



**Characterization of First Phosphate's Bégin-Lamarche Phosphate Deposit
(*Mountain Zone*), Lac-Saint-Jean Anorthositic (LSJA) Suite, Quebec, Canada:
Implications for Supplying Lithium Ferro (Iron) Phosphate (LFP) Batteries**

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EXECUTIVE SUMMARY

The purpose of this report is to describe and interpret the mineralogy, petrology, and geochemistry of First Phosphate's Mountain Zone property of the Bégin-Lamarche igneous (anorthosite-hosted) phosphate deposit. This project is an extension of a previous project on First Phosphate's North and South Zone properties of the Bégin-Lamarche deposit. The Bégin-Lamarche is a part of the 1.14 Ga Lac-Saint-Jean Anorthositic (LSJA) Suite, Québec, which is the largest anorthosite complex in the world. The study reveals:

- Fluorapatite is the primary ore mineral and the ore mineral from (only) oxide-apatite ultramafic rocks (dunite, harzburgite, olivine websterite, and olivine orthopyroxenite) and apatite-rich nelsonite of the Mountain zone was investigated. These mineralized rocks mostly contain variable amounts of olivine, orthopyroxene, fluorapatite, ilmenite, magnetite, and Al-spinel.
- In the Bégin-Lamarche deposit (Mountain, North, and South Zone), oxide-apatite ultramafic rocks (~ 0% plagioclase) contain a higher amount of apatite than those of oxide-apatite mafic rocks (> 10% plagioclase). **The oxide-apatite ultramafic rocks contain an equivalent amount of apatite to that of 'nelsonite' rocks (~ 30-40 % apatite + 60-70% oxide minerals) or even higher than that of the 'nelsonite'. The study on the Bégin-Lamarche deposit first reports that ultramafic rocks (dominated by silicate minerals) can contain a higher amount of apatite than that of the 'nelsonite'.**
- The oxide-apatite ultramafic rocks crystallized before the oxide-apatite mafic rocks. Therefore, a high amount of apatite crystallized at the initial stages of magma crystallization and the amount of apatite crystallization decreased progressively.
- **Analysis from a limited number of ultramafic rocks and apatite-rich nelsonite from the Mountain Zone indicates that the fluorapatite has low Cl content (620 ± 110 ppm; $n=7$).** Similar to the North and South Zone, Cl content of (fluor)apatite from the Mountain Zone decreased with progressive crystallization,
- Initial results indicate that the apatite from the Mountain Zone has **a high-quality phosphate ore** for producing phosphoric acid because the apatite has high P_2O_5 concentrations (42.0 ± 0.1 wt.%; $n=7$) but low Si, Fe, Al, Mg, Ti, Na, As, Cd, Pb, Th, and U concentrations. The fluorapatite with low concentrations of trace elements is expected to produce **high-quality phosphogypsum (with low toxic elements)** during phosphoric acid production. Furthermore, high-quality ilmenite and magnetite *can be* recovered from the deposit as saleable by-products for Ti and Fe, respectively.
- Therefore, high-quality (fluor)apatite with low contents of toxic trace elements and sulfide minerals (< 1%) make the Bégin-Lamarche deposit (Mountain, North, and South zones) an **attractive ESG (environmental, social, and governance)-compliant source** of North American P for the LFP battery industry.

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1. Introduction

First Phosphate Corp. (or First Phosphate) is the only company developing greenfield phosphate deposits to source phosphate for the lithium iron phosphate (LFP; LiFePO_4) battery industry. A high-quality phosphate ore with low trace elements is essential for manufacturing LFP batteries (BM Review, 2022; Banerjee 2023a; Banerjee et al., 2024b). The company targeted massif anorthosite-hosted, environment-friendly igneous phosphate deposits from Quebec, Canada for such high-quality phosphate ore (Banerjee, 2023a; Banerjee et al., 2024a; 2024b). No phosphate ore is, however, currently supplied from mafic-ultramafic rocks hosted in massif anorthosite. This type of rock was never exploited previously for phosphate ore. Most of the igneous phosphate ore is produced from carbonatite and associated silica-undersaturated alkali rocks (e.g., Banerjee et al., 2024c; Pufahl and Groat, 2017).

This project is an extension of a previous project on First Phosphate's Bégin-Lamarche property, Quebec, Canada (Fig. 1A-C). The Bégin-Lamarche property is hosted in the Lac-Saint-Jean Anorthositic (LSJA) Suite (Fig. 2), which is the world's largest Proterozoic massif-type anorthosite body (Ashwal, 1993, 2010). The last project characterized the petrography and mineralogy of the North and South zones of the property (Banerjee et al., 2024b). This study will characterize the petrography and mineralogy of the Mountain Zone of the Bégin-Lamarche property, which is located just northeast of the North Zone.

2. Objectives and deliverables

A recent drilling program by First Phosphate reveals that mafic and ultramafic rocks from the South, North, and Mountain zones of the Bégin-Lamarche property, Quebec contain multiple cumulate layers of phosphatic ore (Fig. 1A-C). Detailed geological mapping around the deposit is currently underway through an MSc project of Jonathan Katako Diyoyo at UQAC, Quebec (Diyoyo et al., 2024). A comprehensive petrography and mineralogical study have been performed on the rock samples from the South and North zones (Banerjee et al., 2024b). This study will provide comprehensive information on the petrography and mineralogy of the rock samples from the Mountain Zone. This information is essential for future exploration, site feasibility study, mine planning, and ore processing with the least environmental impact possible.

The study was performed on 20 drill core samples collected from 10 drill holes from the Mountain Zone (Fig. 3 and 4). The collaborative research will yield the following key deliverables:

- 1) Comprehensive mineralogy and geochemical characterization of the Mountain Zone of the Bégin-Lamarche deposit (property),
- 2) Establish mineral paragenesis of the Mountain Zone,
- 3) Use of mineral paragenesis and geochemical characteristics to identify a tool to trace high-quality phosphate ore in the deposit.

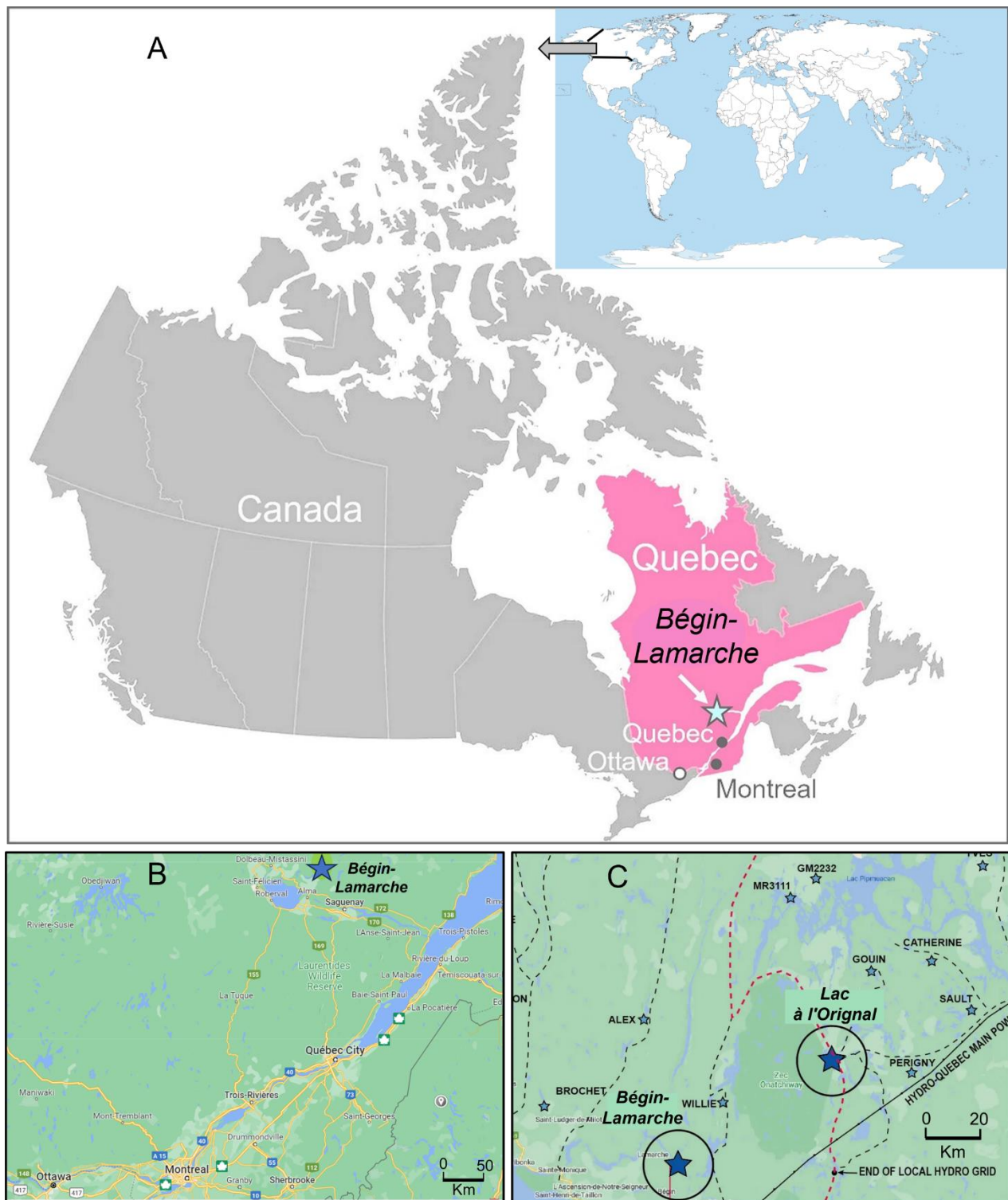


Fig. 1. Location map (A, B, and C) showing the Bégin-Lamarche property of First Phosphate Corp., Quebec, Canada. The Lac à l'Original property of First Phosphate Corp. is also shown in panel C (panels B and C are modified from Google Maps, July 2, 2024).

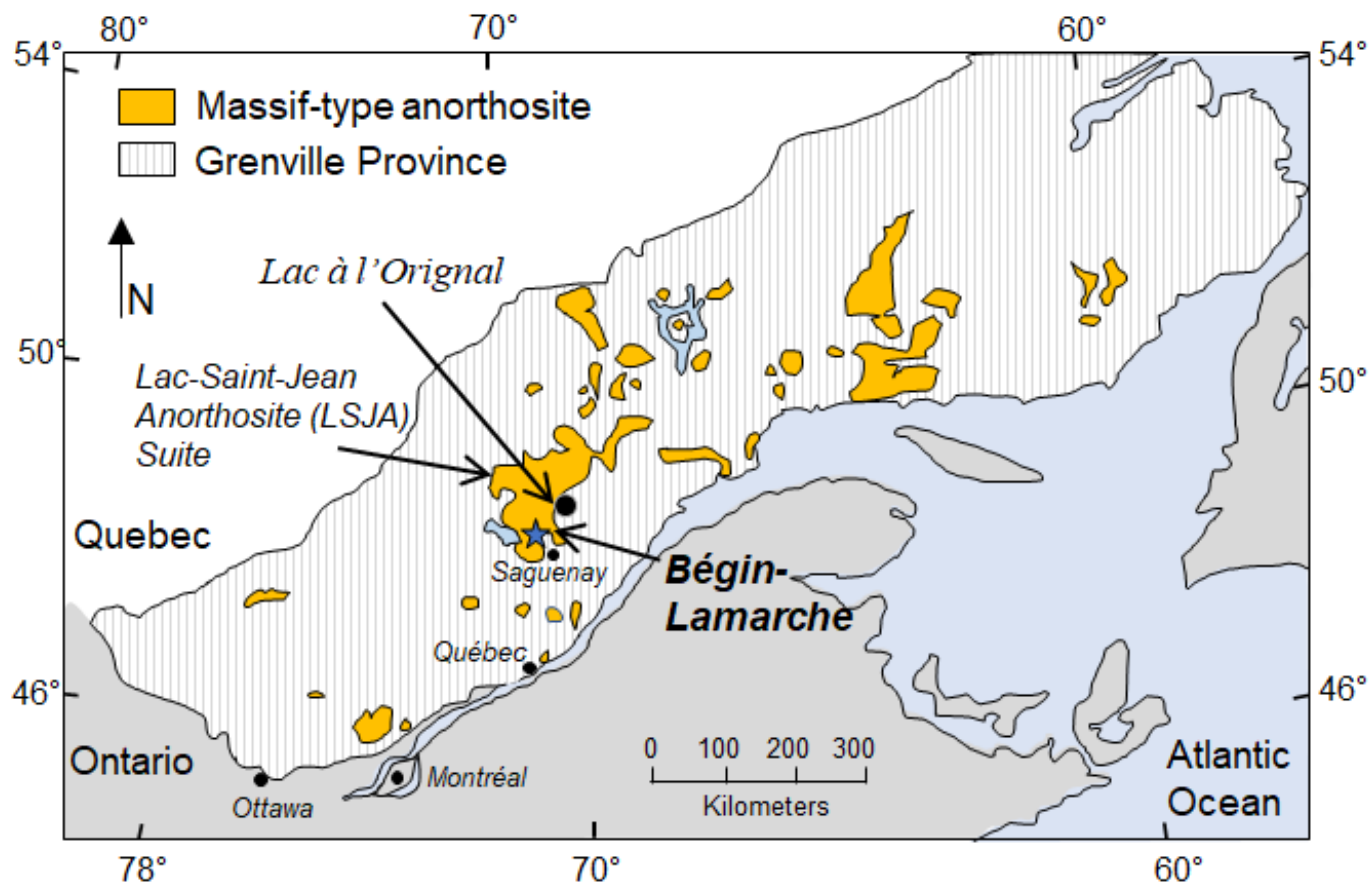


Fig. 2. Location map showing massif-type anorthosite bodies and the Bégine-Lamarche deposit, Quebec within the Grenville Province in Canada (modified after Banerjee et al., 2024c, Bédard, 2009; and Higgins et al., 2002). The Lac à l'Original property of First Phosphate Corp. is also shown.

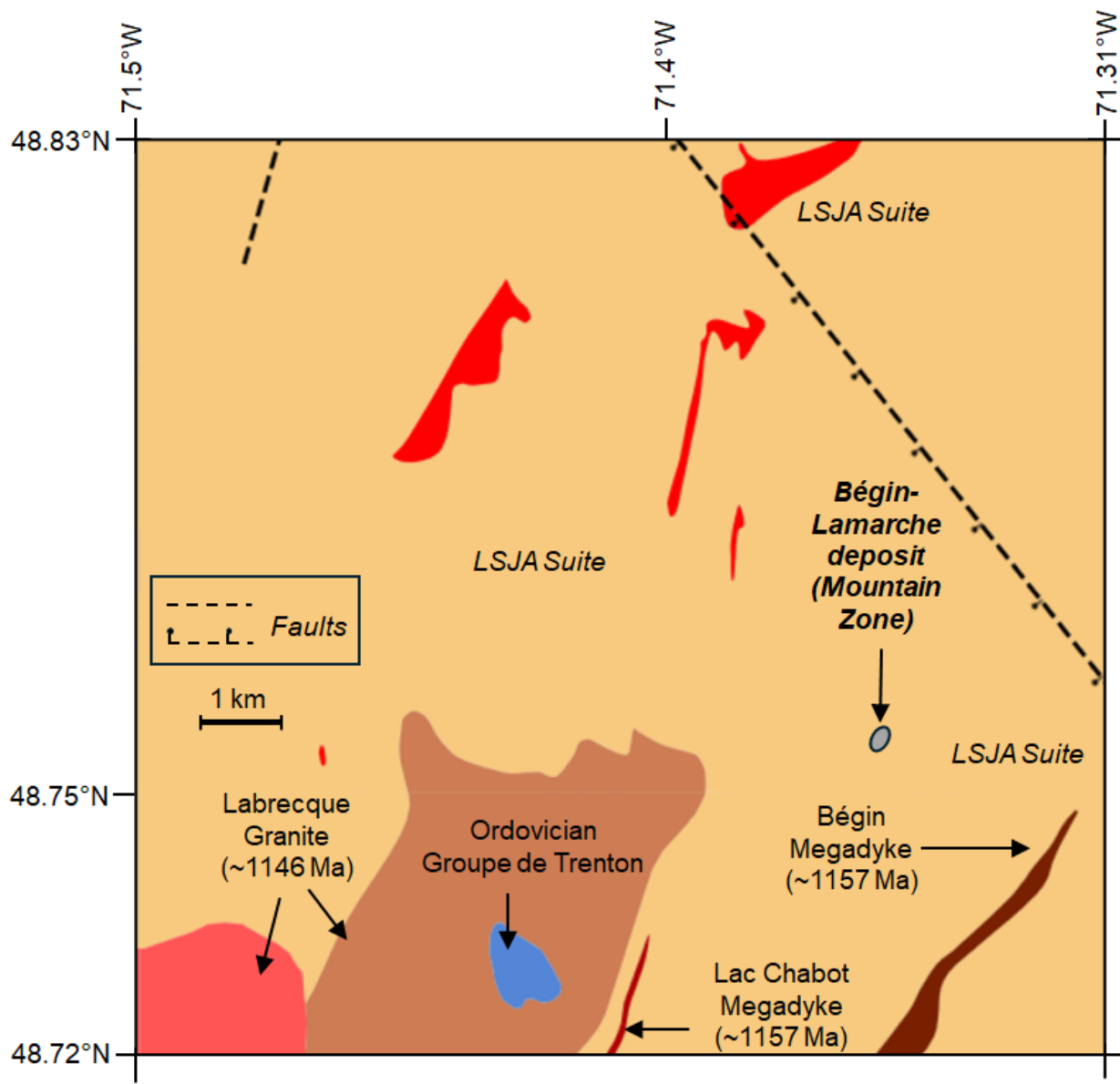


Fig. 3. Simplified location map of the Mountain Zone of the Bégin-Lamarche deposit showing distributions of the Labrecque Granite, Bégin, and La Chabot Megadykes within the LSJA Suite. The age data are within the parentheses and from Higgins and van Breemen (1996). Geological map modified after SIGEOM (Quebec System of Geomining Information; Hébert and Lacoste, 1998; Laurin and Sharma, 1972; Intissar et al., 2021).

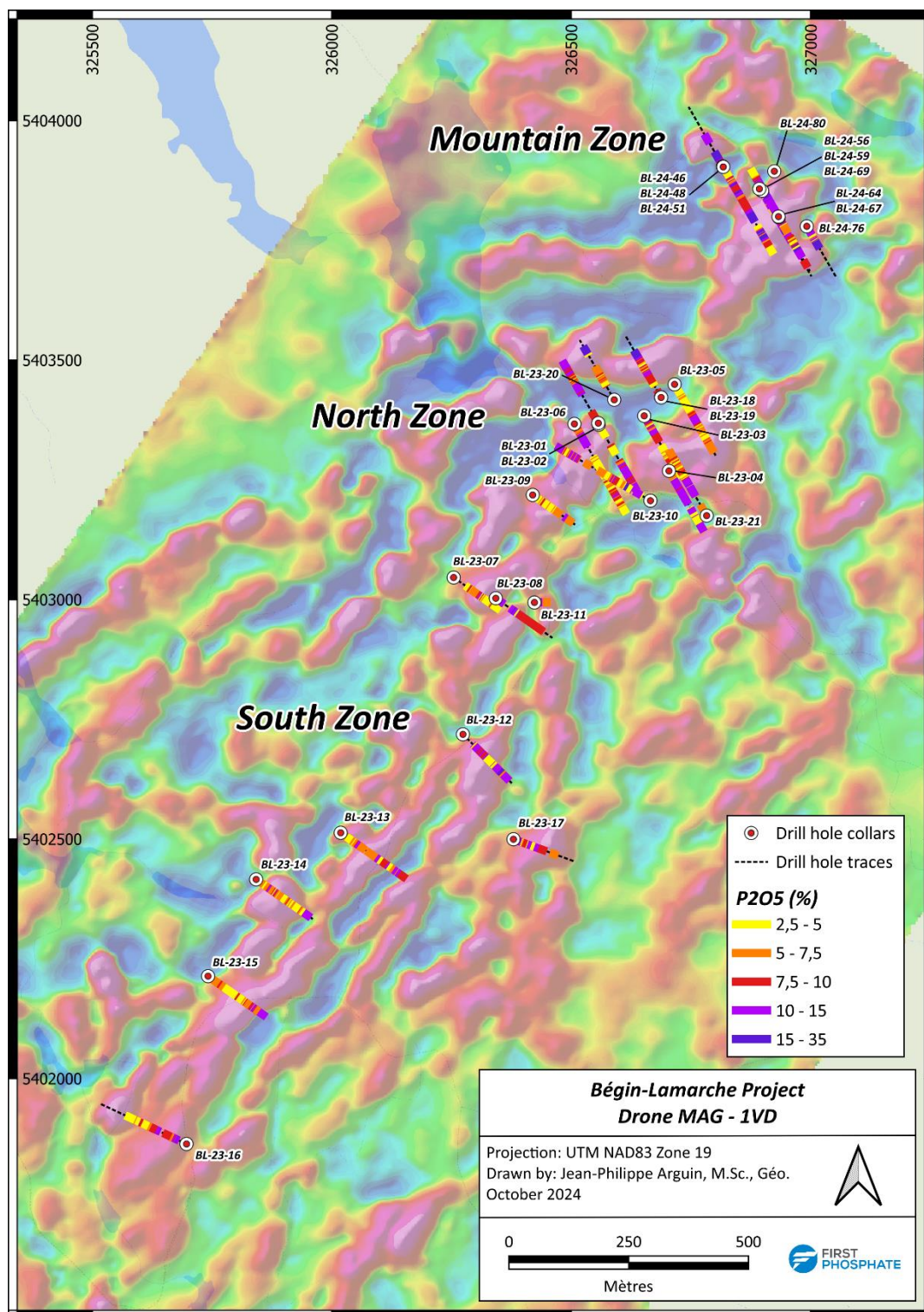


Fig. 4. Drill hole distributions within the Mountain Zone of the Bégin-Lamarche property of First Phosphate Corp. Drill hole distributions within the North and South zones of the Bégin-Lamarche property are also shown.

3. Location

First Phosphate's Bégin-Lamarche property is located ~ 270 km north of Québec City, Quebec, Canada, and ~ 75 km northwest of Port Saguenay, Quebec (Fig. 1B). The property is part of the LSJA Suite (Fig. 2 and 3). The Mountain Zone of the Bégin-Lamarche property (deposit) is located on NTS sheet 22D14. The Mountain Zone is located at longitude 71.35° W and latitude 48.76° N (UTM NAD83 Zone 19N coordinates: 326,900 m E and 5,403,750 m N) (Fig. 3 and 4).

4. Geological setting

4.1. Regional geology

The Bégin-Lamarche deposit is part of the LSJA Suite which occurs in the central part of the Grenville Province (Fig. 2; Higgins and van Breemen, 1992). The Grenville Province is a Mesoproterozoic orogenic belt along the southeastern margin of the Canadian Shield (Fig. 2). The Grenville Province contains numerous massif-type anorthosite, also called anorthosite-mangerite-charnockite-granite (AMCG) suites, including the LSJA Suite (Hébert et al., 2005).

The Grenville Province is a tectonically complex region that developed due to a continent-continent collision between the southeastern margin of the Laurentia craton and the western margins of the Amazonian and Kalahari cratons (Jacobs et al., 2008; Ibanez-Mejia et al., 2011). The Himalayan-type continental collision during the Grenville Orogeny occurred in three distinct phases (Shawinigan, 1190–1140 Ma; Ottawan, 1080–1020 Ma; and Rigolet, 1000–980 Ma), which were separated by periods of crustal extension and intra-plate magmatism (Rivers, 1997). The Grenville Orogeny produced intense crustal thickening associated with high-grade metamorphism (amphibolite-granulite facies; Darling et al., 2004; Hynes and Rivers, 2010; Ludden and Hynes, 2000).

The LSJA Suite dominantly consists of a complex assemblage of intrusive anorthosite plutons that are difficult to differentiate based on field relationships and mineralogy. Other intrusive rocks include leuconorite, leucotroctolite, norite, olivine-bearing gabbro, gabbro, pyroxenite, peridotite, dunite, nelsonite (~30-40% apatite + 60-70% oxide; Philpotts 1967), magnetitite, and rare charnockite-mangerite units (Hébert et al., 2005). Two large (> 30 km in length) north-northeast oriented mafic dykes (Lac Chabot and Bégin megadykes) occur in the LSJA Suite to the south of the Bégin-Lamarch property. All rocks including two large dykes are composed of plagioclase with variable amounts of pyroxene and olivine (Higgins et al., 2002). Plagioclase is primarily of the andesine (An₃₀-An₅₀) and labradorite varieties (An₅₀-An₇₀; e.g., Hassen Ali et al., 2023; 2024; Diyoyo et al. 2024; Higgins and van Breemen, 1992). Aluminum-rich orthopyroxene megacrysts are also locally present (Higgins and van Breemen, 1992).

The host country rocks of the LSJA Suite are the Chicoutimi Gneiss Complex (~ 1530 Ma), the Saguenay Gneiss Complex (~ 1506 Ma), the Hulot Complex (~ 1434 Ma), the Cap à l'Est Gneiss Complex, and the Cyriac Rapakivi Granite (~ 1393 to 1383 Ma; Higgins and van Breemen, 1996; Hébert et al., 2005). The anorthositic rocks of the LSJA Suite are interpreted to

have intruded in multiple phases over 35 million years starting at ~ 1160 Ma and finishing at ~1135 Ma (Higgins et al., 2002).

The U-Pb analyses of zircon and baddeleyite from the south-central and southeastern parts of the LSJA Suite provide an igneous crystallization age ranging from 1157 to 1142 Ma (Higgins et al., 2002). The eastern border of the LSJA suite hosts two younger anorthosite suites, Vanel, and Mattawa anorthosite which crystallized at 1080 ± 2 and 1016 ± 2 Ma, respectively (Hébert et al., 2009). Some granitoids record emplacement ages between 1028 and 988 Ma, i.e., during the latter stages of the Grenville Orogeny (Higgins et al., 2002). When considered in the context of all geochronological data from the LSJA Suite region, these ages define three periods of magmatism recording a complex and protracted emplacement history. The first period occurred between 1160 and 1140 Ma, the second between 1082 and 1050 Ma, and the third between 1020 and 1000 Ma (Higgins and van Breemen, 1996).

Phosphate (or apatite) mineralization is present in several areas in the anorthosite (or AMCG) massifs in the central part of the Grenville Province (e.g., Hébert et al. 2005; Banerjee et al., 2024c). The apatite mineralization developed during the three periods of magmatic activities in the form of lenses, dykes, and small layered intrusions and is associated with Fe-Ti oxide minerals (Miloski et al., 2023; 2024; Hébert et al., 2005).

4.2. Local geology

The Bégin-Lamarche deposit is one of the phosphate deposits associated with Fe-Ti oxides in the southern margin of the LSJA Suite. The Bégin-Lamarche deposit is north-northeast oriented and parallel to the two megadykes (Lac Chabot (ferro)diorite and Bégin leucotroctolite megadykes of ~ 1157 Ma; Higgins and van Breemen, 1992; Fig. 3). The deposit consists of three zones: South, North, and Mountain zones (Fig. 4). The overall strike length of the deposit is ~ 3 km (First Phosphate press release, July 25, 2024). The Mountain Zone is located just northeast of the North Zone (Fig. 4) and is semicircular in shape with a diameter of ~ 0.5 km (Fig. 4). The Labrecque Granite (~ 1146 Ma; Higgins and van Breemen, 1996) is located further west or southwest of the deposit (Fig. 3).

The emplacement age of the First Phosphate's Bégin-Lamarche deposit has not been determined but may or may not be contemporaneous with the two megadykes. Recently two phosphate deposits (Lac Mirepoix and Lac à l'Original from the younger Vanel Anorthosite), ~ 75 km northeast of the Bégin-Lamarche, are dated between ~ 1070 and 964 Ma (Miloski et al. 2023; 2024), significantly younger than the two megadykes of the LSJA suite.

Table 1. Core samples, with depths, of the 10 drill holes from the Mountain Zone of the Bégin-Lamarche property investigated in this study. Analysis type is also included.

Ser. no	bore hole	depth (m)	petrographic thin section	SEM (MLA)	EMPA	LA-ICP-MS
<i>Mountain Zone</i>						
MZ1	BL-24-46	32.9	✓	✓	✓	
MZ3	BL-24-46	126.1	✓			
MZ4	BL-24-46	176.9	✓			
MZ5	BL-24-48	37.7	✓	✓	✓	
MZ6	BL-24-51	70.4	✓	✓	✓	
MZ7	BL-24-51	101.3	✓			
MZ8	BL-24-51	135.7	✓		✓	
MZ10	BL-24-56	7.1	✓			
MZ12	BL-24-56	71.3	✓			
MZ14	BL-24-56	154.85	✓	✓	✓	✓
MZ15	BL-24-56	165.65	✓			
MZ16	BL-24-59	8.3	✓			
MZ18	BL-24-59	151.6	✓			
MZ19	BL-24-64	5	✓	✓	✓	✓
MZ20	BL-24-64	33.7	✓			
MZ21	BL-24-64	106.6	✓			
MZ22	BL-24-67	47.3	✓			
MZ24	BL-24-69	63.1	✓			
MZ25	BL-24-76	60.35	✓			
MZ26	BL-24-80	46	✓	✓	✓	✓
<i>Total</i>			<i>20</i>	<i>6</i>	<i>7</i>	<i>3</i>

5. Sampling

In this study, samples with high abundances of apatite (visual estimation from core samples) were selected from the mineralized zones of the Mountain Zone. A total of 20 drill core samples were collected from 10 drill holes from the Mountain Zone of the property or deposit (Table 1, A1, and Fig. 4). The 10 drill holes include BL-24-46 (n=3), BL-24-48 (n=1), BL-24-51 (n=3), BL-24-56 (n=4), BL-24-59 (n=2), BL-24-64 (n=3), BL-24-67 (n=1), BL-24-69 (n=1), BL-24-76 (n=1), and BL-24-80 (n=1).

The half-core samples were cut in half to make quarter-core using a rock saw at the Department of Geological Sciences and Geological Engineering, Queen's University, Canada. A total of 20 polished thin sections were prepared. The polished thin sections were used for petrographic, scanning electron microscopy (SEM), electron probe microanalysis (EPMA), and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analysis (Table 1).

6. Methods

6.1. Mineral liberation analysis (MLA)

Six samples from the mineralized zone (1 thin section each from BL-24-46, BL-24-48, BL-24-51, BL-24-56, BL-24-64, and BL-24-80; Table 1, 2, A1, and A2) were analyzed with the FEI Quanta 400 scanning electron microscope (SEM) utilizing the Mineral Liberation Analysis (MLA) to quantify mineral abundances in the samples. Samples were measured under a high vacuum at a chamber pressure of 10^{-5} torr. Energy-dispersive X-ray spectroscopy (EDS) was performed with Bruker 4th generation XFlash silicon drift detector using an accelerating voltage of 25kV and a working distance of 12 mm. Each sample was analyzed with a closely spaced grid of X-ray measurements overlaying a backscattered electron (BSE) image. The GXMAP (grain-based-X-ray map) method was used with a 1.5×1.5 mm frame size at a 500-pixel frame resolution. The analyses were performed at the Core Research Equipment and Instrument Training (CREAIT) Network, Memorial University of Newfoundland, Canada.

6.2. Electron-probe micro-analysis (EPMA)

In situ mineral compositions of major to minor elements (SiO_2 , Al_2O_3 , TiO_2 , Cr_2O_3 , FeO , MnO , MgO , CaO , Na_2O , K_2O , P_2O_5 , F, and Cl; Table 3) were determined on seven polished thin sections (1 thin section each from BL-24-46, BL-24-48, BL-24-56, BL-24-64, and BL-24-80, and 2 thin sections from BL-24-51; Table 1) for olivine (n=3 samples), orthopyroxene (n=5), apatite (n=7), ilmenite (n=7), and magnetite (n=6).

The electron-probe micro-analyses for olivine, orthopyroxene, magnetite, and ilmenite were acquired on a JEOL JXA-8530F field emission electron microprobe at the Earth and Planetary Materials Analysis laboratory at Western University, Canada. Magnetite and ilmenite measurements were taken using an accelerating voltage of 20kV and a beam current of 20nA. Olivine and pyroxene measurements were taken using an accelerating voltage of 20kV and a beam current of 15nA. A beam diameter of 1 μm was used for all measurements (Table A3). The electron-probe micro-analyses of apatite were acquired on a fully automated JEOL JXA-iHP200F field emission electron microprobe at the University of British Columbia, Canada. Apatite

measurements were taken using an accelerating voltage of 15 kV, a beam current of 10 nA, and a defocused beam diameter of 10 μm (Table A3). The defocused beam was used to limit F and Cl migration in apatite during beam exposure of EPMA (e.g., Marks et al., 2012; Kieffer et al., 2023; Banerjee et al., 2024c). Decreasing the beam current (e.g., from 15 nA to 10 nA) can also limit the F and Cl migration but detection limits increase (Mark et al., 2012). A defocused beam of 15 nA with a beam diameter of 10 μm , however, can substantially decrease the F and Cl migration (Kieffer et al., 2023; Banerjee et al., 2024c). The reported data represent an average of three or more analyses of each mineral from different parts of each thin section (Table A7-A11). Natural standards from the Smithsonian Institute were used for the analysis of all phases.

6.3. Laser ablation–inductively coupled plasma-mass spectrometry (LA-ICP-MS) analysis

In situ trace (and minor) element compositions were determined on a subset of 3 polished thin sections (1 thin section each from BL-24-56, BL-24-64, and BL-24-80) for apatite (n=3 samples), magnetite (n=3), and ilmenite (n=3). A trace element is an element that is present in a rock or mineral in concentrations of less than 0.1 wt% or 1000 ppm (Rollinson, 2014). Depending on the mineral structure one element can be present as a major element in one mineral and the same element can be present as a trace element in another mineral.

Isotopes (^{25}Mg , ^{27}Al , ^{29}Si , ^{43}Ca , ^{45}Sc , ^{49}Ti , ^{51}V , ^{52}Cr , ^{55}Mn , ^{57}Fe , ^{59}Co , ^{60}Ni , ^{65}Cu , ^{66}Zn , ^{69}Ga , ^{72}Ge , ^{75}As , ^{85}Rb , ^{88}Sr , ^{89}Y , ^{90}Zr , ^{91}Zr , ^{93}Nb , ^{95}Mo , ^{111}Cd , ^{115}In , ^{116}Sn , ^{137}Ba , ^{139}La , ^{140}Ce , ^{141}Pr , ^{146}Nd , ^{147}Sm , ^{153}Eu , ^{157}Gd , ^{159}Tb , ^{163}Dy , ^{165}Ho , ^{166}Er , ^{169}Tm , ^{172}Yb , ^{175}Lu , ^{178}Hf , ^{181}Ta , ^{181}Hf , ^{202}Hg , ^{204}Pb , ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th , ^{235}U , and ^{238}U) in these minerals were analyzed using a GeoLas 193nm ArF excimer Laser (Coherent) connected to a Thermo Scientific Element XR sector field ICP MS at CREAT Network, Memorial University of Newfoundland.

The laser ablation system was set to 5 Hz and 200 pulses (corresponding to 40s ablation time). Ablation employed a spot diameter of 30 μm wherein a fluence of 4 J/cm² was maintained. Sample introduction was achieved by a constant He flow (~ 1 L/min) through the ablation cell with Ar (sample gas, ~0.90 L/min, tuned daily) mixed into the sample introduction tubing via a quartz glass T-piece right entering the injector. The instrument was fitted with Ni sample and H cones, the analyses were performed in low-resolution mode. For each spot, a gas blank was analyzed for 30s.

Primary reference material was the NIST glass 610. Secondary reference materials, NIST glass 612 and BCR2G, were used to better gauge the accuracy of the method (Jochum et al., 2005; Pearce et al., 1997; Raczek et al., 2001). The precision and accuracy of the standards are provided in Table A4-A6. Data reduction was performed offline using the iolite package (version 3; Paton et al., 2011). Data for apatite, ilmenite, and magnetite were normalized using constant Ca, Ti, and Fe values (values determined from EPMA), respectively. The reported data represent an average of analyses of each mineral from different parts of each thin section (Table A9-A11).

7. Results

7.1. Mineralogy and mineral chemistry of the ultramafic rocks

The phosphatic ore mineral of the Mountain Zone is apatite (specifically fluorapatite). The major minerals comprising the mineralized rocks are olivine (2-47 modal%), orthopyroxene (6-36 %), clinopyroxene (0-2 %), apatite (29-86 %), magnetite (0-20 %), ilmenite (0-10 %), and Al-spinel (0-3 %). Abundances of other minerals, such as amphibole, biotite, and chlorite are very low (<2%; Table 2). Many olivine crystals are altered to iddingsite. Finally, sulfide minerals occur as an accessory phase (<1 %).

Plagioclase is absent in these rocks and therefore, the mineralized rocks in this study are grouped as oxide-apatite ultramafic rocks (oxide-apatite dunite, oxide-apatite harzburgite, apatite olivine websterite, oxide apatite olivine orthopyroxenite, and apatite olivine orthopyroxenite; Fig. 5A and B, Table 2). The nelsonite-type samples were also identified. However, those rocks contain a higher amount of apatite than oxide minerals. Therefore, those rocks are named as apatite-rich nelsonite (MZ8 and MZ18; Table 2). The oxide-apatite prefix was used in the rock name only when the modal abundances of oxide and apatite were $\geq 5\%$. Although apatite abundance is higher than that of the oxide minerals (Table A2), we considered the commonly used prefix 'oxide-apatite' for the nomenclature of these rocks. All rocks exhibit cumulate texture.

The modal abundances of the minerals of the mineralized rocks of the Mountain Zone (as well as the North and South Zone) of the Bégin-Lamarche deposit reveal a few prominent characteristics that are described below.

- (i) Silicate minerals, plagioclase, (ortho+clino) pyroxene, and olivine determine the nomenclature of the rocks (oxide-apatite ultramafic rocks versus oxide-apatite mafic rocks; Fig. 5A and B) of the Bégin-Lamarche deposit (as well as the Lac à l'Original deposit). The mineralized rocks of the Lac à l'Original deposit, however, do not contain any olivine – they are oxide-apatite (gabbro)norites (Fig. 5A).
- (ii) The majority of the ultramafic rocks (i.e. $\sim 0\%$ plagioclase in this study; Fig. 6A) from the Mountain Zone (as well as from the North and South Zone) of the Bégin-Lamarche deposit contain a large amount of apatite (e.g. > 30 modal%, which is equivalent to the apatite content of nelsonite or higher than that of nelsonite). Nelsonite (~ 30 -40% of apatite + 60-70% of oxide minerals; Philpotts, 1967) is a rock that contains only oxide minerals (ilmenite+magnetite) and apatite (i.e., devoid of silicate minerals).
- (iii) Mafic rocks ($> 10\%$ plagioclase) from the Bégin-Lamarche (North and South zones) and Lac à l'Original deposit contain a lower amount of apatite than that of the nelsonite (Fig. 6B). In this study, no mafic rocks from the Mountain Zone were investigated, which would not affect the interpretation.
- (iv) The proportion of plagioclase determines the distribution of apatite (Fig. 7A) in the mineralized rocks. As plagioclase is absent in the ultramafic rocks, these

rocks contain a higher amount of apatite (Fig. 6A, 7A, and B). Furthermore, a limited number of mafic rock samples from (the North and South Zone) of the Bégin-Lamarche deposit exhibits an antithetic (i.e., negative) correlation between their plagioclase and apatite contents, i.e., the amount of apatite in the rock decreases with increasing plagioclase content (Fig. 7A).

- (v) The antithetic correlation between apatite and plagioclase is not prominent for the mafic rocks (oxide-apatite norite and gabbro-norite) of the Lac à l'Original deposit (Fig. 7B). Here, it is important to mention that plagioclase crystals of the mafic rocks of the Lac à l'Original exhibit reverse compositional zoning (i.e., an increase of Ca content from the core to the edge of the plagioclase crystal) (Banerjee et al., 2024c), which is not the case for the mafic rocks of the Bégin-Lamarche deposit (Banerjee et al., 2024b).
- (vi) The mineralized rocks from the Mountain, North, and South zones of the Bégin-Lamarche, Lac à l'Original, and Lac à Paul (another anorthosite-hosted phosphate deposit from the northern margin of the LSJA suite in Quebec) deposits contain a larger proportion of silicate minerals (Fig. 8). Therefore, these rocks are different from the *sensu stricto* nelsonite.
- (vii) Oxide-apatite ultramafic rocks from the Mountain Zone of the Bégin-Lamarche deposit contain a higher proportion of apatite compared to the oxides (magnetite and ilmenite; Fig. 9). A similar relationship also exists for some of the oxide-apatite mafic and ultramafic rocks from the North and South zones of the Bégin-Lamarche deposit and the oxide-apatite norite and gabbro-norite of Lac à l'Original deposit (Fig. 9).

Table 2. Mineral proportions (modal%) of the rocks from the Mountain Zone of the Bégin-Lamarche deposit analyzed through MLA and under an optical microscope (visual estimation). The rock types (nomenclature of rocks) are also included.

<i>Modal abundances of minerals analyzed through MLA</i>						
Sample name	MZ1	MZ5	MZ6	MZ14	MZ19	MZ26
	(modal%)					
Olivine	25.8	3.9	2.2	13.3	46.8	3.1
Serpentine	0.1	0.1	0.0	0.2	0.1	0.0
Orthopyroxene	10.8	8.1	35.5	24.6	5.9	18.1
Clinopyroxene	1.0	1.0	2.0	1.2	0.0	0.8
Plagioclase	0.1	0.0	0.0	0.0	0.0	0.0
Amphibole	0.3	0.2	0.8	0.9	0.1	0.3
Biotite	0.0	0.4	0.4	0.1	0.0	0.0
Chlorite	0.8	0.4	1.6	1.9	0.7	0.3
Apatite	38.2	85.6	50.9	29.8	29.0	72.9
Magnetite	11.8	0.0	3.1	16.8	8.8	2.3
Ilmenite	9.0	0.1	2.8	7.2	6.3	0.5
Al-spinel	2.1	0.0	0.1	3.0	2.3	0.2
Carbonate	0.0	0.2	0.7	1.0	0.0	1.4
Rock name	Oxide-apatite ultramafic rock	Apatite ultramafic rock	Oxide-apatite ultramafic rock	Oxide-apatite ultramafic rock	Oxide-apatite ultramafic rock	Apatite ultramafic rock
Name of oxide-apatite ultramafic rocks	Oxide-apatite harzburgite (OAH)	Apatite-olivine websterite (AOW)	Oxide-apatite olivine orthopyroxinite (OAOO)	Oxide-apatite- olivine orthopyroxinite (OAOO)	Oxide-apatite Harzburgite (OAH)	Apatite-olivine orthopyroxinite (AOO)

Modal abundances of these minerals are normalized to 100%.
Sulfide mineral abundances are < 1%.

(Table 2 continued)

<i>APPROXIMATE modal abundances of minerals based on visual estimation under optical microscope</i>							
Sample name	MZ3	MZ4	MZ7	MZ8	MZ10	MZ12	MZ15
Olivine	45	-	15	<1	<1	-	-
Serpentine'/iddingsite	-	10	5	<1	10	20	-
Orthopyroxene	1	-	10	<1	<1	-	2
Clinopyroxene	1	-	1	-	-	-	-
Plagioclase	-	-	-	-	-	-	90
Amphibole	-	1	-	-	-	-	2
Biotite	-	-	-	-	-	-	3
Chlorite	-	1	-	-	-	-	-
Apatite	35	60	58	70	65	55	1
Magnetite	10	15	5	15	12	12	1
Ilmenite	7	10	5	10	8	10	1
Al-spinel	1	1	1	3	2	1	-
Carbonate	-	2	-	2	3	2	-
Rock name	Oxide-apatite ultramafic rock	Oxide-apatite ultramafic rock	Oxide-apatite ultramafic rock	(Apatite-rich) nelsonite	Oxide-apatite ultramafic rock	Oxide-apatite ultramafic rock	Anorthosite
Name of oxide-apatite ultramafic rocks	Oxide-apatite dunite (OAD)	Oxide-apatite dunite (OAD)	Oxide-apatite harzburgite (OAH)		Oxide-apatite dunite (OAD)	Oxide-apatite dunite (OAD)	
<i>APPROXIMATE modal abundances of minerals based on visual estimation under optical microscope</i>							
Sample name	MZ16	MZ18	MZ20	MZ21	MZ22	MZ24	MZ25
Olivine	25	-	<1	<1	10	5	5
Serpentine'/iddingsite	15	2	25	20	15	15	10
Orthopyroxene	<1	-	2	<1	2	2	10
Clinopyroxene	-	-	-	-	-	-	1
Plagioclase	-	-	-	-	-	-	-
Amphibole	-	-	-	-	-	-	-
Biotite	-	-	-	-	-	-	-
Chlorite	-	-	-	-	-	-	-
Apatite	35	84	40	55	40	45	50
Magnetite	15	5	15	12	20	20	12
Ilmenite	7	5	12	10	10	10	8
Al-spinel	3	1	3	2	2	2	3
Carbonate	-	3	3	1	1	1	1
Rock name	Oxide-apatite ultramafic rock	(Apatite-rich) nelsonite	Oxide-apatite ultramafic rock	Oxide-apatite ultramafic rock	Oxide-apatite ultramafic rock	Oxide-apatite ultramafic rock	Oxide-apatite ultramafic rock
Name of oxide-apatite ultramafic rocks	Oxide-apatite dunite (OAD)		Oxide-apatite dunite (OAD)	Oxide-apatite dunite (OAD)	Oxide-apatite dunite (OAD)	Oxide-apatite dunite (OAD)	Oxide-apatite harzburgite (OAH)

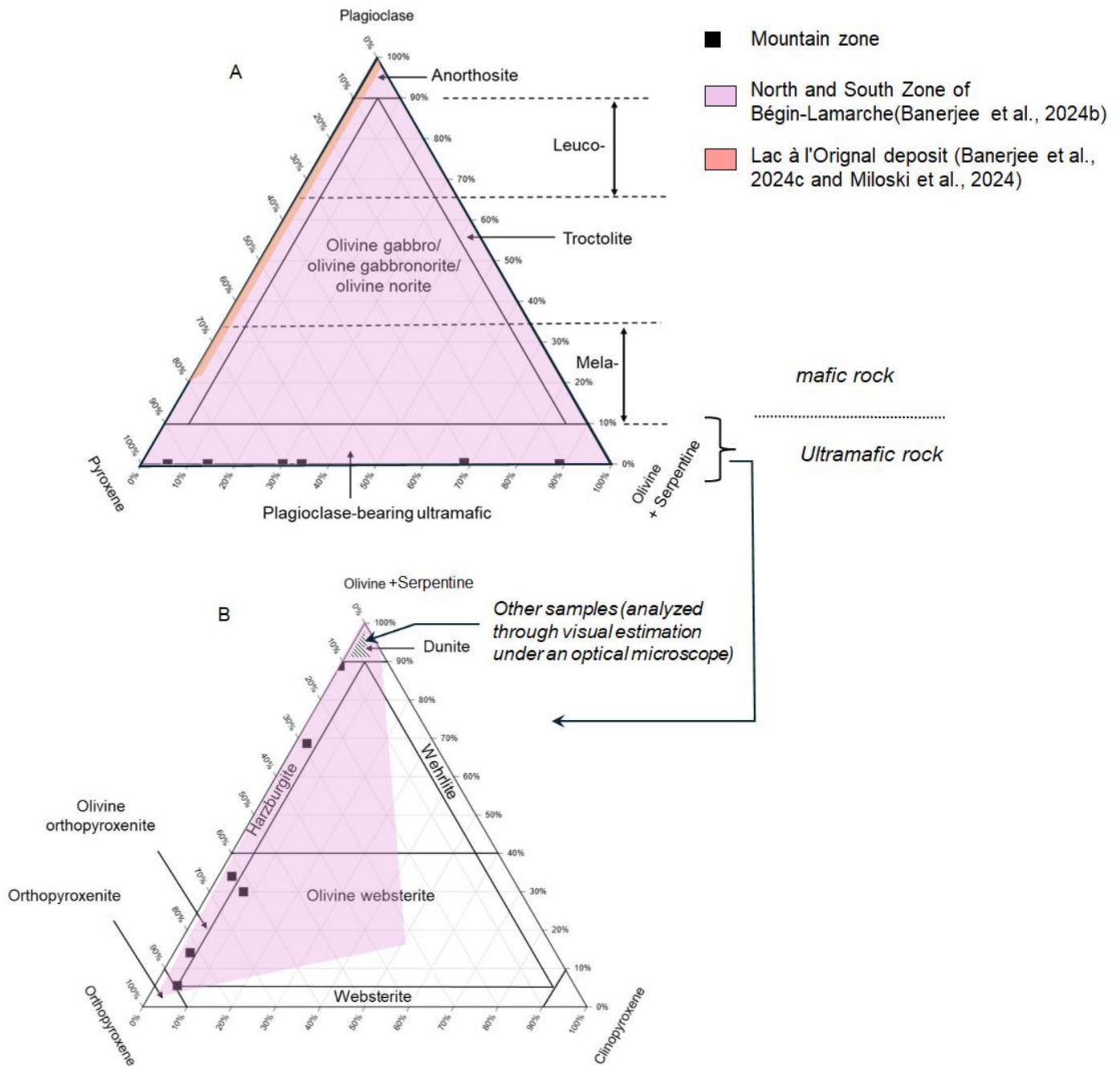


Fig. 5. (A and B) Classification of oxide-apatite ultramafic rocks of the Mountain Zone of the Bégin-Lamarche deposit. The modal proportions of plagioclase, (ortho+clino)pyroxene, and olivine+serpentine of the rocks from the North and South zones of the Bégin-Lamarche deposit, and the Lac à l'Original are also shown. For the nomenclature of the rocks, olivine + serpentine was considered as olivine because serpentine is an altered product of olivine. Data points are only shown for the rocks (from the Mountain Zone) analyzed through MLA.

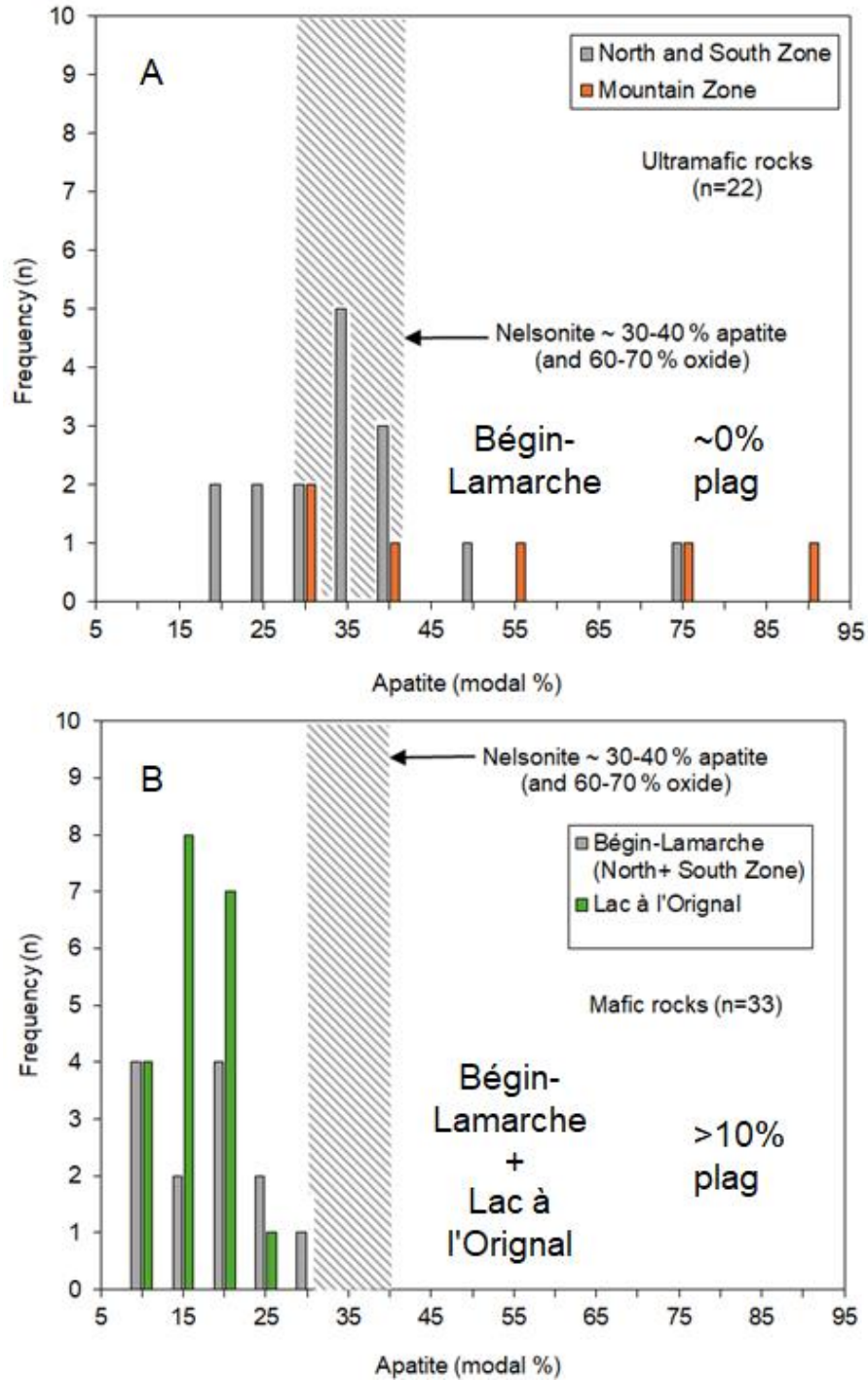


Fig. 6. (A) Frequency distributions of apatite contents in oxide-apatite ultramafic rocks (~ 0 % plagioclase in this study) from the Mountain, North, and South zones of the Bégin-Lamarche deposit. **(B)** Frequency distributions of apatite contents in oxide-apatite mafic rocks (> 10 % plagioclase) from the North and South zones of the Bégin-Lamarche deposit (data from Banerjee et al., 2024b) and the Lac à l'Original deposit (data from Banerjee et al., 2024c).

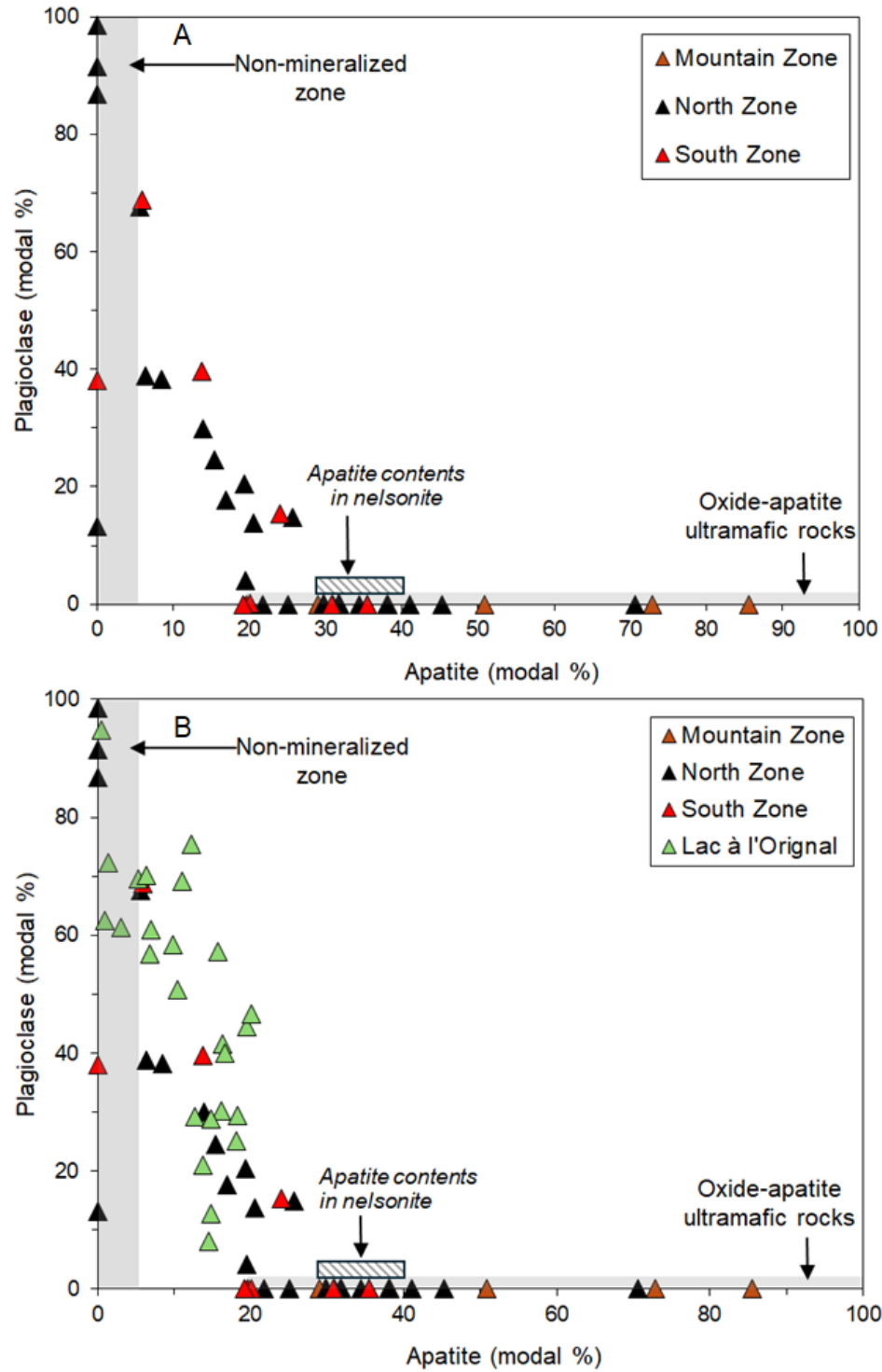


Fig. 7. (A and B) Variations of apatite and plagioclase contents in the rocks from the Mountain, North, and South zones of the Bégin-Lamarche deposit (data from this study and Banerjee et al., 2024b). Variations of apatite and plagioclase contents in the rocks of the Lac à l'Original deposit are also shown in Fig. B (data from Banerjee et al., 2024c). Data points are only shown for the rocks (from the Mountain Zone) analyzed through MLA.

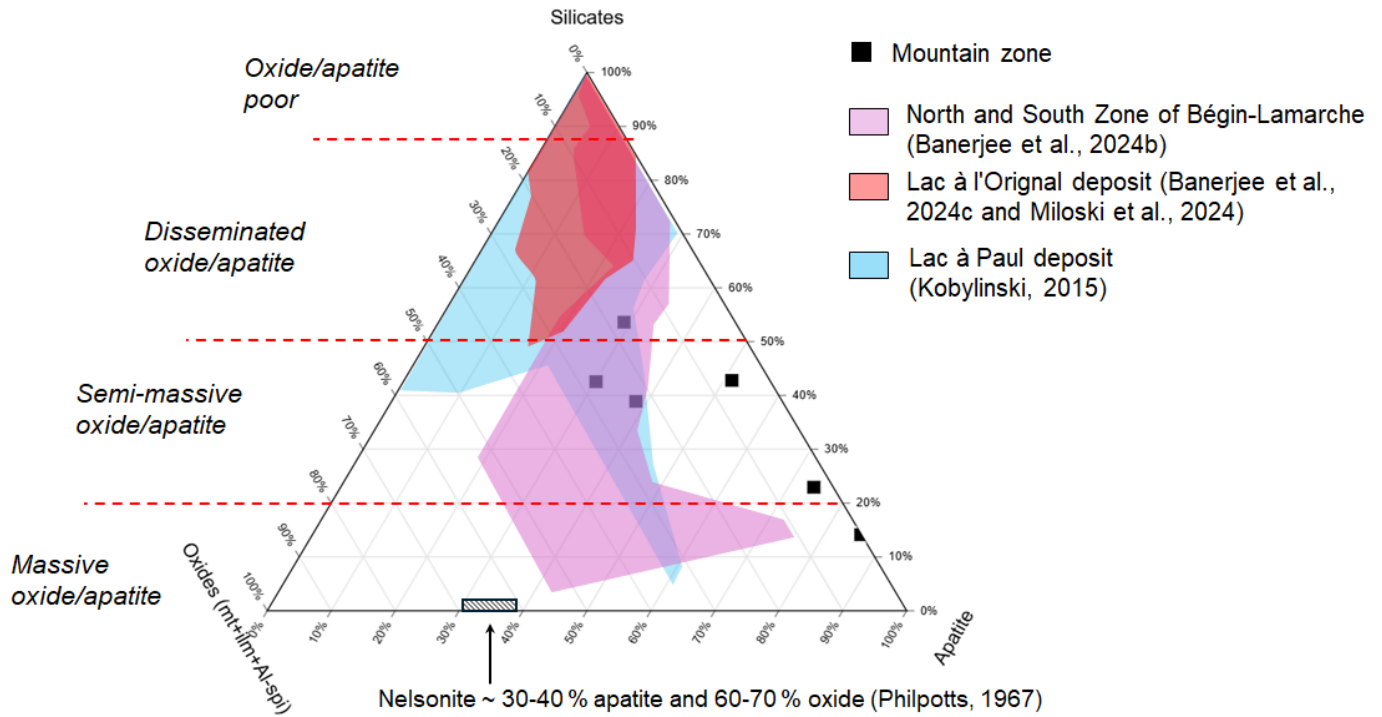


Fig. 8. Relative modal proportions of silicate and oxide minerals, and apatite in the oxide-apatite (plagioclase-bearing) ultramafic rocks from the Mountain Zone of the Bégin-Lamarche deposit. The relative distributions of the three types of minerals in the oxide-apatite mafic and ultramafic rock types from the North and South zones of the Bégin-Lamarche, Lac à l'Original, and Lac à Paul deposits (from Quebec) are also shown. Data points are only shown for the rocks (from the Mountain Zone) analyzed through MLA. Abbreviations: magnetite, mt; ilmenite, ilm; Al-spinel, Al-spi.

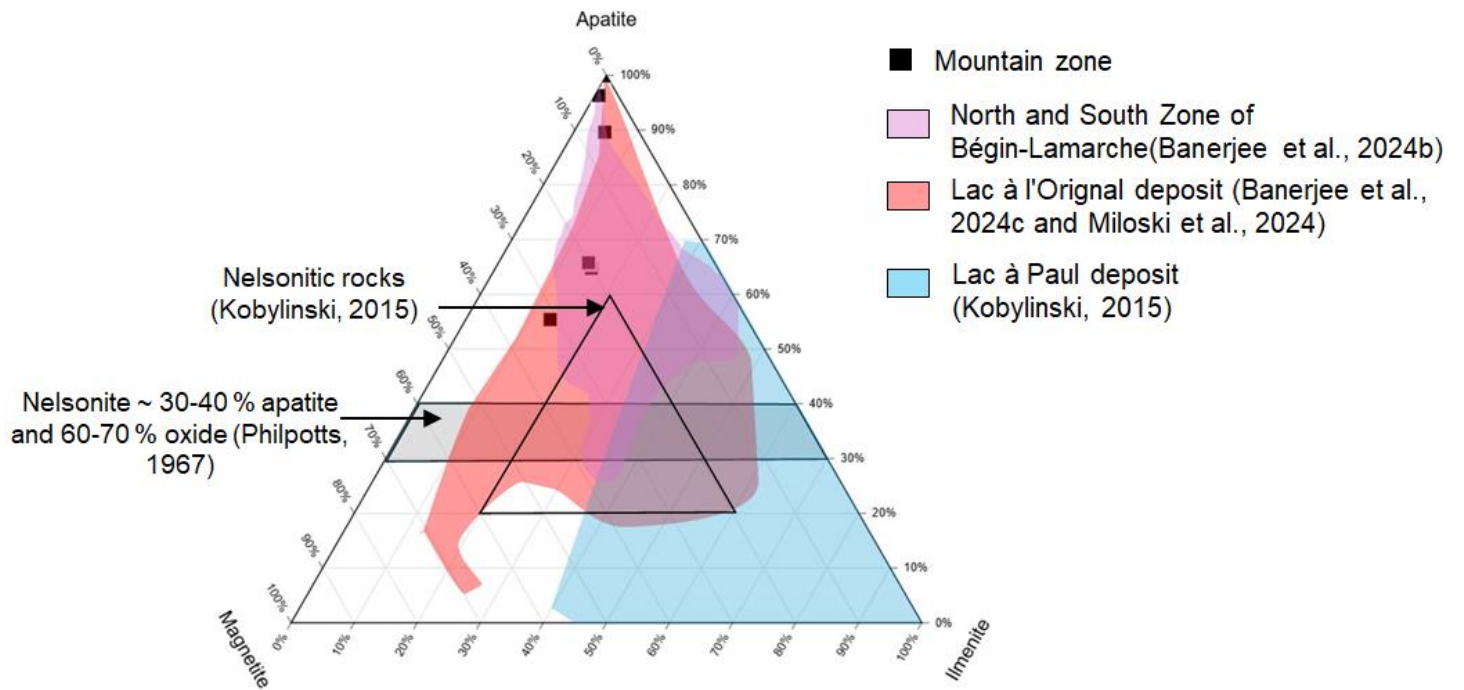


Fig. 9. Relative modal proportions of apatite, magnetite, and ilmenite in the oxide-apatite ultramafic rocks from the Mountain Zone of the Bégin-Lamarche deposit compared to that from the mafic and ultramafic rock types from the North and South zones of the Bégin-Lamarche, Lac à l'Original, and Lac à Paul deposits (from Quebec). Data points are only shown for the rocks (from the Mountain Zone) analyzed through MLA.

A description of petrographic and geochemical characteristics of individual minerals of the oxide-apatite ultramafic rocks from the Mountain Zone of the Bégin-Lamarche deposit is provided below.

Olivine ($\text{Mg}_2\text{SiO}_4\text{-Fe}_2\text{SiO}_4$): Olivine (2-47 modal%) is one of the major mafic minerals of the oxide-apatite ultramafic rocks of the Mountain Zone (Fig. 10A-F). The mineral is subhedral to anhedral in shape (Fig. 10A-D). The crystals range in size from ~ 0.1 to 4 mm. The crystals are typically fractured (Fig. 10C). The olivine crystals are mostly associated with apatite and oxide minerals (magnetite+ilmenite+Al-spinel). Many olivine crystals are altered (10E-F). Iddingsite (Fig. 10F) is also observed in many samples (Table 2), a common alteration product of olivine in ultramafic rocks.

Olivine has end-member compositions of forsterite (Mg_2SiO_4 ; 52.9-62 mol% Fo) and fayalite (Fe_2SiO_4 ; 38.0-47.1 mol% Fa; Table 3 and A7). The magnesium number [$\text{Mg\#} = \text{Mg}/(\text{Mg} + \text{Fe}^{2+})$] of olivine (52.9-62.0) is similar to their forsterite contents (52.9-62 mol%), which is typical for olivine. The Mg# of mafic silicate minerals is an indicator of the degree of magmatic differentiation (Zieg and Wallrich, 2018), i.e. the extent of magmatic crystallization (early vs late-stage crystallization). There is little variability in SiO_2 (34.7-35.8 wt.%), MnO (0.55-0.61 wt.%), CaO (≤ 0.2 wt.%), TiO_2 (0.01-0.04 wt.%), Al_2O_3 (≤ 0.01 wt.%), and Cr_2O_3 (≤ 0.01 wt.%) contents (Table 3). The trace element compositions of olivine (using LA-ICP-MS) were not analyzed in this study. It is, however, expected that the trace element compositions of olivine of the Mountain Zone will be similar to those analyzed from the North and South zones (Fig 10 and Table 4 in Banerjee et al., 2024b).

Orthopyroxene ($\text{Mg}_2\text{Si}_2\text{O}_6\text{-Fe}_2\text{Si}_2\text{O}_6$): Orthopyroxene (6-36 modal%) is the other dominant mafic mineral of the oxide-apatite ultramafic rocks (Fig. 11 A-F). The crystals are mostly subhedral and range in size from ~ 0.1 to 3 mm. Orthopyroxene crystals are associated with olivine (Fig. 11A and E), apatite (Fig. 11A-F), and oxide minerals (Fig. 11C and E). In a few samples, exsolution of rutile in orthopyroxene was also observed (Fig. 11F). Alteration of orthopyroxene to amphibole (<1 %) is not common in the ultramafic rocks of the Mountain Zone.

Orthopyroxene has end-member compositions of enstatite ($\text{Mg}_2\text{Si}_2\text{O}_6$, 62.4-69.4 mol.%), ferrosilite ($\text{Fe}_2\text{Si}_2\text{O}_6$, 29.7-37.3 mol.%), and wollastonite (CaSiO_3 , 0.3-1.7 mol.%). The Mg# of orthopyroxene exhibits a moderate variation (62.4-69.4). The Al_2O_3 (1.2-2.5 wt.%), MnO (0.4-0.5 wt.%), Na_2O (0.01-0.07 wt.%), and TiO_2 (0.1-0.3 wt.%), and Cr_2O_3 (≤ 0.02 wt.%) contents of orthopyroxene are low (Table 3 and A8). The Al_2O_3 contents (1.2-2.5 wt.%; Table 3) of orthopyroxene do not show any correlation with their Mg# (62.4-69.4; Fig. 12), which is typical of orthopyroxene crystallized in mid- to low-pressure intrusions (DeBari and Coleman, 1989; Helmy et al., 2014; Kharbish et al., 2022; Banerjee et al., 2024c). In the case of polybaric crystallization, the Al_2O_3 content of orthopyroxene decreases with decreasing pressure of crystallization (Fig. 12). The trace element compositions of orthopyroxene (using LA-ICP-MS) were not analyzed in this study. It is, however, expected that the trace element compositions of orthopyroxene of the Mountain Zone will be similar to those analyzed from the North and South zones (Fig 13 and Table 4 in Banerjee et al., 2024b).

Table 3. Abundances and chemical compositional ranges of minerals in oxide-apatite ultramafic rocks from the Mountain Zone of the B  gin-Lamarche deposit analyzed by EPMA.

	Olivine	Orthopyroxene	Apatite	Ilmenite	Magnetite
	modal abundance (%)				
Modal (%)	2-47	6-36	29-86	0-10	0-20
# (n) of spot	n=27	n=48	n=94	n=63	n=48
	(wt%)				
SiO ₂	34.7-35.8	51.9-53.0	0.02-0.05	0.01-0.57	0.05-0.21
Al ₂ O ₃	≤0.01	1.2-2.5		0.01-0.03	0.01-0.7
TiO ₂	0.01-0.04	0.1-0.3		51.6-52.9	0-1.7
Cr ₂ O ₃	≤0.01	≤0.02		0.01-0.1	0-1.2
FeO	31.9-39.2	18.7-22.9	0.17-0.46	44.8-47.2	89.5-92.4
MnO	0.55-0.61	0.4-0.5	0.05-0.16	0.2-0.9	0.01-0.1
MgO	24.7-29.2	21.6-24.6	0.07-0.25	0.4-1.9	0.03-0.1
ZnO	0.03	0.02-0.04		0.01-0.04	0.01-0.05
CaO	≤0.2	0.2-0.8	54.4-55.4	≤0.05	0-0.3
Na ₂ O	≤0.01	0.01-0.07	0.04-0.08		
K ₂ O	≤0.01	≤0.01			
P ₂ O ₅			41.9-42.2		
F			2.72-3.22 (27200-32200 ppm)		
Cl			0.04-0.07 (400-700 ppm)		
H ₂ O			0.3-0.7		
X ^{Ap} _{FAp} (mole fraction of fluorapatite)			0.72-0.85		
X _{hem} (mole fraction of hematite in ilmenite)					
Mg#	52.9-62.0	62.4-69.4			
End members	Fo _{52.9-62.0} Fy _{38.0-47.1}	En _{62.4-69.4} Fs _{29.7-37.3} Wo _{0.3-1.7}			

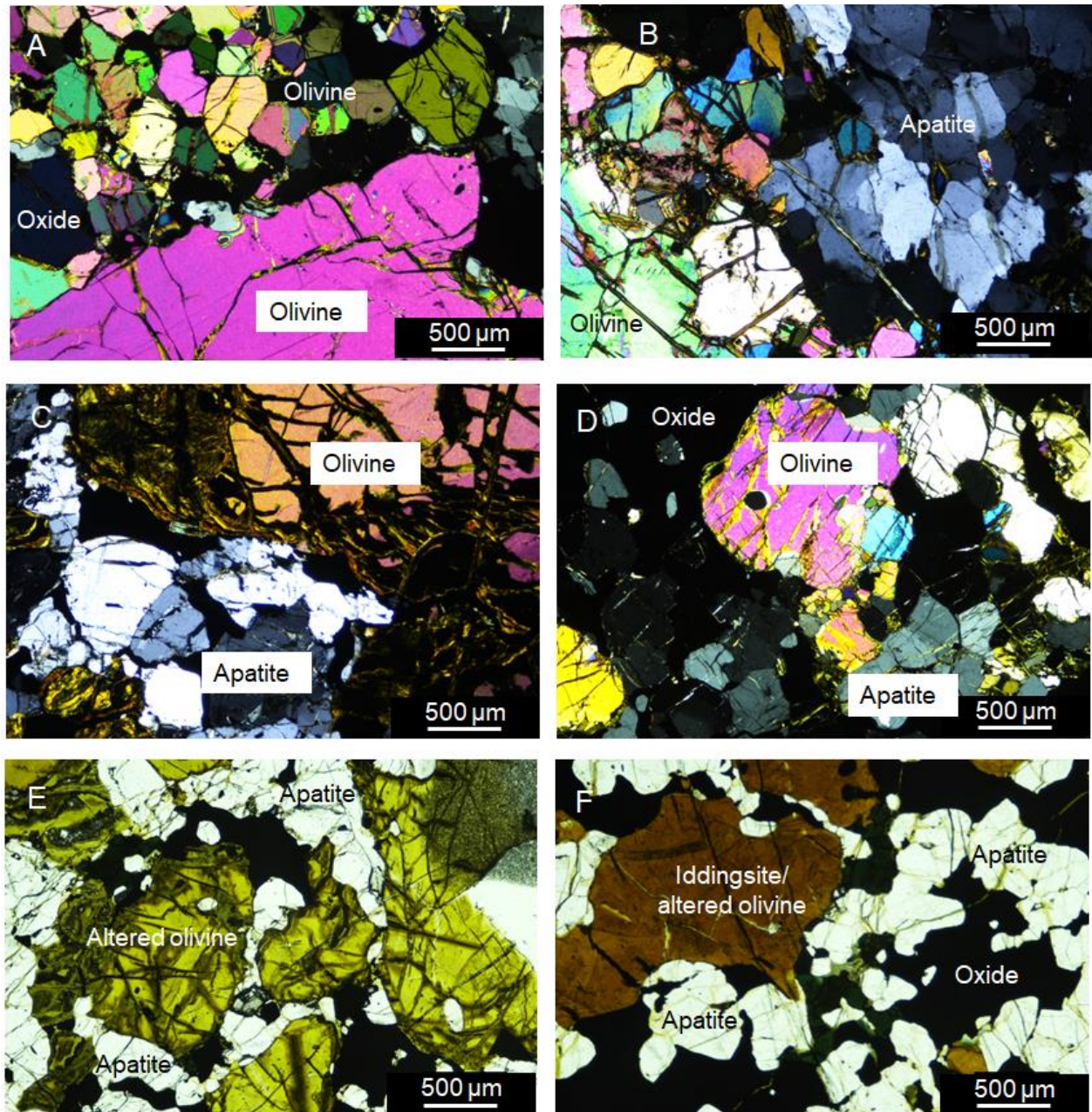


Fig. 10. Textural relationships of olivine from the Mountain Zone of the Bégín-Lamarche deposit (under transmitted light). (A) Different sizes of olivine crystals (sample MZ3; cross-polarized light); (B) Olivine associated with apatite (sample MZ19; cross-polarized light); (C) Fractured olivine associated with apatite (sample MZ16; cross-polarized light); (D) Cumulate texture of olivine and apatite (sample MZ1; cross-polarized light); (E) Altered olivine associated with apatite (sample MZ10; plane-polarized light); (F) Iddingsite (altered olivine) associated with apatite and oxide minerals (sample MZ12; plane-polarized light).

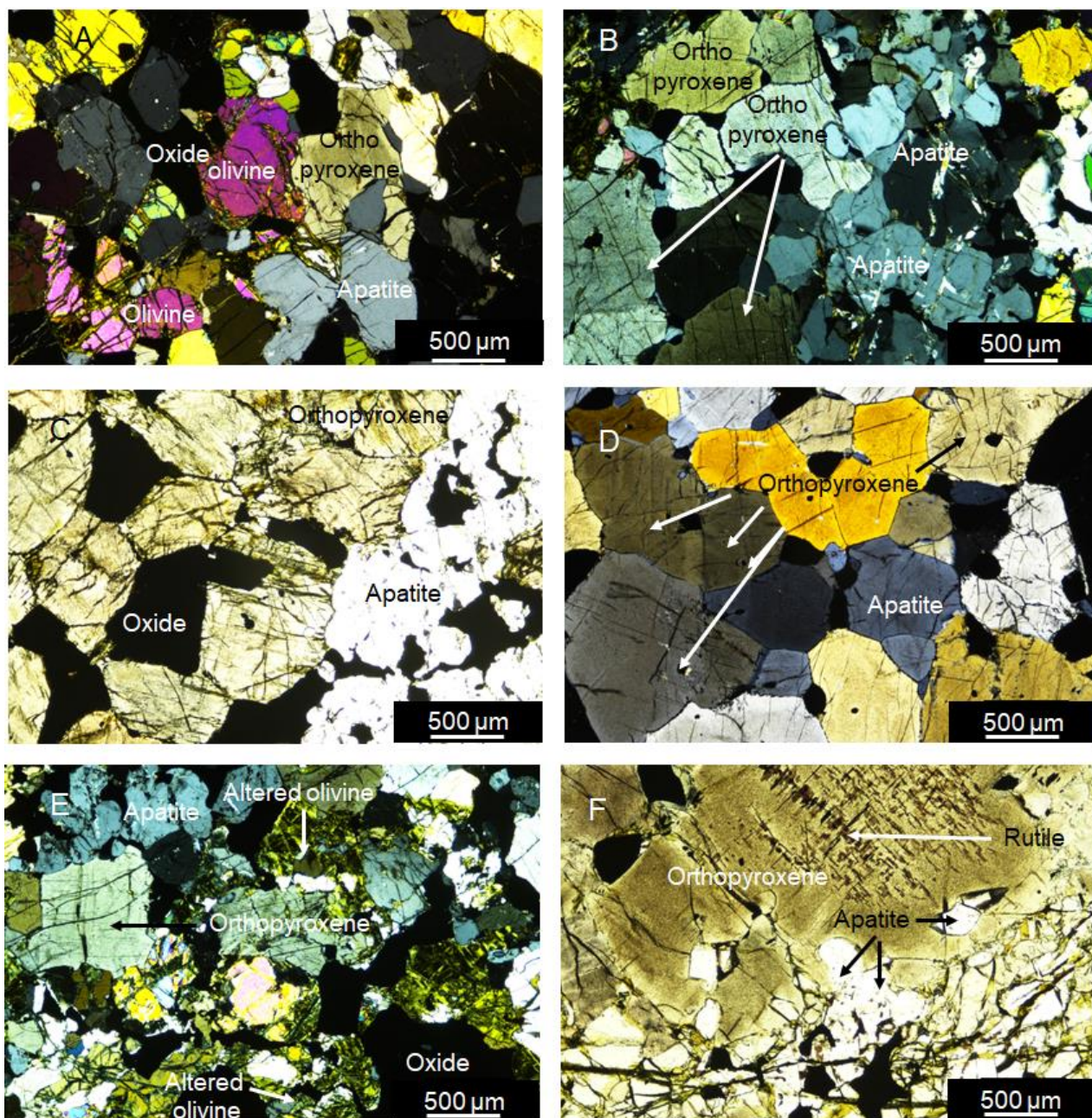


Fig. 11. Textural relationships of orthopyroxene from the Mountain Zone of the Bégin-Lamarche deposit (under transmitted light). (A) Interstitial oxide mineral associated with cumulate orthopyroxene, olivine, and apatite (sample MZ1; cross-polarized light); (B) orthopyroxene associated with apatite (sample MZ14; cross-polarized light); (C) Orthopyroxene associated with apatite, and oxide minerals (sample MZ6; plane-polarized light); (D) Orthopyroxene associated with apatite (sample MZ26; cross-polarized light); (E) Orthopyroxene associated with altered olivine, and apatite (sample MZ14; cross-polarized light) and (F) Rutile exsolutions in orthopyroxene (sample MZ7; plane-polarized light).

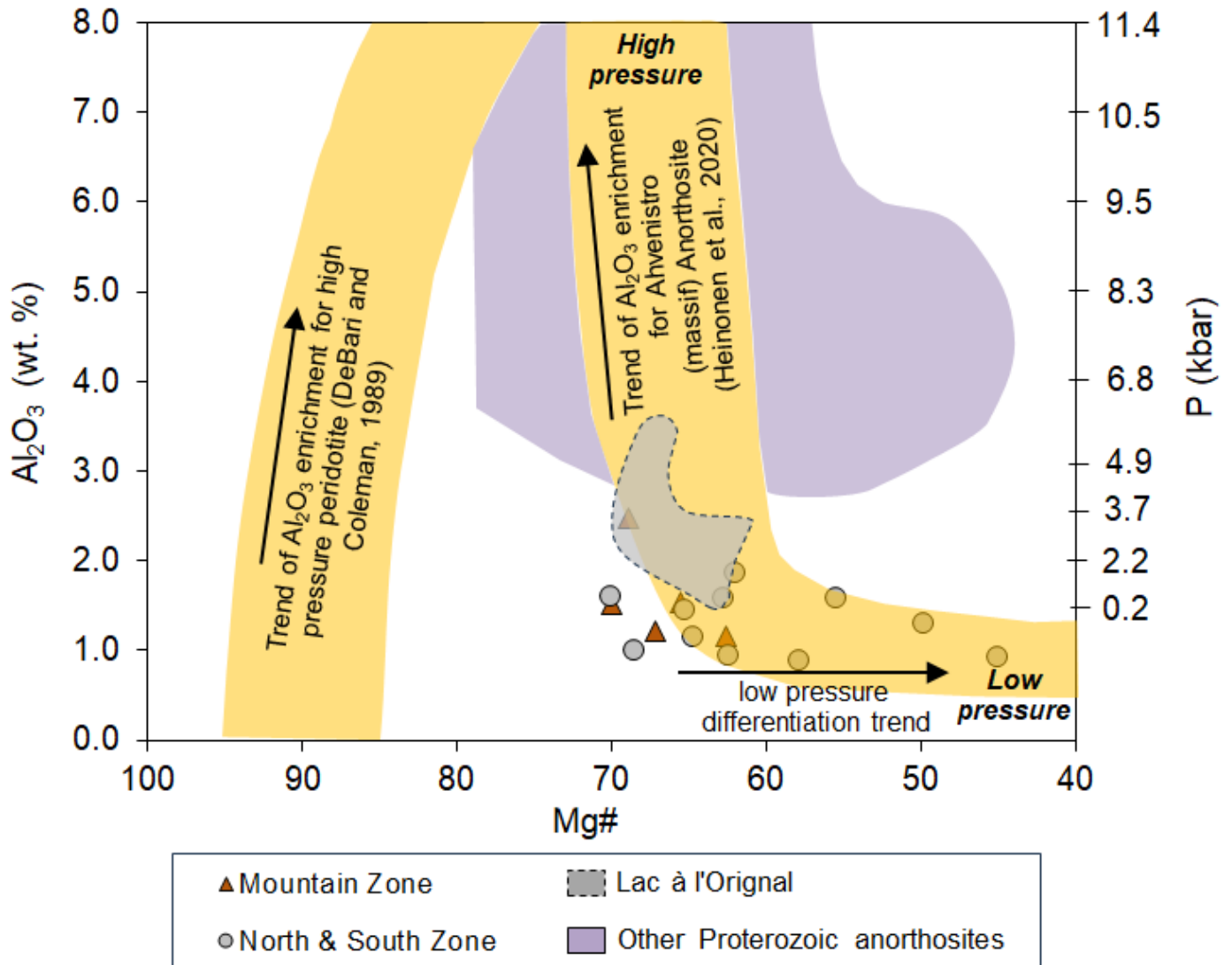


Fig. 12. Relationship between Al_2O_3 content and Mg# of orthopyroxene in the oxide-apatite-ultramafic rocks of the Mountain Zone of the Bégin-Lamarche deposit. Orthopyroxene from the North and South Zone of the Bégin-Lamarche deposit (Banerjee et al., 2024b), the Lac à l'Original deposit (Banerjee et al., 2024c; Miloski et al., 2024; Grant, 2020) and other Proterozoic anorthosites (Mealy Mountains Intrusive Suite, Nain Plutonic Suite, Canada; Bybee et al., 2014; Rogaland Anorthosite Province, Norway, Bybee et al., 2014; Charlier et al., 2010) are also shown. The Mg# of orthopyroxene from Miloski et al. (2024) and Grant (2020) are calculated from their $\text{FeO}_{\text{total}}$ and MgO data of orthopyroxene. The pressures of orthopyroxene crystallization were calculated using the Al content of orthopyroxene from the Ahvenisto Anorthosite, Finland (Heinonen et al., 2020) according to the geobarometric relationship of Emslie et al. (1994).

Clinopyroxene [(Ca,Mg,Fe) (Mg,Fe)Si₂O₆]: The modal abundances of clinopyroxene (0-2%) are minor, and significantly lower than that of orthopyroxene (Fig. 13A and B). Clinopyroxene, similar to orthopyroxene, is mostly subhedral. The crystals range in size from ~ 0.1 to 0.5 mm and are generally associated with orthopyroxene (Fig. 13A and B). Elemental compositions of clinopyroxene were not analyzed in this study.

Plagioclase (NaAlSi₃O₈ – CaAl₂Si₂O₈): Plagioclase crystals (Fig. 14A and B) were identified from one anorthosite sample (MZ15) and the sample exhibits a granoblastic texture. Anorthosite is not a mineralized rock. A mineralized rock is considered a rock with >2.5 wt.% of P₂O₅ (Yassa, 2024), equivalent to ~6.25 wt% of apatite. Therefore, for convenience, a rock with ≥ 5 modal% of apatite is considered as a mineralized rock in this study.

Biotite (K(Mg,Fe)₃AlSi₃O₁₀(F,OH)₂), amphibole [(Ca,Na)₂(Mg,Fe,Al)₅(Al,Si)₈O₂₂(OH)₂] and chlorite [(Mg,Fe)₃(Si,Al)₄O₁₀(OH)₂·(Mg,Fe)₃(OH)₆] were identified from the anorthosite sample (MZ15) under optical microscope (Fig. 14A and B). Other samples contain an insignificant amount of biotite, amphibole, and chlorite (< 2%, Table 2). Elemental compositions of these minerals were not analyzed in this study.

Apatite (Ca₅(PO₄)₃F): Apatite crystals (29-86 modal%) are dominantly associated with olivine, (Fig. 15A and B), orthopyroxene (Fig. 15C), and oxide minerals (Fig. 15B and D). Apatite crystals are subhedral to anhedral and range in size from ~ 0.1 to 2 mm. In some cases, apatite is cross-cut by late-stage “serpentine”-type (Fig. 15E) and carbonate (Fig. 15F) veinlets.

Apatite crystals have narrow ranges of CaO (54.4-55.4 wt.%) and P₂O₅ (41.9-42.2 wt.%) contents. The MnO (0.05-0.16 wt.%), MgO (0.07-0.25 wt.%), Na₂O (0.04-0.08 wt.%) and SiO₂ (0.02-0.05 wt.%) contents are low (Table 3 and A9). Fluorine (2.72-3.22 wt.%) concentrations are higher than Cl concentrations (0.04-0.07 wt.%; Table 3 and 4).

Mole fraction values of fluor-(F)Ap, chlor-(Cl)Ap, and hydroxylapatite (HAp) are calculated following the procedure described by Piccoli and Candela (2002) (Table 4). The mole fraction values of FAp (0.72-0.85) are higher than those of ClAp (0.01), and HAp (0.14-0.22; Table 4), and therefore, the apatite of the oxide-apatite ultramafic rocks of the Mountain Zone of **the Bégin-Lamarche deposit is predominantly fluorapatite** (Fig. 16). The relative proportions of HAp in apatite from the oxide-apatite mafic and ultramafic rocks of the **Bégin-Lamarche deposit (Mountain, North, and South zones) are higher than that of the** oxide-apatite mafic rocks of the Lac à l'Original deposit (Fig. 16).

Apatite crystals of the oxide-apatite ultramafic rocks from the Mountain Zone have a narrow range in their CaO/P₂O₅ ratios (1.29-1.32), but relatively higher variability in their F/Cl ratios (41-85, Fig. 17). The similar types of relationships were also observed for the apatite from the mineralized zones of the North and South Zone of the **Bégin-Lamarche deposit** and Lac à l'Original deposit (Fig. 17).

The Cl content of (fluor)apatite and Mg# of the coexisting orthopyroxene of the oxide-apatite ultramafic rocks from the Mountain Zone shows a good positive correlation (i.e., Cl contents of apatite decrease with decreasing Mg# of coexisting orthopyroxene; Fig. 18). The similar relationship was also observed for the one group of samples from the North and South

Zone of the Bégin-Lamarche deposit (Fig. 18). Overall Cl contents of (fluor)apatite of the Mountain Zone are, however, lower than those of the North and South Zone (Fig. 18).

Common trace elements in apatite include Fe (860-3201 ppm), Mg (482-1916 ppm), Sr (794-924 ppm), Mn (424-1200 ppm), Al (13-66 ppm), Ti (4-20 ppm), Ge (9-13 ppm), and As (~ 4 ppm; Table 5). Concentrations of radioactive elements, such as U, Pb, and Th, are very low (≤ 2 ppm for each; Table 5 and A9). The REE concentrations of apatite are, however, high (2096-2538 ppm in total; Table 5).

Ilmenite ((Fe,Ti)₂O₃): Ilmenite (0-10 modal%) is one of the two major oxide minerals (Fig. 19A and B). Ilmenite crystals are mostly subhedral. Hematite exsolution lamellae were not observed in ilmenite crystals in this study. Ilmenite crystals are predominantly associated with magnetite (Fig. 19B), Al-spinel, and apatite (Fig. 19A). The ilmenite/magnetite ratios vary between 0.2 and 2.0 (based on MLA; Table A2). The relative modal abundances of ilmenite and magnetite in mineralized rocks of the Bégin-Lamarche and Lac à l'Original deposits are comparable. However, the abundance of ilmenite in the Lac à Paul deposit is higher than that of the other two deposits (Fig. 9).

Ilmenite crystals possess a narrow range of TiO₂ (51.6-52.9 wt.%) and FeO (44.8-47.2 wt.%) contents. The MnO (0.2-0.9 wt.%), MgO (0.4-1.9 wt.%), and Cr₂O₃ (0.01-0.1 wt.%) contents are low (Table 3 and A10). The low X_{hem} (mole fraction of hematite in ilmenite) of ilmenite (0.0-0.03; Table 3 and A10) also suggests the near absence of hematite in ilmenite crystal in this study.

Common trace elements include Si (641-799 ppm), Al (156-181 ppm), V (163-173 ppm), Co (75-105 ppm), Sc (35-67 ppm), Cr (21-53 ppm), Nb (18-44 ppm), Zn (12-17 ppm), Sr (1-9 ppm), Ni (4-5 ppm), Sn (1-6 ppm), Ba (1-3 ppm), and Mo (<1 ppm; Table 5 and A10). Concentrations of radioactive elements (such as U, Pb, and Th; < 1 ppm for each) and REE (< instrumental LOD; Table 5) are very low.

Magnetite (Fe₃O₄): Magnetite (0-20%) is the other major oxide phase (Fig. 20A and B). Abundances of total oxide minerals (magnetite + ilmenite) in the deposit are 3–24% (based on MLA; Table A2). Magnetite crystals are mostly subhedral. Magnetite crystals are associated with ilmenite, Al-spinel, and apatite (Fig 20A and B). Fine-scale trellis oxy-exsolutions of ilmenite (< 10µm) are very common in magnetite (Fig. 20B).

Magnetite crystals also exhibit a narrow range of FeO content (89.5-92.4 wt.%). The TiO₂ (0.0-1.7 wt.%), MgO (0.03-0.1 wt.%), and MnO (0.01-0.1 wt.%) contents of magnetite are low (Table 3 and A11).

Common trace elements include Cr (347-937 ppm), Mn (501-831 ppm), Zn (58-450 ppm), Co (98-200 ppm), Ni (56-275 ppm), Ga (50-78 ppm), Sr (4-5 ppm), Ge (~ 3 ppm), and Mo (1-3 ppm; Table 5 and A11). Concentrations of radioactive elements (such as U, Pb, and Th; < 1 ppm for each) and REE (< instrumental LOD; Table 5) are very low.

Al-spinel (MgAl₂O₄-FeAl₂O₄): Al-spinel (0-3%) mostly occurs as individual crystals associated with ilmenite, magnetite (Fig. 19B, 20A, and B), and apatite (Fig. 15D). Elemental compositions of Al-spinel were not analyzed in this study. Al-spinel forms by exsolution from magnetite (Grant 2020).

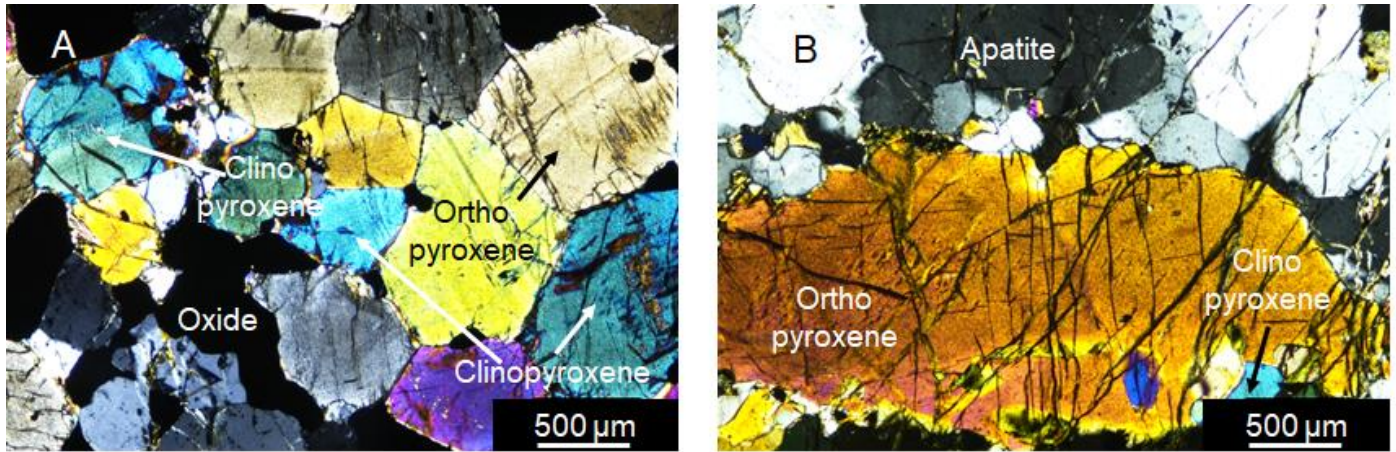


Fig. 13 Textural relationships of clinopyroxene (a minor phase) from the Mountain Zone of the Bégin-Lamarche deposit (under transmitted light). (A) Clinopyroxene associated with orthopyroxene and oxide minerals (sample MZ6; cross-polarized light); (B) Clinopyroxene associated with orthopyroxene (sample MZ7; cross-polarized light).

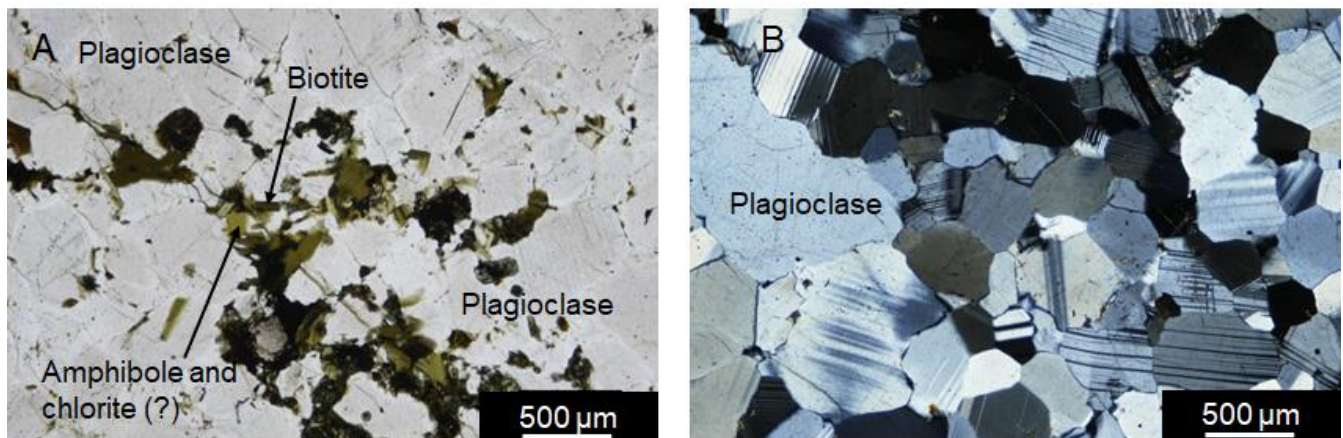


Fig. 14 Textural relationships of plagioclase from an anorthosite sample (MZ15) from the Mountain Zone of the Bégin-Lamarche deposit (under transmitted light). (A) Biotite, amphibole, and chlorite associated with plagioclase (plane-polarized light); (B) Granoblastic texture of plagioclase (cross-polarized light).

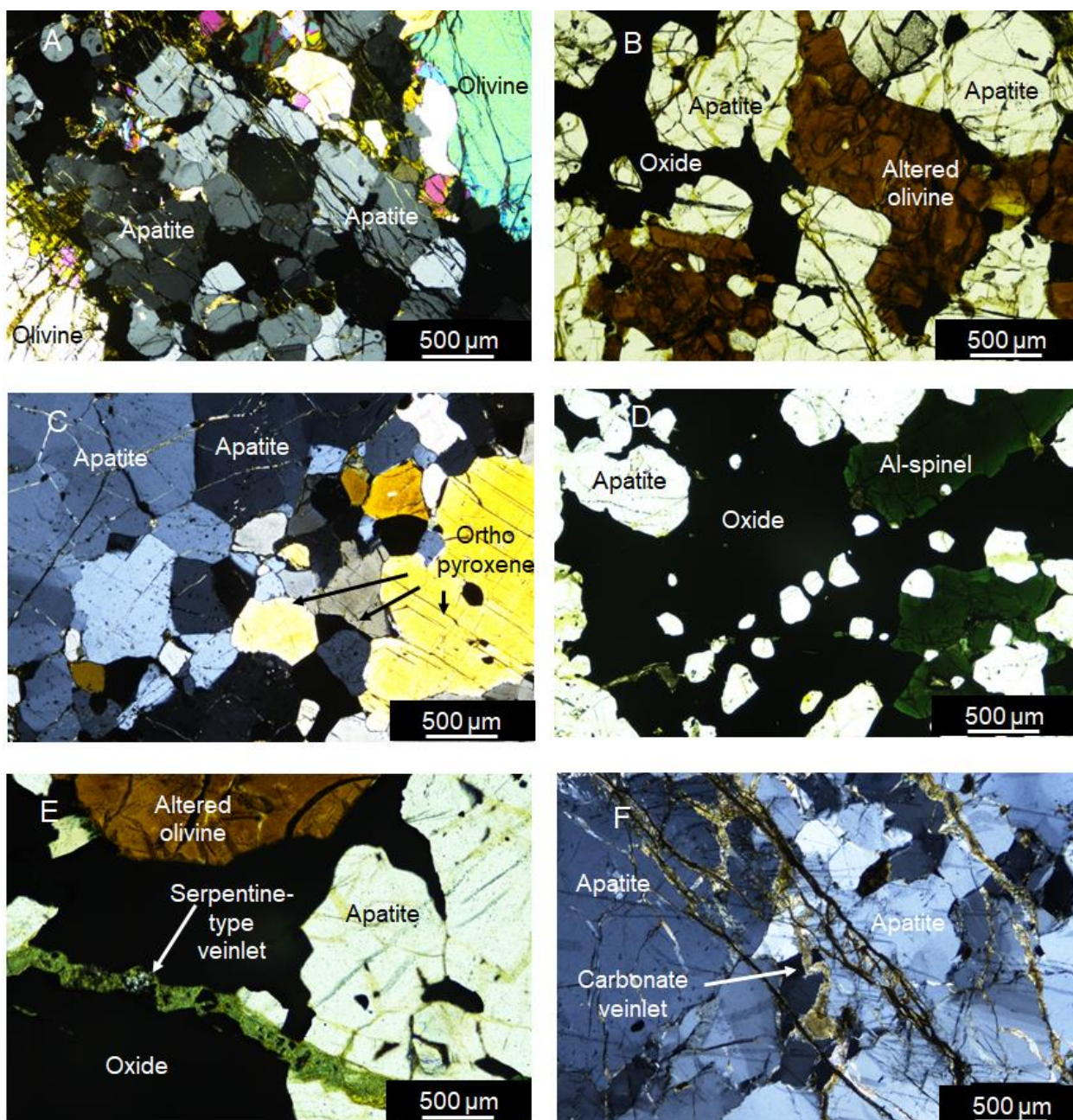


Fig. 15. Textural relationships of apatite from the Mountain Zone of the Bégin-Lamarche deposit (under transmitted light). (A) Cumulate texture of apatite and olivine (sample MZ1; cross-polarized light); (B) Apatite associated with altered olivine (iddingsite) and oxide minerals (sample MZ4; plane-polarized light); (C) Apatite associated with orthopyroxene (sample MZ26; cross-polarized light); (D) Different sizes of apatite crystals associated with oxide minerals (magnetite + ilmenite) and Al-spinel (sample MZ14; plane-polarized light); (E) Late-stage serpentine-type veinlet cross cut apatite (MZ12; plane-polarized light); (F) Carbonate veinlets cross-cut apatite (MZ18; cross-polarized light).

Table 4. F and Cl contents ($\pm 1\sigma$) of apatite from the Mountain Zone of the B  gin-Lamarche deposit analyzed by EPMA at the University of British Columbia. The average FAp (fluorapatite), CAp (chlorapatite), and HAp (hydroxyapatite) components of apatite crystals are also included.

		University of British Columbia				
Sample	spots	F	Cl	X (FAp)	X (CAp)	X (HAp)
		(wt%)	(wt%)	avg. molar fractions		
Mountain Zone						
MZ1	n=13	2.91±0.16	0.06±0.01	0.77	0.01	0.22
MZ5	n=12	3.22±0.09	0.04±0.01	0.85	0.01	0.14
MZ6	n=11	3.03±0.10	0.07±0.02	0.80	0.01	0.19
MZ8	n=14	2.86±0.12	0.07±0.01	0.76	0.01	0.23
MZ14	n=15	3.00±0.11	0.07±0.01	0.80	0.01	0.19
MZ19	n=14	2.72±0.14	0.07±0.01	0.72	0.01	0.19
MZ26	n=15	3.03±0.21	0.06±0.01	0.80	0.01	0.19

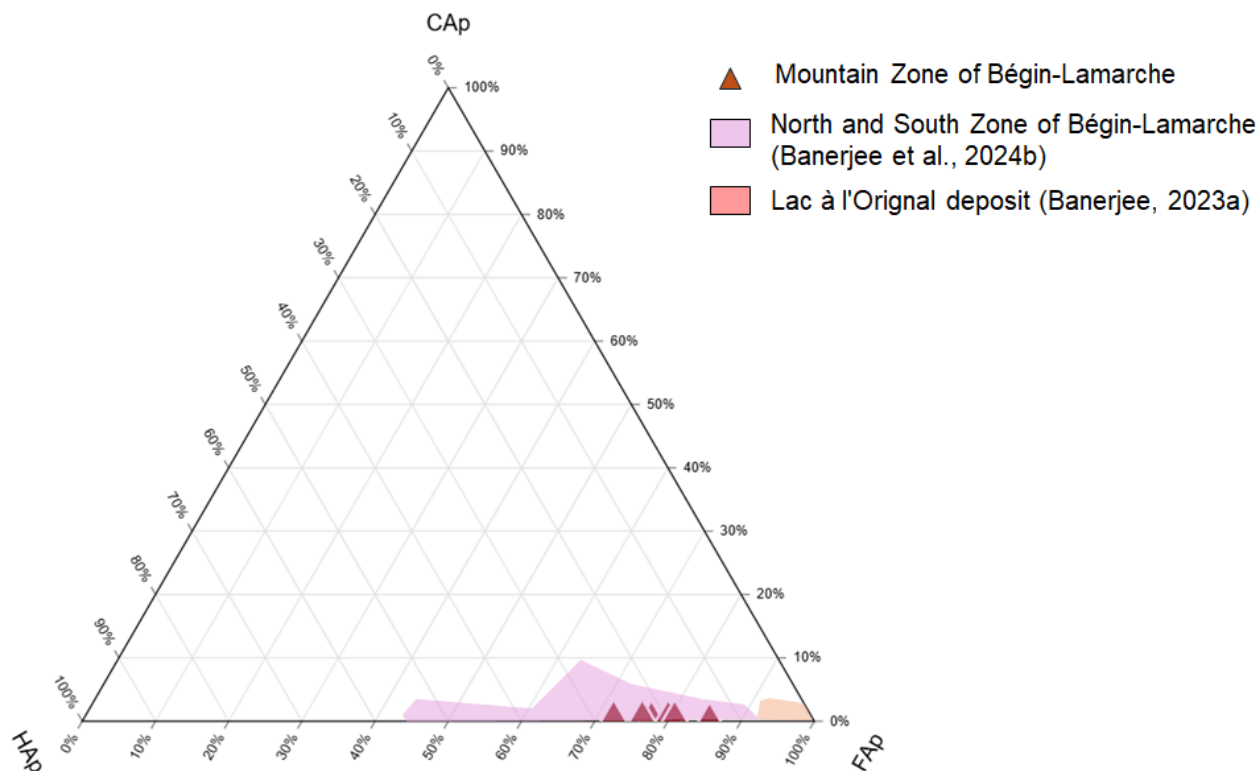


Fig. 16. Ternary plot of fluor- (FAp), chlor-(CAp), and hydroxyl-apatite (HAp) showing the variability of F-Cl-OH in the halogen-site of apatite from the Mountain Zone of the Bégin-Lamarche deposit, compared to those from the North and South Zone of the Bégin-Lamarche deposit and Lac à l'Original deposit.

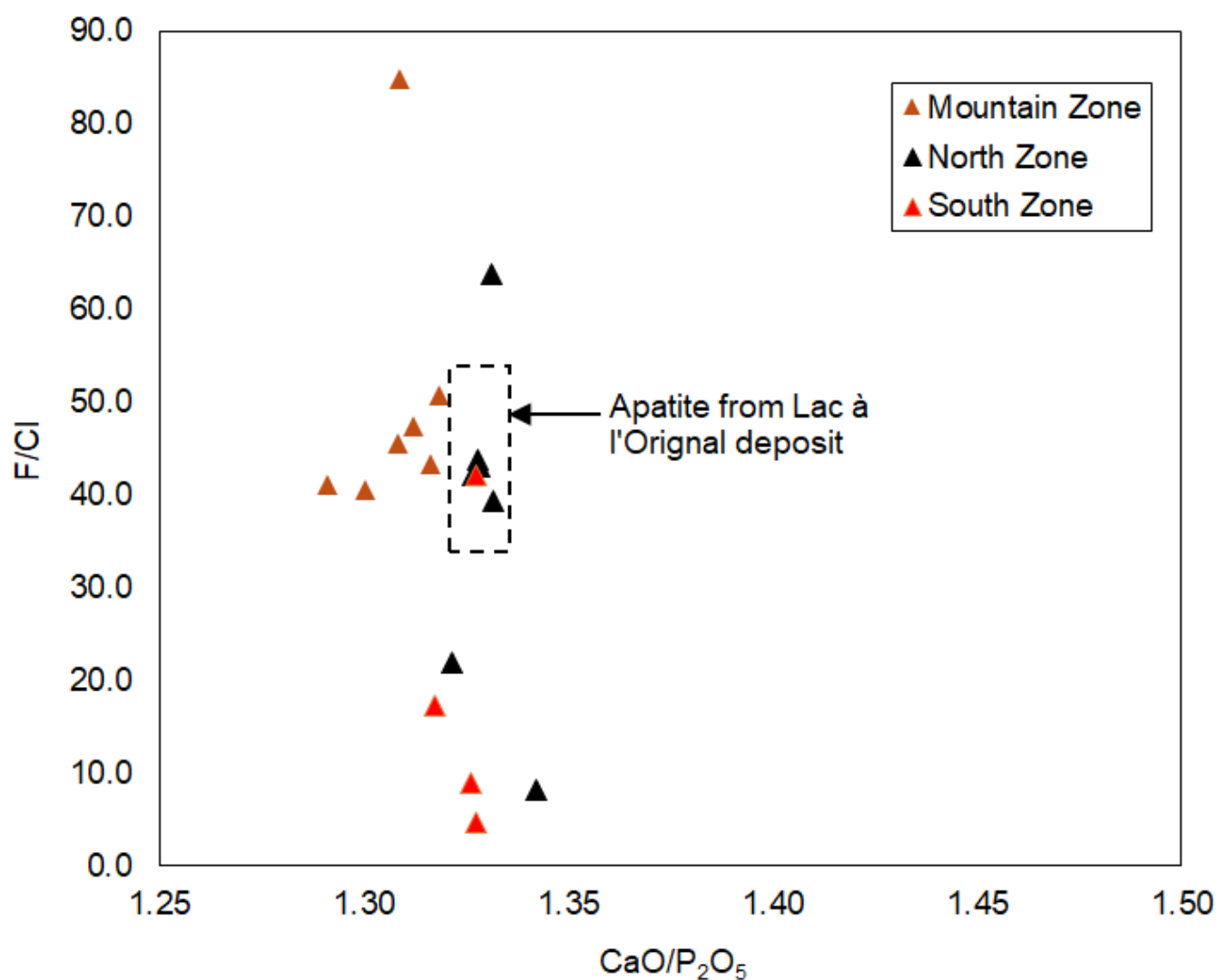


Fig. 17. Variations of F/Cl and CaO/P₂O₅ ratios (from EPMA analysis) of *in situ* apatite crystals from the Mountain Zone of the Bégin-Lamarche deposit. The variations of F/Cl and CaO/P₂O₅ ratios of apatite crystals of the North and South Zone of the Bégin-Lamarche deposit (Banerjee et al., 2024b) and Lac à l'Original deposit (Banerjee, 2023a) are also shown.

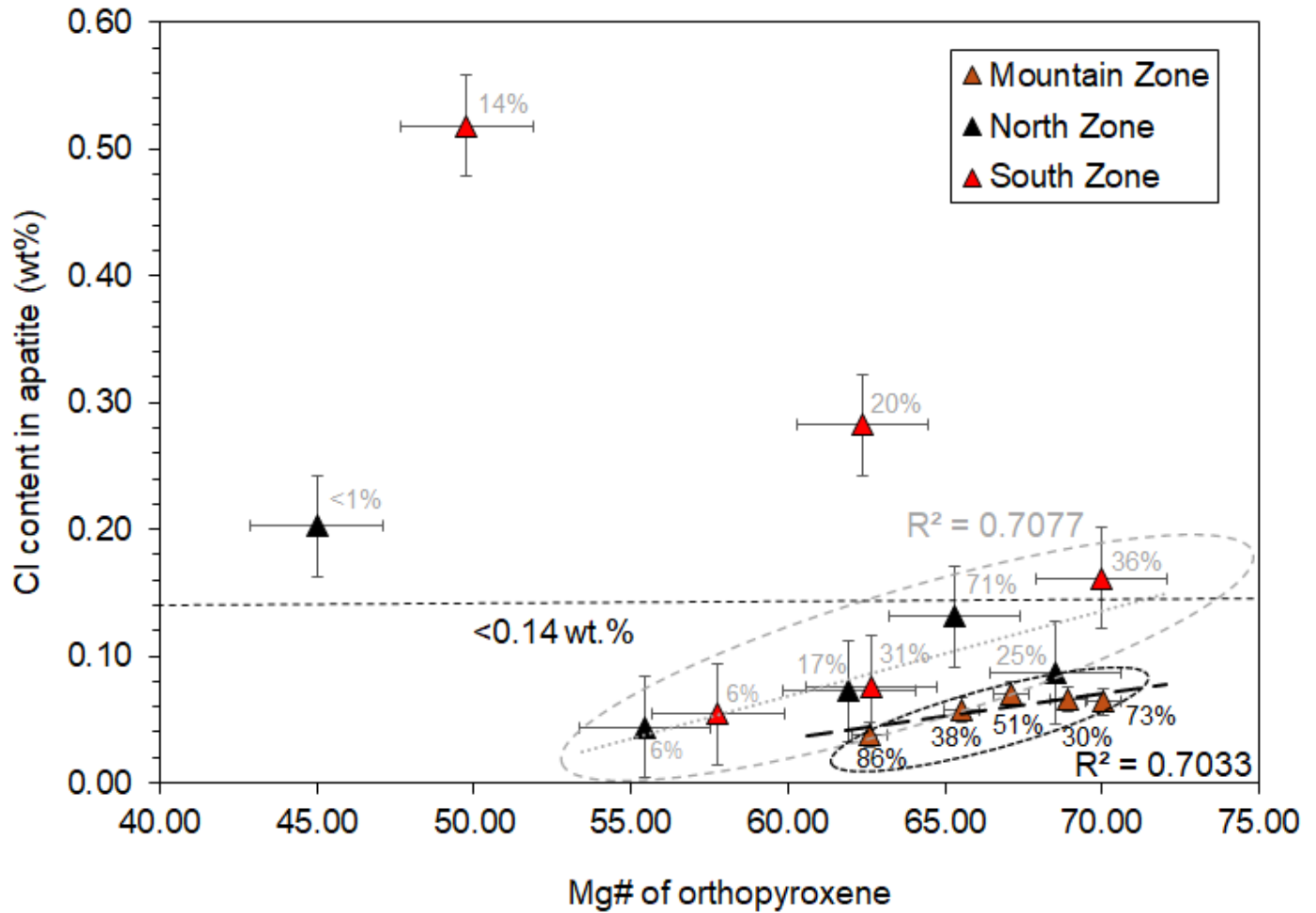


Fig. 18. Relationships between Cl contents of apatite (fluorapatite) and Mg# of coexisting orthopyroxene from the oxide-apatite ultramafic rocks of the Mountain Zone of the Bégin-Lamarche deposit. The same relationships from the rocks of the North and South Zone of the Bégin-Lamarche deposit are also shown (Banerjee et al., 2024b). Apatite abundances (in % values) are shown in the figure. The upper limit of Cl contents of saleable phosphate ore (< 0.14 wt.%) suggested by Yara International is also shown (Paiement et al., 2013). The average standard deviations of data (bar and whiskers) are also shown in the figure, as calculated using avg. $SD = \sqrt{(S_1^2 + S_2^2 + \dots + S_k^2)/k}$; where S_k = standard deviation for the 'k'th sample and k = total number of samples (Cohen, 1988).

Table 5. Ranges of trace (and minor) element compositions of minerals (in ppm) from oxide-apatite -ultramafic rocks of the Mountain Zone of the Bégin-Lamarche deposit analyzed by LA-ICP-MS.

	Apatite	Ilmenite	Magnetite
#(n) of spot	49	47	58
Mg	482-1916	7982-9920	1555-15635
Al	13-66	156-181	7620-22088
Si	643-2562	641-799	647-16683
Ca	-	<LOD	<LOD
Sc	0.3-1.0	35-67	3.0-6.0
Ti	3.9-20.0	-	11444-17783
V	0.2-0.6	163-170	2155-2596
Cr	<LOD	21-53	347-937
Mn	424-1200	5227-6303	501-831
Fe	860-3201	-	-
Co	<LOD	75-105	98-200
Ni	<LOD	4.0-5.0	56-275
Zn	<LOD	12.0-17.0	58-450
Ga	0.4-0.6	<LOD	50-78
Ge	9.4-12.6	<LOD	3
As	3.5-4.0	<LOD	0.5-1.1
Rb	<LOD	<LOD	<LOD
Sr	794-924	1.0-9.0	4.0-5.0
Ba	1.8-11.7	1.0-3.0	<LOD
Zr	0.5-17.5	16.0-33.0	1.4-10.0
Nb	<LOD	18.0-44.0	<LOD
Mo	<LOD	0.3-0.7	1.0-3.0
Cd	<LOD	<LOD	<LOD
Sn	<LOD	1.0-6.0	2.0-3.0
Pb	0.6-1.1	0.2-0.3	0.2-0.4
Th	1.1-2.2	0.02-0.09	0.01-0.06
U	0.5-1.8	0.7-0.8	<LOD

(Table 5 continued)

	Apatite	Ilmenite	Magnetite
REE+Y			
La	239-304	0.1-0.3	<LOD
Ce	689-866	0.1-0.4	0.03-0.7
Pr	110-132	0.02-0.04	0.02-0.1
Nd	575-680	<LOD	<LOD
Sm	136-155	<LOD	<LOD
Eu	28-33	<LOD	<LOD
Gd	135-156	<LOD	<LOD
Tb	16-19	<LOD	<LOD
Dy	88-103	<LOD	<LOD
Ho	15-18	<LOD	<LOD
Er	36-44	<LOD	<LOD
Tm	4.0-5.0	<LOD	<LOD
Yb	21-25	<LOD	<LOD
Lu	3.00	<LOD	<LOD
Y	415-495	0.04	0.03-0.33
Σ REE	2096-2538	<LOD	<LOD

Note: If the majority of any elemental concentration data of a mineral are < LOD (lower limit of detection), the data are reported as < LOD. The average concentration of each element of each mineral is provided in the Appendix tables.

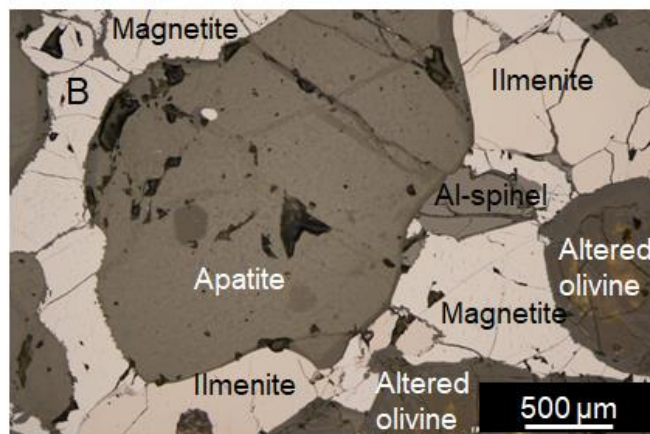
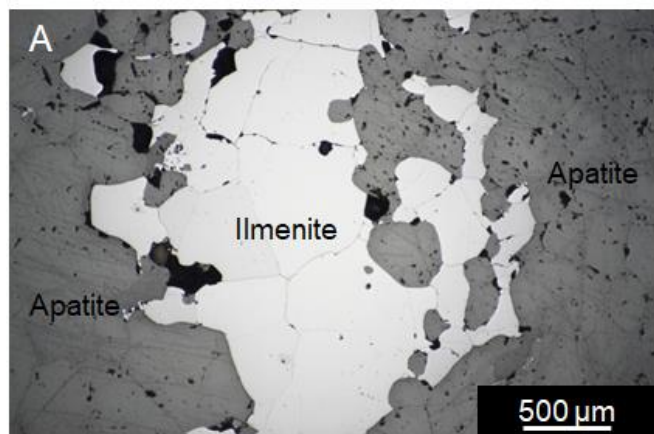


Fig. 19. Textural relationships of ilmenite from the Mountain Zone of the Bégin-Lamarche deposit (under reflected light). (A) Ilmenite associated with apatite (sample MZ 8) and (B) Ilmenite associated with magnetite, Al-spinel, and altered olivine (sample MZ4).

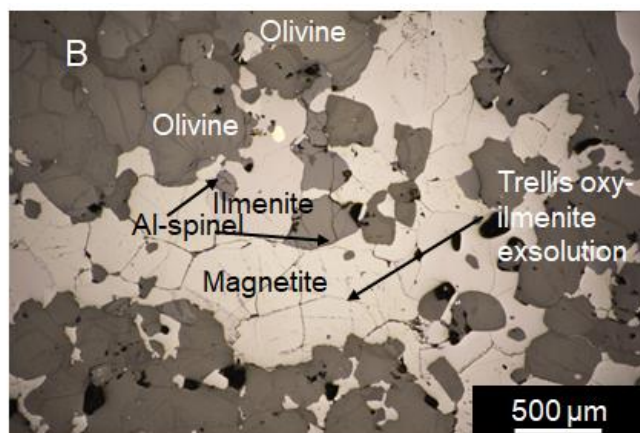
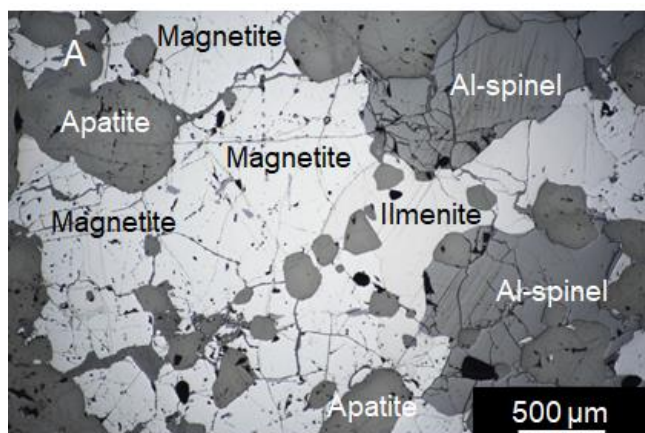


Fig. 20. Textural relationships of magnetite from the Mountain Zone of the Bégin-Lamarche deposit (under reflected light). (A) Magnetite associated with ilmenite, Al-spinel, and apatite (sample MZ14); (B) Magnetite associated with ilmenite, Al-spinel, and olivine; Note the presence of trellis oxy-ilmenite exsolution in magnetite (sample MZ3).

7.2. Rare earth elements (REE) of apatite

The REE are trace elements with atomic numbers of 57-71 (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu). Y is also commonly included in this series. Total concentrations of REE in apatite crystals (REE=2096-2538 ppm, Y=415-495 ppm) are significantly higher than the other minerals because REE preferentially partition into the Ca site of apatite (Banerjee et al., 2024c; Prowatke and Klemme, 2006; Owens et al., 2019; Ayers and Watson, 1993). Concentrations of REEs are conventionally represented as normalized (ratios) values with respect to chondrite, which is a type of meteorite (Fig. 21; Pourmand et al., 2012). Chondrite-normalized REE patterns of apatite reveal (Fig. 21):

a) Similar to the North and South Zone, apatite from the Mountain Zone shows a slight negative Eu anomaly. The negative Eu anomaly is defined by chondrite-normalized Eu concentrations that are lower than that of its neighboring Sm and Gd concentrations (Rollinson, 2014).

b) Apatite has higher concentrations of light rare earth elements (LREE include La, Ce, Pr, Nd, Sm, Eu, Gd) than heavy rare earth elements (HREE include Tb, Dy, Ho, Er, Tm, Yb, Lu), typical of apatite from mafic intrusions (Banerjee et al., 2024c; Kieffer et al. 2023; Miloski et al. 2024).

The REE concentrations of apatite and its modal abundances from the mineralized rocks of the Bégin-Lamarche deposit (Mountain, North and South zones) exhibit a good positive correlation, i.e., REE concentrations of apatite increase with increasing its modal abundances (Fig. 22). The relation also indicates that apatite from the ultramafic rocks (~ 0% plagioclase in this study) contains higher amount of REE than those from the mafic rocks (> 10% plagioclase). Furthermore, Mg# of coexisting orthopyroxene from the mafic rocks (< 60) have lower values than those from the ultramafic rocks (> 60; inset of Fig. 22).

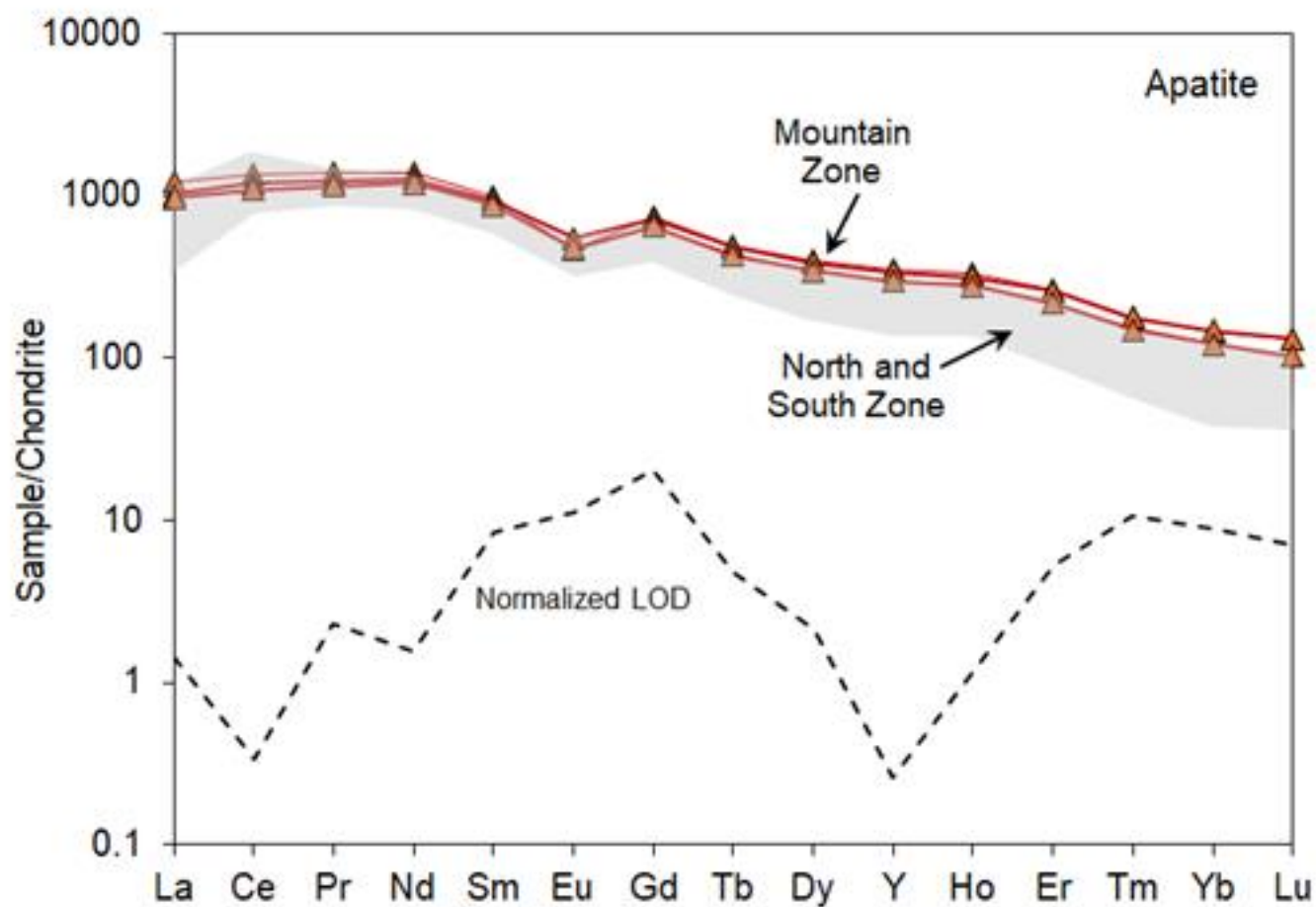


Fig. 21. Chondrite-normalized REE patterns of apatite crystals from the oxide-apatite ultramafic rocks of the Mountain Zone of the Bégin-Lamarche deposit. The REE patterns of apatite from the oxide-apatite ultramafic and mafic rocks from the North and South Zone (Banerjee et al., 2024b) are also shown.

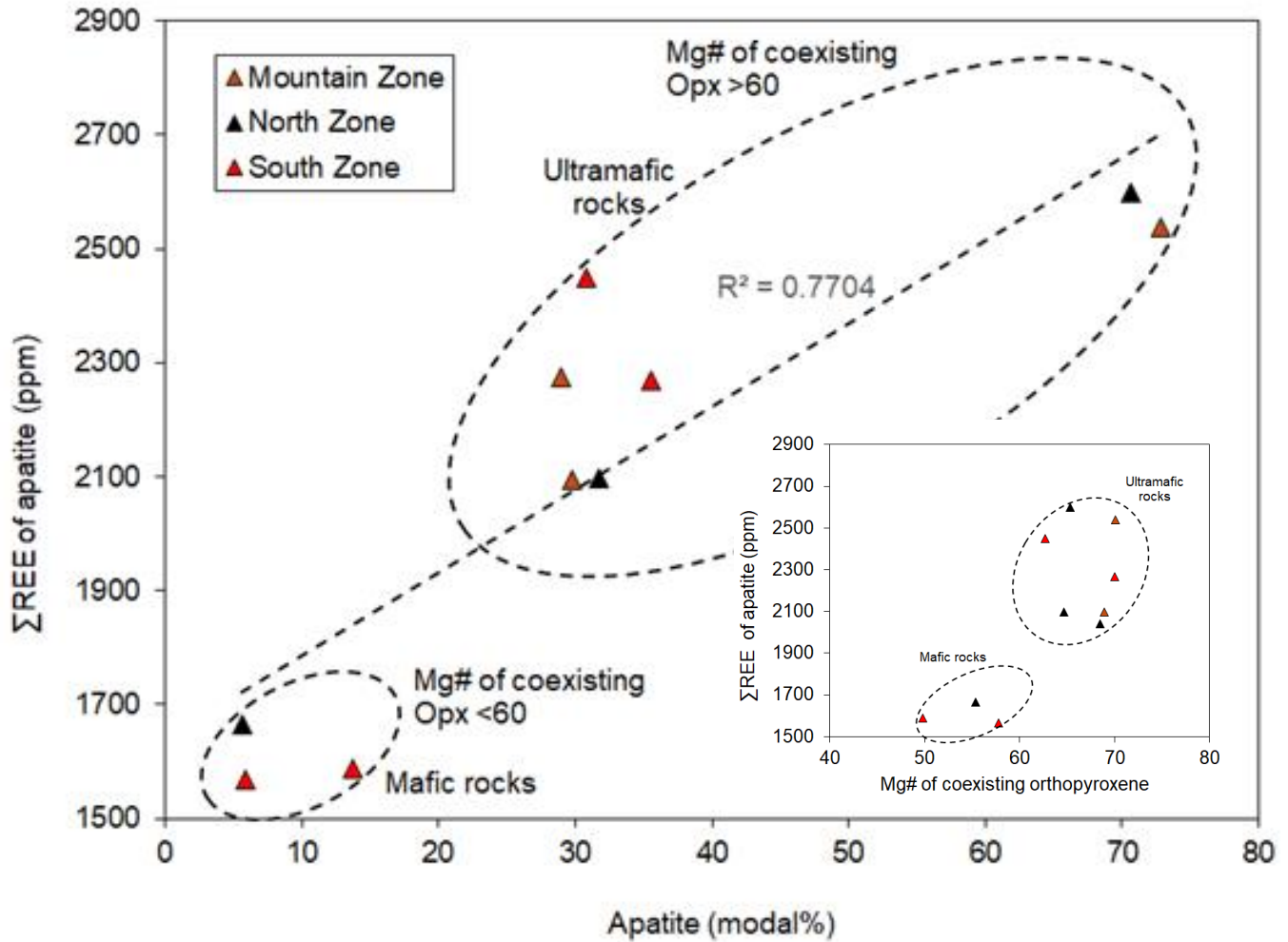


Fig. 22. Relationships between REE concentrations of apatite and apatite contents of the mineralized rocks from the Bégin-Lamarche deposit (Mountain, North, and South Zone). The inset shows the relationships between REE concentrations of apatite and Mg# of coexisting orthopyroxene (Opx) of the same rocks from the Bégin-Lamarche deposit (data of apatite of the North and South Zone from Banerjee et al, 2024b).

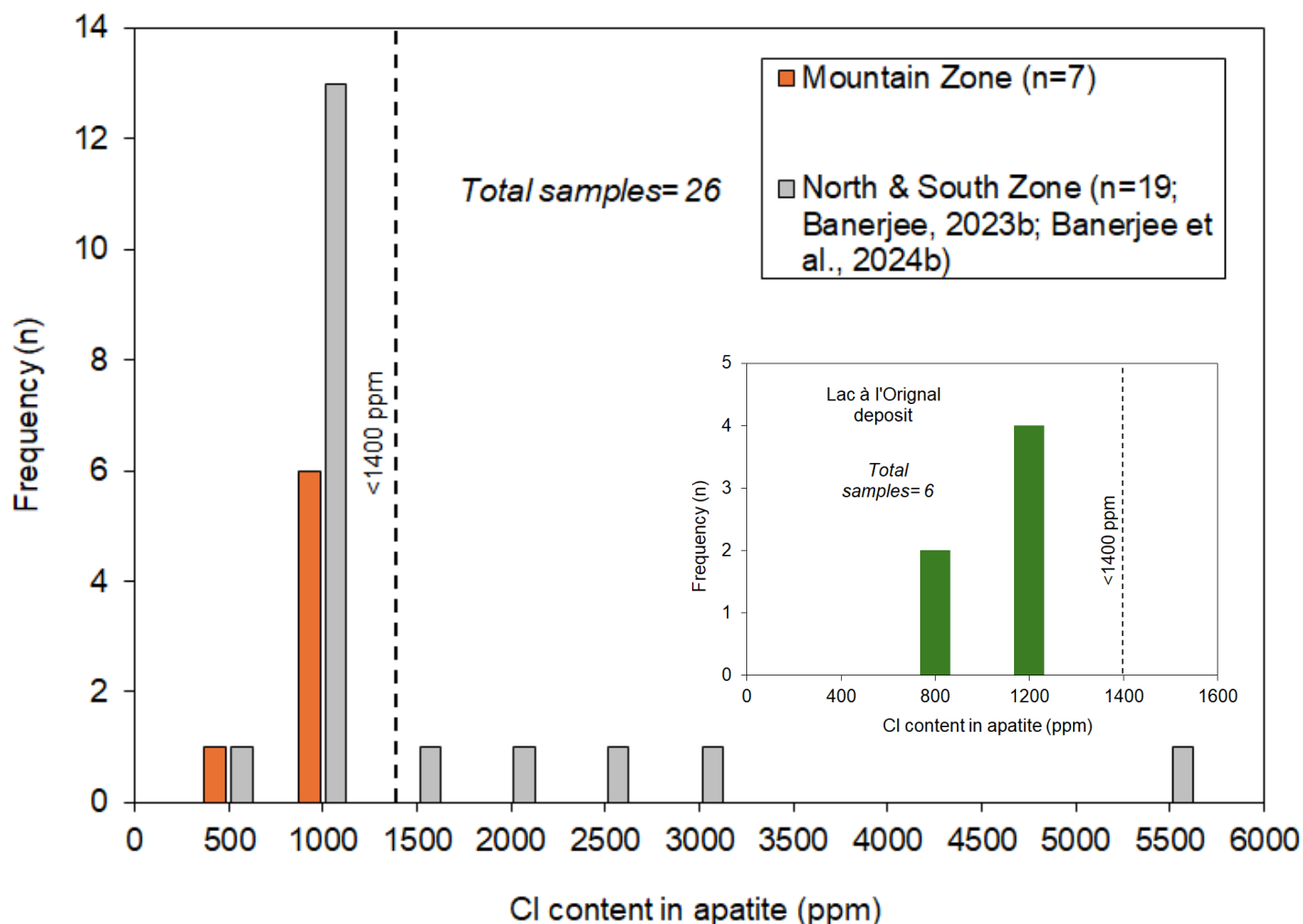


Fig. 23. Frequency distributions of Cl contents of *in situ* apatite from the oxide-apatite ultramafic rocks (and one sample from the apatite-rich nelsonite) of the Mountain Zone of the Bégin-Lamarche deposit. The frequency distributions of Cl contents of *in situ* apatite crystals from the oxide-apatite mafic and ultramafic rocks of the North and South Zone of the Bégin-Lamarche deposit are also shown. The inset shows frequency distributions of Cl contents of *in situ* apatite crystals from the oxide-apatite mafic rocks [gabbro(norite)] of the Lac à l'Original deposit (data from Banerjee et al., 2024c). The upper limit of Cl contents of saleable phosphate ore (< 1400 ppm) suggested by Yara International is also shown (Païement et al., 2013).

8. Discussion

8.1. Apatite of the Mountain Zone as an ESG-compliant source of phosphate

The apatite must meet certain chemical assay criteria for producing phosphoric acid (Table 6). The P_2O_5 (42.0 ± 0.1 wt.%), and CaO (55.0 ± 0.3 wt.%; Table 6) contents and CaO/ P_2O_5 ratios (1.31 ± 0.01 ; Table 6) of *in situ* apatite crystals of ultramafic rocks from the Mountain Zone are better than that required for producing phosphoric acid.

The F concentrations of *in situ* apatite crystals (3.0 ± 0.3 wt%; Table 6) are lower than required (< 3.5 wt%; Table 6). The Cl concentrations of *in situ* apatite crystals (620 ± 110 ppm; Table 6) are slightly higher than the required Cl content of ideal phosphate concentrate for producing phosphoric acid (< 600 ppm, Prayon, 2022; Table 6). Yara International, however, specified that the Cl content of apatite concentrate should be < 0.14 wt.% (or 1400 ppm) in order to be saleable (Paiement et al., 2013). Therefore, the average Cl contents of *in situ* apatite crystals from a minimal number of samples ($n=7$) are significantly lower than the Cl content value specified by Yara International. Here, it is important to note that the average value of Cl of *in situ* apatite crystals is not a weighted average. The Si, Fe, Al, Mg, Ti, Na, As, Cd, Th, and U concentrations of apatite are lower than their required values proposed by Prayon (Table 6).

In addition, the apatite from the Mountain Zone contains a very low amount of radioactive elements, such as Pb, U, and Th (each element < 2 ppm; Table 6). The apatite concentrate with such low amounts of radioactive elements will produce phosphogypsum with very low amounts of radioactive elements during phosphoric acid production. As the phosphogypsum can potentially be recycled into plaster and wallboard, the high-quality and environment-friendly phosphogypsum could be an attractive saleable product. Finally, the low abundances of sulfide gangue minerals ($< 1\%$) suggest that the environmental impacts of acid mine drainage from tailings would be minimal. Thus, the high-quality apatite of the Mountain Zone, similar to that from the North and South Zone, with low contents of toxic trace elements, and low abundances of sulfide minerals make the phosphate of the Mountain Zone an attractive ESG-compliant source of North American P for the LFP battery industry.

8.2. Cl content of (fluor)apatite of the Mountain Zone

In general, (fluor)apatite can contain a low amount of Cl (< 1000 ppm; Andersson et al., 2019). The Cl is corrosive to equipment for the production of phosphoric acid from apatite concentrate (Chandra et al., 2017; Schorr and Valdez, 2017). As Cl cannot be extracted before the production of phosphoric acid (Salas et al., 2017), phosphate ores with low Cl contents are preferred. Prayon suggested that Cl contents should be < 600 ppm for producing phosphoric acid (Table 6) and Yara International suggested that Cl contents should be < 1400 ppm for saleable phosphate ore (Paiement et al., 2013). Therefore, understanding the Cl distributions of apatite ore of a deposit is critical.

Cl contents of (fluor)apatite were analyzed from a limited number (n=7 samples) of ultramafic rocks from the Mountain Zone. The Cl content varies from 400 to 700 ppm (0.04 to 0.07 wt.%; Fig. 23 and Table 4) with an average of 620 ± 110 ppm (Table 6), which is slightly higher than the required Cl content for producing phosphoric acid and significantly lower than the required Cl content for saleable phosphate ore. **The Cl content of the majority of (fluor)apatite samples (22 of the 26 samples, i.e., 85% of the total samples) from the Bégin-Lamarche deposit (North, South, and Mountain Zone) are below 1400 ppm (Fig. 23). Therefore, Cl data of apatite from the Bégin-Lamarche deposit suggests that apatite with high Cl contents (> 1400 ppm) may occur locally in the deposit.** Cl content analysis of (fluor)apatite from a limited number (n=6 samples) of gabbro(norite) samples from the Lac à l'Original deposit indicates that all samples (100% of the total samples) of the deposit are below 1400 ppm.

8.3. Geological processes controlling the Cl content of (fluor)apatite of the Bégin-Lamarche

This study indicates that F/Cl contents of apatite of the Mountain Zone vary moderately (41-85) and the variations are lower than that of the total variations found in the apatite from the North and South Zone (4-64; Fig. 17).

The positive correlation between the Cl content of apatite and the Mg# of coexisting orthopyroxene of the Mountain Zone (Fig. 18) suggests that the Cl content of the apatite progressively decreased with differentiation (i.e., with progressive crystallization). The high versus low Mg# for orthopyroxene is indicative of early versus late stage of crystallization, respectively. A nearly parallel trend was also observed for the one group of samples from the North and South Zone (Fig. 18). The overall Cl concentrations of the apatite samples from the North and South Zone are, however, higher than those of the Mountain Zone (Fig. 18). This relation suggests that the initial Cl concentration of the magma of the North and South Zone were higher than that of the Mountain Zone; but the rate of decrease of Cl content of the magmas (with respect to magmatic differentiation which was inferred from the Mg# of orthopyroxene; Fig. 18) were similar.

The Cl content of apatite and the Mg# of coexisting orthopyroxene of the Lac à l'Original deposit, however, showed a negative correlation, which suggests that the Cl content of apatite increases with differentiation (i.e., with progressive crystallization; Banerjee et al., 2024c). The negative correlation is expected because Cl behaved incompatibly during its crystallization (Kieffer et al. 2023; Banerjee et al., 2024c), and therefore, the Cl content of the magma increased progressively with magmatic differentiation. Furthermore, REE contents of apatite of the Lac à l'Original deposit also increase with increasing its Cl contents because both behave as incompatible elements during magma crystallization (data from Banerjee et al., 2024c; not shown here).

Another proposition for modifying Mg# of orthopyroxene is through subsolidus exchange between orthopyroxene and other silicate (such as clinopyroxene or olivine) and/or oxide minerals (such as ilmenite and magnetite; for details see Tanner et al., 2014; Nex et al., 2002). The Mg# of orthopyroxene of the Bégin-Lamarche (55-70, Fig. 18) and the Lac à l'Original deposits (62-69; Banerjee et al., 2024c) exhibit a wide variation. This much variation of Mg# of orthopyroxene due

to diffusional exchange (of Mg and or Fe) between orthopyroxene and clinopyroxene is not viable considering the presence of a very small amount of clinopyroxene in both deposits (predominantly <5 modal% of clinopyroxene; Banerjee et al., 2024b and c). If Mg# of orthopyroxene was affected by subsolidus diffusion (of Fe or Mg) between orthopyroxene and oxide minerals or olivine, it is expected to have a systematic variation between the amount of those minerals and Mg# of orthopyroxene. However, there is a poor correlation (i.e., no correlation) between Mg# of orthopyroxene and modal abundances of oxide minerals ($R^2=0.25$ for the North and South Zone, and $R^2=0.06$ for the Mountain Zone; not shown here). Similarly, there is a poor correlation between Mg# of orthopyroxene and modal abundances of olivine ($R^2=0.25$ for the North and South Zone, and $R^2=0.01$ for the Mountain Zone; not shown here). Therefore, the diffusional exchange of Fe or Mg between orthopyroxene and olivine or oxide minerals can not be considered to be a critical mechanism to modify the Mg# of orthopyroxene. The Mg# variations of orthopyroxene in the Bégin-Lamarche (as well as in the Lac à l'Original) are predominantly related to the differentiation (or stages of crystallization) of the magma.

In the case of the Bégin-Lamarche deposit, the Cl content of the melt progressively decreased during the crystallization. One reason for the progressive decrease of the Cl content of the melt is the progressive evolution of Cl-rich (exsolved) fluid during the crystallization of the magma (e.g., Webster et al. 2020). The alteration of olivine crystals to iddingsite (e.g., Fig. 10F) in the three zones of the Bégin-Lamarche deposit, the presence of corona structure, and the alteration of orthopyroxene to amphibole from the North and South zones indicate involvement of fluid during the crystallization of the magma (Banerjee et al., 2024b). The previous study also indicates that the Cl content of altered olivine and late-stage veinlets cross-cutting apatite have higher Cl content than that of the apatite (Banerjee, 2023b). Furthermore, it is expected that the exsolution of Cl-rich fluid from the magma affected the H_2O/Cl ratio of the magma, which resulted in higher variabilities of hydroxyl-apatite (HAp) component in the apatite from the Bégin-Lamarche deposit (e.g., Li et al., 2024) than that of the Lac à l'Original deposit (Fig. 16). **Therefore, this study indicates that fluid evolved from the magma of the Bégin-Lamarche deposit during its progressive crystallization and that fluid was responsible for the alteration of olivine and (also orthopyroxene).**

Another possibility is that a high amount of apatite crystallization at the initial stages of magma crystallization decreased the Cl content of the magma and therefore, apatite crystallized at the late stages has low Cl content. **Considering the geochemical and petrographical characteristics of the deposit we are inferring that both mechanisms (evolution of Cl-rich fluid and high amount of apatite crystallization at the initial stages of magma crystallization) were possibly responsible for producing the negative correlation between the Cl content of apatite and the Mg# of coexisting orthopyroxene.**

Table 6. Comparison between threshold concentrations of selected elements (and oxides) in an ideal phosphate concentrate for producing phosphoric acid (provided by Prayon, 2022) and elemental (and oxide) concentrations of apatite from the ultramafic rocks of the Mountain Zone of the Bégin-Lamarche deposit.

	Threshold concentrations in an ideal phosphate concentrate	Apatite from the Mountain Zone (<i>in-situ analysis</i>)
P ₂ O ₅	36-39 wt%	42.0±0.1 wt% (n=7 samples)
CaO	48-52 wt%	55.0±0.3 wt% (n=7)
CaO/P ₂ O ₅	<1.5	1.31±0.01 (n=7)
F	<3.5 wt%	3.0±0.3 wt% (n=7)
Cl	<600 ppm	620±110 ppm (n=7)
Si	2.33 wt%	0.02 ±0.01 wt.% (n=7)
Fe	<0.49 wt%	0.21 ±0.09 wt.% (n=7)
Al	<0.37 wt%	13-66 ppm ((n=3)*)
Mg	<0.12 wt%	0.08 ±0.04 wt.% (n=7)
Ti	<2600 ppm	4-20 ppm (n=3)*)
Na	<0.56 wt%	0.04 ±0.01 wt.% (n= 7)
As	<5 ppm	3-4 ppm (n= 3)*)
Cd	<3 ppm	<0.8 ppm (n= 3)*)
Pb		0.6-1.1 ppm (n=3)*)
Th	<22 ppm	1-2 ppm (n= 3)*)
U	<7 ppm	0.5-2.0 ppm (n= 3)*)

* Al, Ti, As, Cd, Pb, Th, and U concentrations were analyzed by LA-ICP-MS.
Si, Fe, Mg, and Na concentrations were calculated from their oxides analyzed
by EPMA. F and Cl concentrations were analyzed by EPMA.

8.4. Mineral paragenesis and the timing of apatite crystallization

Mineral paragenesis describes the sequence or timing of mineral formation in any rock. Understanding mineral paragenesis is critical for properly characterizing ore bodies and waste rocks, which helps to determine exploration and exploitation strategies. **This project only investigated ultramafic rocks (~ 0% plagioclase in this study) from the Mountain Zone.** The major minerals of the ultramafic rocks of the Mountain Zone are olivine, orthopyroxene, apatite, ilmenite, and magnetite. Apatite associated with ilmenite and magnetite (e.g., Fig. 10A, 10D, 10F, 11C, 11E, 15B-C, 15D, 19A-B, and 20A-B) suggests that those minerals coprecipitated. Similarly, apatite associated with olivine (Fig. 10A-F) and orthopyroxene (Fig. 11A-F) suggests that those minerals (olivine, orthopyroxene, and apatite) coprecipitated. The petrographic study could not reveal if the olivine started to crystallize before orthopyroxene. The rocks of the Bégin-Lamarche deposit are cumulate rocks and therefore, mineral paragenesis should be established most effectively through high-frequency sampling of a drill hole (e.g., Charlier et al., 2008; Namur et al., 2010). This type of sampling, however, was not done in this study.

This study (along with the North and South Zone) reports a few important aspects of mineralization, which are

i) The ultramafic rocks (~ 0% plagioclase in this study) contain a higher amount of apatite than those of the mafic rocks (> 10% plagioclase; Fig. 6A and B), which suggests that the crystallization of plagioclase decreased the amount of apatite crystallization. Therefore, a high amount of Ca concentration in the melt before the crystallization of plagioclase favored a high amount of apatite saturation (e.g., Tollari et al., 2006). Furthermore, modal abundances of apatite from the mafic rocks from the North and South Zone exhibit an overall antithetic correlation, i.e., the amount of apatite decreases with an increasing amount of plagioclase in the mafic rocks of the Bégin-Lamarche deposit (North and South zones; Fig. 7A). The similar antithetic correlation, however, was not very prominent for the mafic rocks of the Lac à l'Original deposit (Fig. 7B). Here, it is important to note that the plagioclase crystals of the mafic rocks from the Lac à l'Original deposit exhibit reverse compositional zoning (Fig. 3A in Banerjee et al., 2024c); i.e., Ca concentration of plagioclase increased from cores to the edges of the crystals. The reverse compositional zoning of plagioclase could reflect an increase of the Ca concentration of the magma during its progressive polybaric crystallization (Charlier et al., 2010; Banerjee et al., 2024c).

ii) The positive correlation between the REE concentration of apatite and the amount of apatite in the rock (Fig. 22) indicates that **apatite started to crystallize at the initial stages of magmatic crystallization. A positive correlation between the REE concentration of apatite and Mg# of coexisting orthopyroxene (inset of Fig 22) strongly supports the proposition of early crystallization of apatite.** Furthermore, a lower amount of REE in apatite from the mafic rocks than that of the ultramafic rocks of the Bégin-Lamarche deposit suggests that the REE concentration of the melt decreased with progressive crystallization of the magma. This relation is just opposite to that observed in the Lac à l'Original deposit (Fig. 10A in Banerjee et al., 2024c). The high amount of apatite crystallization in the Bégin-Lamarche deposit made the REEs behave as compatible elements (compatible with rock).

iii) The absence of plagioclase in the ultramafic rocks, and orthopyroxene with higher Mg# from those rocks (> 60 ; Fig. 22) than those from the mafic rocks also suggests that plagioclase appeared at the later stages of crystallization. Another possibility is that the plagioclase crystals from the ultramafic rocks were ‘completely’ removed by the floatation mechanism due to their positive buoyancy (due to lower density of plagioclase than that of the melt) within the crystallizing melt (e.g., Namur et al., 2011).

iv) Apatite from the Bégin-Lamarche deposit is not from “nelsonite” rock (i.e., only composed of apatite and oxide minerals). The mineralized rocks also contain a significant amount of silicate minerals (~14-90 modal%; Fig. 8).

v) The mineralized rocks of the Mountain, North, and South Zone crystallized at medium-low pressure conditions (ca. < 4 kbar; Fig.12).

8.5. Use of ilmenite and magnetite

Ultramafic-mafic rocks containing apatite-oxide are relatively new exploration targets for phosphate, Ti, and potentially Fe (e.g., Banerjee et al 20024b). Similar to the North and South Zone, ilmenite from the Mountain Zone has a lower hematite component (X_{hem} of 0.0-0.03) than that of the Lac à l’Original deposit (X_{hem} of 0.07-0.6; Miloski et al., 2024, Banerjee et al., 2024c). **The TiO_2 content of ilmenite of the Mountain Zone (51.6-52.9 wt.%) is therefore slightly higher than that of the Lac à l’Original deposit (46.2-50.0 wt.%; Banerjee et al. 2024c).** Furthermore, ilmenite of the Mountain Zone has low contents of Mg (MgO of 0.4-1.9 wt.%; Table 3) and Cr (Cr_2O_3 of ≤ 0.1 wt.%; Table 3). During beneficiation, elevated Mg in ilmenite decreases the reduction rate of ilmenite to form TiO_2 (Kim, 2015) and high Cr contents decrease the whiteness of TiO_2 pigments for paints (Bonsack, 1970). A recovery of ~52 wt.% of TiO_2 should be possible from the ilmenite of the Mountain Zone (Table 3). However, metallurgical testing is necessary to implement the proper technique to recover ilmenite from gangue minerals (such as olivine).

Magnetite could also be an important secondary commodity as a source of Fe. It can be concentrated as a by-product of the metallurgical processing of phosphatic ore from the Mountain Zone. The low TiO_2 (0-1.7 wt.%), MnO (≤ 0.1 wt%), and MgO (≤ 0.1 wt%; Table 3) contents of magnetite of the Mountain Zone are comparable to those of the North and South Zone ($\text{TiO}_2=0.15-1.36$ wt.%, $\text{MnO}=0-0.07$ wt.%; and $\text{MgO}=0.03-0.14$ wt.%; Banerjee et al., 2024b).

In addition to the steel industry, magnetite nanoparticles can be used for magnetic resonance imaging, manufacturing of catalysts, synthesizing of pigment, and magnetic storage (Darezereshki et al., 2018).

8.6. Use of mafic silicate minerals for CO_2 sequestration

Olivine and pyroxene react with CO_2 -rich aqueous fluids at surficial temperature conditions and the reaction rates increase with temperatures (Kelemen et al., 2019; Rasool and Ahmad, 2023, Palandri and Kharaka, 2004). Therefore, mafic silicate mine tailing could be used for CO_2 sequestration through enhanced weathering (Kelemen et al., 2019). Although the reaction rates for the minerals are low at surficial conditions, high surface area-to-volume ratios of mine

tailing can increase reactivity. Carbon mineralization in mine tailings can be enhanced by several methods, such as sparging air, air-saturated water, or CO₂-rich gas through the tailings, stirring the tailings to have a turnover of reactive surfaces in contact with air, or adding microorganisms that accelerate the formation of carbonates (Kelemen et al., 2019 and references therein). Another option is grinding the mafic silicate minerals smaller than mine tailing sizes and mixing them with agriculture soil, forest soil, or along beaches and the CO₂ sequestration process can be enhanced by microbial processes in soils (Beerling et al., 2018, Power et al., 2013, Kelemen et al., 2019).

It is important to mention that this study did not analyze the trace element composition of olivine and orthopyroxene. The trace element compositions of those minerals from the North and South Zone were analyzed (Banerjee et al., 2024b). Similar to olivine and orthopyroxene of the North and South Zone (Banerjee et al., 2024b), we infer that those minerals of the Mountain Zone also contain very low concentrations of trace elements. Therefore, the mafic minerals of the Mountain Zone would be suitable for CO₂ sequestration. The assessment of heavy metal contents (such as Cr, Ni, Co, Cr, and Zn) of the minerals and their impact on the environment (e.g., in soil) needs to be investigated before the use of mafic silicate minerals for CO₂ sequestration.

9. Conclusions

1. Oxide-apatite ultramafic rocks (~ 0% plagioclase in this study) contain a higher amount of apatite than that of the oxide-apatite mafic rocks (> 10% plagioclase) in the First Phosphate's Bégin-Lamarche deposit (Mountain, North, and South Zone). The ultramafic rocks of the deposit contain apatite equivalent to that of nelsonite rock or even higher than that. In this study, only oxide-apatite ultramafic rocks (dunite, harzburgite, olivine websterite, and olivine orthopyroxenite) and (apatite-rich) nelsonite from the Mountain Zone were investigated.
2. The mineralized ultramafic rocks mostly contain variable amounts of olivine, orthopyroxene, apatite, ilmenite, and magnetite. Fluorapatite is the primary ore mineral and ilmenite, and magnetite are potentially important secondary commodities of Ti and Fe respectively.
3. The P₂O₅ concentration of *in situ* apatite is 42.0 ± 0.1 wt.% and CaO/P₂O₅ ratio is 1.31 ± 0.01, which are better than required for phosphoric acid production. Therefore, the Bégin-Lamarche deposit is a potentially viable source of P for the LFP battery market.
4. Si, Fe, Al, Mg, Ti, Na, As, Cd, Th, and U concentrations of apatite are lower than their required values for producing phosphoric acid. Low concentrations of trace and radioactive elements (Pb, Th, and U) in apatite will produce high-quality and environment-friendly phosphogypsum as a by-product during phosphoric acid production. The phosphogypsum could potentially be recycled into plaster and wallboard.
5. The low abundance of sulfide gangue minerals (< 1%) suggests that the environmental risks of acid mine drainage from tailings would be minimal. Such low concentrations of toxic trace elements and sulfide minerals make the Bégin-Lamarche deposit an attractive ESG-compliant source of North American P for the LFP battery industry.

6. The average Cl content of (fluor)apatite from the oxide-apatite ultramafic rocks and (apatite-rich) nelsonite of the Mountain Zone (620 ± 110 ppm, $n=7$ samples) is comparable to the required Cl content for producing phosphoric acid (< 600 ppm). The Cl contents of the majority of apatite samples (85% of the total samples) from the Bégin-Lamarche deposit (North, South, and Mountain Zone) are below 1400 ppm, which is the upper limit of Cl content for saleable phosphate ore. Apatite with high Cl contents (> 1400 ppm), however, may present locally in the deposit.
7. Similar to the North and South Zone, a positive correlation between the Cl content of (fluor)apatite and Mg# of coexisting orthopyroxene suggests the low Cl content of apatite will be associated with a low Mg# of orthopyroxene. As halogen component (F and Cl) analysis of apatite is challenging, Mg# of orthopyroxene can be used to trace the locations of high-quality phosphate ore in the Bégin-Lamarche deposit.
8. The mafic silicate minerals (e.g., olivine and pyroxene) and plagioclase of the deposit can be used for CO₂ sequestration, which can reduce the carbon footprint of the atmosphere. The use of gangue minerals to mitigate climate change and environmental protection could add value to the ESG.
9. Paragenetic relationships indicate that apatite started to precipitate at the initial stages of magmatic crystallization and the amount of apatite crystallization decreased during the progressive crystallization of the magma of the Bégin-Lamarche deposit.

10. Recommendations

This study only investigated oxide-apatite ultramafic rocks and apatite-rich nelsonite from the Mountain Zone. Other mineralized rocks, such as oxide-apatite mafic rocks of the Mountain Zone were not investigated. Similarly, Cl contents of apatite were only investigated from a limited number of samples. Knowledge of distributions of ultramafic and mafic rocks from the Mountain Zone as well as from the North and South Zone will be helpful in understanding the ore grade distributions of the Bégin-Lamarche deposit. Therefore, high-frequency sampling from at least one drill core from the Mountain, North, and South Zone is recommended for petrography and geochemistry study. This type of study will help delineate the patchy (or local) distributions of apatite with high Cl content.

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