

Assessment of the possibility of obtaining selected critical elements (boron, magnesium, strontium) in Poland

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A b s t r a c t. In recent years, the authorities within the European Union have shown an increased interest in assessing the continent's potential to source several critical elements essential to the economy from its own mineral and anthropogenic deposits. There are 34 of these critical elements, and the potential of Poland to source three of them, boron (B), magnesium (Mg) and strontium (Sr), is presented in the paper.

The review of registered and potential occurrences of these three elements in Poland included both active and inactive deposits, prospective areas with reserves of raw materials, underground waters (natural, mining, from deep wells, geothermal and from hydrocarbon accumulations), as well as anthropogenic dumps and waste ponds. Preliminary calculations of the reserves of these elements have shown that in Poland the reserves of magnesium are the largest (>19 million tonnes), especially in potash salts (~19 million tonnes). Less magnesium is concentrated in magnesite deposits (255 thousand tonnes) and in underground waters (>44 thousand tonnes). Strontium – ~256.8 thousand tonnes – could be obtained from old dumps and waste ponds, residues accumulated after sulphur exploitation and abandoned sulphur open pits. Underground waters provide only >1.5 thousand tonnes of strontium. The possible sources of boron are local underground waters with a predicted boron production of >270 tonnes per year.

Keywords: selected critical elements, resource potential, Poland

INTRODUCTION

In recent years, the European Union's governing bodies have become increasingly interested in Europe's potential for extracting a number of elements essential for the economy from mineral and anthropogenic deposits (so-called critical elements; Mazurek *et al.*, 2021).

This group includes 34 elements, e.g., boron (B), magnesium (Mg) and strontium (Sr), whose assessment of the possibility of extraction from primary natural deposits and secondary accumulations in Poland is the subject of this study.

Rock salt (halite) and potassium (potash) salts appear to be particularly useful for the extraction of these elements because of their ability to dissolve and separate the desired elements or their compounds from the resulting brine. During the last 30 years, the content of some critical elements has been analysed in salt rocks from the Polish area (e.g., Garlicki, 1991; Garlicki, Szybist, 1991; Garlicki *et al.*, 1991; Czapowski *et al.*, 2001, 2022a, b, 2023). Miocene and Upper Permian salt rocks have been studied for this purpose (Table 1).

BORON (B)

Characteristics of occurrence

Boron (B) is a mobile element present in the composition of many mineral. The Clark value of boron in the Earth's crust is $5.6 \times 10^{-4}\%$ (Polański, Smulikowski, 1969; Konstantynowicz, 1989). The most important boron-bearing minerals include borates (e.g., borax, carnite, pandermite, hydroboracite, sassolite, ulexite, colemanite, ascharite, calborite, susnitite, kotoite) and borosilicates, e.g. datolite and danburite (Konstantynowicz, 1989; Manecki, 2019). In alkaline magmatic rocks, the concentration of boron is 2–5 g/t, in acidic ones (granitoids) it is 3–10 g/t, seawater contains on average 4.7–4.8 g/t, freshwater – 0.01–2 g/t (Pasieczna, 1983), and in saline lakes the content of boron oxide varies from 0.5–2.2% (Konstantynowicz, 1989) up to 10.8 g/L in the salars of Peru and Chile (Czapowski *et al.*, 2022b and references therein). The largest amounts of boron are found in clay rocks (boron is incorporated into

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Table 1. Salt deposits in Poland studied for the content of selected critical elements

Commented salt deposits in Poland	
Name and symbol of the salt unit	
Miocene salts – Wieliczka Formation	
rock salt	
zubers	
Upper Permian (Zechstein) salts	
Lithostratigraphic units	Cyclothem
Red Zuber (Na4t)	PZ4
Youngest Halite (Na4a)	
Brown Zuber (Na3t)	PZ3
Upper Younger Halite (Na3b)	
Younger Potash (K3)	
Lower Younger Halite (Na3a)	
Older Potash (K2)	PZ2
Older Halite (Na2)	
Oldest Potash (K1)	PZ1
Oldest Halite (Na1)	

the structures of layered silicates, forming a wide range of clay minerals): in marine sediments, its concentration is 90–380 g/t, while in freshwater sediments, it is 10–90 g/t (Pasiczna, 1983).

Boron-bearing minerals have formed predominantly in lacustrine and marine environments in hot and dry climates characterized by high evaporation, and in areas of hot springs associated with volcanic processes. Depending on their origin, the following types of boron deposits can be distinguished (Gruszczczyk, 1984; Konstantynowicz, 1989; <https://pl.wikipedia.org>): skarn, exhalation, volcanic-sedimentary, sedimentary, weathering, and infiltration deposits.

Skarn deposits include the following rock types:

- Calcereous skarns formed as a result of metasomatic alteration of limestones near granitoid massifs; they are characterized by various geometric forms (beds, veins and lenses); the main boron minerals are datolite $[\text{CaBSiO}_4(\text{OH})]$, danburite $[\text{CaB}_2\text{Si}_2\text{O}_8]$ and axinite $[\text{Ca}_2(\text{Fe, Mg, Mn})\text{Al}_2(\text{BO}_3)(\text{OH})(\text{Si}_4\text{O}_{12})]$, the average boron oxide content is 7–10%;
- Magnesium skarns are the product of alteration of dolomites in contact with magmatic intrusions, and have various geometric forms (beds, nests and lenses); the main boron minerals are ludwigite $[\text{Mg}_2\text{FeBO}_5]$, suanite $[\text{Mg}_2(\text{B}_2\text{O}_5)]$ and kotoite $[\text{Mg}_3\text{B}_2\text{O}_5]$; the average boron oxide content (depending on the dominant mineral) ranges from 4 to 17%.

Exhalation deposits comprise hot mineral springs (fumaroles and solfataras), which contain up to 0.5% boric acid.

Volcanic-sedimentary deposits are accumulations of boron in lakes as a result of volcanic activity or the weathering of volcanic rocks. They are divided into:

- Freshwater lake deposits: bedded deposits (tens of metres thick); the main minerals are colemanite $[\text{CaB}_3\text{O}_4(\text{OH})3\text{H}_2\text{O}]$, boracite $[\text{Mg}_3(\text{B}_7\text{O}_{13})\text{Cl}]$, ulexite $[\text{NaCaB}_5\text{O}_9 \times 8\text{H}_2\text{O}]$ and kernite $[\text{Na}_2\text{B}_4\text{O}_6(\text{OH})_2 \times 3\text{H}_2\text{O}]$; the boron oxide content

ranges from 15 to 40%, averaging 20–25% (Gruszczczyk, 1984; Konstantynowicz, 1989). One of the world's largest deposits of this type is the Kirka deposit in Turkey, where the borate series is 70–145 m thick and the boron oxide content is 20–25% (Poborska-Młynarska, Tomassi-Morawiec, 2012);

- Sediments of depressions in the vicinity of active volcanoes, associated with solfataras and fumaroles; the thickness of sedimentary series is about 1 m, the main mineral is ulexite, the boron oxide content is 25–40% (Gruszczczyk, 1984; Konstantynowicz, 1989);
- Salt lake sediments (boron released by the weathering of volcanic rocks or boron deposits and supplied to the reservoir); the main boron minerals are borax $[\text{Na}_2\text{B}_4\text{O}_7 \times 10\text{H}_2\text{O}]$ and ulexite; boron oxide content is 0.5–2.5%.

Chemical sedimentary deposits, formed by the process of seawater evaporation (Macioszczyk, Dobrzyński, 2002), accompany rock salt and potassium salt deposits; boron minerals occur as aggregations and small concentrations, e.g., boracite nodules in the Zechstein Younger Potash of the Kłodawa diapir (Fijał, 1970; Cybulski, 1974; Wachowiak, Pieczka, 2012; Smakowski *et al.*, 2014); the boron oxide content in these deposits reaches several percent (Konstantynowicz, 1989). Borate minerals have also been reported in Miocene salt deposits of the Carpathian Foredeep (e.g., Zhao *et al.*, 2021).

Weathering and infiltration deposits include (Gruszczczyk, 1984; Konstantynowicz, 1989):

- Weathering deposits formed within sulphate caps on top of salt diapirs as a product of hypergene weathering of boron occurrences in salt rocks of the diapir stock, they are lenticular in shape; the main boron minerals are ascharite $[\text{MgBO}_2(\text{OH})]$ and ulexite; the boron oxide content is 10–25%;
- Secondary dissolution of weathering deposits by groundwater leads to the formation of infiltration deposits within the cap of salt diapirs; the main minerals are borax and ulexite.

Global boron production is based on evaporite rocks and boron-rich brines (U.S. Geological Survey, Mineral Commodity Summaries, 2024).

Boron deposits with economic potential in Poland

Rocks. Occurrences of boron compounds of mineralogical importance have been found in the Kłodawa salt diapir in the Zechstein potassium-bearing cyclothem PZ2 and PZ3 (boron content 75.6–438 g/t) and in rock salt (halite) of the PZ3 and PZ4 cyclothem (Wachowiak, Tobola, 2014). Presence of borates has also been documented in potassium-magnesium salts in the Inowrocław salt diapir (Prochazka, 1957; Cybulski, 1974). In sulphate deposits of potassium-magnesium salts (polyhalites) in northern Poland, documented in the 1970s, the boron content ranged from 10 to >500 g/t, while in chloride salts (carnallites) it reached 240 g/t (Czapowski *et al.*, 2022a). The boron-bearing minerals has been documented in the insoluble fraction of potassium-magnesium salts and rock salt, so the variable boron content in brines (see below) indicates the presence of also more easily soluble such minerals and/or the occurrence of boron dispersed in soluble minerals.

Lack of documented borate deposits in Poland such as the Kirka deposit mentioned above, enabling boron economical extraction on an industrial scale caused that precise criteria for economic viability for boron accumulations have not been developed (cf. Dziennik Ustaw 2001.153.1774; Dziennik Ustaw, 2015 item 987). Boron extraction from clay, magmatic or metamorphic rocks is not economically viable.

Groundwater (fresh groundwater, thermal water, mine brines, and brines from bitumen accumulations)

The main sources of boron in groundwater are the above-mentioned volcanic and post-volcanic processes, the weathering of minerals of magmatic origin, and borates found in sedimentary salt-bearing rocks. Boron accumulation, as an essential component of many plant and animal organisms, often results as its content increase in the brines associated with bitumen deposits. The highest concentrations of boric acid (H_2BO_3), the most common form of boron in ground-

water, are found in thermal waters (Dowgiało *et al.*, 1969, 2002; Pazdro, Kozerski, 1990; Kapuściński *et al.*, 1997) from areas of active volcanism. The natural boron content of these waters depends on the lithology of geological structure, the borate content of the rocks, the water-rock reaction, the formation temperatures, the presence of magmatic intrusions, also local magmatic degassing processes as well as secondary processes such pH change and precipitation of carbonate minerals (Tomaszewska, 2011, 2014; Yuan *et al.*, 2014).

Particularly high boron concentrations of >500 mg/L have been found in high-temperature geothermal deposits occurred, among others, in Indonesia, Mexico and Turkey (Mott *et al.*, 2022). In low-temperature deposits, characteristic of the Poland territory, the boron content of groundwater has so far been found to range from just over 0.02 to about 100 mg/L (Fig. 1 and Table 2).

Physicochemical analyses of available 2403 samples of groundwater (from deep boreholes, mines and geothermal plants – Razowska-Jaworek *et al.*, 2022) showed that boron content was determined in only 324 ones (Table 3). Boron content was higher than 1 mg/L in 133 samples, it is >20 mg/L

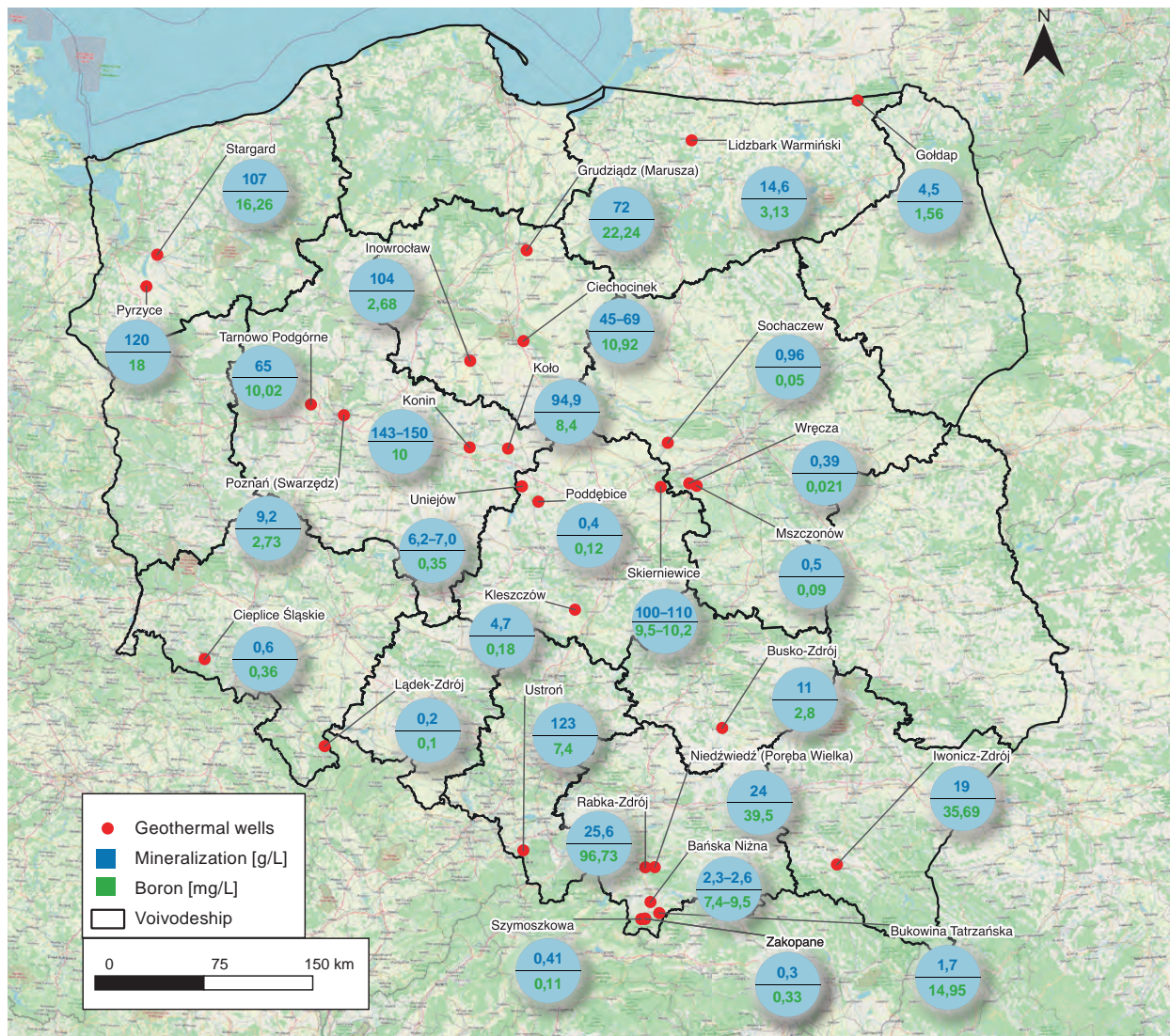


Fig. 1. Boron content in the thermal waters from Poland (after Kępińska, Ciągło, 2008; Wiktorowicz, Karwacka, 2009; Tomaszewska *et al.*, 2010; Gała, 2011; Kępińska, Bujakowski, 2011; Tomaszewska, Bodzek, 2013; Noga *et al.*, 2013a, b; Tomaszewska, 2014; Chowaniec *et al.*, 2016; Bujakowski *et al.*, 2017; Kielczawa, Liber-Małkowska, 2018; Czubernat, Tomaszewska, 2021; Felter *et al.*, 2021; Sokołowski, 2021; Śliwa *et al.*, 2021)

Table 2. Boron in the thermal waters from geothermal wells in Poland (based on: Kępińska, Ciągło, 2008; Wiktorowicz, Karwacka, 2009; Tomaszewska *et al.*, 2010; Gała, 2011; Kępińska, Bujakowski, 2011; Tomaszewska, Bodzek, 2013; Noga *et al.*, 2013a, b; Tomaszewska, 2014; Chowaniec *et al.*, 2016; Bujakowski *et al.*, 2017; Kielczawa, Liber-Małkowska, 2018; Czubernat, Tomaszewska, 2021; Felter *et al.*, 2021; Sokołowski, 2021; Śliwa *et al.*, 2021; supplemented by the results of B. Tomaszewska's own research)

Location	Depth [m]	Aquifer stratigraphy	Lithology (main rock) of the aquifer	Temperature [°C]	Water mineralization [g/L]	Boron concentration [mg/L]
Bańska Niżna	2450–5261	Middle Eocene and Middle Triassic	Numulitic and marly limestones (Middle Eocene) and limestones and dolomites (Middle Triassic)	84–86	2.3–2.6	7.4–9.8
Bukowina Tatrzańska	3780	Upper Jurassic, Lower Cretaceous	marly limestones	67	1.7	14.95
Busko-Zdrój	663	Upper Cretaceous	sandstones, sands	25	11	2.8
Ciechocinek	1378.1	Lower Jurassic	sandstones	27–34.8	45–69	10.92
Cieplice Śląskie (Jelenia Góra)	2002.5	Upper Carboniferous	granites	87	0.6	0.36
Gołdap	851	Upper Cretaceous/ Lower and Middle Jurassic	sands	22	4.5	1.56
Grudziądz (Mariusza)	3070.5	Lower Jurassic	sandstones	40	72	22.24
Inowrocław	495	Upper Jurassic	limestones	23	104	2.68
Iwonicz-Zdrój	1013–1151.5	Paleogene	sandstones	25	19	35.69
Kleszczów	1620	Lower Jurassic	sandstones	52	4.7	0.18
Koło	3156.2–3905	Upper/Lower Cretaceous	sandstones	84	94.9	8.4
Konin	2660	Lower Jurassic	sandstones	92	143–150	10
Lądek-Zdrój	700.5–2500	Precambrian	gneisses	45	0.2	0.1
Lidzbark Warmiński	1035	Lower Jurassic	sandstones	21	14.6	3.13
Mszczonów	4119	Lower Cretaceous	sandstones	40.5	0.5	0.09
Poddebice	2101	Lower Cretaceous	sandstones	68	0.4	0.12
Niedzwiedź (Poręba Wielka)	2002.5	Paleogene–Cretaceous	sandstones, mudstones	42	24	39.5–42
Pyrzyce	1637	Lower Jurassic	sandstones, claystones	62	120	18–20.3
Rabka-Zdrój	1215	Paleogene	sandstones	28	25.6	96.73–101.7
Skierniewice	3001	Lower Jurassic	sandstones	57	100–110	9.5–10.2
Sochaczew	1540	Lower Cretaceous	sandstones	44	0.96	0.05
Stargard	3080	Lower Jurassic	sandstones	68.9	107	16.26
Poznań (Swarzędz)	1306	Lower Jurassic	sandstones	36–42	9.2	2.73
Szymoszkowa	1737	Paleogene, Jurassic, Triassic	dolomites	27	0.41	0.11
Tarnowo Podgórne	1200	Lower Jurassic	sandstones	36–43	65	10.02
Uniejów	2031–2100	Lower Cretaceous	sandstones	69	6.2–7.0	0.35–2.5
Ustroń	1320–1750	Devonian	limestones	21–23	123	6.5–7.7
Wręcza	1688	Lower Cretaceous	sandstones	40	0.39	0.021
Zakopane	1113–3073.2	Middle Eocene, Middle Triassic and Lower Jurassic	numulitic limestones (Middle Eocene), dolomites (Middle Triassic) and marls and limestones with cherts (Lower Jurassic)	26–37	0.3	0.33

Boron concentrations in natural groundwater in Poland range from 0.005 to 0.3 mg/L

Table 3. Statistical parameters of boron content in 324 water samples from deep boreholes and medicinal and mine waters

Boron [mg/L]	
Maximum	645
Minimum	0.007
Median	0.6
Average	10.2

in 23 analyses and in only nine samples it exceeds 100 mg/L but three analyses evidenced boron content >300 mg/L. The highest boron concentrations were found in brines from the salt mines at Mogilno (100–645 mg/L; Wachowiak, Kasprzak, 2014), Łapczyca (343 mg/L) and Kłodawa (14.65 mg/L – d’Obyrn *et al.*, 2018, up to 340 mg/L). Boron concentrations >100 mg/L were noticed in waters at

a depth >2 km taken from two boreholes (boreholes Wieluń-5 and Czarna Wieś-3), in the geothermal borehole Turek GT-1 (154 mg/L), and in the mineral waters of Szczawnica, Rabka Zdrój, Wysowa and Krościenko.

The boron content in groundwater is not dependent on the depth or temperature of the water, but it slightly depends on mineralization, chloride or lithium content and slightly more on sodium (Table 4).

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favourable conditions such as high market prices or the presence of other valuable elements. Costs may be lower if the possibility of co-recovery of other critical elements from these waters, such as magnesium and strontium, is considered.

A number of prospective areas for geothermal brines have been identified in Poland, which offer the possibility of co-recovery of boron, magnesium and strontium (Fig. 2).

MAGNESIUM (Mg)

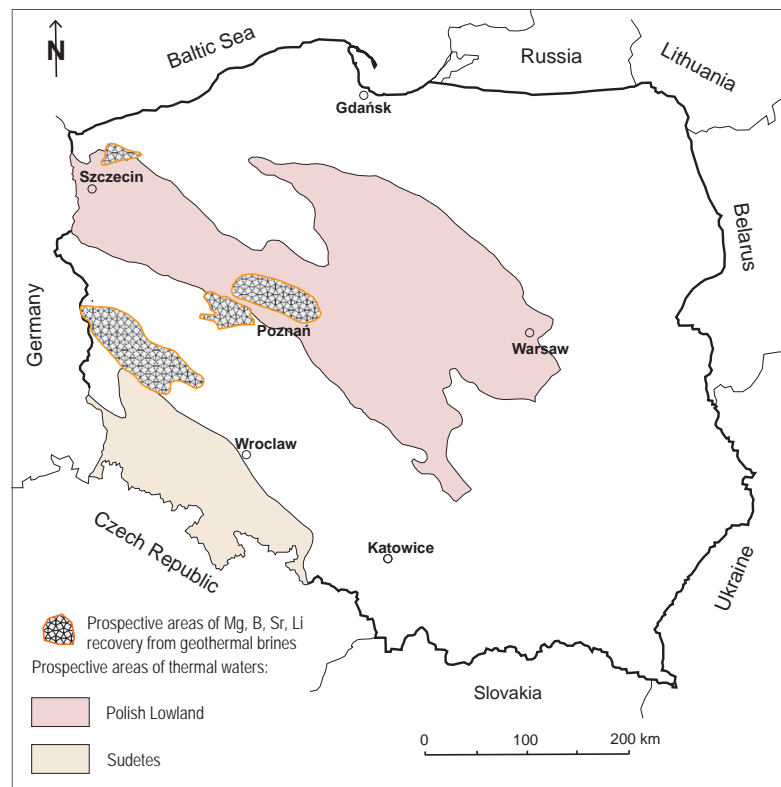
Characteristics of occurrence

Magnesium (Mg) is one of the most abundant elements in the Earth’s lithosphere (Clark value 2.1% – Gruszczuk, 1984) and hydrosphere. Its total Clark value is 8.69% by weight (Polański, Smulikowski, 1969). It coexist with other elements forming >300 minerals, from oxides to silicates and aluminosilicates (Konstantynowicz, 1989; Manecki, 2019), being one of the rock-forming minerals of magmatic, effusive, vein and sedimentary rocks. The most common magnesium minerals are carbonates, e.g. dolomite [CaMg(CO₃)₂], magnesite (MgCO₃) or kieserite (MgSO₄),

Table 4. Correlation coefficients of boron content with other parameters and constituents in underground waters

Constituent	HCO ₃	SO ₄	Cl	Ca	Mg	Na	K	Fe	Br	Ba	Li	Sr
Boron	-0.064	0.382	0.743	0.327	0.489	0.815	0.712	0.387	0.664	0.258	0.686	0.615
Parameter	Depth	Temperature	pH	Mineralization								
Boron	0.359	0.480	0.224	0.710								

Last study (Razowska-Jaworek *et al.*, 2021) focused on estimating the feasibility of recovering boron from geothermal and mine water, as well as from water pumped during the extraction of natural gas in Poland. Boron content in 75 samples ranged from 0.005 to 340.0 mg/L, but in about 70% of the analysed samples the boron concentration was <5.0 mg/L (median – 2.1 mg/L, mean – 9.6 mg/L). The highest boron content was found in water from the Kłodawa salt mine (340 mg/L), in boreholes drilled by PGNiG, in water from copper ore mines, and in concentrated brine from the mine water sampled in the desalination plant at Dębnieńsko. The feasible boron resources in groundwater have been estimated at >270 tonnes/year (for the most prospective plants/facilities). The largest boron amounts are available from mine waters of the Rudna (>80 tonnes) and Polkowice-Sieroszowice (>30 tonnes) copper mines, and from the Stargard geothermal plant (<20 tonnes). The boron content of water pumped from active and inactive coal mines ranges from a few to several mg/L, enabling the boron recovery of >10 tonnes per year, as the volume of water pumped from these mines is huge. The generally accepted threshold for economic recovery of boron from geothermal brines is about 100 mg/L. Below this limit value, the costs associated with extraction and processing may outweigh the benefits, unless there are

**Fig. 2.** Prospective areas for lithium, boron, magnesium and strontium extraction from geothermal brines in Poland

and chlorides and sulphates in which magnesium co-occurs with potassium, e.g. carnallite ($KMgCl_3 \times 6H_2O$), kainite ($KCl \times MgSO_4 \times 3H_2O$) and langbeinite ($K_2SO_4 \times 2MgSO_4$), or with calcium, e.g. polyhalite [$2KMg_2Ca(SO_4)_4 \times 2H_2O$ – Konstantynowicz, 1989; Manecki, 2019]. Due to its ubiquity, magnesium occurs in various types of deposits: magmatic, sedimentary and weathering. Magnesium enters the hydrosphere as a weathering product of many rock types, mainly carbonates (dolomites, magnesites) and aluminosilicates (clay rocks). The magnesium content of freshwater is controlled by the carbonate balance and depends on the CO_2 content and the pH of the water (Witczak *et al.*, 2013).

Magnesium occurrences with economic potential in Poland

Rocks. In Poland, magnesium is currently extracted from magnesite deposits. It is also possible to extract it from potassium-magnesium (K-Mg) salts and from highly mineralized

groundwater with increased magnesium content. The occurrence distribution of registered deposits and prospective areas of rock salts, potash salts and magnesite is shown in Figure 3.

The criteria of economic viability of magnesite deposits in Poland are defined in Journal of Laws (Dziennik Ustaw 2001.153.1774; Dziennik Ustaw, rok 2015 poz. 987). The maximum documentation depth is 150 m, the maximum overburden/deposit thickness ratio is 0.5, the minimum thickness of the deposit is 2 m, the minimum magnesite recovery from the deposit is 4% by weight, and the minimum MgO content in magnesite is not <35%. Economically viable parts of magnesite deposits for refractory products should have a minimum deposit grade (veins over 5 cm thick) of at least 15%, with a maximum SiO_2 content of 8% and a minimum MgO content of 40%. In the case of magnesite deposits for fertilizer production, the proportion of MgO in the magnesite-bearing rock should not be <35% (Szamałek *et al.*, 2020).



Fig. 3. Location of registered deposits and prospective occurrences of rock salts (halite), potash salts and magnesite in Poland (after Czapowski, Bukowski, 2013; modified). Letter symbols of the magnesite deposits: **B** – Braszowice, **G** – Grochów, **Sz** – Szklary, **W** – Wiry; prospective areas for magnesite: **O.G-J** – Gogołów-Jordanów, **O. Sz** – Szklary

With regard to occurrences of potassium-magnesium salts, from which magnesium can be acquired by electrolysis of brines obtained through leaching, there is no specification on the limiting MgO content to define these salts as magnesium deposits. It is therefore necessary to treat the salts as a source of mineralized magnesium brines and to adopt the criterion of magnesium concentration of 2000 mg/L, as in the case of geothermal brines.

Magnesite occurrences

Magnesite (MgCO_3) deposits are known in Poland only from Lower Silesia. They occur within serpentinite massifs exposed at the surface near Sobótka and Ząbkowice Śląskie (Szuflicki *et al.*, 2024) and represent a type of chemical-residue weathering deposits (Gruszczyk, 1984). They are the product of hypergenic weathering of serpentinites belonging to the Middle Paleozoic Ophiolite Complex in the margin of the Sowie Mountains Block (Szamałek *et al.*, 2020). Six magnesite deposits have been documented, located in three serpentinite massifs: Gogołów-Jordanów (Wiry, Wiry-Gogołów and Wiry-Łapadła deposits) in the northern margin of the Sowie Mountains Block, and the Szklary, Grochów and Braszowice deposits in the southeastern margin of the block.

Magnesite mineralization occurs in peripheral parts of the massifs. It developed within the serpentinites below the zone of intense weathering, reaching a depth of about 200 m. In documented deposits, magnesite is cryptocrystalline, massive and compact; it sometimes contains a significant admixture of silica (up to 10%) in the form of opal, chalcedony or quartz (Szamałek *et al.*, 2020). The variable colour of the mineralized rocks: white, yellow or pink, is due to the admixture of iron oxide in quantities ranging from <1 to 2–3%. The mineralization usually takes the form of a network of veins and veinlets a few centimetres to tens of centimetres thick in the near-surface zone. Less frequent are observed thicker (up to several metres thick) veins, tens of metres long. Occasionally the veins are over 100 m long and up to 4 m thick were noticed (Szamałek *et al.*, 2020).

The Wiry magnesite deposit, located east of Świdnica, occupies the western part of the Gogołów-Jordanów serpentinite massif and forms a zone 4.5 km long and 200–750 m wide (Osika, 1987). Serpentinites contact with granites, gabbros, and amphibolite-pyroxene rocks (Fig. 4). Magnesite occurs as veins, 3–4 m thick and up to 200 m long, and also forms a network of veinlets 5–20 cm thick (Osika, 1987).

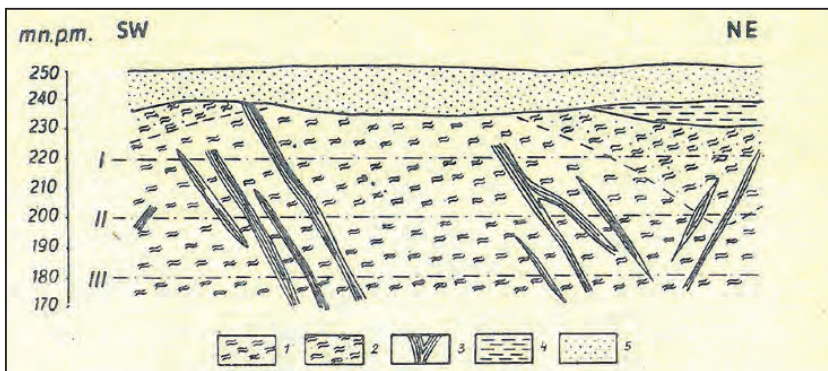


Fig. 4. Geological cross-section of the Wiry magnesite deposit (Osika, 1987): **1** – serpentinites, **2** – silicified serpentinites, **3** – magnesite veins, **4** – Tertiary deposits, **5** – Quaternary deposits, **I–III** – exploitation levels

The Sobótka deposit, exploited until the early 1950s and located in the western part of the town of Sobótka on the NE slope of the Ślęza Massif, had a similar structure. The underground mine in Wiry, several tens of metres deep, operated in 1959–1996 using four mining levels and a decline adit connecting mining pits. The anticipated economic resources left are 4,110 thousand tonnes (Szuflicki *et al.*, 2024).

The Braszowice magnesite deposit (Fig. 5), located south of Ząbkowice Śląskie, like the small Szklary deposit (Fig. 3), occurs within two serpentinite hills separated by a fault zone along which weathering processes have developed. Magnesite occurs as veins and veinlets, 0.5–2 m thick, in areas of heavily fractured serpentinites (Osika, 1987). The maximum percentage of MgO in the veins is 46.47%. The mineralization decreases with depth and eventually disappears completely (*op. cit.*). In the currently exploited deposit, the maximum MgO content is 45.31% (average – 41.88%), the CaO content is up to 1.4% (average – 0.89%) and the thickness of the deposit varies from 2 to 150 m (average 40.8 m – Podoliński, 2023).

The anticipated economic resources of the Braszowice deposit, which has been exploited since 1997 [magnesite was originally mined in the “Konstanty” underground mine since 1938 (Krzyżanowski, Wójcik, 2009), and it is currently extracted in an open pit – Fig. 6], are estimated at 4278.3 thousand tonnes, including industrial resources of 3213.57 thousand tonnes. In 2023, the output was 28.63 thousand tonnes (Szuflicki *et al.*, 2024). The opencast mining method is used to extract low-grade magnesite-serpentinite ore, which is then processed into a concentrate containing 43–45% MgO. The concentrate is used to produce ground magnesite, which is used mainly in the production of fertilizers and, to a lesser extent, in metallurgy and the chemical industry (Szamałek *et al.*, 2020; Podoliński, 2023).

Four deposits: Grochów, Szklary, Wiry-Gogołów and Wiry-Łapadła, with the total anticipated economic resources estimated at 5919.8 thousand tonnes, have been preliminarily explored (Szuflicki *et al.*, 2024) and their static sufficiency, including the estimated resources of the Braszowice deposit, is 135 years (Szamałek *et al.*, 2020).

Prospective magnesite resources in the Gogołów-Jordanów area are estimated at 1.8 million tonnes, while in the Szklary Massif at 0.6 million tonnes. In better-explored areas, in the surroundings of the above-mentioned deposits, the total prospective resources of magnesites are estimated at about 3.25 million tonnes (Szamałek *et al.*, 2020).

In the Grochów-Braszowice Massif (Fig. 5) there are possible occurrences of magnesite in the northeastern part of the Grochów Hills (single veins of magnesite up to 1 m thick, and altered serpentinite with magnesite mineralization; prospective resources about 0.85 million tonnes). Similarly, reticulated magnesite and veinlet-shaped magnesite (in altered serpentinite at the contact with gabbros) have been reported west of Mnich Hill (Szamałek *et al.*, 2020).

Due to the existence of documented and exploited magnesite deposits and prospective areas in Poland, there is no need for costly extraction of magnesium from quite common occurrences of dolomite deposits (calcium-magnesium carbonate,

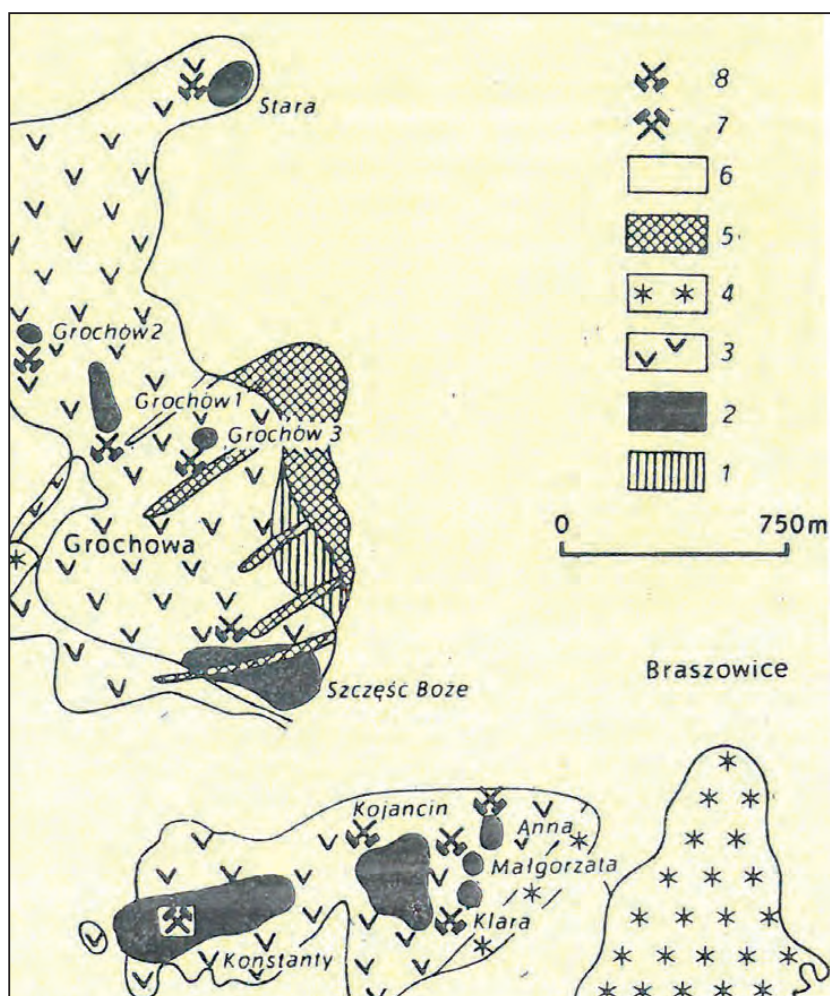


Fig. 5. Magnesite deposits near Braszowice (Osika, 1987): 1 – crystalline schists, 2 – magnesite deposits, 3 – serpentines, 4 – gabbros, 5 – syenites, 6 – Quaternary deposits, 7 – active mines, 8 – closed mines

see – Smakowski *et al.*, 2014), even in the case of a significant expansion of their exploitation. It is only a matter of refining the technologies to improve the quality of the mined material, e.g. through appropriate roasting.

Occurrences and deposits of rock salt and potassium-magnesium salts

Rock salt and potassium-magnesium salts may contain magnesium in the form of salt minerals (magnesium chlorides and sulphates along with potassium and calcium: the above-mentioned kieserite, carnallite, kainite, langbainite and polyhalite) or as a carbonate (magnesite, dolomite) admixture and in the structure of clay minerals. The distribution of documented rock salt and potassium salt deposits and prospective areas in Poland is shown in Figure 3. There are three complexes of salt-bearing deposits in Poland: Upper Permian (Zechstein), Lower and Upper Triassic, and Miocene (Table 1). Triassic salts are found in western and central Poland and range in thickness from several tens of metres (Lower

Triassic) to >140 m (Upper Triassic). However, they occur at great depths of >1680 and >3000 m, respectively (Czapowski, Tomassi-Morawiec, 2016), so their economic potential has not yet been assessed.

Rock salts. The concentration of magnesium (arithmetic mean) in Zechstein rock salt is 216 g/t and is associated with the presence of sulphates (anhydrite), relics of carbonates (Czapowski *et al.*, 2022a) and locally with dispersed magnesite (Czapowski, 1998 and references therein). In Miocene rock salt, the percentage of magnesium varies from 0.01 to 0.23% (Czapowski, Bukowski, 2024).

In Zechstein and Miocene clayey salts and zubers, the content of magnesium (which is concentrated mainly in the structure of clay minerals and carbonate admixtures) has not been determined due to the high proportion of clay substance (15–85%) and sulphates.

The anticipated economic resources of rock salt documented in 19 deposits amounted to >112.39 billion tonnes in 2023 (Szuflicki *et al.*, 2024), while all anticipated resources (predicted reserves including both prospective undiscovered and prognostic ones) of rock salt, estimated to a depth of 2 km (Fig. 3), amount to nearly 4.06 trillion tonnes, including Permian salts – >4.05 trillion tonnes, and Miocene salts – 6.9 billion tonnes (Szamałek *et al.*, 2020).

Potassium and magnesium salts (K-Mg). Only the Zechstein evaporitic complex contains potassium-magnesium salts that are attributed to three evaporite cyclothems and form correlative lithological levels (Czapowski *et al.*, 2023): the Oldest Potash (K1), Older Potash (K2) and Younger Potash (K3) (Table 1).



Fig. 6. Magnesite open pit near Braszowice (source: <https://www.facebook.com/share/151nVueFTY/>)

By the mid-1970s, five potassium-magnesium salt deposits had been documented: four deposits in the Puck Bay region, northern Poland: Chłapowo, Miosroszyno, Swarzewo and Zdrada (sulphate-type deposits, composed mainly of polyhalite as a product of secondary mineralization of primary calcium sulphates; they correspond to the Oldest Potash unit) and the Kłodawa 1 deposit (chloride-type K-Mg salts, attributed to the Younger Potash unit) in the Kłodawa salt diapir, central Poland (Fig. 3). The anticipated economic resources of polyhalite deposits, estimated on the concept of stratiform polyhalite occurrence, are >579 million tonnes, and the anticipated sub-economic resources are >18 million tonnes (Szuflicki *et al.*, 2024). The percentage of MgO in these deposits – with an average K₂O content ranging from 7.745 to 13.78% – can be estimated at about 3.4%. Hence, magnesium oxide resources in these deposits can be estimated at >20 million tonnes.

Data on the magnesium content in the Puck Bay area, which are more comprehensive, will be included in a new geological documentation report (currently under approval procedure) on the Miosroszyno deposit.

Small amounts of potassium and magnesium salts – chloride-type salts (carnallite with a slight admixture of sylvinit) and magnesium salts (kieserite) – with the anticipated economic resources of >89 million tonnes, occur in the Kłodawa salt diapir within the documented Kłodawa 1 rock salt deposit. The average content of MgO is 8.1%, magnesium content is 2.28% (Czapowski *et al.*, 2012), and the possible amount of extractable magnesium can be estimated at >2 million tonnes. However, the variable thickness of the seam (from a few metres to 50 m) and the difficulty of the beneficiation process are the reasons for the low economic interest in this deposit (Szuflicki *et al.*, 2024).

Extracting magnesium from sulphate-type deposits (polyhalite) is difficult because of the relatively low content of Mg in polyhalites, the need to build an underground mine, and the method of extracting the element from the mineral (sulphate dissolution, magnesium separation, etc.). A simpler and cheaper way is to extract it from chloride-type deposits that can be mined by underground leaching. The resulting brine can be concentrated to increase the content of the desired components, and eventually potassium and magnesium are separated. While leaching of this type of salt is not an option for the Kłodawa 1 deposit (active underground mine), it is possible to develop in numerous bedded deposits for which prospective areas have been identified and their predicted resources estimated (e.g., Czapowski *et al.*, 2015, 2023; Czapowski, Bukowski, 2015; Czapowski, 2017). The anticipated resources (prospective and prognostic) of Permian potassium and magnesium salts in Poland, estimated to a depth of 2 km in bedded deposits, amount to almost 3.64 billion tonnes (Szamałek *et al.*, 2020).

In Gdańsk Pomerania and NW Warmia areas (Fig. 3), primary chloride K-Mg salts of the Oldest Potash (K1) unit are locally found in salt deposits of the PZ1 Zechstein cyclothem. In Gdańsk Pomerania, these deposits have been pierced in three boreholes in the Chłapowo-Władysławowo-Chałupy area and in one borehole near Lisewo (Czapowski *et al.*, 2008, 2023). Their thickness varies from 2.7 to 25.1 m; the main minerals are carnallite and halite, with admixtures of anhydrite and polyhalite. The magnesium content varies from 0.06 to 1.49% (Werner, 1979). In the Lidzbark Warmiński region (Warmia area), K-Mg salts, ranging in thickness from 6 to 26 m, have been found so far in three

boreholes (Czapowski, Bukowski, 2015). However, there is no data on their mineral and chemical composition, but it can be assumed that they were formed in a similar way to the deposits described from Gdańsk Pomerania. In the nearby Königsberg (Kaliningrad) region, similar deposits (Pregola Svita), 30–37 m thick, represented by rock salt and K-Mg salts and containing sylvinit, carnallite, kieserite, polyhalite and kainite, are characterized by an average magnesium content of 1.06–4.08% (Czapowski *et al.*, 2023). The anticipated resources of these Oldest Potash occurrences in northern Poland are estimated at 359.5 million tonnes. Assuming the low average magnesium content of the occurrences of 1%, the magnesium resources of the deposits can be estimated at >3.6 million tonnes.

Chloride-type K-Mg salts, representing the younger potassium-bearing series such as the Older Potash (K2) and the Younger Potash (K3) units, occur – as at Kłodawa – in the salt stocks of a number of diapirs in central and NW Poland, e.g., at Góra, Inowrocław, Wapno, Damasławek, Mogilno and Goleniów (Fig. 3). However, their complex geological structure makes them extremely difficult to assess and mine. It is much easier to explore and estimate stratiform occurrences of these deposits, which are located mainly in the Fore-Sudetic area (Figs. 7 and 8).

In the Fore-Sudetic area, the Older Potash (K2) unit occurs at a depth of 975 m in the SW and S parts, and down to depths of 1700–1925 m in the northern part. Its thickness varies from a few to 30 m (Czapowski *et al.*, 2023 and references therein). The K-Mg salt seam is formed by alternating layers (0.1–1.0 m thick) of rock salt, rock salt with sylvinit, and so-called hard salt composed of halite, anhydrite, polyhalite and kieserite (*op. cit.*). The magnesium content of these deposits in the Zielona Góra area is 0.02–0.22% (Podemski, 1972).

In the area where K2 deposits have been found, seven prospective areas (OPs) of K-Mg salt occurrences have been distinguished: OP Chlebowo-Luboszyce, OP Dachów, OP Drzonków-Droszków, OP Nowa Sól K2, OP Piaski-Jeleniów, OP Pomorsko K2 and OP Radnica-Chyże (Fig. 7 and Table 5). They have been delineated on the basis of so-called positive boreholes, where the thickness of the K-Mg salt seam is not <2 m, while the depth of seam bottom does not exceed 2 km.

The bottom of the K2 salt seam in the seven indicated prospective areas is located at depths ranging from 940.5 m (OP Piaski-Jeleniów) to 1988.0 m (OP Chlebowo-Luboszyce), and its thickness varies from 2 to 92 m (OP Chlebowo-Luboszyce; Table 5).

The total area of the seven prospective areas of the Older Potash seam occurrences in the Fore-Sudetic area, documented by 98 boreholes, is 454 km². The anticipated resources of the mineral resource are estimated at 3.2 billion tonnes (Table 5). The estimated magnesium resources are 64 thousand tonnes, assuming the its lowest average content of 0.02%.

The K-Mg salt seam, corresponding to the of Younger Potash (K3) unit, forms a series of peculiar “islands” in the Fore-Sudetic area, distributed in a belt extending from Sulechów in the west to the Nowa Sól region in the east. The top of the seam lies at a depth ranging from 838 m in the SW and S parts of the area to 1068 m in the northern part. The thickness of the seam is highly variable, ranging from 1 to >50 m in the Ługi-Kondratowo region (Czapowski *et al.*, 2023 and references therein).

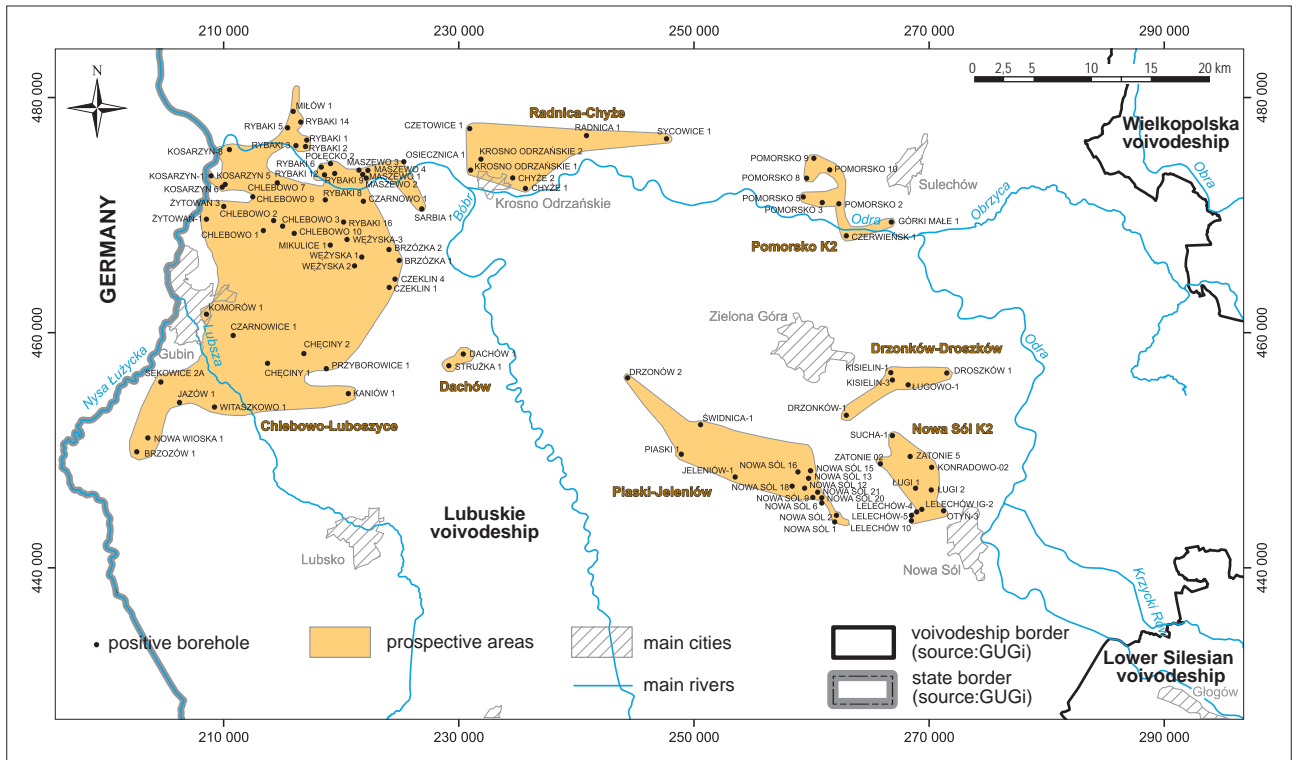


Fig. 7. Prospective areas with the Older Potash (K2) seam in the Fore-Sudetic area (Czapowski *et al.*, 2023)

The seam consists of two potassium-bearing zones separated by a several-metre thick series of rock salt:

- The lower zone, up to 6 m thick, is composed of rock salt with admixtures of anhydrite and interbeds of polyhalite, the percentage of $MgSO_4$ is 2.7–4.6%;

- The upper zone, up to 12 m thick, represented by sylvinite, kieserite and polyhalite, and the percentage of $MgSO_4$ is 2.0–49.0% (*op. cit.*).

Based on the so-called positive boreholes, six prospective areas have been identified: OP Nowa Sól K3, OP Pomorsko K3, Klenica, Lubcin 1, Lubcin 2 and Lubcin 3 (Fig. 8 and Table 6).

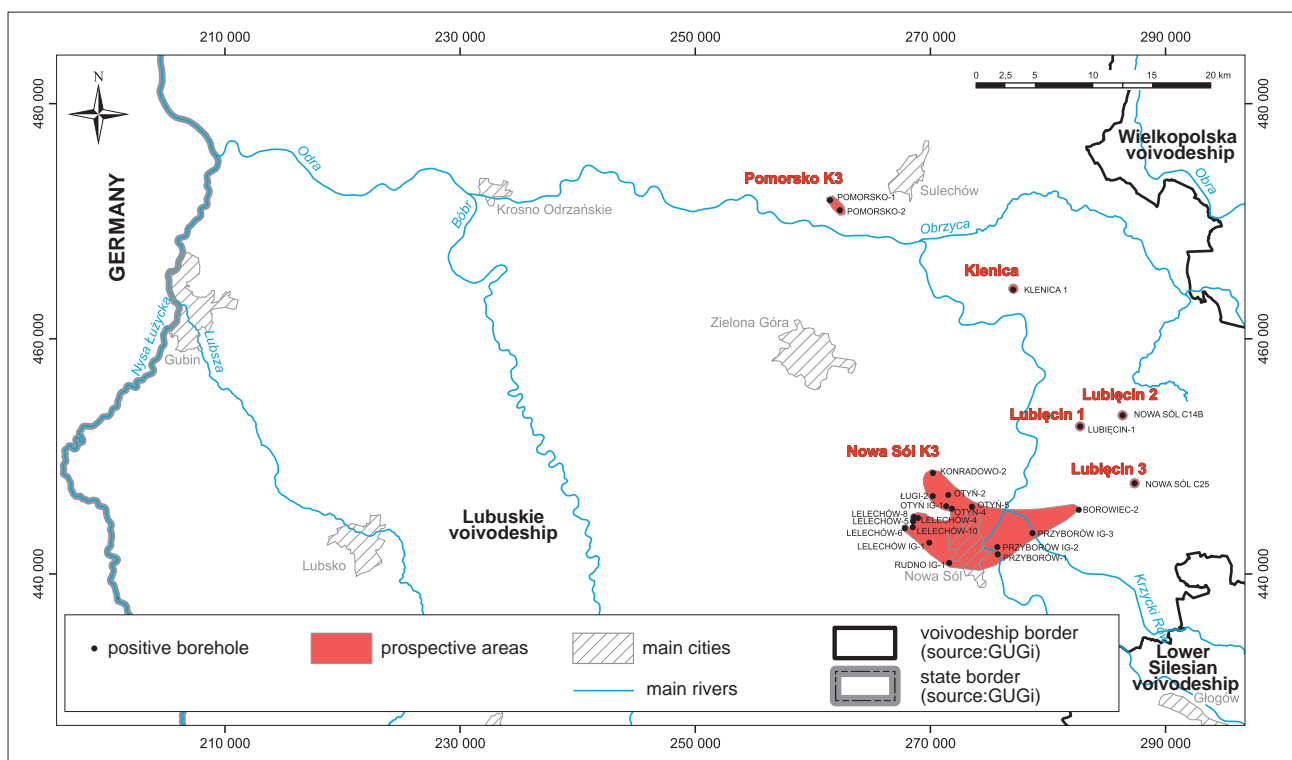


Fig. 8. Prospective areas with the Younger Potash (K3) seam in the Fore-Sudetic area (Czapowski *et al.*, 2023)

Table 5. Characteristics of prospective areas with the Older Potash (K2) seam in the Fore-Sudetic area (Czapowski *et al.*, 2023)

Area name	Area [km ²]	Predicted reserves [million tonnes]	Geological exploration [number of wells]	Parameters of potash seam	
				Bottom depth (min-max/average) [m]	Thickness (min-max/average) [m]
Chlebowo-Luboszyce	330.8	2 461.7	50	1026.5–1988.0/ 1583.22	2.0–92.0/11.81
Dachów	2.9	6.4	2	960.0–1073.0/1016.5	3.0–4.0/3.5
Drzonków-Droszków	14.2	91.8	5	1506.5–1800.5/ 1669.6	6.0–16.5/10.3
Nowa Sól K2	23.1	131.6	11	1032.5–1477.5/1248.22	3.0–18.5/9.04
Piaski-Jeleniów	62.0	395.0	15	940.5–1295.0/ 1124.38	3.5–24.4/10.1
Pomorsko K2	15.8	102.4	8	1840.5–1985.0/ 1914.44	5.0–16.5/10.25
Radnica-Chyże	5.2	54.45	7	1813.5–1960.0/ 1882.86	5.5–39.5/16.58
Number of areas	Total area [km²]	Total reserves [million tonnes]	Total number of wells		
7	454.0	3 243.35	98		

Table 6. Characteristics of prospective areas with the Younger Potash (K3) seam in the Fore-Sudetic area (Czapowski *et al.*, 2023)

Area name	Area [km ²]	Predicted reserves (million tonnes)	Geological exploration (number of wells)	Parameters of potash seam	
				Bottom depth (min-max/average) [m]	Thickness (min-max/average) [m]
Nowa Sól K3	57.4	265.58	17	980.0–1369.5/1098.79	2.0–50.8/7.35
Pomorsko K3	1.4	14.3	2	1778.0–1832.0/1805.0	6.0–27.0/16.5
Klenica	0.5	3.16	1	1750.0	10.0
Lubięcín 1	0.5	3.16	1	1495.0	10.0
Lubięcín 2	0.5	1.27	1	1544.0	4.0
Lubięcín 3	0.5	1.27	1	1450.0	4.0
Number of areas	Total area [km²]	Total reserves (million tonnes)	Total number of wells		
6	60.8	288.79	23		

The bottom of the K3 salt seam in the indicated six prospective areas is located at depths ranging from 980.0 m (Nowa Sól K3 OP) to 1832.0 m (Pomorsko K3 OP), and its thickness varies from 2 to 50.8 m (Nowa Sól K3 OP; Table 6).

The total area of the six prospective areas of the Younger Potash (K3) seam in the Fore-Sudetic area, documented by 23 boreholes, is >60 km², while the anticipated resources of the mineral resource are estimated at 288.8 million tonnes (Table 6). The estimated resources of MgSO₄ are 5.8 million tonnes, assuming the lowest magnesium sulphate content of 2%.

The total resources of the mineral resource in the 13 indicated prospective areas of stratiform K-Mg salt deposits, representing the Older Potash (K2) and the Younger Potash (K3) units in the Fore-Sudetic area, documented by 121 boreholes, are estimated at 3.53 billion Mg, and their total area is 514.8 km².

Estimated magnesium resources in Poland are as follows:

- Magnesite (MgCO₃) in the six documented deposits – 16.5 million tonnes; assuming a minimum magnesite content of 4% in the mineral resource and converting

to pure magnesium (Łaszkiwicz, 1967) gives >188 thousand tonnes;

- Magnesite (MgCO₃) in the prospective areas – 5.65 million tonnes; using similar assumptions, it gives >67 thousand tonnes as converted into pure magnesium;
- Magnesium oxide (MgO) in the documented four polyhalite deposits – >20 million tonnes, converted to pure magnesium (Łaszkiwicz, 1967) gives >12 million tonnes;
- Magnesium in the documented Kłodawa 1 deposit – >2 million tonnes;
- Magnesium in the three prospective areas of northern Poland – >3.6 million tonnes;
- Magnesium in the seven prospective areas of the K2 salt seam in the Fore-Sudetic area – 64 thousand tonnes;
- Magnesium sulphate (MgSO₄) in the 13 prospective areas of the K3 salt seam in the Fore-Sudetic area – 5.8 million Mg, converted to pure magnesium (Łaszkiwicz, 1967) gives >1.16 million tonnes.

In summary, magnesium resources in proven deposits are >14.19 million tonnes, and those in the prospective areas can be estimated at >4.89 million tonnes. It should be emphasised that

the above estimates are based on the assumption of the lowest proportion of magnesium or its compounds in the mineral resource for prospective K-Mg salt deposits, and that the amount of mineral resources in the Fore-Sudetic area is reduced by 70% due to the complex tectonic structure of this region (Czapowski *et al.*, 2023). Thus, the potential magnesium resources in Poland in the above-mentioned deposits may be multiplied.

Groundwater. Magnesium concentrations in natural groundwater in Poland, which includes fresh groundwater, thermal water, mine brine, and brine from gas deposits, range from 0 to 30 mg/L. A review of available databases of deep boreholes, mine waters and geothermal installations in Poland (Razowska-Jaworek *et al.*, 2022) showed that out of 2411 water analyses, magnesium content was determined in 2378 cases (Table 7). In 432 analyses, the magnesium concentration was >2,000 mg/L, i.e. more than the prospective value (2000 mg/L) for the extraction of this element from waters. In 103 analyses it was >5000 mg/L, and in 51 analyses – >10,000 mg/L, of which as many as 23 were higher than 40,000 mg/L. The highest magnesium concentrations

Table 7. Analyses of magnesium content in waters from deep boreholes and in medicinal and mine waters

Magnesium [mg/L]	
Number of analyses	2378
Maximum	75,421
Minimum	0.2
Median	221
Average	1511

were found in brines from the Jastrzębsko 2 borehole (75.42 g/L), Mogilno salt mine (74.07 g/L), Babimost 1 borehole (67.75 g/L) and Września IG 1 borehole (64.31 g/L). The magnesium content of groundwater depends to some extent on depth, but more so on mineralization and the contents of sodium, chloride and potassium (Table 8). Last study (Razowska-Jaworek *et al.*, 2021) focused on the possibility of recovering magnesium from geothermal waters, mine waters, and waters pumped during natural gas production in Poland. The magnesium concentration in the waters (75 samples) varied from 2.9 to 52.8 g/L, averaging 1587.45 mg/L. The highest values were found in the Kłodawa salt mine (52.8 g/L) and in the brine from the Dębnie desalination plant (19.2 g/L). At seven mining plants, concentrations exceed those considered prospective for extraction (2000 mg/L). Magnesium resources in groundwater have been estimated for the most prospective plants and facilities so the largest magnesium resources are found in the Dębnie desalination plant (>36,000 tonnes), the Janina coal mine (>4000 tonnes) and the Rudna copper mine (>3000 tonnes).

Chruszcz-Lipska *et al.* (2017) analysed the chemical composition of 52 groundwater samples from the Fore-Sudetic Monocline. The average concentration of magnesium ions in waters from Zechstein carbonates is 2173.0 mg/L, with

a maximum of 6782 mg/L. Magnesium concentrations in waters from Buntsandstein deposits of the Fore-Sudetic Monocline are lower (average 683.6 mg/L). In the Fore-Sudetic Monocline, the waters preferred for magnesium extraction come from Zechstein carbonates hosting tens of natural gas reservoirs (including Żakowo, Tarchały, Uników, Antonin, Rawicz, Kąkolewo, Janowo, Bogdaj-Uciechów) and oil reservoirs (Czerwieńsk, Pomorsko, Gomunice), which are currently being exploited or have already been abandoned. In the areas of hydrocarbon fields, there are exploratory and production wells. There are also wells that have been abandoned due to unprofitability. These wells can be used to access saline water horizons with significant levels of valuable elements, including magnesium. Good examples are the Wróbliniec 2 (Mg content – 1552 mg/L) and Szklarka 5 (Mg content – 2777 mg/L) boreholes located ~1 km from the outline of the deposit in the active Bogdaj-Uciechów gas mine. In the case of magnesium extraction from brines, it is possible to delineate prospective areas (Razowska-Jaworek *et al.*, 2022) that host geothermal brines enriched in boron, magnesium and strontium (Fig. 2), where magnesium could be extracted as part of the co-recovery process.

STRONTIUM (Sr)

Characteristics of occurrence

Strontium is a relatively rare element in the Earth's crust; its Clark value is 0.045%, making it the 15th most common element (MacMillan *et al.*, 1994). In sedimentary rocks, the percentage of strontium varies according to lithology, from 0.002% in sandstones, 0.0177–0.03% in clay rocks, to 0.0495–0.061% in carbonates (Ważny, 1969).

Strontium is present in 97 known minerals, but occurs mainly as a sulphate (celestite – SrSO₄) and a carbonate (strontianite – SrCO₃). Among these minerals, celestine is the most common one in quantities that allow its mining and commercial use. Only a few strontianite deposits have been discovered that are suitable for use and economic extraction. Under certain hydrothermal conditions, barite-celestine is observed (Nowińska-Jarzębińska, 2022).

Global strontium production is based mainly on celestine deposits (U.S. Geological Survey, Mineral Commodity Summaries, 2024). The common occurrence of strontium in evaporite rocks makes these rocks and the brines circulating within them an alternative source of strontium.

Strontium occurrences with economic potential in Poland

The main strontium mineral in Poland is celestine, while strontianite and barite-celestine are only of mineralogical significance. Concentrations of celestine, including in deposits, have been found in Miocene sulphate deposits of the Carpathian Foredeep, in Upper Silesia, and near Kraków, Tarnobrzeg and Staszów.

Table 8. Correlation coefficients of magnesium content with other parameters and components in the waters studied

Component	HCO ₃	SO ₄	Cl	Ca	Na	K	Fe	Br	Ba	B	Li	Sr
Magnesium	-0.128	0.484	0.832	0.911	0.815	0.712	0.387	0.664	0.258	0.489	0.667	0.696
Parameter	Depth	Temperature	pH	Mineralization								
Magnesium	0.747	0.407	-0.395	0.894								

Strontium has also been recorded in Zechstein carbonate and sulphate deposits of the Polish Lowlands, Fore-Sudetic Monocline and Bay of Puck and barite veins in Lower Silesia. The strontium content in Zechstein carbonates depends on the facies type and ranges from 0.007 to 0.55% (Ważny, 1969). In Zechstein salt-bearing deposits in the Puck Bay area, the strontium content of polyhalite and anhydrite samples from six boreholes ranged from 0.06 to 2.26% (Stepniewski, 1973). Celestine has been found in barite veins in the Sudetes at Boguszów, Stanisławów and Jeźów Sudecki (Lis, Sylwestrzak, 1986). In samples from Boguszów, the average SrSO_4 content was 3.51% (Kowalski, 1977), while in Stanisławów it was 2.05% (Osmólski, 1987). Mineralogical occurrences of celestine are also known from several other locations in Poland: from the Kłodawa Salt Mine in Zechstein salts and drillcores from the Myszków Cu-Mo deposit.

No uniform criteria of economic viability have been established for strontium resources worldwide. In the past, the number of valuable components (SrSO_4 or SrCO_3) in the mineral resource and the structure of the rock were critical due to the manual nature of the process. The manual method enriched the ore from ~30% SrSO_4 to a concentrate of >85% SrSO_4 . Currently, medium-grained varieties of the mineral resource are processed using a gravity method of ore concentration, and fine-grained varieties of strontium minerals are processed by flotation to 85–96% SrSO_4 . As a result, a number of mineral deposits, previously considered non-industrial, can currently be exploited provided they are large enough and the celestine content in the ore is at least 5–15% (Morawiecki, 1975). Dispersed, fine-grained and coarse-grained celestine rocks are profitable to mine and can be beneficiated (Strzelska-Smakowska, 1979).

In Poland, there are no established criteria of economic viability for deposits containing strontium minerals. When documenting the resources of the celestine deposits at Czarkowe (Domaszewska, 1955), a minimum content of 10% SrSO_4 was assumed. The celestine ore contained from 10.69 to 31.75% SrSO_4 , with an average of 20.17% SrSO_4 . In later years, lower qualitative and geological-mining indicators were proposed (Kasprzyk, Osmólski, 1989) for the strontium-bearing sediments of the Carpathian Fore-deep (Table 9).

Strontium resources are currently not included in the register of mineral resources of Poland (e.g., Szuflicki *et al.*, 2024).

The generally accepted threshold for economic recovery of strontium from geothermal brines is about 500 mg/L. Below this level, the cost of extraction and processing may outweigh the benefits unless favourable conditions exist, such as high market prices or the presence of other valuable elements.

Rocks

Rock salt and potassium and magnesium salts

Salt deposits are the best source of sought-after elements. They are easy to dissolve and the resulting brine can be easily processed.

However, an important thing is the content of elements. Zechstein (Upper Permian) rock salt in Poland contains an average of 19.99–151.65 ppm of strontium (due to the presence of admixtures of sulphates and carbonates) while clayey rock salt and zuber contain 79.12 to 120.77 ppm (Tomassi-Morawiec *et al.*, 2019; Czapowski *et al.*, 2022b). A higher average percentage of strontium is recorded in potassium-magnesium salts – 102.3 to 1075 ppm (Czapowski *et al.*, 2022a, b), nevertheless, the average strontium content in the Zechstein salts in Poland does not exceed 0.1%.

Miocene rock salt in Poland contains an average of up to 0.0074% strontium (Czapowski *et al.*, 2001), while zuber of this age contains 782 ppm (Czapowski *et al.*, 2023). Recently investigated Zechstein anhydrites with K-Mg sulphate mineralization (polyhalite; Lower Anhydrite of the PZ1 cyclothem in northern Poland) contain an average of 1075 ppm strontium (median 723 ppm; Czapowski *et al.*, 2020).

Wieliczka rock salt deposit

The Wieliczka deposit has an average strontium concentration of about 0.04% (Nowińska-Jarzębińska, 2022), which is similar to the average strontium content of the Bochnia salt deposit (0.02%). Rock salt with elevated strontium content of up to 3.3% (presence of celestine: Prochazka *et al.*, 1969; Nowińska, 2017) occurs only locally. Dolomitic salts are characterized by a strontium content of up to 0.8% (Nowińska-Jarzębińska, 2022).

Sulphate rocks

Strontium concentrations of economic importance in Poland are found in Miocene sulphate and sulphur-bearing deposits of the Carpathian Foredeep (Fig. 9). The strontium content in these rocks is generally low. The highest strontium concentrations, averaging up to 0.67 wt.%, are found in the Staszów area (Kasprzyk, 1988, 1993), while in the Osiek-Baranów Sandomierski sulphur deposit area – 0.56% (Gąsiewicz, 1997).

The average strontium content of sulphur-bearing deposits is significantly higher than that of sulphates. The average strontium content of sulphur-bearing limestones is significantly higher than that of gypsum and is generally associated with the release of this element from Badenian sulphates during epigenetic reduction processes (Krajewski, 1935; Parafiniuk, 1987; Osmólski, 1987). One of the reasons for

Table 9. Quality and geological-mining indicators of strontium-bearing sediments in Poland

Specification	According to existing criteria (Kasprzyk, Osmólski, 1989)	Proposed new criteria for anthropogenic deposits (heaps)
I. Quality Indicators:		
useful component Sr converted to SrSO_4 – average content of the entire deposit	not <7% SrSO_4	not <2% SrSO_4
– minimum content in a sample	not <5% SrSO_4	not <1% SrSO_4
II. Geological and Mining Indicators:		
– thickness of strontium-bearing sediments [m]	not <0.5 m	not <0.5 m
– maximum occurrence depth [m]	30 m	10 m
– maximum overburden-to-deposit thickness ratio	10:1	10:1

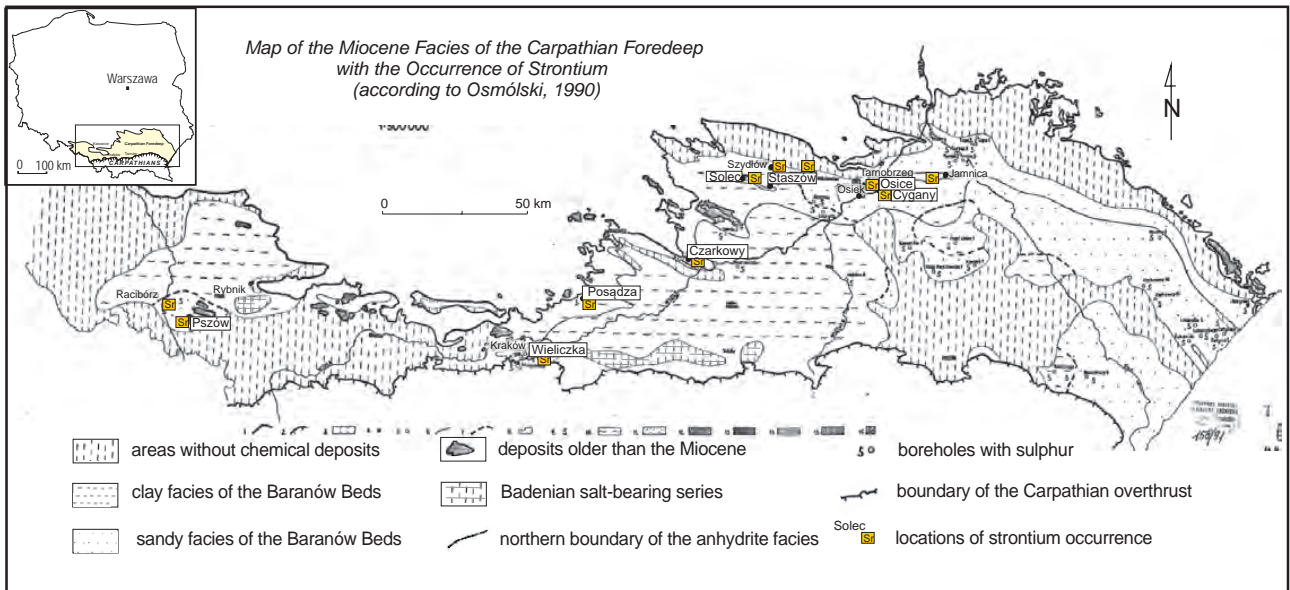


Fig. 9. Map of Miocene facies in the Carpathian Foredeep shows strontium occurrences (Osmólski, 1990)

the strontium enrichment of limestone-gypsum deposits may be the weathering of strontium-bearing gypsum, as is the case in Czarkowy (Morawiecki, Domaszewska, 1956).

Czarkowy celestine deposit

The strontium-bearing deposits are associated with gypsum and marls and occur mainly in the vicinity of sulphur-bearing carbonates (Krajewski, 1935). The mineral deposit is lenticular in shape and extends E–W along the slope of the Nida valley. In the geological cross-section

(Fig. 10), Miocene (Badenian) deposits unconformably overlie Cretaceous (Campanian, Maastrichtian) rocks, and are overlain by Badenian olivine marls with glauconite (Baranów Beds), which wedge out in the Czarkowy because the evaporites (gypsum and limestones with sulphur or strontium) overstep the immediately underlying Cretaceous marls.

The evaporites (gypsum) are a few metres thick near the outcrops, while in areas of bedrock depressions their thickness reaches 20 m. These deposits are metasomatically altered into sulphur-rich limestones. In the Czarkowy

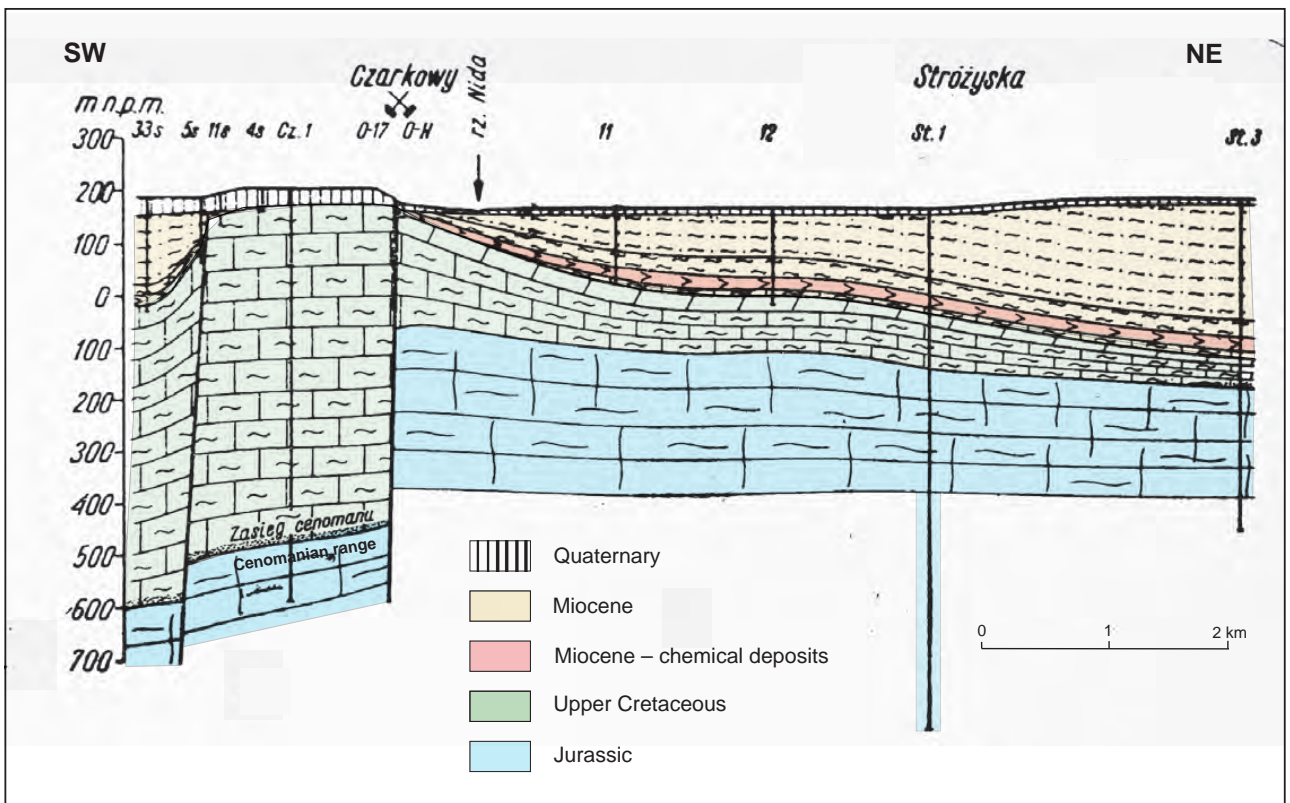


Fig. 10. Schematic cross-section of the Czarkowy deposit according to Osmólski (1972)

region, they are 4–6 m thick, but the thickness of the limestones with strontium reaches a maximum of 4 m (Osmólski, 1979). The rocks on the surface are remnants of a sulphur deposit that was once mined in the area (Krajewski, 1935).

The concentration of celestine, which occurs in irregular agglomerates up to 2 cm in diameter, can reach several percent locally. In massive overgrowths, it can exceed 10% of the rock volume.

- Celestine-bearing conglomerate – occurs as whitish, angular clasts of various sizes, cemented with a darker binder. The clasts are represented by very fine celestine pelite containing up to ~30% SrSO₄, and the cement is mainly strontium-enriched calcium carbonate (~15% SrSO₄ content);
- Celestine clay – a product of the weathering of celestine-bearing breccia, with variable strontium content from >0.1 to >60% SrSO₄;
- Porous celestine-bearing, brittle marly rock, containing >20% SrSO₄;
- Celestine-bearing gypsum – this is usually coarsely crystalline gypsum, the individual crystals being cemented by carbonate-calcareous cement containing celestine pelite. Celestine content varies from a few percent to 24% SrSO₄.

The strontium-bearing deposits from Czarkowy must have originally formed an elongated irregular lens, over 600 m long and a few to 20–30 m wide (Domaszewska, 1955). In the central part, the celestine-bearing deposits have been almost completely eroded (*op. cit.*), so that today the mineral deposit consists of two lobes: the western and the eastern. During geological work in 1954, the western lobe was provisionally documented in category C2, and later the deposit was upgraded to category C1. The eastern lobe has been preliminarily explored but not documented (Osmólski, 1979).

The 150 m-long western lobe contains 13,750 Mg of strontium ore, which contains 2704 tonnes of celestine (Domaszewska, 1955). The average thickness of the deposit bed is 2.79 m, covering an area of 2123 m². The SrSO₄ content varied from 10.69 to 31.75% SrSO₄ in individual pits of the mineral deposit. The calculated average SrSO₄ content was 20.17% (*op. cit.*).

Interpretation of satellite and aerial images (Osmólski *et al.*, 1979; Krysiak, 1987) showed that the deposits with elevated strontium levels are associated with a latitudinal tectonic zone (Fig. 11). In the undocumented eastern lobe, the mineral resource occurs in pits and in a trench at a depth of 1–2 m. In places, solid celestine-bearing rock, containing about 20% SrSO₄, is found at the surface. Towards the south, the strontium-bearing seam wedges out and rests on sulphur-bearing marl containing up to 12% SrSO₄ (*op. cit.*).

Between 1954 and 1974, ~3000 Mg of celestine-bearing rock was extracted from the Czarkowy celestine deposit and exported after processing (70–80% SrSO₄) (Osmólski, 1987).

The Czarkowy celestine deposit was the only strontium raw material deposit listed in the Poland's mineral resources register. In the 1960s (Przeniosło, 1960–1970), resources of 13,735 tonnes of ore (celestine-bearing rock), including 2700 tonnes of celestine, were documented in category C1. In the 1970s, this figure was recorded as the estimated resources in the register of mineral resources and amounted to 23,400 tonnes of ore (Przeniosło, 1971–1980). In the early 1980s, the volume of estimated resources for the Czarkowy deposit was increased to 31,500 tonnes of ore, including 5300 tonnes of celestine (Przeniosło, 1980–1985). Since 1986, no strontium-bearing raw materials in Poland have been recorded in the annual register of mineral resources, and no exploitation of this raw material has been carried out. The verified volumes of strontium-bearing raw material resources in the Czarkowy deposit are shown in Table 10.

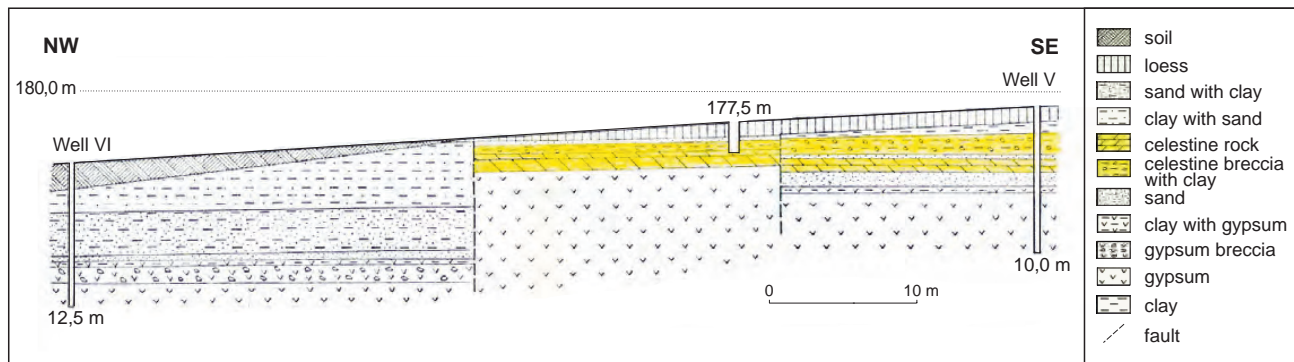


Fig. 11. Geological cross-section through the western part of the Czarkowy deposit (after Osmólski *et al.*, 1979)

Table 10. Historical resource quantities in the Czarkowy deposit and prospects for their expansion

Specification	Strontium raw material (ore) [t]	Average SrSO ₄ content [%]	Celestine SrSO ₄ [t]
SrSO ₄ resources documented in category C1 in 1954 in the western seam (Domaszewska, 1955), classified as subeconomic (Osmólski, 1990)	13,750	20.38	2704
Economic SrSO ₄ resources in the eastern seam (Osmólski, 1990)	31,506	16.90	5324
Extracted raw material resources from the eastern seam (1954–1974)	3000	16.90	507
Estimated SrSO ₄ resources in sulphur ore roasting heaps in 1953	116,500	8.50	9900
Economic reserves in heaps, verified by Osmólski (1990)	31,591	9.25	2922

The area of the former sulphur mine at Posądz

The Posądz sulphur deposit is located ~30 km north-east of Kraków. The deposit was exploited intermittently between 1915 and 1921 (Biltek, 1919). The only traces of the former exploitation are the remains of pits and heaps (Nowińska-Jarzębińska, 2022).

The Posądz deposit is situated in the core of an NW-SE-stretching anticline, cut by two longitudinal faults. The anticline core is represented by Upper Cretaceous deposits of siliceous limestone (opoka), gazes and marls, covered by Miocene deposits. In the northeastern part of the anticline, near faults, there are sulphur-bearing limestones.

The typical features of the Posądz deposit are rock voids in the porous and fractured limestones, which are filled by sulphur with visible celestite crystals. The average depth of the sulphur-bearing deposits ranges from 6 to 12 m, with an average thickness of about 10 m. The average sulphur content was between 10 to 18% (Bąbel, 1999). No data on the celestine content of sulphur ore mined in the past are available. Drilling between 1958 and 1962 showed sulphur content of 24 and 0.43% SrSO_4 in only one borehole (Osmólski, 1987).

New studies (Nowińska-Jarzębińska, 2022) indicate relatively high strontium content of 0.53 to 1.10% in rock samples from the deposit. In addition, weathered loess-type rocks with a relatively low average strontium content of about 330 ppm are present at the mine site.

Strontium mineralization in the surroundings of Solec, Staszów and Żurawica

Celestine occurs also in sulphur-bearing deposits in the vicinity of Staszów, Solec near Szydłów, and Żurawica. Analysis of strontium distribution in the sections of 14 boreholes (Kasprzyk, Osmólski, 1989) showed that the element tends to concentrate at the top of the evaporite sedimentary complex and its proportion increases with the increase in the proportion of carbonates. The highest concentrations of strontium are found in carbonate rocks, e.g. the proportion of

strontium in porous limestones of the sulphur-bearing series is >15% (Kasprzyk, Osmólski, 1989). Brecciated limestones, commonly found in carbonate rocks, contain much less strontium – 0.1–1.0%. Higher concentrations – up to 3.7% – have been found in clays overlying the porous limestones.

Anthropogenic accumulations

„Cygany” flotation tailings pond

The “Cygany settling pond is located on the Vistula River terrace (Fig. 12) in the industrial area of the “Machów” Sulfur Mine with an area of 196 ha, near the village of Cygany. In the period 1969–1993, the pond was being filled mainly with tailings from the sulphur production process, and – until 1996 – with dust and gypsum from the thermal power plant at Machów. A total of 33.25 million tonnes (dry matter) of tailings have been deposited in the settling pond. The total amount of ash deposited in the pond is 1.34 million tonnes (dry matter) and 3000 tonnes of gypsum from the desulfurization plant. The chemical composition of the averaged waste sample showed a strontium content of 0.48%, i.e. about 1% SrSO_4 . Theoretically, the waste in the settling pond may contain 158,400 tonnes of strontium, or 331,056 tonnes of SrSO_4 .

The results of chemical analyses (Kirejczyk *et al.*, 1997) show that the main components of the tailings are calcium carbonate (~80%), silica (~7.5%) and sulphur (~4.3%). Barium and strontium sulphides (barite and celestine – poorly soluble forms) and clay mineral constituents are present in small amounts (Table 11).

“Ocice” flotation tailings pond

The tailings pond at Ocice is located within the boundaries of the Tarnobrzeg II mining area (“Machów” Sulfur Mine). The settling pond area forms an extensive plain of about 90 ha with a slight depression in the central part (Fig. 13).

Between 1960 and 1969, tailings from the Machów Sulfur Production Plant were dumped into the settling pond. According to current estimates, >6.5 million tonnes of waste remain in the pond. The average strontium content of the waste is



Fig. 12. Satellite image of the “Cygany” flotation tailings pond. Current state (Google Earth, image dated 12.03.2023)

Table 11. Chemical composition of flotation waste in a single sample from the “Cygany” settling pond (Kirejczyk *et al.*, 1997)

No.	Designation of chemical composition	Content [%]
1.	CaO	45.32
2.	CO ₂	34.53
3.	SiO ₂	7.50
4.	Al ₂ O ₃	2.01
5.	MgO	0.89
6.	Ba	0.15
7.	Sr	0.48
8.	Na ₂ O	1.99
9.	K ₂ O	0.30
10.	SO ₃	2.34
11.	Fe ₂ O ₃	0.55
12.	sulphides	no detected
13.	elemental sulphur	4.29
14.	loss on ignition at 1000°C	38.82

1.55% (Pilichowska, 1979) and the theoretical strontium resources would be about 94,000 tonnes (Osmólski, 1987).

Sulphur smelting heaps, so called “burn-outs”, in the Czarkowy region

Potential areas of strontium occurrence of practical importance include sulphur-smelting heaps (so-called “burn-outs”) left after the exploitation of the Czarkowy sulphur deposit (Osmólski, 1979).

The heaps consist of waste from the sulphur smelting process and occur near the former sulphur mine at Czarkowy. In 1953, the estimated amount of waste in two heaps was 116,500 tonnes (Table 10). The average SrSO₄ content of the heaps was determined to be 8.5%, giving a prospective SrSO₄ resource of 9900 tonnes. Later work (Osmólski *et al.*, 1982a, b) showed that the thickness of one of the heap in the Czarkowy meadows (Fig. 14) ranged from 1.0 to 3.8 m; with an average of 2.6 m. The SrSO₄ content measured in the shafts and ditches in the heap, calculated from the analysis of furrow samples, ranged from 8.03 to 11.84%.

Heaps left after sulphur mining in the Kokoszyce and Pszów areas near Rybnik

Sulphur economic concentrations in Rybnik Silesia have been known since 1878 (Mikolajczyk, 1879) when sulphur was found in nine boreholes at a depth of 35–54 m (Osmólski, 1969). Mines were located between Zawady and Kokoszyce (Fig. 15; Osmólski, 1990). In samples of Miocene limestones from the Doły Pszowskie area near Pszów, occurrences of crystalline celestine have been found (Borne, Weiss, 1855), while in the Krzyszkowice area, outcrops of celestine deposits have been described (Fiedler, 1863, after: Osmólski, 1990).

In the Kokoszyce area, a heap is left over from sulphur mining 100 years ago (Fig. 16) with a potential SrSO₄ content of about 10% (Osmólski, 1990).

The estimated amounts of strontium recoverable from abandoned Miocene sulphur-bearing deposits and anthropogenic accumulations (tailings ponds, heaps) are as follows:

- The abandoned Czarkowy deposit and mine: the amount of celestine (SrSO₄) can be estimated at 5324 tonnes, which gives 2535.3 tonnes of pure strontium;



Fig. 13. Satellite image of the “Ocice” flotation tailings pond (red contour) (Google Earth, image dated 12.03.2023)

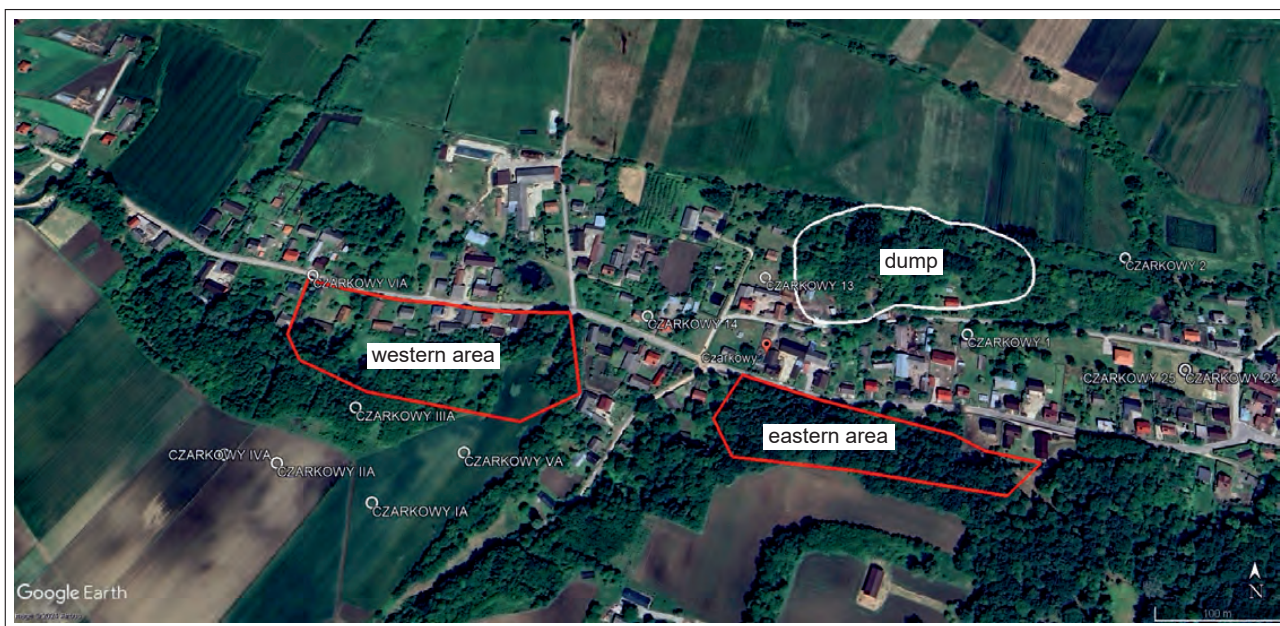


Fig. 14. Projection of the contours of the Czarkowy deposit, exploration boreholes, and heaps from sulphur smelting onto a satellite image from Google Earth. The deposit contours are based on the celestine deposit documentation (Domaszewska, 1955). Borehole locations according to the CBDG database

- ❑ Cygany settling pond: the amount of celestine (SrSO_4) can be estimated at 331,000 tonnes, which, converted to pure strontium, is 155.57 thousand tonnes;
- ❑ Ocice settling pond: the amount of pure strontium is estimated at 94,000 tonnes;

- ❑ Spoil heaps from sulphur mining: the amount of celestine (SrSO_4) can be estimated at 9.9 thousand tonnes, which gives 4.65 thousand tonnes of pure strontium.

The total strontium resources recoverable from the abovementioned facilities can be estimated at >256.75 thousand tonnes.

Groundwater. Strontium is present in groundwater due to the weathering and leaching of rock-forming minerals and is one of a group of micronutrients commonly found in water (Macioszczyk, Dobrzyński, 2002). Strontium concentration in natural groundwater in Poland ranges from 0.03 to 4.7 mg/L. The highest levels are recorded in aquifers of sedimentary clastic and carbonate rocks.

Strontium concentrations of around 1831 mg/L have been found in formation brines from the Kłodawa salt diapir (d’Obyrn *et al.*, 2018), while up to 632 mg/L – from the Mogilno salt diapir (Wachowiak, Kasprzak, 2014).

Analysis of available databases of deep boreholes, mine waters, and geothermal waters in Poland, including the results of 2411 physicochemical tests, revealed that the strontium levels were determined in 808 cases (Table 12). Strontium concentration was >10 mg/L in 256 analyses, over 50 mg/L in 137 analyses, in 88 analyses >100 mg/L, and in 26 analyses over 500 mg/L, of which 8 ones showed strontium content >1000 mg/L.

The highest strontium concentrations were found in brines from the boreholes Bańska PGP-1 (6525.0 mg/L) and Zakrzyn IG-1 (2785.0 mg/L).

The strontium content in groundwater does not depend on the depth or temperature of the groundwater, but on mineralization, and content of sodium, potassium, chloride and calcium (Table 13).

Table 12. Analyses of strontium content in waters from deep boreholes and medicinal and mine waters

Strontium [mg/L]	
Number of analyses	808
Maximum	6525
Minimum	0.002
Median	3.1
Average	60.1

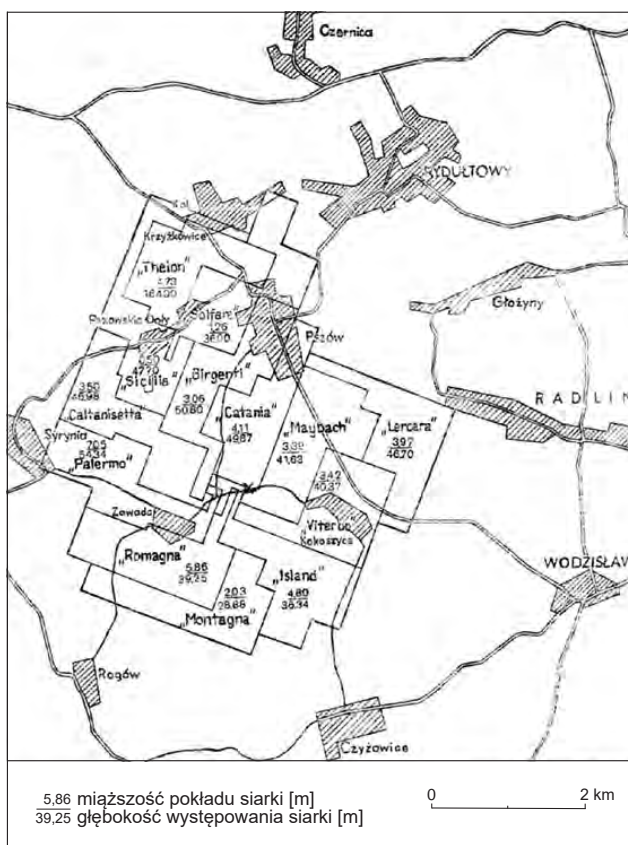


Fig. 15. Mining license plan for the proposed sulphur mines from 1878 (Osmólski, 1990)

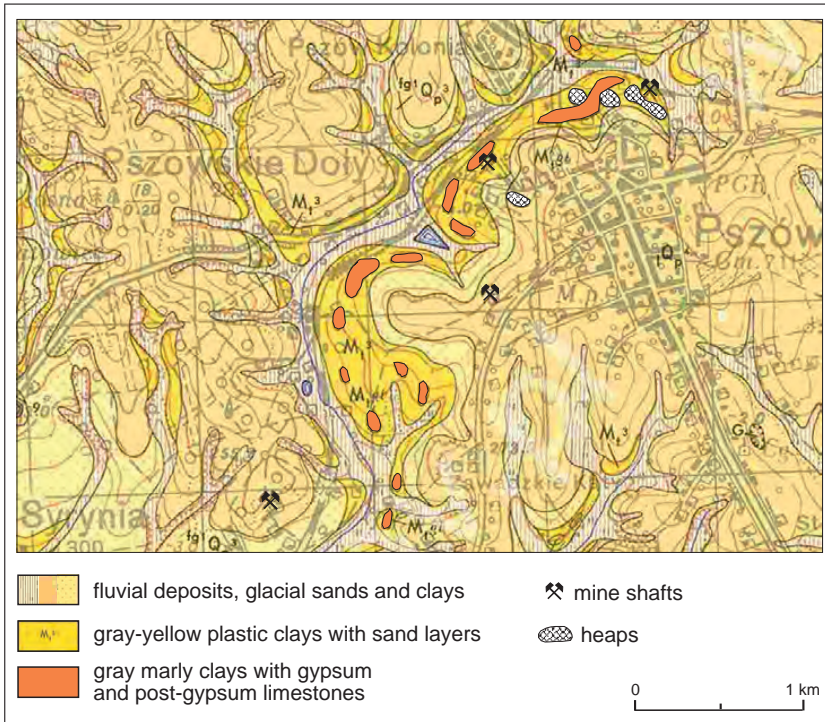


Fig. 16. Occurrence of Miocene deposits and outcrops of gypsum and sulphur-bearing limestones in the Pszów area; excerpt from the 1:50,000 geological map, Rydułtowy sheet (Sarnacka, 1956)

Recent studies (Razowska-Jaworek *et al.*, 2021) indicate that geothermal, mine and natural gas extraction waters in Poland mostly contain no >50 mg/L strontium, with an average of 103.06 mg/L. The highest levels of strontium were found in water from the Kłodawa salt mine (1950 mg/L) and from PGNiG boreholes in the Wielkopolska region (775–1100 mg/L). These concentrations were higher than those considered prospective (500 mg/L) for the extraction of this element from water (Gallup, 1998; Neupane, Wendt, 2017). Also estimated the strontium resources in groundwater for most prospective plants/facilities. The highest

magnesium from these salts is relatively inexpensive (leaching of salts and separation of magnesium from the resulting brine) compared to the more costly exploitation of the deposits and prospective occurrences of magnesite (255,000 tonnes in total). Much less magnesium – about 44,000 tonnes – can be extracted from groundwater enriched in this element, and the costs can be reduced by the simultaneous extraction of co-occurring critical elements such as boron and strontium. It should be noted that the estimates of magnesium resources in potassium-magnesium salts and magnesites are downgraded. This is due to the fact that

resources were found for the Dębieńsko desalination plant (>500 tonnes), the Rudna (>400 tonnes) and Polkowie-Sieroszowice copper mines (>200 tonnes), the Olza collector (<200 tonnes) and the Stargard and Pyrzyce geothermal plants (>100 tonnes).

Co-recovery of strontium with magnesium and boron is possible in several prospective areas for geothermal brines in Poland (Fig. 2).

CONCLUSIONS

On the basis of available published and archival data, it is possible to present a review of documented (mineral deposits) and potential accumulations of three selected critical elements: boron, magnesium and strontium and the characteristics of their occurrence in the area of Poland. Estimates of their potential resources are also given (Table 14).

The greatest potential for extraction exists for magnesium (>19 million tonnes), particularly from potassium-magnesium salts, from both proven salt deposits (>14 million tonnes) and prospective areas (almost 5 million tonnes). Extraction of

Table 13. Correlation coefficients of strontium content with other parameters and components in studied waters

Component	HCO ₃	SO ₄	Cl	Ca	Mg	Na	K	Fe	Br	Ba	Li	Sr
Strontium	-0.0828	0.4999	0.7525	0.7088	0.6957	0.7890	0.7755	0.3503	0.7225	0.3837	0.6152	0.6895
Parameter	Depth	Temperature	pH	Mineralization								
Strontium	0.5468	0.4205	0.0267	0.8414								

Table 14. Estimated reserves of selected critical elements accessible in the area of Poland

Element occurrences		Boron (reserves in tonnes)	Magnesium (reserves in tonnes)	Strontium (reserves in tonnes)
Magnesites	deposits	—	188 × 10 ³	—
	prospective areas	—	67 × 10 ³	—
Potash salts	deposits	—	>14 × 10 ⁶	—
	prospective areas	—	>4.82 × 10 ⁶	—
Deposits (sulphate rocks & sulphur-bearing limestones)		—	—	2 535
Anthropogenic cummulates		—	—	254.22 × 10 ³
Underground waters		>270/year	~44 × 10 ³	>1600
TOTAL		>270/year	>19.02 × 10 ⁶	>258 × 10 ³

the lowest content of magnesium-bearing minerals was assumed for the calculations, and the volumes of the mineral product itself in the prospective areas were estimated at a low level.

Significant amounts of strontium, almost 256.8 thousand tonnes, can be recovered from anthropogenic accumulations (waste from mining sulphur deposits: tailings ponds and heaps) and abandoned sulphur-bearing limestone deposits. Groundwater provides only >1500 tonnes of strontium.

In the case of boron, its only economic sources appear to be local groundwater occurrences that can yield >270 tonnes of boron per year.

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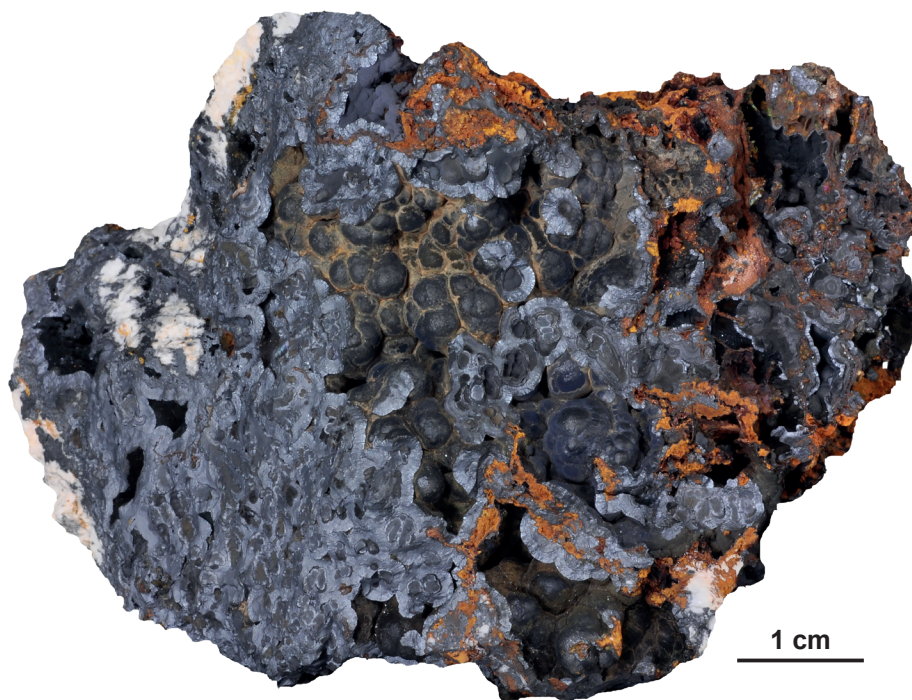
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Psilomelane, Barite mine in Stanisławów near Złotyja, Sudetes. From the collections of the PGI-NRI Geological Museum.
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