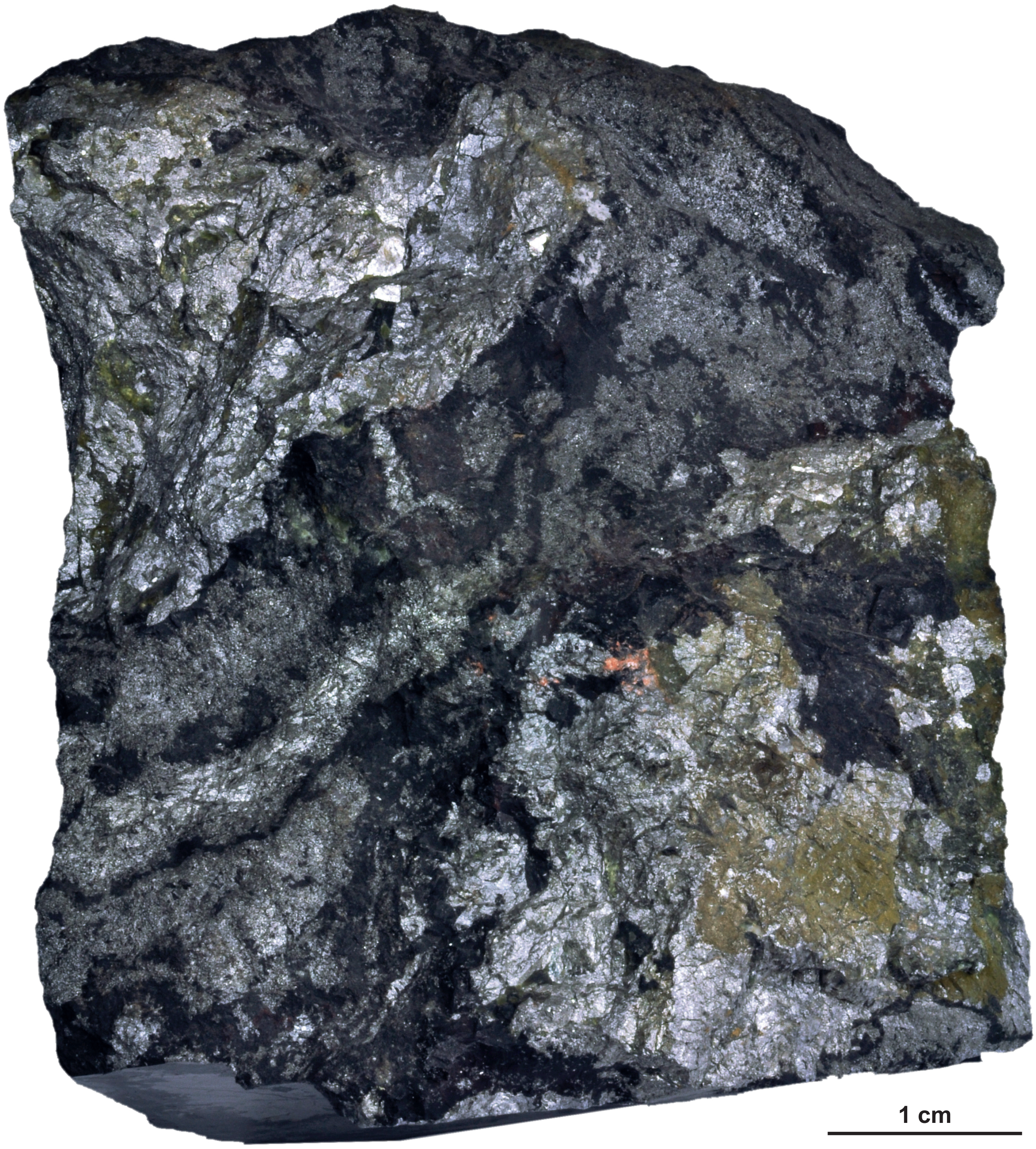

Arsenopyrite, Złoty Stok, Sudetes.
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