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SŁAWOMIR MAZUREK[1], JOANNA ROSZKOWSKA-REMIN[2], TOMASZ BIENKO[3]

New geological criteria for domestic phosphorite deposits – a discussion

1. Background

Since the abandonment of the extraction of phosphorites in 1971 and the depletion of phosphorite deposits from the balance of resources in 2006 (Bońda 2022), no geological exploration or mining activities have been performed in this regard. However, this raw material is critical for the economy and its current supply relies entirely on import into Poland. Therefore, it is important to reduce the dependence of the national economy on the import of this raw material by developing domestic production.

One of the goals of the Polish Geological Survey in the recent years has been to examine the possibilities of expanding the resource base of ore deposits for the production of critical

✉ Corresponding Author: Sławomir Mazurek; e-mail: Slawomir.Mazurek@pgi.gov.pl

[1] Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, Poland; ORCID iD: 0000-0002-7068-5151; e-mail: Slawomir.Mazurek@pgi.gov.pl

[2] Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, Poland; ORCID iD: 0000-0002-0696-4404; e-mail: Joanna.Roszkowska@pgi.gov.pl

[3] Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, Poland; ORCID iD: 0000-0001-5975-2918; e-mail: Tomasz.Bienko@pgi.gov.pl

raw materials, including the documentation of phosphorite deposits in Poland. It is important to assess both the resources and ore quality in the most prospective region for the occurrence of phosphorites in south-eastern Poland. For this reason, an attempt was made to determine the possibilities of resuming the extraction of phosphorites ore, which is a critical raw material for the Polish economy (PSP2050 2022).

Phosphate rock were assigned a high research priority under the *Five-year plan of documenting prognostic areas in category D (an equivalent of inferred resources according to the JORC Code) of resources intended for the acquisition of economically critical raw materials by the State Geological Service* – constituting a tangible effect of the task called: *The acquisition of mineral reserves from ore deposits – documentation* (Młynarczyk ed. 2021).

It is worth stressing that due to historical underground phosphate mining, the boundary parameters defining the deposit are much more restricted than in the case of open-pit mining (Regulation 2015). Resuming the considerations involving the possible development of phosphorite deposits in Poland, which occur at shallow depths and are intended for open-pit extraction, would require establishing new parameters delimiting (defining) a mineral deposit and its boundaries.

2. Phosphorites as a CRM and scarce commodity

In English nomenclature, *phosphorites* are often regarded as synonymous with *phosphate rock*, and they stand for a rock containing a high concentration of phosphates – minerals constituting phosphorus compounds in oxide form: P_2O_5 (van Kauwenbergh 2010). The origin of phosphate rock may be sedimentary or magmatic. In Polish nomenclature, phosphorites are the part of phosphate rocks which have a sedimentary origin. For clarity, in this article, a *phosphate rock* shall be regarded as any rock containing significant amounts of phosphates (regardless of the origin) and *phosphorites* shall be considered as a sedimentary rock.

Phosphate rock is a material commonly used as one of the primary components of fertilizers in agricultural production. Due to the constantly growing global demand for food, it is expected that the demand for phosphate rock will increase, especially considering there are no replacements for phosphorus and phosphates used as an important component of fertilizers and fodders. For example, global demand for P_2O_5 in fertilizers grew by 7% in 2022 compared to 2021 (USGS Mineral Commodity Summaries 2022).

The phosphate market is very limited – only a few countries possess the majority of the global resources and supply the world with phosphate rock and phosphate materials. Morocco is the absolute leader in terms of phosphorite resources. It is estimated that this country has resources exceeding 50 billion metric tons of ore, while the second largest country is China with their resources amounting to 3.2 billion metric tons of ore (USGS Mineral Commodity Summaries 2022).

The global extraction of phosphate rock in 2021 was 75,370,830 metric tons (P_2O_5), and it was dominated by several countries. The largest producers include China (a 40.96% share in the global production), Morocco (a 16.16% share in the global production), and the United States (an 8.05% share in the global production). Only Russia and Peru are among other countries which have also reached a share exceeding 5% of the global production (Reichl and Schatz 2023).

A summary of phosphate rock prices from the multiannual period shows that until the beginning of the 21st century, the prices were rather stable. However, in 2007 and 2008, an increase in agricultural production, an increase in the costs of energy, devaluation of the dollar, and elevated export duties caused the highest price surge in history (Huang 2009) (Figure 1). Another dramatic increase in the prices of phosphate rock and phosphate fertilizers has been taking place since 2021. It is caused, inter alia, by a rapid increase in the demand for fertilizers by emerging markets, the reimposition of high export duties by China, and also by Russia and Belarus (in response to international sanctions against Russia after its invasion on Ukraine). An example of this is that Russia imposed export duties until June 2022, effectively eliminating almost 15% of the phosphate rock supply from the global market (Jons and Nti 2022). This proves how sensitive the phosphates market is to the geopolitical situation.

In the European Union, phosphate rock has been on the list of critical raw materials since 2014. On the 2017 list, elemental phosphorus was added as a separate raw material, despite it being a product created from phosphate rock.

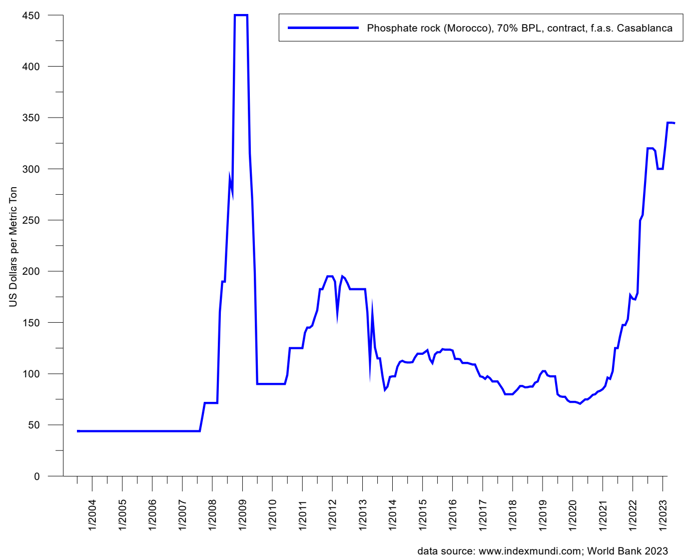

Fig. 1. The average prices of phosphate rock in the years 2003–06-2023
Source: (indexmundi.com after the World Bank, 2023 (access August, 2023)

Rys. 1. Średnie ceny fosforytów w latach 2003–06.2023

With the exception of a small magmatic deposit in Finland, no mining extraction of phosphate rock is pursued in Europe. The main suppliers of phosphate rock to the Union include Morocco (27%), Russia (24%), Finland (17%), and Algeria (10%).

3. Historical aspects of phosphorite deposit exploitation in Poland

In 1923, the discovery of phosphorites in the Rachów–Annopol region in Poland by Prof. Samsonowicz was related to the search for sandstone for road construction (PGI-NRI 2019), and it involved the observation of numerous phosphatic concretions in Upper Cretaceous glauconitic sandstones (Samsonowicz 1924a, b). The mining extraction in Rachów started in 1924, initially manually and in an open pit (Machalski 2011). The production of fertilizers took place in nitrogen compound factories in Chorzów and Mościce.

In 1952, after World War II, a phosphorite underground mine was established in Annopol followed by another in Chałupki soon after. Almost 1 million metric tons of phosphorites were extracted in total from the Annopol mine, the peak output being approximately 80 thousand metric tons/year (Machalski 2011). Mining extraction in Annopol (the Jan I mine) was discontinued in 1971 for economic reasons. The mine in Chałupki was shut down earlier, in 1961 (the so-called Jan II mine).

Simultaneously, since the early 1950s, drilling and documenting operations were performed in the previously unexplored regions of the northern margin of the Holy-Cross Mountains, which resulted in the discovery of a number of deposits meant for underground extraction (discussed in Section 4). For this reason, the economic criteria at that time were adjusted to the characteristics of this mining method. The minimum P_2O_5 content of the concretions assumed at a level of 15% was an exception from the above, related more to the conditions laid down by the Institute of Sulfuric Acid and Phosphate Fertilizers for products such as thermophosphates and superthomasine (Putrym 1954a).

A drop in the extraction rate and high costs of underground mining resulted in the intensification of the search for new phosphorite deposits. The Palaeogene phosphorites of eastern Poland became a new target of the research performed by the Geological Institute under the supervision of J. Uberna (e.g. Uberna 1972). Unfortunately, the decision (in the centralized socialist system) involving the discontinuation of extraction, the shutdown of the mines, and the use of import to meet the country's demand meant the end of the financing of geological exploration. For this reason, no new phosphorite deposits were documented in Poland after 1972.

4. Characteristics of phosphorite resources and reserves in Poland

In the past, the polygon method was used to calculate resources in geological documents of Polish phosphorite deposits. Boreholes/exploration excavations constituted the vertices of the polygons (triangles) used for the calculations. The principle of lines connecting the outermost positive boreholes/exploration excavations as the contours of the resource calculation area was used when delimiting the area of the deposit. The productivity of phosphorite concretions, expressed in kg/m^2 and kg/m^3, was calculated for each polygon. In order to calculate the productivity, in Annopol and Chałupki, the collected ore samples were separated while wet, on 2, 7 and 11 mm sieves. As a result, 4 grain sizes were obtained: >11 mm, 7–11 mm, 2–7 mm and <2 mm – regarded as waste (it should be noted that the Eocene phosphorites in eastern Poland had slightly different gradation, and in the tests from the nineteen-sixties and early nineteen-seventies, sieves with mesh sizes of 2, 4 and 10 mm were used). The material regarded as concentrate had a grain size above 2 mm or as in the Annopol and Chałupki deposits, a grain size above 10 mm. Upon drying, each grain size was tested for the P_2O_5 content. The average P_2O_5 content was also calculated for the ore (the sum of differently sized grains). On this basis, it was possible to calculate the productivity of the ore, the concretions (concentrate >2 mm or >10 mm), and of the valuable component (P_2O_5). The resources were calculated by multiplying the average productivities of the individual polygons by their surface areas.

The calculation of proven and probable resources took into account the following assumptions and parameters:

1) the minable interval of the deposit could not exceed 2 m;
2) the ore should be within the minable interval supposed to be extracted in its entirety, transported to the surface, and sieved while wet on a 2 mm sieve;
3) the average P_2O_5 content of the concentrate after sieving could not be lower than 14 wt%;
4) the average yield of >2 mm concentrate could not be lower than 14% (which resulted from the conditions imposed by the Institute of Sulfuric Acid and Phosphate Fertilizers – see chapter 3).

As a result, for most phosphorite deposits, the anticipated economic resources were calculated within the minable interval, and subeconomic resources were calculated beyond the interval but within the boundaries of the deposit (Table 1). For example, in the Iłża–Chwałowice deposit, the average height of the minable interval was 1.8 m, with the average thickness of the deposit being equal to 3.2 m (Putrym 1954b).

By following such guidelines and principles, a number of deposits were documented (for underground extraction) (Table 1), which, with the exception of the Annopol and Chałupki deposits, were never developed, and in 2006 they were deleted from the balance of mineral deposits in Poland.

As mentioned in Section 3, simultaneously with the shutdown of the mines, the termination of the financing of the research did not enable the documentation of shallow deposits in eastern Poland. There, the performed preliminary exploration resulted in identifying resource prospects (Gąsiewicz 2020) in the following areas (Uberna 1982):

- Radzyń Podlaski–Parczew,
- Puławy–Kock,
- Between Vistula and Bug, east of Warsaw.

Table 1. Resources of Polish phosphorite deposits and their most important quality parameters (after Uberna 1982; Bońda 2022)

Tabela 1. Zasoby polskich złóż fosforytów i ich najważniejsze parametry jakościowe

Deposit	Economic geological resources				Subeconomic resources[1]	Thickness (m)	Diameter of phosphorite concretions (mm)	P_2O_5 content (%)	Productivity of phosphorite concretions (kg/m^2)
	Total	A + B	C_1	C_2					
Annopol	7,600 ***1,030***	4,620 ***630***	2,980 ***400***	–	–	0.3	>10	13.5	568
Burzenin	–	–	–	–	2,740 ***490***	0.7	>2	18.1	385
Chałupki	3,170 ***440***	150 ***20***	3,020 ***420***	–	–	0.4	>10	14.9	354
Gościeradów	1,420 ***210***	–	–	1,420 ***210***	–	no data	>2	15.2	496
Iłża–Krzyżanowice	1,860 ***390***	–	–	1,860 ***390***	860 ***115***	1.3	>2	18.6	791
Iłża–Chwałowice	620 ***140***	–	–	620 ***140***	625 ***90***	0.4	>2	22.3	891
Iłża–Łączany	10,230 ***1,900***	–	–	10,230 ***1,900***	1,340 ***257***	0.6	>2	18.6	654
Iłża–Walentynów	1,690 ***330***	–	–	1,690 ***330***	–	0.7	>2	19.9	470
Radom–Dąbrówka Warszawska	6,760 ***1,210***	–	–	6,760 ***1,210***	–	1.8	>2	16.5	317–460
Radom–Krogulcza	8,470 ***1,610***	–	–	8,470 ***1,610***	3,114 ***592***	0.5	>2	19.1	218–504
Radom–Wolanów	590 ***90***	–	–	590 ***90***	98 ***19***	0.7	>2	15.4	170–447

Ore resources (thousand Mg).
P_2O_5 resources (thousand Mg).

Prognostic and prospective resources in the D_1 and D_2 documented categories (used at that time) were estimated at approximately 300 million metric tons of P_2O_5 in an area of approximately 10,000 km^2.

5. Phosphate rock import to Poland – quantities and prices

The import of phosphate rock into Poland collapsed in 2021, along with an increase in prices (Figure 2):

Stable prices in 2014–2020, oscillating between PLN 294 and 372/t, started to grow in 2021, exceeding PLN 400/t. The plot of the scale of import (Figure 2) does not present data from the first quarter of 2023, when only 8,677 tonnes of phosphate rock were imported. The increase in the prices of imported phosphate rock into Poland is a direct result of the increase in global phosphate rock prices (cf. Figure 1 in Section 2). The latest forecasts indicate that prices should drop in the nearest future (Fitch Ratings report 2023), and in 2025, they could return to the values from before 2022 (approx. USD 100/Mg of FOB phosphorites from Morocco). The dramatic increase in the prices of phosphate rock imported into Poland corresponds to its reduction to approx. 12–15% of the multiannual scale. Taking into account the magnitude of import into Poland after 2021, it was assumed that the critical price for the cost-effective production of phosphate fertilizers in the country based on the imported phosphate rock may be close to approx. PLN 350/t. Such an assumption was the starting point for establishing new threshold values of parameters defining an ore deposit and its boundaries for the country's deposits intended for open-pit extraction.

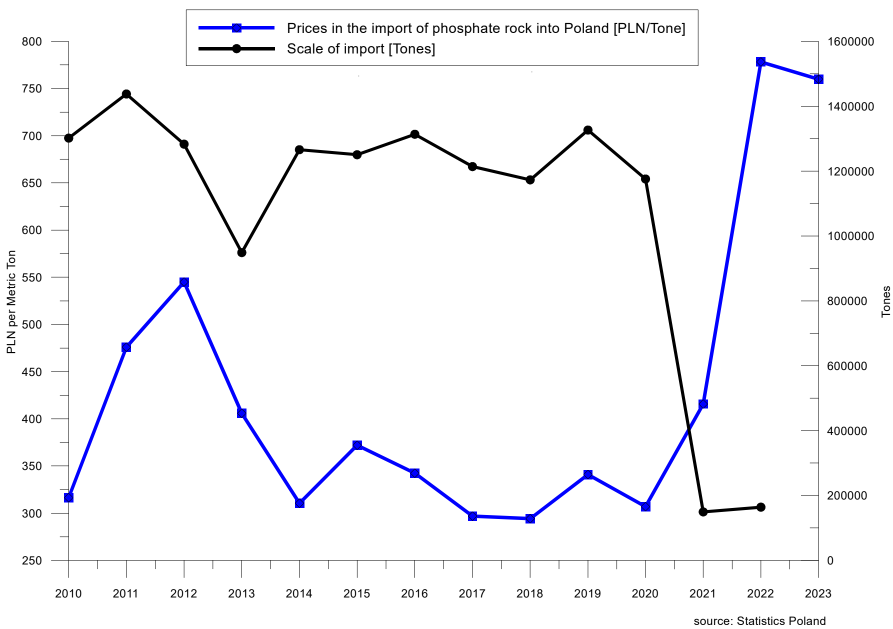

Fig. 2. The development of the prices and scale of the import of phosphate rock into Poland in the recent years according to Statistics Poland
Source: author's graph based on data from: SWAID 2023

Rys. 2. Kształtowanie się cen i skali importu fosforytów do Polski w ostatnich latach według GUS

Imported phosphate rock contains almost 30% P_2O_5. Local phosphorites (Albian) contain slightly above 20% (in the Iłża-Chwałowice deposit); as indicated by the geological documentations, the average P_2O_5 content falls within the range of 15–20%.

6. Geological and chemical parameters of open cast exploited phosphorite deposits – world benchmark

Globally, the vast majority of phosphate rock is extracted from sedimentary deposits of a marine origin. Large resources with a high quality of the raw material are limited to only a few areas in the world, and are usually associated with the sediments of past continental shelves (Edixhoven et al. 2014). According to the data from the USGS (Simandl et al. 2012), over 90% of these deposits have resources exceeding 26 million metric tons of ore, 50% have more than 330 million metric tons, and 10% have resources exceeding 4,200 million metric tons. Among these, 90% of the deposits have average P_2O_5 contents above 15%, 50% of the deposits have an average P_2O_5 content above 25%, while 10% of the deposits have a P_2O_5 content above 32%.

The deposits of phosphorites are usually mined using the open-pit method, followed by refining and processing for the production of high quality fertilizers. Ore with a lower P_2O_5 content may be used to produce phosphorite meal.

Analyzing the geological parameters of the deposits worldwide, it can be observed that there are no strict quantitative geological parameters which would define the profitability of the deposits. Therefore, there are no universal 'economic' criteria for sedimentary phosphorite deposits in the world. Their profitability is the sum of multiple geological and mining factors, such as the properties of the ore itself, and also geographic factors, e.g. the availability of proper infrastructure, the access to a water supply, electrical energy necessary to process the ore, etc. Geological factors affecting the economics of the deposits include:

- the thickness/volume of the ore-bearing horizon;
- the percentage of P_2O_5 and heavy metals (arsenic and especially cadmium) in the ore;
- the form of P_2O_5 ore (mineralization, concretions or rocks enriched in phosphate minerals), which would affect the choice of the concentrate production method;
- the percentage of other mineral compounds in the ore (such as quartz, calcite, iron oxides, organic matter and clay minerals), which would affect the process of extracting P_2O_5;
- the thickness of the overburden.

Historically, only deposits with over 25% P_2O_5 were considered profitable. However, as rich deposits become depleted and new technological capabilities for concentration of the mineral arise, the threshold values of the P_2O_5 content become lower. The deposits of Florida are a good example, where considering other favorable geological factors and excellent infrastructure, even ore with an average P_2O_5 content of 3% may be a subject of economic extraction and processing (Simandl et al. 2012). Regulations of the European

Commission (Regulation EU 2019/1009) indicate that the term 'phosphate fertilizers' means macro-element fertilizers or organic-mineral fertilizers with a minimum P_2O_5 content of 5%.

The high CaO/P_2O_5 level leads to an increase in the consumption of sulphuric acid during the production of phosphoric acid. High concentrations of Mg and SiO_2 result in problems with filtration, and high concentrations of Na and K cause the deposition of scale on filtration devices. Organic substances cause foaming during the production of phosphoric acid. A high concentration of Cl causes premature corrosion of the devices (Simandl et al. 2012) For technological reasons, the ratio of the sum of aluminum and/or iron oxides to phosphorus oxide (R_2O_3/P_2O_5) should not exceed 0.1, and the ratio of the sum of aluminum and/or iron oxides and magnesium oxide to phosphorous oxide (R_2O_3 + MgO/P_2O_5) should not be higher than 0.12 (van Kauwenbergh et al. 2010).

A high level of toxic elements (e.g. Cd, Se and As) would be a factor excluding phosphorites from the production of fertilizers (van Kauwenbergh *op. cit.*). In the European Union, the permitted concentration of cadmium in fertilizers is 60 mg/kg of fertilizer (Regulation EU 2019/1009).

An important part of the economic evaluation of a deposit is the calculation of potential losses which may occur at each stage of extraction. The cut-off grade of a deposit assumes leaving some of the phosphorites in the rock mass due to their extensive dispersion (the impoverishment of ore), or other factors which make extraction economically unfeasible. It is assumed that ore which has less than half of the average percentage of P_2O_5 should be left in the deposit (Mew et al. 2018). Losses also occur at the stage of processing/concentration of the ore. Ore recovery may range from 90% (low quality magmatic ore in Russia) to 50% (e.g. as a result of multi-stage flotation of phosphate ore in Florida). The average recovery rates in the world oscillate around 67% (Mew et al. 2018).

A review of the world's phosphorite projects based on sedimentary rocks shows that, apart from the undoubtedly gigantic deposits, such as in Morocco or the United States, there is a growing trend for mining companies to search for and invest in smaller deposits, providing local access to raw material for fertilizers.

One such example is found in Australia, extensive exploratory and mining operations are performed in the area of the Northern Territory. Large projects are being developed within the Georgina Cambrian sedimentary basin, such as Ammaroo, with documented total inferred, indicated and measured resources of 1.141 billion metric tons of ore containing 14% P_2O_5 (Verdant Minerals 2018; accessed in August 2023), or Wonorah (473 million metric tons of measured+indicated resources, with an average 14.4% content of P_2O_5 in ore (with a cut-off of 5% P_2O_5) (MPR Geological Consultants Pty Ltd 2012, accessed in August 2023). However, smaller projects are also taken into consideration, such as **Highland Plains** with documented inferred resources of 56 million metric tons with an average P_2O_5 content of 16% (a cut-off of 10%), and 14 million metric tons with an average P_2O_5 content of 20% in the target extraction zone (Western Mine Target Zone). This deposit consists of two phosphorite-bearing strata with thickness ranging from 1.5 to 17 m, and from 1.5 to 11 m.

The depths of the bottommost deposit zone do not exceed 46 m below ground level. All the phosphate-bearing sediments have various levels of impurities. For unrefined ore with a P_2O_5 content of 22.9%, they are as follows: C (0.2%); S (0.06%); F (1.82%); Cl (112 ppm); Cd (4 ppm); (38 ppm) (Gibb River Diamonds, accessed in August, 2023).

Project **Bayovar 12** is being developed in Peru, where sixteen phosphorite-bearing horizons have been documented in an area of 34 km^2, with inferred resources of 135 million metric tons, with a P_2O_5 grade of 13.11%, indicating resources of 277.1 million metric tons with a P_2O_5 grade of 13.04%, and measured resources of 23.4 million metric tons with a P_2O_5 grade of 13.16%. The calculations did not use a cut-off grade for the deposit. Proven + probable reserves have been calculated for thirteen horizons, and they amount to 54.77 million metric tons of ore with a P_2O_5 grade of 12.99% and minimum thickness of a stratum amounting to 30 cm (M3 2016).

In Kazakhstan, a low quality phosphorite deposit was documented in the **Chilisai** open-pit mine. The JORC reserves (proven+probable) of this deposit have been calculated at 505.1 million metric tons of ore with an average P_2O_5 content of 9.5% (a cut-off of 6%). The average thickness of the overburden is approx. 6 m. The productivity of ore is 2.1 metric tons/m^3 of the extracted material. The recovery of raw material from the ore was calculated as 78.5%. These phosphorites are extracted and sold as phosphorite meal (Sunkar Resources PLC 2013).

In Europe, the extraction of phosphate rock (apatite) is only performed from the magmatic rocks of the Siilinjärvi mine in Finland, and this is the largest open-pit mine in this country. The total resources are over 1 billion metric tons of ore with a P_2O_5 grade of 3.8% (USGS Mineral Resources Data System 2023; Rasilainen et al. 2023). The mine has been active since 1979 and the annual extraction rate is over 10 million metric tons of ore. Flotation is a major processing technology. The concentrate is used to produce phosphoric acid and fertilizers.

At present, European countries do not extract phosphorites from sedimentary deposits, although documented resources of such deposits are known. One of the most prospective examples is in Serbia. The Lisina deposit has documented (JORC) total resources of 72 million metric tons of ore with an average P_2O_5 content of 9%, but with high iron oxide content (up to 5%). Due to its location in the mountains, and the ore-bearing horizon dipping at an angle of 22 deg., possible underground extraction is predicted for that site (Torbica and Lapčević 2012).

7. Phosphorite processing – review

In the interwar period, ore flotation was introduced in the Chałupki deposit, using phosphorite concretions with an average P_2O_5 content of 18.5% to produce a concentrate with 23–25 wt% P_2O_5 (with a 76% recovery from the ore; Uberna 1982). The flotation method was also used after 1945 and in this way, phosphorites from the Annopol and Chałupki mines were refined, and technological tests were performed for the ore from the Iłża–Radom region. Ore with a P_2O_5 content of 9.5 wt% was used to produce a medium quality concentrate with 21 wt% P_2O_5 (a yield of 28.34%), and an intermediate product containing 13.38 wt% P_2O_5 (a yield of 13.28%). Between 1952 and 1955, attempts at experimental flotation of phosphorites were made for the Annopol deposits. The average P_2O_5 content of the ore was 15 wt%, and the resulting concentrate contained 25.4 wt% P_2O_5 (a yield of 30.33%). The tests also resulted in the production of phosphorite meal with a P_2O_5 content of 13–15 wt%. In the same period, there were attempts at concentration in hydrocyclones with a good result –23% P_2O_5 in the concentrate. Despite attempts, at the beginning of the 1960s, the obtained Polish concentrates still had lower quality compared to those imported from northern African countries (of a sedimentary origin) and the Soviet Union (of a magmatic origin).

It was proven that the refinement of Annopol phosphorites with a concentrate of a magmatic origin (apatite) reduced the performance of the final product as a fertilizer. It transpired that apatite used as phosphorus meal is almost not absorbed by plants at all.

It was concluded that the best method for refining the ore from Polish Cretaceous phosphorite deposits is the so-called Polfos I technology, consisting of three stages:

- hydrothermal separation (slaking and deluding on a sieve, milling and separation in hydrocyclones, filtration and drying of semi-finished products);
- extraction of phosphoric acid from silicon phosphate;
- production of concentrated phosphorus fertilizers from the phosphorite concentrate.

In the area of Łąkoć and Glinny Stok, phosphorite concretions occur in Eocene sediments. These ores differ from the Annopol phosphorites due to the higher amount of silica in the form of sands, silts and clays, as well as a considerably lower share of carbonate substance. The Polfos I method was used for this type of ore, with slight modifications. In contrast to the ore from the Annopol region, the roasting of sandy ore is unnecessary since the valuable component can be separated from the sands easily resulting in a product with an average P_2O_5 content of 18–20% as early as at the first stage of processing. In the processing of phosphorites from Radom, fragmentation of the ore also proved to be unnecessary. As a result of the processing of ore from the Radom and Iłża region, a considerable portion of (fine) phosphorites moved to the waste, in which the content ranged from 0.7 to 1.5% P_2O_5. For comparison, the P_2O_5 content of the output ore ranged from 5 to 9 wt%.

The phosphorite processing methods used nowadays are not much different from those described above (Polish Mineral Engineering Society 2007). The necessity to process various types of ore (e.g. phosphorite concretions, massive phosphorites, sandy phosphorite concretions and shelly phosphorites) has led to modifications of the refinement method, depending on the feed type.

Most processing plants use the simplest method of washing the extracted material. The feed is washed with water from hydromonitors, and if the ore contains large amounts of clayey components, its coarse-grained components are additionally fragmented in a drum crusher. The washing is repeated in several cycles with the use of trough washers.

The extracted material is subsequently dried and fine nodules of phosphorite are recovered from sludge, which constitutes waste in this process, by means of separation in hydrocyclones. In this way, ore with an average P_2O_5 content of 7–10 wt% can be used for the simple production of concentrates with 16–17.5 wt% P_2O_5 (ore containing 11.5–12% P_2O_5 may be used to produce a concentrate with up to 23 wt% P_2O_5).

In the case of sandy ore, it is necessary to fragment the extracted material before washing it. This results in large amounts of sludge and loss of the valuable component. During washing, grains below 1 mm are regarded as waste. Coarser grains are fragmented to 10 mm, and subsequently ground to a grain size of 0.1 mm. Sludge with a high P_2O_5 content (up to 19%), which has been separated from the finest grains, can be used as phosphorite meal. The remaining grains are refined through flotation, resulting in a concentrate of 21–22 wt% P_2O_5. In this method, losses of the valuable component may reach up to 40%. The use of phosphorite meal in agriculture, instead of the costly process of producing phosphorus fertilizers, has been proposed and studied due to the high prices of imported phosphate rock (Korzeniowska and Stanisławska-Gubiak 2011). Their use is legally possible – the European Union's regulations define a lower limit of the P_2O_5 content of fertilizers at 5%, with a cadmium content of up to 60 mg/Mg – with the exception of <20 mg/Mg in Slovakia (Regulation EU 2019/1009).

If there are glauconite grains in the feed, the operation of magnetic purification is added to the processing scheme. In this case, ore with a P_2O_5 content of 11–12 wt% and with approx. 10 wt% Fe_2O_3 can be used to produce a concentrate containing 26% P_2O_5.

8. New geological and quality criteria for open cast exploited phosphorite deposits in Poland

Phosphorites in Annopol and Chałupki have been mined using the underground method. Eocene phosphorites, lying at shallow depths in eastern Poland, are intended for open-pit mining. They occur in the quartz-glauconitic sands, locally more calcareous and clayey, which are covered by detrital deposits of Neogene (Miocene) and Quaternary. The thickness of the Quaternary and Neogene overburden is in the range of 0.3–70.8 m, with a mean value of 28.9 m. The detailed research by Uberna (1972) in Łąkoć area shows that phosphate-bearing strata are tri-partite (Figure 3). The highest layer contains pellet phosphorite in quartz-glauconitic sands, the middle layer contains phosphatic sands and covers the lowest layer of clays and muds with intercalations of phosphorite-bearing sands (Figure 3). In the Łąkoć and Glinny Stok area, the uppermost horizon is perspective to host economic concentrations of phosphorites. Its thickness ranges from less than 0.5 to 3.3 m (Uberna 1972).

Potential quantities of REE in this kind of phosphate rock in SE Poland aren't well recognized, but based on single analyses, elevated values are not expected, which is unlike the case for Lower Cretaceous phosphorites (Zglinicki et al. 2020).

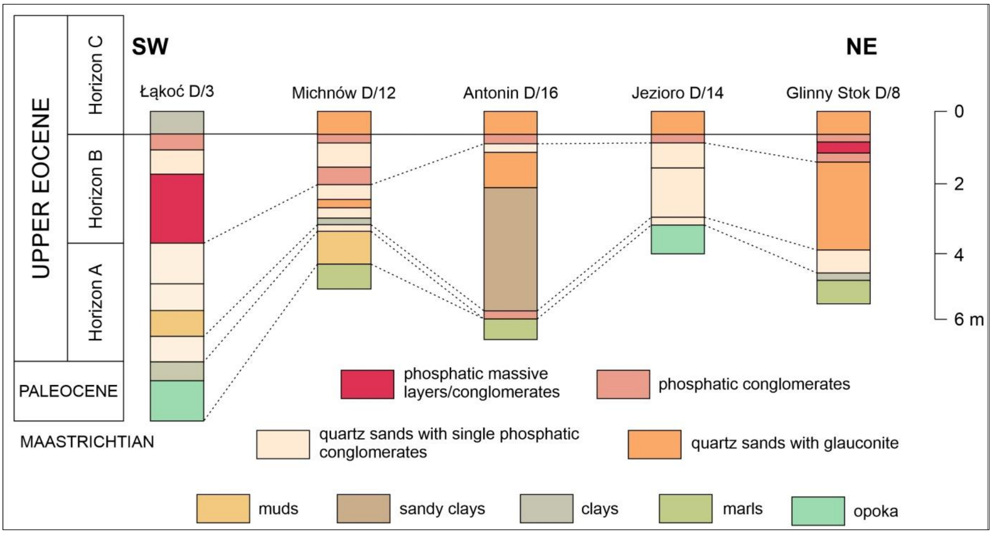

Fig. 3. Correlation between boreholes documenting phosphatic layers in Łąkoć–Glinny Stok area (Mazurek et. al 2023, modified after Uberna 1972)

Rys. 3. Korelacja pomiędzy otworami dokumentującymi warstwy fosforanowe w rejonie Łąkoci–Glinny Stok

According to data from the literature (Uberna 1972), P_2O_5 contents oscillate around 15% in the main phosphorite strata. Such a value was also indicated as a threshold in the past economic criteria, so there is no need to redefine the minimum percentage of P_2O_5 in the concretions. Chemical analyses of a concretion collected from the overburden (Palaeogene) in an open-pit chalk mine in Mielnik, performed in the chemical laboratory of the PGI-NRI in 2022, confirm the conformity of these values (14.2% P_2O_5 and 0.71 ppm Cd) with the data from the literature (Domaszewska 1967). The P_2O_5 content of 22.86 wt% in the Niedźwiada II deposit in the Lubartów county is puzzling and unprecedented anywhere else in Poland, giving that phosphate rock is considered there as an associated mineral (Bońda 2022). Therefore, the proposed new criteria have adopted (maintained) a minimum P_2O_5 content of the concretions in the profile of a deposit amounting to 15 wt%.

An analysis of phosphorite projects in the world indicates that all the data refer to the percentage of P_2O_5 either in the ore or in the concentrate (containing at least 28 wt% P_2O_5). The productivity of a single m^2 or m^3 previously determining the economic criteria for phosphorite deposits are no longer applicable in the world. The point of reference for the minimum P_2O_5 content of a deposit (ore), not in concretions, should be the application of the ore, without its refinement, as the so-called phosphorite meal. Requirements in this regard come down to the determination of two parameters – the minimum P_2O_5 content of such a fertilizer from direct grinding of the ore (5%), and a maximum cadmium content of 60 mg/Mg P_2O_5 (Regulation EU 2019/1009) – in Slovakia, this is no more than 20 mg/Mg.

The low average P_2O_5 content of Polish deposits (not the concretions themselves) and the high prices of phosphorites from the last 2–3 years enable considering the use of Polish phosphorite deposits for the production of phosphorite meal more than for heavily processed commercial fertilizer products. This is actually not a new proposal (Korzeniowska and Stanisławska-Gubiak 2011). World examples of such a use include the Chilisai project in Kazakhstan.

Because the cost of removing the overburden and extracting the phosphorite ore de facto corresponds to the profile of an open-pit aggregate mine, an analysis of the profitability (economics) of open-pit extraction of phosphorite deposits requires addressing the threshold values of cost-effectiveness of such an open-pit aggregate (sand and gravel) mine in the country. As indicated by the data acquired due to the courtesy of Industri Kruszywa Spółka z o.o. (Pietkiewicz 2021), the threshold value of profitability for an aggregate mine (company) when performing extraction with a single-bucket excavator – without further processing – should be determined as being close to PLN 8/Mg, on the basis of the prices in 2022. The extraction of aggregates from below the water table down to a depth of no more than 30–35 m has been well documented by Kozioł et. al. (2017), where the NPV is estimated at 0 for projects with PLN 11.00/Mg. For further considerations of the economics of extraction and refinement of phosphorite ore, a mixed mining model was assumed (level I with a single-bucket excavator, from below the water table), assuming an average simplified threshold price of approximately PLN 10/Mg. This kind of extraction (below the water table) is one of two ways of ambers open pit extraction near Lubartów (White Amber Mine on Górka Lubartowska deposit) and can be considered for the extraction of phosphorite nodules.

Another key factor with respect to the profitability of extraction of a phosphorite deposit is a comparison of the costs of extracting a ton of raw material to the price of a ton of product suitable for further sale. It is very difficult in the case of phosphorites because there is no available data to separate the costs of extraction from flotation and it depends strongly on quality of the phosphorite deposits. However, to calculate the economically acceptable strip ratio, some assumptions are needed. Therefore, taking into account how rough they are, the authors made the following calculations based on the import prices of natural phosphates (which contain at least about 30% of P_2O_5) the cost of acquiring 1% of P_2O_5 in last years is as follows in Table 2.

In the case of the average cost of acquisition from the years 2010–2021 and the level of profitability for an aggregate mine, it would be no more than PLN 61.4 for acquiring a single ton of 5% P_2O_5, which means a cost of PLN 51.4 /Mg for removing the overburden and a cost of PLN 10 for extracting 1 Mg of ore containing 5% of phosphate. This corresponds to a threshold strip ratio (overburden: deposit) of approximately 5:1. For the average of the years 2022–2023, this cost would amount to PLN 128.2 /Mg in the entire profile of the deposit (the overburden and the ore itself), i.e. approximately PLN 118 /Mg for mining the overburden and PLN 10 /Mg for mining 1 Mg of ore with a P_2O_5 content of 5%. Therefore, to put it simply, it corresponds to a strip ratio of 12:1. It is thus suggested to adopt a threshold value which would allow for including a borehole in an economic field of resources of a deposit if it fulfils

Table 2. The cost of acquiring 1% P_2O_5 in import into Poland after 2010

Tabela 2. Koszt pozyskania 1% P_2O_5 w imporcie do Polski po 2010 roku

Year	Cost of 1% P_2O_5 (PLN)	Mean cost (PLN)
2023	25.33	25.64
2022	25.94	
2021	13.86	12.28
2020	10.23	
2019	11.36	
2018	9.80	
2017	9.89	
2016	11.41	
2015	12.40	
2014	10.35	
2013	13.53	
2012	18.17	
2011	15.86	
2010	10.55	

the conditions of a strip ratio of no more than 12:1, provided that it meets the requirements of the percentage of P_2O_5 in the ore amounting to 5%. The global prices are currently much higher than those declared in import to Poland; however, considering the possible price fluctuations over short periods, the strip ratio parameter should not be increased.

The proposed strip ratio aligns with global phosphorite mining trends, as indicated by strip ratios falling within the range of 3:1 to 12:1 (Taha et al. 2021). Given that the removal of overburden leads to increased management and environmental costs, the 12:1 strip ratio is widely accepted within the mining sector and is considered the upper limit for pho phorite extraction. This standard is exemplified by the Polish glauconite mine, Niedźwiada II, where the strip ratio reaches up to 15:1. Notably, the maximum extraction depth at this facility is 30 meters below ground level, and generally flat-lying ore exhibits a thickness ranging from 2 to 5 meters (https://www.pgi.gov.pl/surowce/skalne-i-inne/surowce-ilaste/14019-osady-glaukonitonosne.html) .

Considering the spatial parameters of extraction from below the water table in an aggregate mine, especially the technical parameters of the machines which are well described and summarized in the literature (e.g. Kozioł et al. 2017), it is appropriate to assume the depth (the bottom of extraction, and thus of documenting the deposit) for a mixed system as being no more than 40 m – approx. 5 m above the water table using a single-bucket excavator, and 35 for a dredger.

As indicated by an analysis of the occurrence of the Eocene in south-eastern Poland, prepared at the PGI-NRI to meet the needs of a plan of geological operations for phosphorite prospecting drilling (Mazurek et al. 2022), the average depth of the horizon with the concretions in a region deemed prospective is 20–30 m, thus the proposed minimum thickness of the deposit (considering the threshold strip ratio) is 1.5 m of the ore stratum.

The amount of economic resources in a deposit is a separate category. Considering a twenty-year lifetime of a mining project, and an annual extraction rate of 0.20 million Mg of ore, the minimum economic resources should be no less than 20 × 0.20 = 4 million metric tons of ore. Taking into consideration the losses – no less than approximately 5 million Mg of economic resources. However, because every mining and processing project is considered individually, this amount may only be assumed as a guideline, not a formal requirement.

Conclusions

To sum up, it is proposed to document phosphorite deposits in Poland intended for open-pit extraction according to the following mining parameters documenting an ore deposit and its boundaries:

- a minimum P_2O_5 content of the ore (deposit) – 5%;
- a maximum cadmium content per metric ton of P_2O_5 amounting to 60 mg/Mg;
- a maximum strip ratio of 12:1;
- minimum thickness of the deposit – 1.5 m.

In contrast to the unprofitable underground exploitation of Lower Cretaceous phosphate deposits, it is necessary to explore and consider the profitability of the open-pit mining of Miocene phosphorite deposits that may occur in SE Poland.

It seems that the relatively low content of P_2O_5 in concretions and ores means that Polish Eocene phosphates can be used in agriculture in the form of phosphate meals – not as high-quality phosphate fertilizers.

Based on the above, the authors proposed completely new geological criteria for geological documentations of open-pit phosphorite deposits, as required by the Geological and Mining Law.

In determining the new criteria, the appropriate strip ratio parameter turned out to be the most problematic. This was caused by a lack of reliable information about the prices of fertilizers containing low-quality phosphorous as a reference point for the economic profitability of the open-pit mining of ore. This forced the use of certain assumptions and simplifications.

The authors used an artificially calculated value of 1% of P_2O_5 as a reference point bearing in mind that this is only a hypothetical value and it is not used in international trade of phosphorus raw materials. The question remains open to discussion whether there is a better way to determine strip ratio parameter.

What is most worth underlining is that the authors proposed new threshold parameters defining ore deposits and its boundaries corresponding to the open pit extraction because the current Polish geological and mining law requires such limits – for country benchmark of this kind of deposits. However modern mining investments are globally based solely on the economic calculations of the investor, not on rigid geological parameters and it is this approach that the authors of this article endorse most. The end product (commodity) quality and methods of ore enriching should determine the geological criteria of each phosphate rock deposit.

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NEW GEOLOGICAL CRITERIA FOR DOMESTIC PHOSPHORITE DEPOSITS – A DISCUSSION

Keywords

phosphorite ores, critical raw materials, deposit parameters, domestic resources, geological documentation, open cast mining, processing of minerals

Abstract

Phosphate rocks and elemental phosphorus are considered to be critical raw materials mainly because of such parameters as the growing prices of phosphate fertilizers, the high concentration of producers limited to several countries in the world, the exceptional significance of phosphorus in agriculture and the inability to substitute it.

In Poland 100% of the demand phosphate rocks relies on import. The expansion and mining of the nation's own resource base may be an alternative to import and a way to provide safety of supplies. Historically, phosphorites from the northern margin of the Holy Cross Mountains were extracted using the underground method, which was abandoned in the beginning of the 1970s due to the unprofitability of extraction. However, in eastern and south-eastern Poland, phosphorite concretions of the Eocene age occur at shallow depths, which can have local significance as mineral deposits and might be extracted in open-pit mines. The economics of mining in shallow opencasts do not require such stringent limiting parameters for phosphate deposits as those currently valid, which were established for underground mining conditions.

In this publication, the authors analyzed contemporary conditions for a cost-effective phosphorite deposit, including the price fluctuations of phosphate rock, a review of threshold parameters of deposits for phosphorite projects in the world, and the economics of open-pit ore extraction, where an aggregate mine with mixed extraction (partially from below the water table) was adopted as a point of reference.

As a result, new threshold parameters defining an ore deposit and its boundaries are proposed for Eocene phosphorites in Poland.

NOWE PARAMETRY GEOLOGICZNE DLA KRAJOWYCH ZŁÓŻ FOSFORYTÓW – DYSKUSJA

Słowa kluczowe

fosforyty, surowce krytyczne, parametry złożowe, zasoby krajowe, dokumentacja geologiczna, górnictwo odkrywkowe, przetwórstwo kopalin

Streszczenie

Rosnące ceny fosforytów i nawozów fosforanowych, silna koncentracja producentów ograniczona do kilku państw na świecie, wyjątkowe znaczenie fosforu w rolnictwie, a dodatkowo brak możliwości jego substytucji to czynniki, które powodują, że fosforyty uznane zostały za surowce krytyczne.

Alternatywą dla importu i sposobem na osiągnięcie bezpieczeństwa dostaw może być rozszerzenie i eksploatacja własnej bazy zasobowej. W Polsce fosforyty z północnego obrzeżenia Gór Świętokrzyskich wydobywane były metodą podziemną, której zaniechano od początku lat 70. XX wieku ze względu na brak opłacalności wydobycia. Jednakże w Polsce wschodniej i południowo-wschodniej występują płytko konkrecje fosforytowe wieku eoceńskiego, które mogą mieć lokalnie znaczenie złożowe, a wydobycie ich może odbywać się metodą odkrywkową. Ekonomika wydobycia w płytkich odkrywkach nie wymaga tak rygorystycznych parametrów granicznych dla złóż fosforytów jak obecnie obowiązujące, które dobrane są pod warunki eksploatacji metodą podziemną.

W publikacji autorzy przeanalizowali współczesne uwarunkowania opłacalności eksploatacji złóż fosforytów, m.in., dynamikę zmian cen fosforytów, przegląd granicznych parametrów złożowych projektów fosforytowych na świecie i ekonomikę odkrywkowej eksploatacji kopaliny, gdzie jako punkt odniesienia (w Polsce) przyjęto kopalnię kruszyw o eksploatacji mieszanej (w części spod lustra wody). W efekcie zaproponowano dla eoceńskich fosforytów w Polsce nowe, graniczne parametry definiujące złoże i jego granice.