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Research Note

Igneous Rock Phosphate: ore grades, concentrates and mining operations around the world

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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 2023a). 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). All of these phosphate igneous deposits are from silica-undersaturated alkali intrusions and carbonatites. ***No phosphate ore is, however, currently supplied from mafic-ultramafic rocks hosted in massif anorthosite or layered intrusions.***

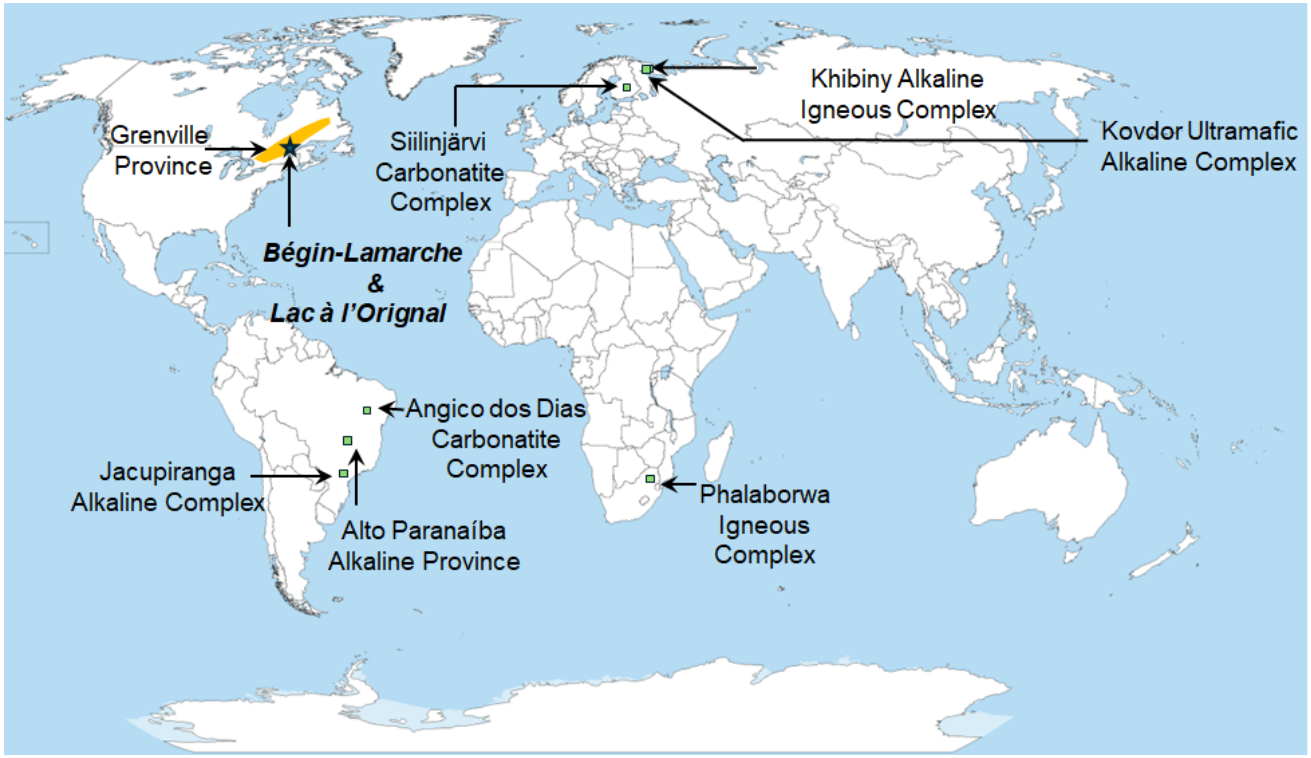

Fig. 1. Major igneous complexes supplying igneous phosphate ore worldwide. First Phosphate's Bégin-Lamarche property in the Grenville Province, Canada is also shown.

Major igneous phosphate deposits and their ore grades

The average P_2O_5 contents of phosphate ore from *the silica-undersaturated alkali intrusion and carbonatite igneous rocks* from major operating mines 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 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).

First Phosphate Corp. published a NI-43-101 technical report on one of their properties, Lac à l'Orignal deposit in the Vanel Anorthosite of the Grenville Province, in Quebec, Canada (Table A2; Yassa, 2022). The average P_2O_5 contents of phosphate ore of the Lac à l'Orignal deposit is 5.18 wt.% (Table A2). The company is exploring another property, Bégin-Lamarche in the Lac-Saint-Jean Anorthositic Suite of the Grenville Province in Quebec. The deposit is larger in size than the Lac à l'Orignal deposit. The igneous phosphate ore found at the First Phosphate's Bégin-Lamarche property is mostly oxide-apatite-mafic- ultramafic rocks (Banerjee et al., 2023b). The company recently published a NI-43-101 technical report on the Bégin-Lamarche (Yassa, 2024). The average P_2O_5 contents of the rocks is 6.01 wt.% (Table A1 and A2). 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).

The average grade versus tonnage plot (Fig. 2) exhibits a wide range of sizes of igneous phosphate deposits, which are presently mined. The deposits range from low-grade-low tonnage (e.g., Angico dos Dias, Brazil) to high-grade-high tonnage (e.g., Apatit's Kirovsk branch, Russia). The deposits that plot along a curvilinear line of Fig. 2 indicate that those deposits are expected to supply a similar amount of apatite (or P_2O_5) during the life span of the mines. The First Phosphate's Lac à l'Orignal deposit plots close to the Angico dos Dias deposit, which suggests if the Lac à l'Orignal deposit starts to supply phosphate ore, it will cumulatively supply a similar amount of apatite as that of the Angico dos Dias deposit during the life of the mine.

Although the phosphate ore (Fig 2 and Table A2) hosted in massif anorthosite (i.e., all igneous phosphate deposits in Canada) is not of high grade, the apatite from these deposits contains a lower amount of toxic elements, such as Pb (1.4-2.9 ppm *vs* 14.3 ppm), Th (4.1-10.0 ppm *vs* 191 ppm), and U (1.4-5.4 ppm *vs* 12.3 ppm; Table A3) than those from carbonatite-hosted igneous deposits worldwide. Similarly, the average REE concentrations in apatite (1945-3711 ppm) hosted in the oxide-apatite-mafic-ultramafic rocks in massif-anorthosite are lower than that of carbonatite worldwide (8224 ppm; Table A3). ***Therefore, the igneous phosphate ore from massif anorthosites is of high quality and environment-friendly (Banerjee et al., 2024)***.

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 (Table A2; Geissler et al., 2015). The igneous phosphate mines in Brazil and Finland are open-pit, whereas igneous phosphate mines in Russia and South Africa use a combination of open-pit and underground mining operations (Table A2). 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).

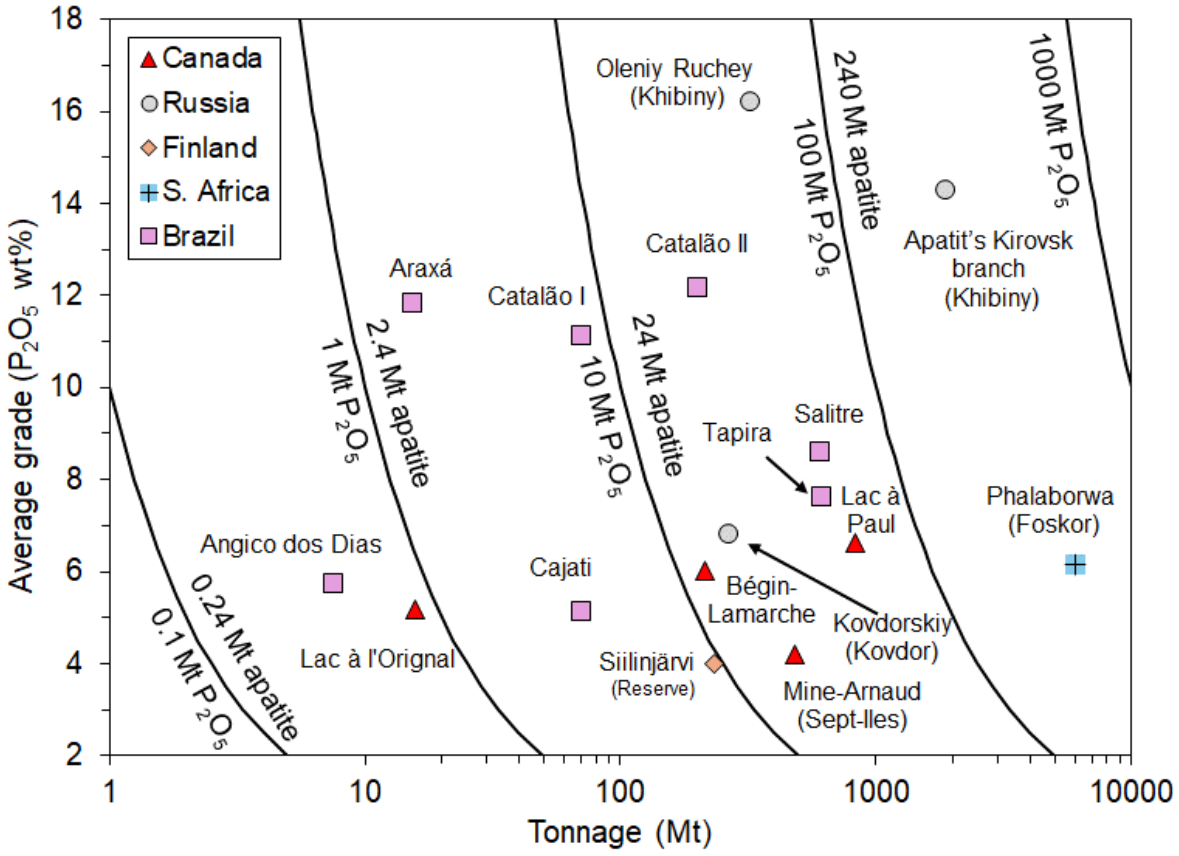

Fig. 2. Average grade versus tonnage (resource) for major igneous phosphate deposits from silica-undersaturated alkali and carbonatite intrusions from various countries around the world. The resources (tonnage) for Russian deposits (Oleniy Ruchey, Apatit's Kirovsk branch, and Kovdorskiy) are considered from the A+B+C1 reserve. Igneous phosphate deposits in Canada (prospective mines) hosted in oxide-apatite-mafic-ultramafic rocks within massif-anorthosites are also shown. Note that the tonnage (x)-axis is on a logarithmic scale. The curvilinear lines indicate the amount (Mt.) of P_2O_5 or apatite within the phosphate ore.

First Phosphate Corp. completed a total of 25,929 m of drilling from 99 holes since February 2024 in three zones of their Bégin-Lamarche property (Mountain zone, Northern zone, and Southern zone). All analyses from the drilling program have been received. The drilling program reveals a nearly continuous phosphate mineralization over a strike length of ~2400 m across the 3 zones (First Phosphate press release, July 25, 2024). 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 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 a subsequent proper mine planning study.

If the First Phosphate starts to mine phosphate ore from its Bégin-Lamarche property, it will be the first phosphate mine in Canada as well as in the world to supply phosphate ore from massif-anorthosite hosted rocks.

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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	6.01	40.9*	

* Prepared and analyzed by SGS-Canada.

Table A2. Average P_2O_5 contents of igneous phosphate ore from major deposits, their host rocks, and geological provinces from four major countries. The companies operating the mines in the deposits, cut-off grades, resources, and mining methods are also included.

Country	Company	Deposit	Avg. ore-grade P_2O_5 (wt.%)	Cut-off grade P_2O_5 (wt.%)	Resource (Mt)	Resource estimation type	Mining method	Host rock	Geological province	References
Russia										
	PhosAgro									PhosAgro annual report, 2022; 2019
	Apatit's Kirovsk branch	Kukisvumchorr	14.1	–	377.7	measured (M)+indicated (I) (reported as A+B+C1 reserve in Russian system)	Open-pit and underground	apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	
		Yukspor	13.8	–	473.4			apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	
		Apatitovy Cirque	13.7	–	96.8			apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	
		Rasvumchorr Plateau	10.7	–	310.5			apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	
		Koashva	17.2	–	587.7			apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	
		Njorkpahk	14.1	–	55.6			apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	
		Apatit's Kirovsk branch	14.3	–	1901.5					
	Acron	Oleniy Ruchey	14.9	–	60.8	M+I	open-pit+ underground	apatite-nepheline-syenite	Khibiny Alkaline Igneous Complex	International economic and energy consulting report, 2011
	Eurochem									
		Kovdorskiy Mine	6.8	–	267	M+I	open-pit	phoscorite–carbonatite pipe	Kovdor Ultramafic Alkaline Complex	Dickson, 2015; Ivanyuk et al., 2016
Finland										
	Yara	Siilinjärvi	4.0	–	234	reserve as reported in O'Brien et al.,2015	open-pit	glimmerite-carbonatite	Siilinjärvi Carbonatite Complex	Decrée et al., 2020; O'Brien et al., 2015
South Africa										
	Foskor and Palabora Mining Company	Phalaborwa	6.1	5.5	6031.7		open-pit+underground	pyroxenite, carbonatite, and phoscorite	Phalaborwa (Palabora) Igneous Complex	Roux et al. ,1989; University of Cape Town
Brazil										
	Mosaic	Tapira	7.6	–	619.5	reported as estimated resources in Silva et al., 2023	open-pit	carbonatite	Alto Paranaiba Alkaline Province	Silva et al., 2023
	Mosaic	Araxá	11.8	–	15.6			carbonatite	Alto Paranaiba Alkaline Province	
	Mosaic	Catalão I	11.1	–	71.4			carbonatite	Alto Paranaiba Alkaline Province	
	CMOC/Mosaic	Catalão II	12.2	–	203.7			carbonatite	Alto Paranaiba Alkaline Province	
	Eurochem	Salitre	8.6	–	609.4			carbonatite	Alto Paranaiba Alkaline Province	
	Mosaic	Cajati	5.1	–	70.8			carbonatite	Jacupiranga Alkaline Complex	
	Fosnor Galvani	Angico dos Dias	5.7	–	7.6			carbonatite	Angico dos Dias Carbonatite Complex	
Proposed projects in Canada from (oxide-apatite-)mafic-ultramafic rocks hosted in massif anorthosite										
Canada	Investissement Québec+ Yara International	Mine Arnaud (Sept-Iles)	4.2	1.8	481.7	M+I	_	(oxide-apatite-) mafic-ultramafic rocks	Sept-Îles Anorthosite Complex (Grenville Province)	Paiement et al., 2013
	Arianne Phosphate	Lac à Paul	6.6	2.4	832.2	M+I	_	(oxide-apatite-) mafic-ultramafic rocks	Lac St-Jean Anorthositic Complex (Grenville Province)	Côté et al., 2013 and updated resource estimate on the Arianne Phosphate website
	First Phosphate	Lac à l'Orignal	5.2	2.5	15.8	I	_	(oxide-apatite-) mafic-ultramafic rocks	Vanel Anorthosite (Grenville Province)	Yassa, 2022
		Bégin-Lamarche	6.01	2.5	214	**Inferred**	_		Lac St-Jean Anorthositic Complex (Grenville Province)	Yassa, 2024

Table A3. Comparisons of apatite trace element composition of the oxide-apatite-mafic-ultramafic rocks hosted in massif-anorthosite, Canada with those of carbonatite worldwide. Both average values (±1σ) and ranges (in parentheses) are provided.

	Oxide-apatite-mafic-ultramafic rocks in massif-anorthosite , Canada					***Worldwide carbonatite***
Elements	*Lac à l'Orignal*	*Lac Mirepoix*	*Lac à Paul*	*Sept-Iles*	*Grader Lake*	
(ppm)	*n=35*	*n=31*	*n=2*	*n=33*	*n=8*	*n=300*
Mn	340±88 (250-680)	368±112 (212-633)	349 (337-360)	306±77 (99-428)	304±61 (241-439)	307±209 (4-1068)
Fe	1028±734 (493-3457)	1844±778 (455-4360)	1044 (899-1190)	1046±499 (328-2708)	—	869±1430 (78-10811)
As	9.1±5.6 (1.5-24.4)	8.6±10.3 (1.9-56.7)	18.4 (3.1-33.8)	4.8±2.6 (1.5-12.3)	—	10.9±4.9 (≤14.3-19.0)
Sr	1030±195 (659-1501)	896±206 (561-1340)	702 (414-990)	666±164 (439-1087)	502±19 (472-522)	7290±3789 (827- 20119)
Y	315±128 (148-763)	478±255 (156-1351)	345 (245-446)	564±205 (324-1197)	308±40 (222-343)	1306±2479 (≤12.8 to 12000)
REE	2502±827 (1407-4992)	3711±1827 (1194-10275)	2252 (1458-3046)	3316±1365 (1931-6943)	1945±299 (1273-2248)	8224 ±7983 (273-45859)
LREE/HREE (ratio)	8.2±0.8 (7.0-10.5)	8.1±0.6 (7.0-9.3)	7.5 (6.8-8.2)	6.6±0.8 (5.1-8.5)	7.8±0.4 (7.1-8.4)	22±14.4 (0.6-70.9)
Pb	1.4±0.7 (0.7-3.4)	2.7±2.9 (0.8-17.5)	2.9 (1.6-4.3)	2.1±1.7 (0.6-6.5)	—	14.3±19 (≤0.8 to 76.9)
Th	4.1±5.5 (1.0-28.3)	5.7±5.1 (0.9-22.1)	8.9 (4.1-13.8)	10.0±8.5 (2.3-39.9)	—	191 ±416 (≤0.3 to 3000)
U	1.4±1.4 (0.5-6.5)	1.9±1.3 (0.4-6.4)	5.4 (2.5-8.3)	2.7±2.0 (0.6-8.5)	—	12.3 ±24.6 (≤0.02 to 105)

REE=Lanthanum (La)+ Cerium (Ce)+ Praseodymium (Pr)+ Neodymium (Nd)+ Promethium (Pm) + Samarium (Sm)+ Europium (Eu) + Gadolinium (Gd)+ Terbium (Tb) +Dysprosium (Dy) + Holmium (Ho)+ Erbium (Er) + Thulium (Tm) + Ytterbium (Yb) + Lutetium (Lu)

LREE= La+Ce+Pr+Nd+Sm+Eu

HREE= Gd+Tb+Dy+Ho+Er+Tm+Yb+Lu

Data:

Lac à l'Orignal (Grant 2020; Miloski et al., 2024; Banerjee et al., 2024), Lac Mirepoix (Miloski et al., 2023), Lac à Paul (Grant, 2020), Sept-Iles (Tollari et al., 2008; Kieffer et al., 2023), Grader Lake (Charlier et al., 2008), Worldwide carbonatite (Banerjee et al., 2024)