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Research Note

Phosphate ore grades and concentrates from igneous and sedimentary phosphate rocks and their associated mining operations

Comparisons of global ore grades and beneficiated ore

The phosphate ore for producing lithium iron phosphate (LFP; $LiFePO_4$) battery requires pure phosphoric acid with low trace element concentrations (BM Review, 2022; Banerjee 2023). Therefore, the production of pure phosphoric acid with low trace elements requires a supply of high-quality phosphate concentrate with high P_2O_5 and low trace elements.

Globally, phosphate ore is largely supplied from sedimentary phosphate rock (~90%; Pufahl and Groat, 2017) and is mostly used for the fertilizer industry (~85%; Spears et al., 2022). Not all sedimentary phosphate ore, however, can be used to attain a high-quality phosphate concentrate (i.e., phosphate concentrate with high P_2O_5 content) even after beneficiation.

Igneous phosphate ore can generally produce a phosphate concentrate with higher P_2O_5 after beneficiation than that produced from sedimentary phosphate ore (Table A1). Although the average P_2O_5 content of igneous phosphate ore is lower than that of sedimentary phosphate ore. For example, the global average P_2O_5 of igneous phosphate ore and sedimentary phosphate ore is 8.1 wt.% and 21.3 wt.%, respectively (Table A1). The average P_2O_5 contents of marketable phosphate concentrates (i.e., phosphate ore after beneficiation) produced from igneous phosphate ore, are, however, significantly higher than those produced from sedimentary phosphate ore. For example, the global average P_2O_5 of marketable phosphate concentrates produced from igneous and sedimentary phosphate ore is 36.9 wt.% and 29.6 wt.%, respectively (Table A1).

Only a small portion of the worldwide phosphate ore (~10%; Pufahl and Groat, 2017) is supplied from igneous rock from Russia, South Africa, Brazil, and Finland. These igneous phosphate deposits are mostly from the Khibiny Alkalic Igneous Complex (Notholt, 1979) and

the Kovdor Phoscorite–Carbonatite Complex (Ivanyuk et al., 2016) from the Kola Peninsula in Russia, the Siilinjärvi Carbonatite Complex in Finland (Decrée et al., 2020), the Phalaborwa (Palabora) Igneous Complex in South Africa (Gómez-Arias et al.2022), and the Alto Paranaíba Alkaline Province in Brazil (Silva et al., 2023) (Fig. 1). These igneous deposits are from silica-undersaturated alkali intrusions and carbonatites.

Major igneous phosphate deposits and their ore grades

The average P_2O_5 contents of phosphate ore from igneous rocks from major deposits in the four major countries (Russia, Finland, South Africa, and Brazil) exhibit significant variations (4.0-17.2 wt.%; Table A2). The salient features of phosphate ore from various deposits from the four countries (Fig. 1) are described below.

1. Phosphate ore (from igneous rocks) with high P_2O_5 contents (6.8-17.2 wt.%; Table A2) is from Russia. The host rock of the ore with the highest P_2O_5 contents (10.7-17.2 wt.%; Table A2) is apatite-nepheline syenite from the Khibiny Alkaline Igneous Complex, Russia. PhosAgro (Kukisvumchorr, Yukspor, Apatitovy Cirque, Rasvumchorr Plateau, Koashva, and Njorkpahk deposits), and Acron (Oleniy Ruchey deposit) are two major companies operating mines in the Khibiny Alkaline Igneous Complex. Eurochem excavates ore from the Kovdor Ultramafic Alkaline Complex (Kovdor Phoscorite–Carbonatite Complex), Russia. The host rock of the phosphate ore of the Kovdor Ultramafic Alkaline Complex is phoscorite-carbonatite. The average P_2O_5 content of the phosphate ore of the Kovdor Ultramafic Alkaline Complex (6.8 wt.%) is lower than that from the Khibiny Alkaline Igneous Complex (10.7-17.2 wt.%; Table A2).

2. In Finland, there is only one operational igneous phosphate deposit, Siilinjärvi, from the Siilinjärvi Carbonatite Complex, which is operated by Yara. The host rock of the deposit is glimmerite-carbonatite and the average P_2O_5 of the ore is 4.0 wt.% (Table A2).

3. The Phalaborwa deposit from the Phalaborwa (Palabora) Igneous Complex is the major igneous phosphate deposit in South Africa. Foskor operates mines in this deposit. The major host rocks of the ore are pyroxenite, carbonatite, and phoscorite and the ore contains an average P_2O_5 of 7.0 wt.% (Table A2).

4. Seven igneous phosphate deposits supply igneous phosphate ore in Brazil. The mines from the Tapira, Araxá, Catalão I deposits from the Alto Paranaíba Alkaline Province are operated by Mosaic. The phosphate mine in the Catalão II deposit from the Alto Paranaíba Alkaline Province is operated by the CMOC Group and Mosaic. Another phosphate deposit, Saltire, owned by Eurochem, is also in the Paranaíba Alkaline Province. Mosaic also operates another phosphate mine in the Cajati deposit in the Jacupiranga Alkaline Complex. Finally, Fosnor Galvani excavates phosphate from the Angico dos Dias deposit in the Angico dos Dias Carbonatite Complex. The major host

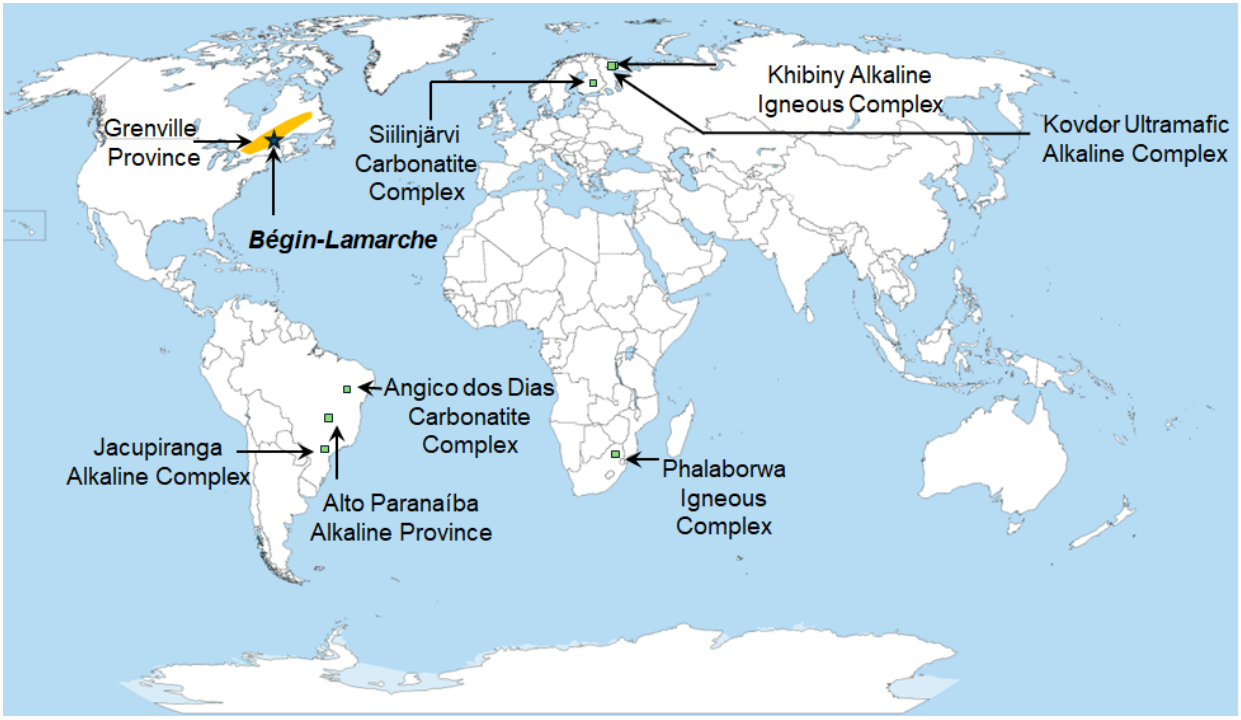

Figure 1. Major igneous complexes supplying igneous phosphate ore worldwide. First Phosphate's Bégin-Lamarche property in the Grenville Province, Canada is also shown.

rocks of the phosphate ore in the seven deposits are carbonatite and the average P_2O_5 contents of the ore ranges between 5.1 and 12.2 wt.% (Table A2).

The igneous phosphate ore found at the First Phosphate's Bégin-Lamarche property in Quebec, Canada is mostly from ultramafic rocks in massif anorthosite from the Grenville Province. The P_2O_5 of the ultramafic rock ranges from 3.0 to 20.0 wt.%. The average P_2O_5 of the phosphate ore will be determined during the NI-43-101 resource estimate. Testing suggests that the phosphate ore from this deposit could produce a high-quality phosphate concentrate with a P_2O_5 content of ~40.9 wt.% (Table A1), which is above the global average P_2O_5 of marketable phosphate concentrates produced from igneous ore from other countries (36.9 wt.%; Table 1).

Comparisons of global igneous phosphate rock mining operations

Depth of ore body, distributions of ore and waste rocks, and grades of ore are the principal factors for selecting open-pit or underground mining operations. Both open-pit and underground mining operations exist for igneous phosphate ore excavation (Geissler et al., 2015). The open-pit mining operations are, however, becoming the primary method of mining over time (Geissler et al., 2015). One of the major Russian igneous phosphate producers, PhosAgro, operates both open-pit and underground mines in the Khibiny Alkaline Igneous Complex, Russia. In the case of the Koashvinsky open-pit mine, the quarry excavation depth

reaches up to 960 m, including the upland part, and up to 580 m in a closed contour (Iliashenko, 2022). Another major igneous phosphate producer in Russia, EuroChem, excavated to a depth of 414 m until 2015 at their Kovdorskiy open-pit mine in the Kovdor Ultramafic Alkaline Complex and has a plan to excavate to a depth of 874 m before starting an eventual underground mining operation (Dickson, 2015).

First Phosphate Corp. completed a total of 23,398 m of drilling since February 2024 in four areas of their Bégin-Lamarche property (Mountain zone, Northern zone, Northwestern zone, and Southern zone). Assays have been completed for a total of 9155 m of drilling to date. Initial results show that one drill hole (BL-24-56) in the Mountain zone intersects a phosphate layer at a depth of 6.5 m from the surface and continues over 92.5 m down the depth with an average P_2O_5 content of 11.8 wt.%. This layer continues toward the south end of the Mountain zone through to the Northern zone. Multiple phosphate layers were also identified in the Northern zone. The overall strike length of the Northern and Mountain zones is nearly 600 m (First Phosphate press release, April 23, 2024). The presence of the phosphate layer close to the surface (~6.5 m below the surface) in the BL-24-56 drill hole suggests that the area close to this drill hole in the Mountain zone could be a prospective location for starting open-pit mining operation at the Bégin-Lamarche property. This needs to be justified with an NI-43-101 resource estimate and subsequent proper mine planning study. The NI-43-101 resource estimate for the Bégin-Lamarche property is expected to begin soon after the end of the drilling program by the end of May 2024.

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Appendix

Table A1. Average P_2O_5 contents of phosphate ore and concentrates from igneous and sedimentary phosphate rocks from various countries around the world.

	Average P_2O_5 (wt.%)		References
Igneous ore	**Ore-grade**	**Concentrate (after beneficiation)**	
Russia	10.1	38.7	Steiner et al., 2015
Finland	4.0	36.0	Geissler et al., 2018; O'Brien et al., 2015
S. Africa	7.0	37.3	Steiner et al., 2015
Brazil	11.1	35.4	Steiner et al., 2015
Global average	***8.1***	***36.9***	
Sedimentary ore			
Morocco	26.4	31.5	Steiner et al., 2015
US	11.8	29.2	Steiner et al., 2015
Jordan	25.5	29.7	Steiner et al., 2015
China	21.6	28.1	Steiner et al., 2015
Global average	***21.3***	***29.6***	
Bégin-Lamarche area, Canada	3.0-20.0 (P_2O_5 range)	40.9*	

* Prepared and analyzed by SGS-Canada.

Table A2. Average P_2O_5 contents of igneous phosphate ore from major deposits from four major countries. The companies operating the mines in the deposits, host rocks, and geological provinces are also included.

Country	Company	Deposit	Avg. ore-grade P_2O_5 (wt.%)	Host rock	Geological province	References
Russia						
	PhosAgro					
		Kukisvumchorr	14.1	apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	PhosAgro annual report, 2022
		Yukspor	13.8	apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	PhosAgro annual report, 2022
		Apatitovy Cirque	13.7	apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	PhosAgro annual report, 2022
		Rasvumchorr Plateau	10.7	apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	PhosAgro annual report, 2022
		Koashva	17.2	apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	PhosAgro annual report, 2022
		Njorkpahk	14.1	apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	PhosAgro annual report, 2022
	Acron					
		Oleniy Ruchey	16.2	apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	International economic and energy consulting report, 2011
	Eurochem					
		Kovdorskiy Mine	6.8	phoscorite–carbonatite pipe	Kovdor Ultramafic Alkaline Complex	Dickson, 2015; Ivanyuk et al., 2016
Finland						
	Yara					
		Siilinjärvi	4.0	glimmerite-carbonatite	Siilinjärvi Carbonatite Complex	Decrée et al., 2020; O'Brien et al., 2015
South Africa						
	Foskor					
		Phalaborwa	7.0	pyroxenite, carbonatite, and phoscorite	Phalaborwa (Palabora) Igneous Complex	Roux et al. ,1989
Brazil						
	Mosaic	Tapira	7.6	carbonatite	Alto Paranaíba Alkaline Province	Silva et al., 2023
	Mosaic	Araxá	11.8	carbonatite	Alto Paranaíba Alkaline Province	Silva et al., 2023
	Mosaic	Catalão I	11.1	carbonatite	Alto Paranaíba Alkaline Province	Silva et al., 2023
	CMOC/Mosaic	Catalão II	12.2	carbonatite	Alto Paranaíba Alkaline Province	Silva et al., 2023
	Eurochem	Salitre	8.6	carbonatite	Alto Paranaíba Alkaline Province	Silva et al., 2023
	Mosaic	Cajati	5.1	carbonatite	Jacupiranga Alkaline Complex	Silva et al., 2023
	Fosnor Galvani	Angico dos Dias	5.7	carbonatite	Angico dos Dias Carbonatite Complex	Silva et al., 2023