INVESTIGATION OF THE RHEOLOGY OF GABBROS: EXAMPLE FROM THE QUEYRAS OPHIOLITES (FRANCE)

by

Chase Lucht

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Approved by

Dr. Raphaël Gottardi (Chair), Associate Professor, Department of Geosciences

Dr. Brian Boston, Assistant Professor, Department of Geosciences

Dr. David T. King, Jr., Professor, Department of Geosciences

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ABSTRACT

The rheology of the lower oceanic crust remains poorly constrained despite its central role in plate tectonics and strain localization at slow-spreading ridges. This study investigates the petrology, deformation mechanisms, and tectonic and metamorphic evolution of gabbros from three Alpine ophiolite localities in the Queyras region (Western Alps, France), interpreted as remnants of a slow-spreading oceanic core complex. Petrographic observations have been integrated with scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS) and X-ray computed microtomography (μXRCT) to characterize mineral assemblages, microstructures, and the spatial distribution of weak phases.

The gabbros are dominated by clinopyroxene, Ca-rich plagioclase, and Fe-Ti oxides, and record a complex history of deformation and metamorphism. Clinopyroxene porphyroclasts exhibit both ductile (undulose extinction, bending) and brittle (fracturing, bookshelf sliding) deformation, indicating a transition across the brittle–ductile regime. Strain localization is associated with Fe-Ti oxides, which occur preferentially in pressure shadows and along foliation, suggesting they act as mechanically weak phases that facilitate deformation. Plagioclase forms a fine-grained recrystallized matrix, while metamorphic assemblages including glaucophane, chlorite, epidote, and actinolite record fluid-assisted alteration under blueschist- to greenschist-facies conditions.

Microstructural and chemical data indicate that deformation initiated near a slow-spreading ridge under high-temperature conditions, followed by hydrothermal alteration and progressive deformation during subduction. Subsequent exhumation was accompanied by fluid infiltration and retrogression under greenschist facies conditions. The absence of eclogite-facies minerals suggests limited subduction depths and relatively rapid exhumation. These results provide new constraints on deformation processes in the lower oceanic crust and highlights the importance of multiphase interactions and fluid-assisted weakening in governing lithospheric strength.

ARTIFICIAL INTELLIGENCE (AI) USE DISCLOSURE

In the preparation of this thesis, no Artificial Intelligence (AI) tools were used.

DIGITAL ACCESSIBILITY USE DISCLOSURE STATEMENT

In the preparation of this thesis / dissertation, the following digital accessibility tools were used to ensure this document complies with federal requirements: Microsoft Word, Adobe Creative Cloud. The author acknowledges full responsibility for the intellectual content of this work and has made a good faith effort to comply with digital accessibility requirements in publishing, wherein the nature of the content does not significantly change in order to do so. Furthermore, all content has been reviewed and revised to meet these requirements prior to final publication.

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1. INTRODUCTION

The oceanic crust plays a critical role in geodynamic processes such as mid-ocean ridge formation and the subduction cycle. Although gabbros are the most abundant rocks in the oceanic crust (e.g., Weaver and Tarney, 1984; Christensen and Mooney, 1995; Dimanov and Dresen, 2005; Dimanov et al., 2007), their rheology remains poorly understood. Strain localization is a fundamental process of plate tectonics resulting in the formation of ductile shear zones that accommodate a high proportion of strain at convergent plate boundaries (e.g., Agar, 1994; Casini et al., 2021). Therefore, understanding strain localization processes is critical to the knowledge of the rheology of the lithosphere and the impact on plate interactions. Fast-spreading mid-ocean ridges have relatively low tectonic strain compared to slow-spreading ones resulting in a lack of OCCs. At slow-spreading mid-ocean ridges, which make up 60% of all spreading-ridges (Tucholke et al., 1998; Buck et al., 2005; Smith et al., 2006; Cannat et al., 2006), strain localization resulting in the formation of oceanic core complexes (OCCs) is an integral part of the plate-spreading process, in most cases making up more than 50% of the spreading along the boundary (e.g., Baines et al., 2008). A consistent angular relationship between the OCC breakaways and their adjacent ridge flank faults indicate that the distribution of strain in the lower oceanic crust and the partitioning of strain along the detachment shear zone is elementary to the understanding of OCC formation and the rheology of the oceanic lithosphere (MacLeod et al., 2009). This lithosphere is in turn subducted or obducted with the anisotropies from OCCs impacting collision processes.

Current knowledge of the rheology of the lower oceanic crust suggests that it is primarily controlled by dry plagioclase (Yoshinobu and Hirth, 2002; Mehl and Hirth, 2008; John and Cheadle, 2010; Allard et al., 2021). However, this concept is challenged by numerous observation from IODP drilling expeditions, that demonstrate that ductile deformation occurs at significant depth below the detachment fault in OCC (Dick et al., 2000; Schroeder and John, 2004; Karson et al., 2006; Miranda and John, 2010; Hansen et al., 2013; MacLeod et al., 2017; Dick et al., 2019; Lissenberg et al., 2024; McCaig et al., 2025). Therefore, there must be mechanisms that allow for strain localization at these depths, or processes that promote weakening of the bulk rheology of the lower oceanic crust.

Decades of invaluable research from the International Ocean Discovery Program (IODP) have significantly improved the collective knowledge of the oceanic crust through numerous drilling campaigns (IODP Holes U1473A, U1309B-D, etc.). IODP cores record near-complete sections of the oceanic floor, providing millimeter-by-millimeter scale observations. However, one drawback of the IODP results is that they lack lateral continuity: it is difficult to extrapolate what is observed down hole laterally. This has been demonstrated by the challenge in correlating units across holes that are no more than 100 meters apart (e.g., IODP Holes U1309B and U1309D, Atlantis Massif, Mid-Atlantic Ridge; Blackman et al., 2006).

To fill this knowledge gap, studies of outcrop exposure found in ophiolites sequences are necessary to pairing of continuous one-dimensional observations from IODP cores to broader aerial exposures of sections of gabbros that have experienced ductile strain. The goal of this study is to investigate the rheology of gabbros from three alpine ophiolite exposures located in the northeastern Queyras region of France. The Queyras ophiolites are inferred to preserve a characteristic igneous suite from a slow-spreading ridge environments (Tricart and Lemoine, 1983; Ambrics and Bertrand, 1999; Lagabrielle et al., 1985, 2015, Agard, 2021). Therefore, they provide an excellent test site to investigate strain localization processes in these lithologies. However, little work has been done regarding the petrogenesis and tectonic evolution of these gabbros. This study aims to fill this knowledge gap. The petrology of gabbros collected at these three ophiolite localities has been investigated through methods including petrography, Scanning Electron Microscopy Energy-Dispersive X-ray Spectroscopy (SEM-EDS) and X-ray computed microtomography (µXRCT). This project's findings are used further constrain the rheology of the oceanic crust and contribute to a deeper understanding of its mechanical properties and the broader implications for geological processes.

2. REGIONAL GEOLOGY

This study focuses on three sites located in the Queyras area of France, that represent well-preserved fragments of the Tethyan oceanic lithosphere (Lombardo et al., 1978) formed along a slow-spreading ridge, and reached eclogite facies then retrogressed to epidote-blueschist or greenschist facies (Lombardo et al., 1978; Blake et al., 1995), with intensive oceanic serpentinization occurring throughout (Ambrics et al., 1999).

Figure 1: Simplified map of the modern-day Alpine tectonic system, and location of the Queyras region of the Alps, bordering France and Italy. The blue-highlighted region indicates the study region of this project. Modified after Pfiffner et al. (2014).

These three localities are the Pelvas d'Abriès, Crête des Lauzes, and Rocca Bianca (Figure 1). The Pelvas d'Abriès is composed of layered, locally pegmatitic, gabbros, typically high-level dominant Ca-Mg and minor Fe-Ti gabbros and troctolites (Tricart and Lemoine, 1983; Ambrics et al., 1999; Lagabrielle et al., 1985, 2015, Agard, 2021). At the SE corner of the Pelvas body, dark m-scale layers of ultramafic composition are interlayered in the gabbros, interpreted as ultramafic intrusions escaped from the base of a magma chamber within higher-level gabbros (Ambrics et al., 1999). The Pelvas d'Abriès metagabbros have been interpreted as cumulate gabbros emplaced in a small magma chamber (Bearth et al., 1975). The Pelvas d'Abriès klippe provides exceptional outcrops, particularly on its southern face. These three ophiolites represent a stack of continental and oceanic nappes formed during the subduction and exhumation of the Tethyan seafloor (Agard et al., 2002) representing some of the largest and deepest ocean crustal pieces detached from a subduction zone (Reinecke, 1998; Angiboust et al., 2009).

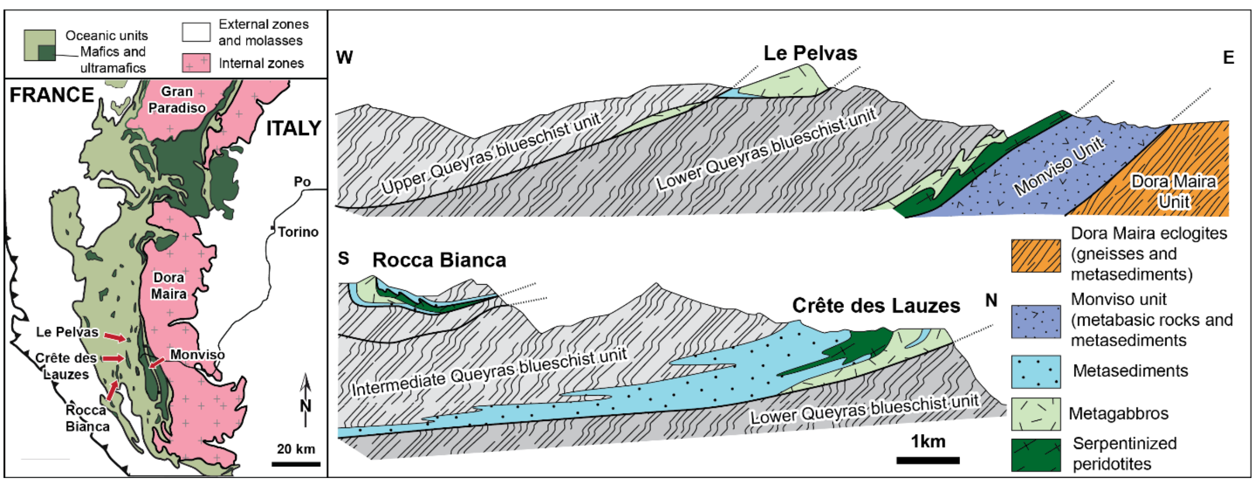

Figure 2: Simplified tectonic map of the Western Alps (left), and location of the three field sites where gabbro samples were collected for this research project: the Pelvas d'Abriès (top), and Rocca Bianca / Crête des Lauzes (bottom). Modified after Angiboust et al. (2011) and Lagabrielle et al. (2015).

3. OBJECTIVE AND SIGNIFICANCE OF THESIS

The objective of this project is to analyze the gabbroic samples gathered from three Alpine ophiolite localities from the Queyras region in France to further constrain their petrogenesis at slow spreading ridge and their tectonic evolution during subduction and obduction. For this project, two research objectives have been specifically defined:

Objective 1 – Investigate the petrology of the Queyras gabbro

The first objective of this project is to characterize the petrology of the gabbro samples through standard petrographic analysis, which will give insight on the sample composition and . Main minerals assemblages will be identified through standard petrographic analysis of thin sections. In addition, SEM-EDS will be used to investigate the major element chemistry of the mineral phases (pyroxene, plagioclase, Fe-Ti oxides) and provide quantifiable datasets to be able to constrain the gabbro samples found in the region. Finally, µXRCT will be conducted on subsamples to visualize volume, and investigate the distribution, of the Fe-Ti oxides.

Objective 2 – Identify the dominant deformation mechanisms

The second objective is to identify the dominant deformation mechanism(s) of each mineral in the main mineral phases. This will be conducted through standard petrographic analysis, as it will provide the best evidence for deformation mechanisms observed within the samples. The results will be integrated in deformation mechanisms maps available for each of the minerals and combined to further constrain the rheology of these gabbros.

This project's findings are used further constrain the origin and evolution of these Queyras ophiolites, and detail analysis of the deformation of the gabbros will improve the understanding of the rheology of the lower oceanic crust.

4. METHODOLOGY

This study focuses on three localities from the Queyras region of the Western Alps of France. These localities were chosen because (1) the origin of the exposed gabbros has been interpreted to be an oceanic core complex before subduction and exhumation (Lagabrielle et al., 2015), and (2) these rocks only suffered minor metamorphism during the Alpine Orogeny, preserving some of their original igneous characteristics. Eighteen samples were collected in summer 2024 by Dr. Gottardi: 10 samples from the Pelvas d'Abries (Samples QPV24-01 through -10), 3 samples from the Crête des Lauzes (QPL24-01 through -03), and 5 samples from the Rocca Bianca area (QLB24-01 through -05). To carry out the research objectives, the following analytical methods will be used.

2.1 Petrographic thin section analysis

Standard petrographic thin section were scanned with a Nikon CoolScan 5000 to produce full thin section scan. Subsequently, a Nikon LV100 Polarizing Microscope and Nikon DS-10 camera were used to conduct a petrographic analysis in order to identify primary mineral assemblages (Objective 1) and identify the dominant deformation mechanisms in each mineral (pyroxene, plagioclase, oxides) (Objective 2).

2.2 Scanning Electron Microscope (SEM) Electron Dispersive X-ray Spectroscopy (EDS)

To further constrain the petrology of the samples (Objective 1), SEM-EDS analyzes were carried out to analyze the major element chemistry of the minerals (pyroxene, plagioclase, oxides). Polished thin sections were first coated in 5 nm carbon using a JOEL EC-32010CC carbon coater. Backscattered electron (BSE) and EDS data were then collected using a Zeiss EVO 15 SEM operated in high vacuum mode and equipped with a 65 mm^2 Oxford Ulti Max energy dispersive spectroscopy (EDS)-silicon drift detector operating with Oxford Aztec software. Typical operating conditions for imaging were a 15-25 keV accelerating voltage and 5-15 nA of beam current at a working distance of 8.5mm.

2.3 X-Ray Computed Tomography (µXRCT)

To investigate the role of oxides on the deformation of pyroxene and plagioclase (Objective 2), µXRCT analyses were carried out on small cubes (2 cm x 2 cm x 2 cm) of relevant samples. µXRCT data were acquired on a Zeiss Xradia 620 Versa hosted in the Center for Polymer and

Advanced Composites at Auburn University, operated at 90-120 kV, 10-20W, and 0.05 acquisition time between frames. The µXRCT data was reconstructed using ZEISS Xradia Context microCT software and processed and analyzed using Nikon Elements Advanced Research software.

5. RESULTS

3.1. Optical Petrography

The deformation textures and preservation of the igneous mineralogy are quite variable across the three sampled localities. The gabbros from the Pelvas d'Abriès show the best preservation of the igneous mineralogical assemblages and modest deformation, while the samples from the Crête des Lauzes and Rocca Bianca show mylonitic to ultra-mylonitic deformation textures and significant blueschist to greenschist alteration. Together, these samples provide a record of the tectonic evolution of the gabbros, from their emplacement to subduction and obduction.

All samples are composed of clinopyroxene, plagioclase, and titanite. Blueschist/greenschist metamorphism is indicated by the presence of glaucophane, epidote, and chlorite. In outcrop, the gabbros appear mildly foliated to ultramylonitic. The Pelvas d'Abriès outcrop are the least foliated. There, the gabbros exhibit compositional layering that other authors have attributed to reflect their igneous texture (Tricart and Lemoine, 1983; Ambrics et al., 1999; Lagabrielle et al., 1985, 2015). Near the basal thrust contact of the Pelvas d'Abriès, the gabbros exhibit a much stronger mylonitic fabric: in outcrop, the macroscopic foliation is expressed by layers of fine grained and porphyroclastic tails of pyroxenes. The samples of both the Crête des Lauzes and Rocca Bianca are much more deformed compared to the Pelvas d'Abriès outcrops, showing mylonitic to ultramylonitic textures. The foliation is expressed by alternating layers of stretched pyroxene and fine-grained plagioclase. In thin sections, the foliation is defined by bands of finely recrystallized plagioclase grains and the tails of pyroxene porphyroclasts (Figure 2A). The dominant top to the southwest shear sense can be inferred from porphyroclasts tails and asymmetry as detailed below.

5.1.1. Pyroxene

CPx grains make up 30-40% of the thin sections, range from mm to cm in size and form beautiful porphyroclasts. They show evidence of both ductile and brittle deformation. CPx are typically fractured along their cleavage planes and stretched in the lineation direction in a bookshelf fashion (Figure 2). Bookshelf sliding commonly occurs in the synthetic direction indicating back-rotation consistent with a top-to-the-southwest sense of shear. Large CPx grains also preserve evidence of ductile deformation, including undulose extinction (Figure 2), and are often bent or kinked (Figure 2). The pressure shadows of the CPx porphyroclasts are filled with finely recrystallized plagioclase and Fe-Ti oxides that conform closely to the large CPx grain (Figure 2B/2C). Chemical alteration indicative of hydrothermal oxidation is also evident in CPx, resulting in either amphibole (Figure 3C/3D) or chlorite (Figure 3E). Chlorite, while commonly seen bordering CPx, is often accompanied by glaucophane in large quantities where recrystallization occurred within pressure shadows surrounding CPx grains.

5.1.2. Oxides

Fe-Ti oxides represent 5-10% of the thin sections and are found most commonly in the pressure shadows of CPx, associated with glaucophane and/or chlorite mixture in the plagioclase matrix (Figure 4B/5C). Larger Fe-Ti oxide grains typically show exsolution of ilmenite to titanite due to a change in metamorphic condition during subduction and/or exhumation of these gabbros (Figure 5E). Rutile appears to be present in minor quantities (Figure 4A). Some Fe-Ti oxides occur as elongated grains strained along the foliation in the lineation direction.

5.1.3. Plagioclase

All samples are composed of 60-70% plagioclase grains. The plagioclase grains are typically fined grained (< 20 μm) and altered, making it difficult to observe. Larger ghost grains (pseudomorphs?) of plagioclase can be seen around large chlorite- and glaucophane-rich pressure shadows (Figure 5A/5E). Plagioclase can also be seen as fill in extensional fractures (Figure 6D), in association with chlorite and epidote.

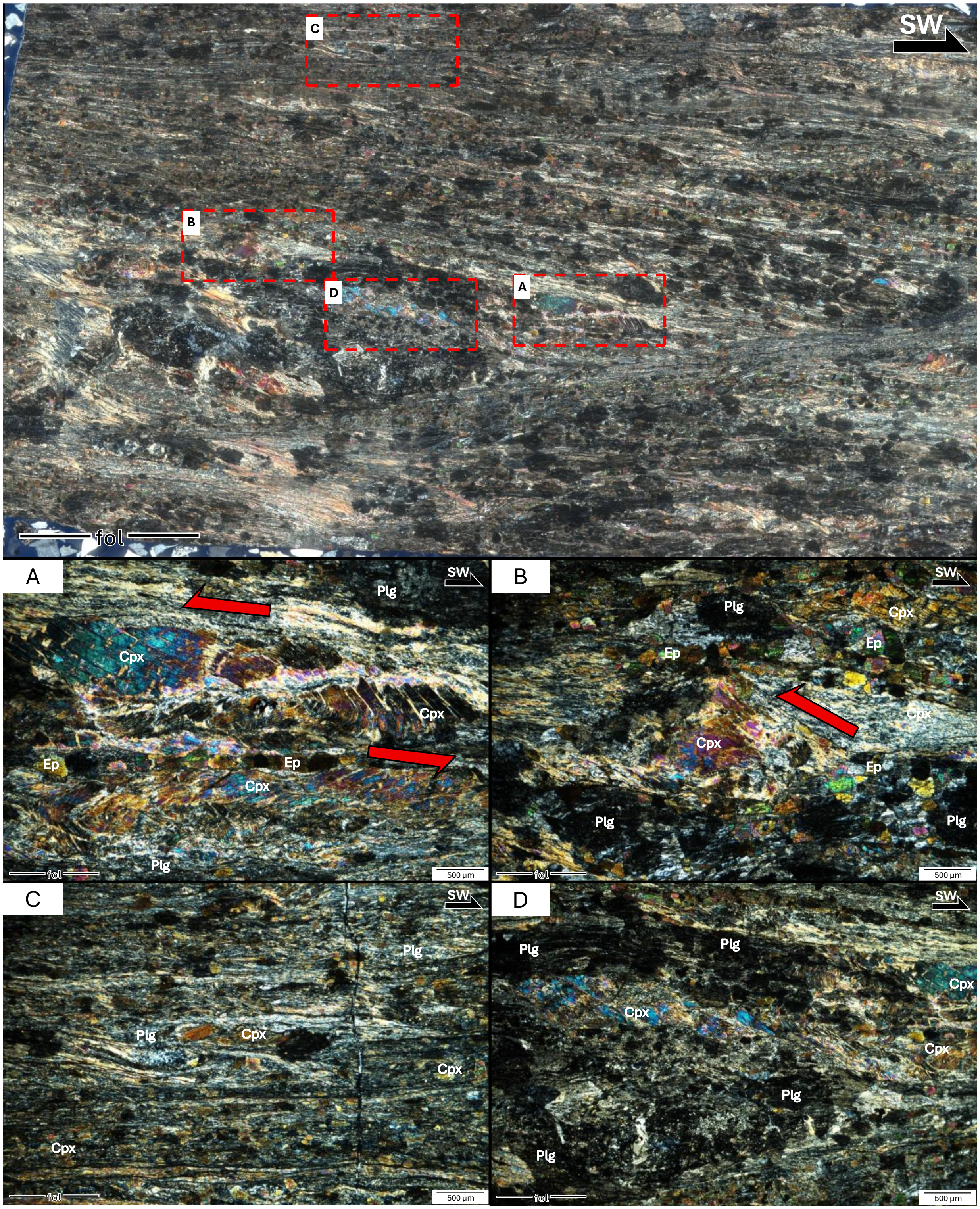

Figure 3: Sample QPV24-3B from the Pelvas d'Abries gabbro shows a variety of deformation textures in pyroxenes. CPx commonly form porphyroclasts displaying bookshelf microstructures (A). The tails of the porphyroclasts or pressure shadows commonly contain epidote and evidence of chemical alteration (B). (C) The asymmetry of porphyroclasts tails typically indicates a top-to-the-southwest sense of shear. (D) Larger Clinopyroxene grains can experience significant bookshelf sliding in the plagioclase matrix.

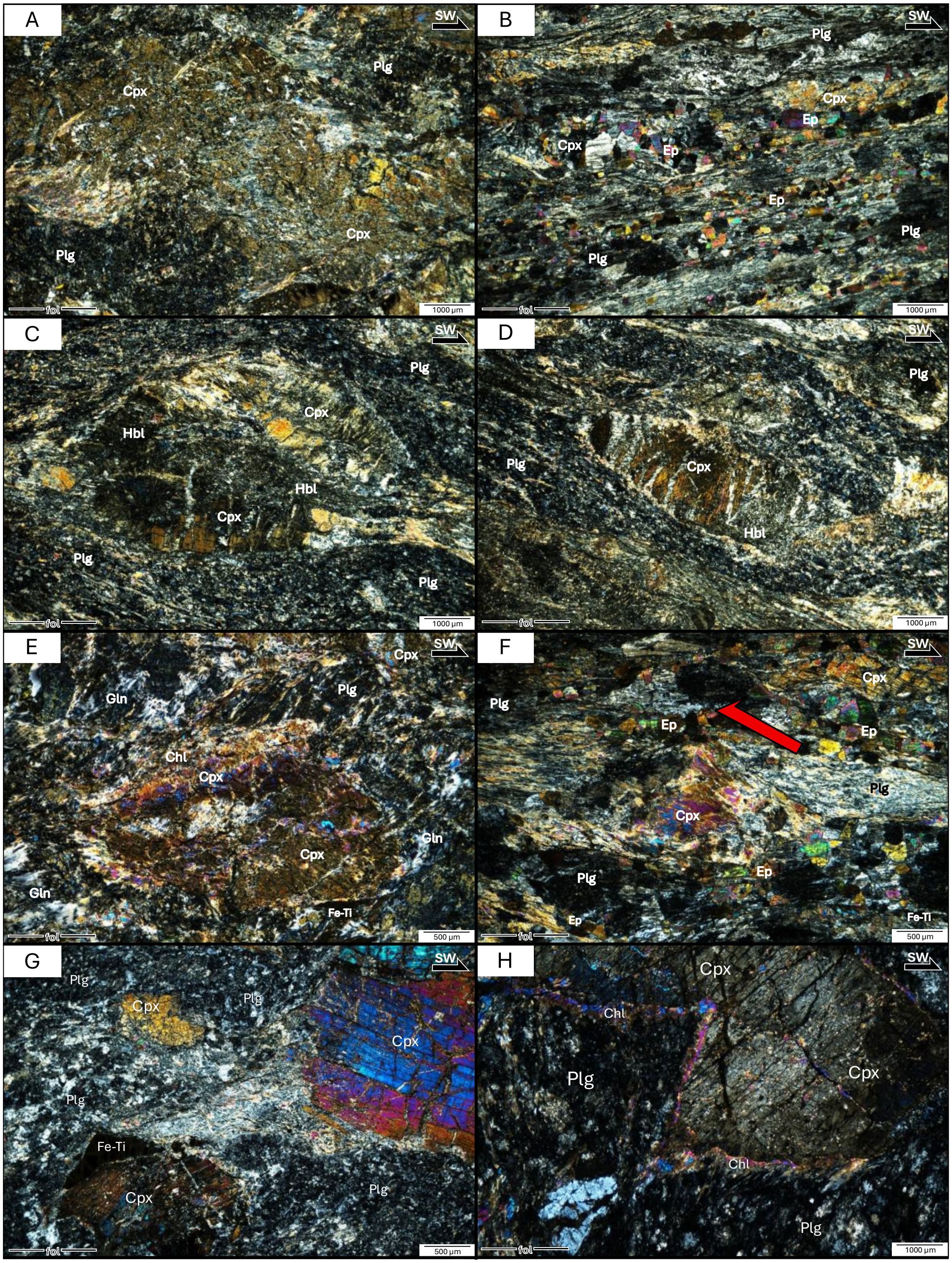

Figure 4: Representative CPx microstructures. (**A**) Many CPX exhibit brittle deformation. (**B**) Epidote commonly forms within shear bands or pressure shadows in close proximity to these CPx grains. (**C, D**) Chemical alteration of CPx to amphibole (hornblende) commonly occurs in areas of high stress especially. Chemical alteration of CPx to chlorite is also common and appears to initiate at the CPx grain boundaries (**E, F, H**). Fe-Ti oxides occur either as large masses in CPs pressure shadows (**G**) or strained grains parallel to the foliation (**F**).

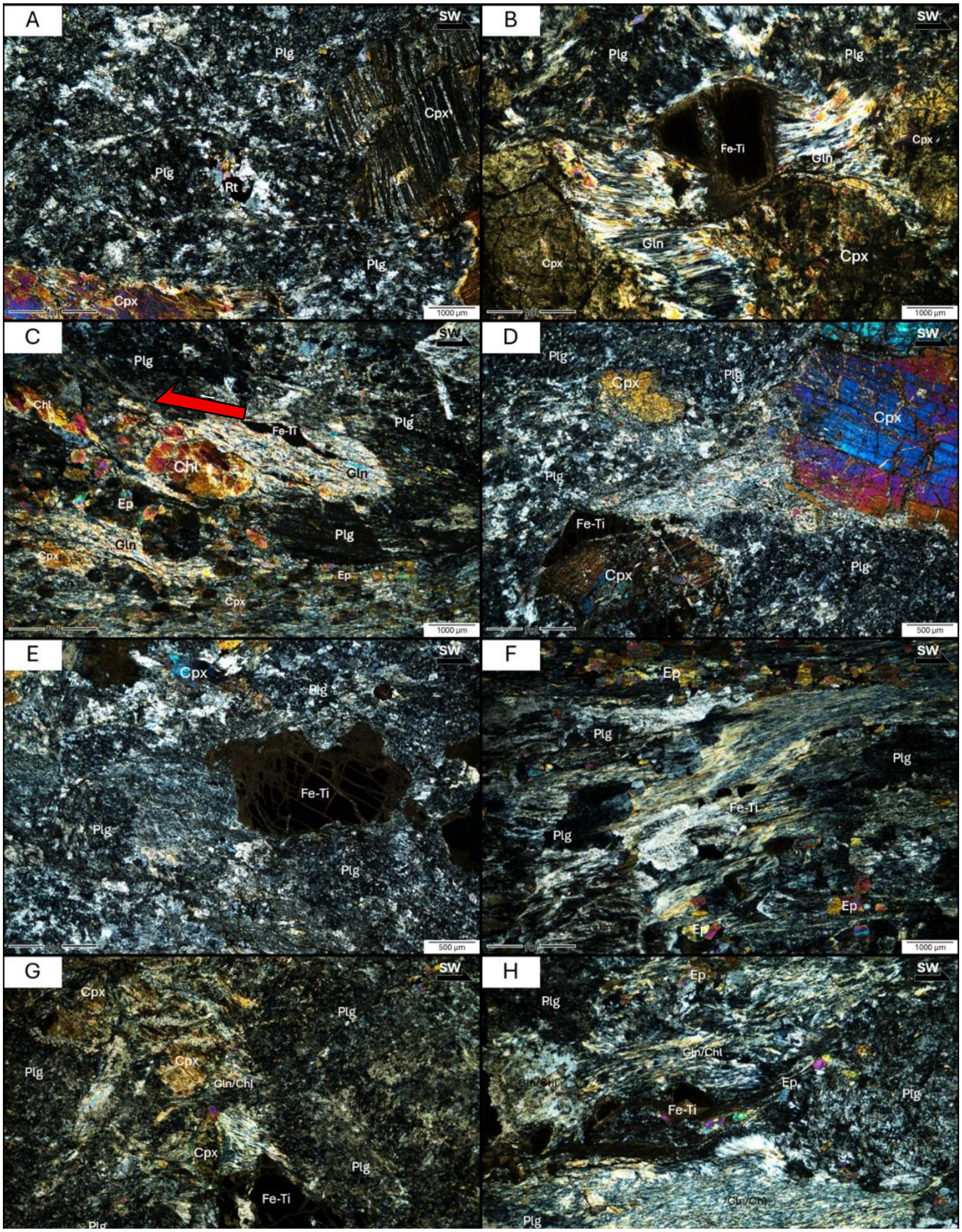

Figure 5: Fe-Ti oxides of multiple variety (ilmenite, titanite, rutile) can be observed in the Queyras gabbro (A). Pressure shadows are easily identifiable surrounding the oxides (B, C, D, E) and are replaced by glaucophane and chlorite. Plagioclase matrices follow the pressure shadows with a sense of flow, and clinopyroxene grains are often accompanying the Fe-Ti oxides (B, C). Chemical alteration from titanite to ilmenite can be seen within large oxide grains (B, E). Clinopyroxene grains can also be heavily deformed in the presence of large oxide grains (G). Smaller oxide grains tend to follow shear sense and have direction of flow (C, F, H).

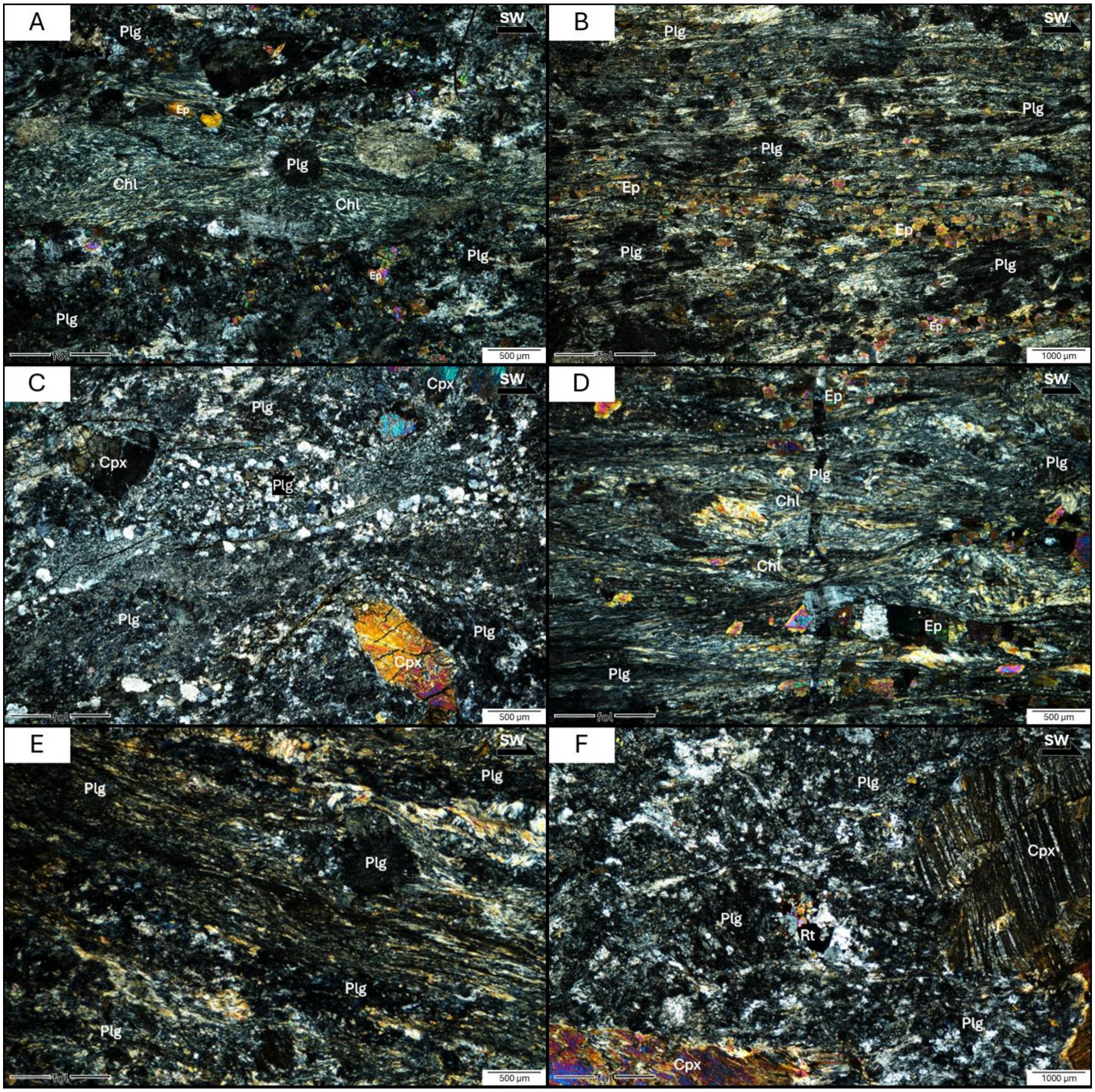

Figure 6: Representative plagioclase microstructures. (A, E) Large plagioclase pseudomorphs are common, and are typically associated with chlorite (A, D). Epidote forms within shear bands in the plagioclase matrix (B, D). Plagioclase can be seen recrystallizating and likely occurs after the formation of Epidote in greenschist facies (D). (F) Plagioclase typically fill the pressure shadows of large CPx, where they are associated with Fe-Ti oxides.

3.2. SEM/EDS

SEM-EDS analyses were carried out to investigate the major element chemistry of the dominant minerals from the three sample localities. Average composition of pyroxene, plagioclase, and oxides are reported in Tables 1, 2, and 3, respectively. Compositional maps of representative samples from the Pelvas d'Abriès, Crête des Lauzes, and Rocca Bianca are shown in Figures &, 8, and 9, respectively.

EDS analyses suggest pyroxenes contain almost equal amounts of Fe, Ca and Mg, suggesting that they are augite (Tables 1-3). The rims of CPx grain as well as cleavage planes appear typically darker in BSE, and are associated with lower Si but higher Al, Fe, and Mg content. Spot analyses suggest that these darker alteration rims could be actinolite, specifically the ferro-actinolite endmember. This epitaxial replacement of CPx (augite) along cleavage planes to actinolite is a common metamorphic and hydrothermal process known as uralitization (e.g., Vernon and Clarke, 2008). This reaction typically occurs under greenschist facies conditions (300 – 450°C) and represents the retrogression of high temperature mafic rocks (metabasalts or metagabbros) (e.g., Fagan and Day, 1997).

The plagioclase grains across all analyzed samples are rich in Ca and poor in Na, consistent with an anorthite composition. Swaths of plagioclase show evidence of alteration in BSE, and it is suspected based on the alteration pattern (flakes) and composition of the altered product that the minerals are sericite, which is a common product of hydrothermal alteration of plagioclase (Figure 6-8).

Oxides are composed of Ti and Ca suggesting that they are titanite (Table 3). Oxides show an interesting compositional zoning, with domains showing relative enrichment of Ti and Ca (Table 3 and Figure 6-8). It is suspected that the original Fe-Ti oxides (ilmenite) transitioned to titanite as Ca replaced Fe. This is a common greenschist facies metamorphic reaction that occurs when ilmenite reacts with Ca-bearing fluids or minerals, such as Ca-rich plagioclase or CPx (Harlov et al., 2006). This reaction also requires high water pressure and oxygen fugacity.

Table 1: Representative major element chemistry of pyroxene porphyroclasts from three sampled localities.

Elemental wt%	Pelvas D'Abriès	Rocca Bianca	Crête des Lauzes
SiO_2	34 ± 4	43 ± 1	44 ± 1
Al_2O_3	3 ± 2	25 ± 2	7 ± 1
FeO	4 ± 2	9 ± 1	9 ± 1
MgO	10 ± 2	3 ± 1	8 ± 1
CaO	13 ± 3	< 1	< 1
Na_2O	< 1	< 1	5 ± 1
MnO	< 1	8 ± 1	< 1
TiO_2	< 1	< 2	< 1

Table 2: Representative major element chemistry of plagioclase from three sampled localities.

Elemental wt%	Pelvas D'Abriès	Rocca Bianca	Crête des Lauzes
SiO_2	22 ± 4	52 ± 5	25 ± 5
Al_2O_3	17 ± 2	26 ± 2	15 ± 2
MgO	< 2	< 1	< 2
CaO	14 ± 2	16 ± 2	5 ± 1
FeO	< 2	< 1	< 2
Na_2O	< 2	5 ± 2	< 1
K_2O	< 1	< 1	4 ± 2

Table 3: Representative major element chemistry of oxides from the three sampled localities. Oxides are composed of Ti and Ca suggesting that they are titanite. Titanite grains show complex zoning, with relative enrichment of Ti and Ca, as shown in the table below and in Figure 6-8.

Elemental wt%	Pelvas D'Abriès	Rocca Bianca	Crête des Lauzes
Ti rich domains			
SiO_2	14 ± 2	29 ± 2	11 ± 1
TiO_2	42 ± 2	41 ± 2	39 ± 2
Al_2O_3	< 1	< 1	< 1
CaO	14 ± 1	28 ± 2	10 ± 1
Ti poor domains			
SiO_2	23 ± 1		13 ± 1
TiO_2	33 ± 1		31 ± 2
Al_2O_3	< 1 ± 1		< 1
CaO	23 ± 1		13 ± 1

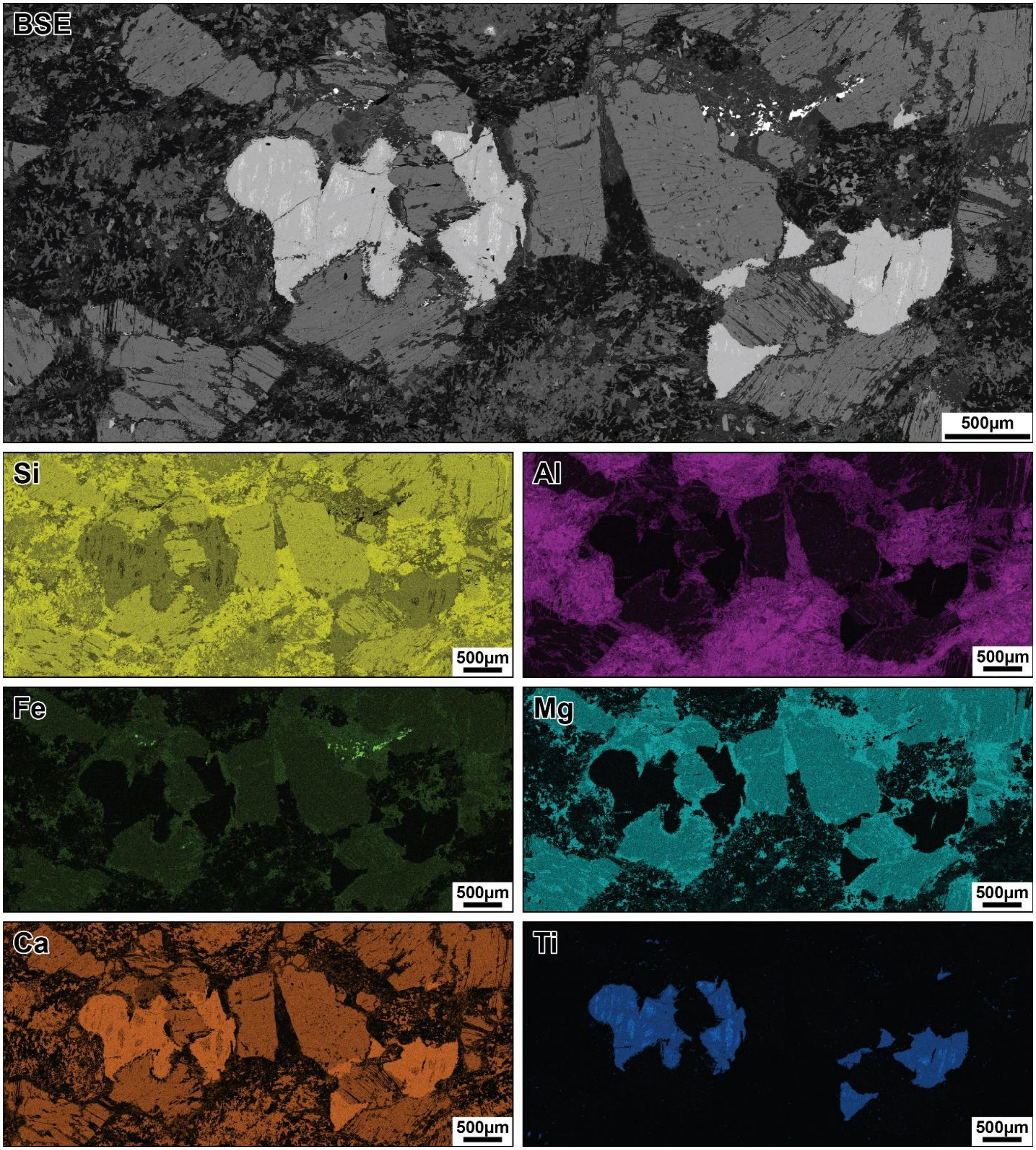

Figure 7: Representative major element chemistry of the gabbros from the Pelvas d'Abriès. The colors shown are chosen for high-contrast purposes only, with brightness increasing based on the presence of the associated element shown in each section (Si, Al, Fe, Mg, Ca, Ti) and a Back-Scatter Electron (BSE) image shown firstly.

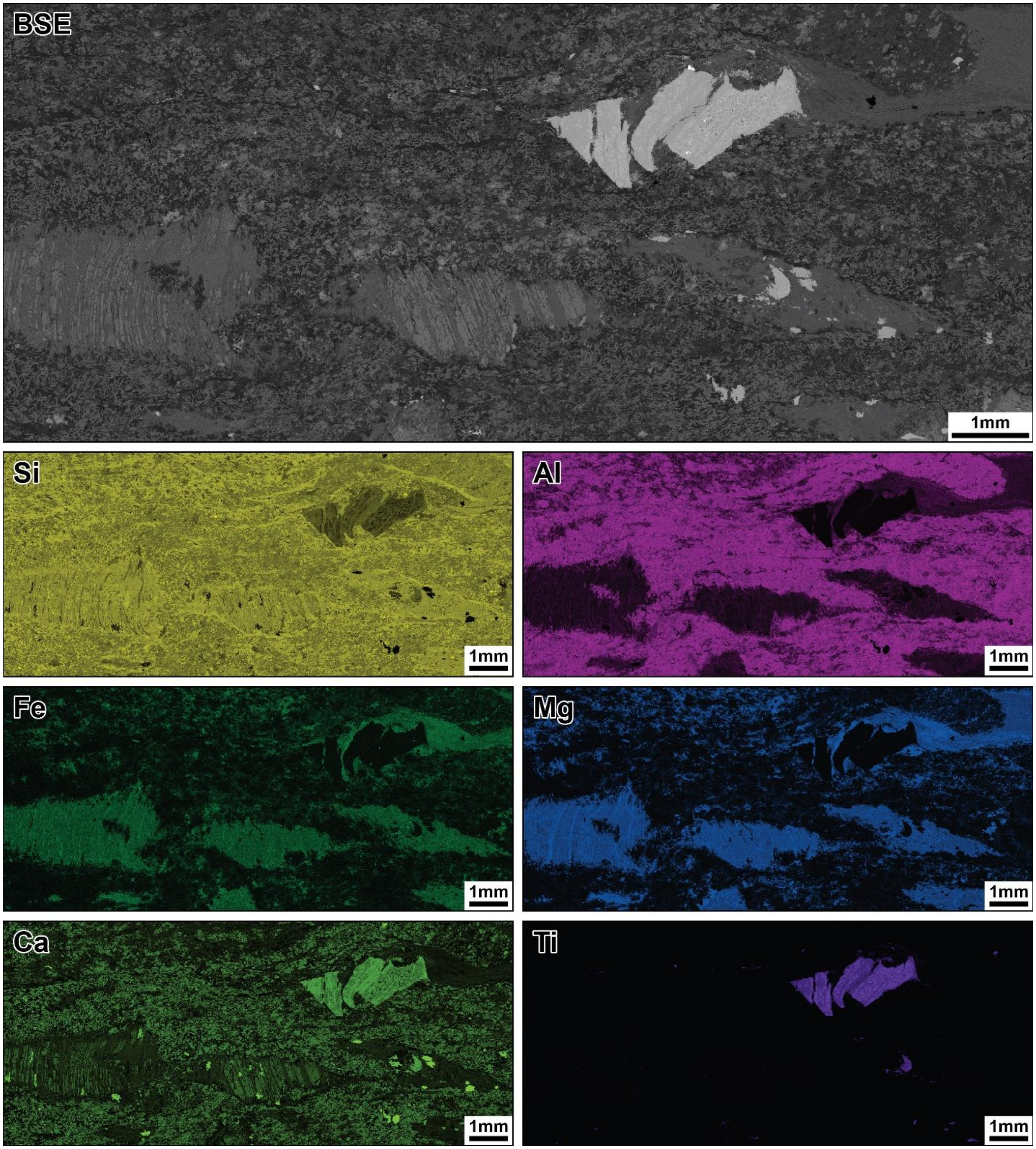

Figure 8: Representative major element chemistry of the gabbros from the Rocca Bianca area. The colors shown are chosen for high-contrast purposes only, with brightness increasing based on the presence of the associated element shown in each section (Si, Al, Fe, Mg, Ca, Ti) and a Back-Scatter Electron (BSE) image shown firstly.

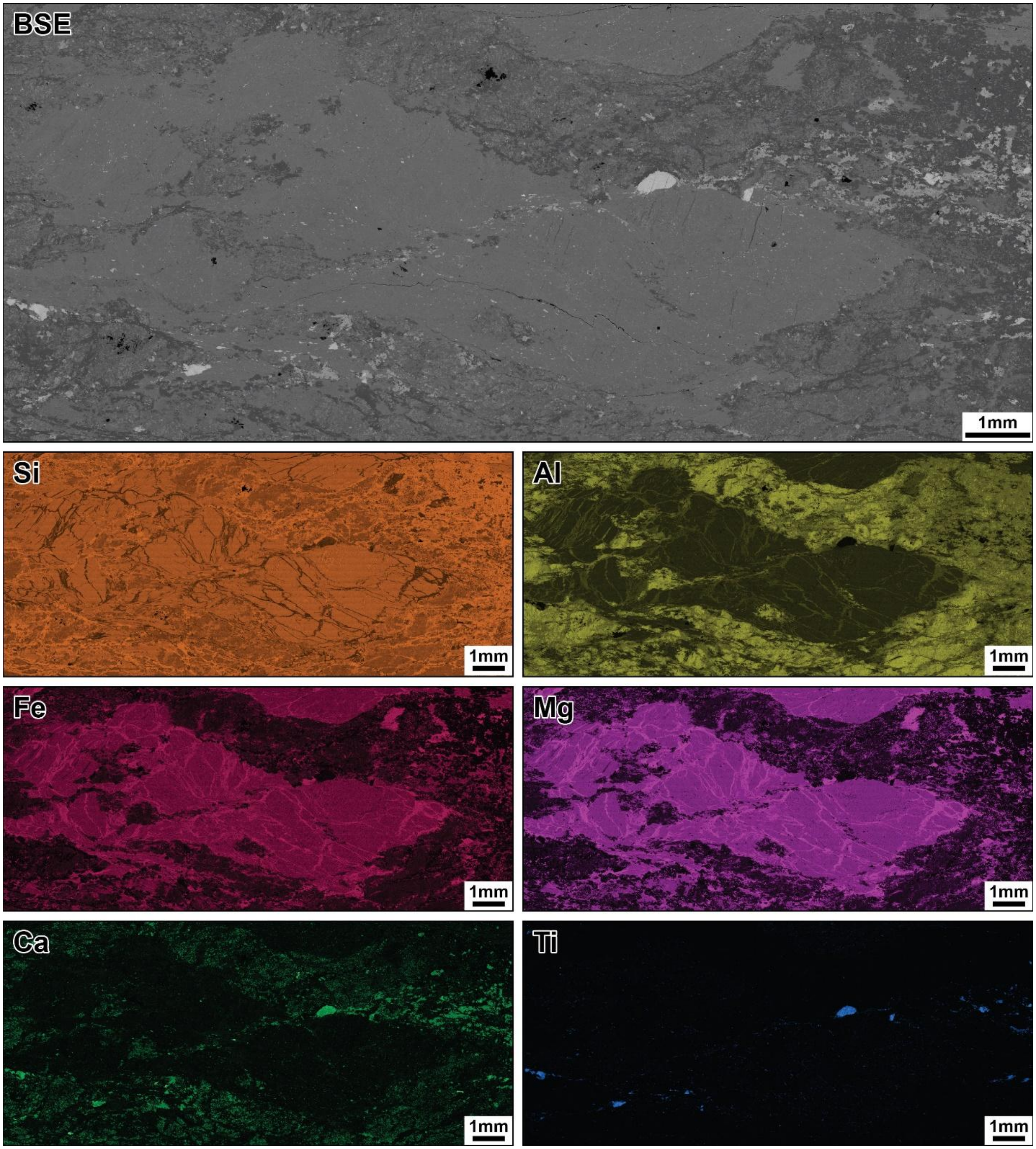

Figure 9: Representative major element chemistry of the gabbros from the Crête des Lauzes area. The colors shown are chosen for high-contrast purposes only, with brightness increasing based on the presence of the associated element shown in each section (Si, Al, Fe, Mg, Ca, Ti) and a Back-Scatter Electron (BSE) image shown firstly.

3.3. µXRCT

The goal of µXRCT analyses was to investigate the spatial distribution and shape and Fe-Ti oxides (Figure 10). Fe-Ti oxides are mechanically weak and could potentially result in strain localization. Although this project's samples contain 1-10% oxides, the analyzed samples were too small to see any preferential distribution. However, the µXRCT results show the close association between the oxides and the CPx (Figure 10) observed in thin section (Figure 2-5).

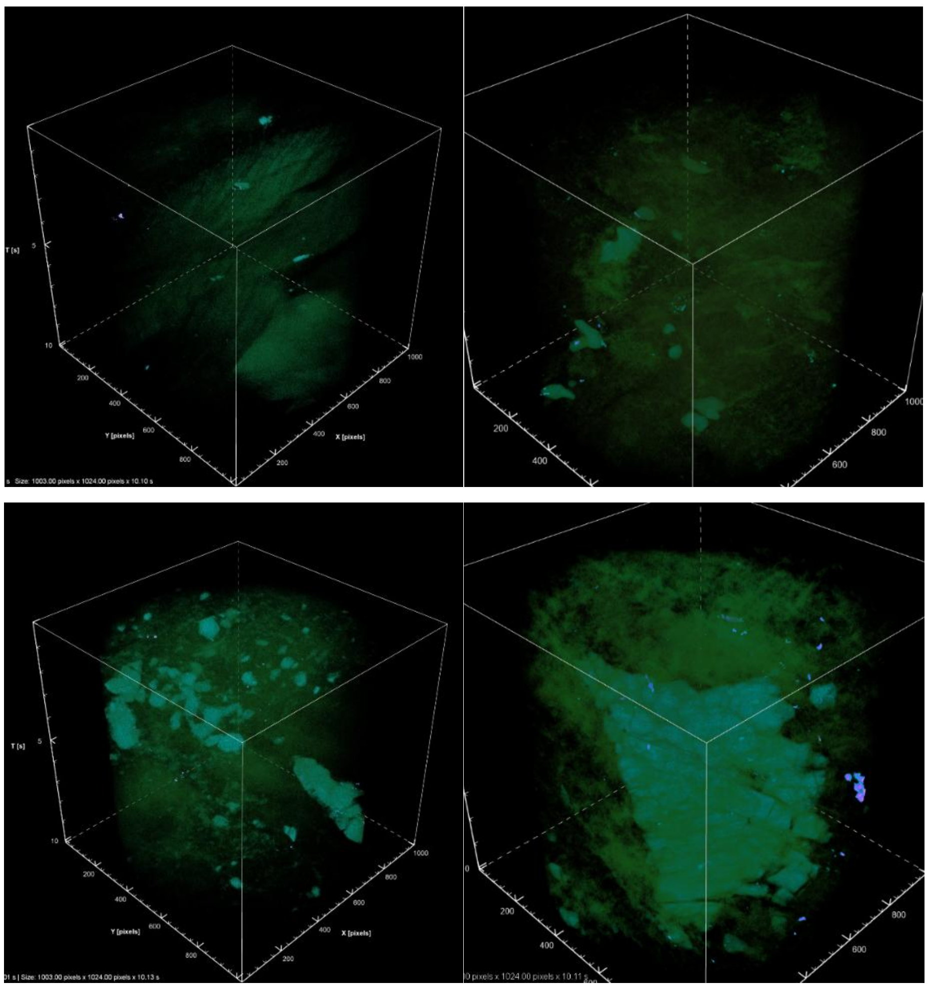

Figure 10: µXRCT scans of various gabbro samples. The analyzed volume was filtered to highlight the dense phases, i.e., oxides. The more subdued colors are associated with CPx. The analyzed volume is ~1cm^3 for each sample. The 4 scans shown were chosen as a representative accumulation of densities within select gabbro samples.

6. DISCUSSION

The goal of this project was to investigate the petrogenesis and tectonic evolution of gabbroic samples from the Queyras ophiolites to improve the understanding of the rheology of lower oceanic crust. These samples record a complex suite of both deformation and metamorphic textures. In the following section, observations that suggest that the Queyras gabbros originated from a slow-spreading ridge as indicated by brittle deformation and fluid infiltration which resulted in hydrothermal alteration before experiencing blueschist- to greenschist-facies metamorphism during the Alpine orogeny.

6.1.Evidence for subduction deformation

Microstructural observations suggest that the gabbros experienced both ductile and brittle deformation associated with their complex and protracted tectonic evolution. Evidence of ductile deformation of the CPx includes patchy undulose extinction and bent cleavage. (Figure 2). Additionally, most CPx grains form also for porphyroclasts, with tails composed of plagioclase and epidote (Figure 2-4), suggesting that the gabbros experience significant ductile deformation for the mylonitic texture to develop. Ductile microstructures are overprinted by brittle deformation, mostly expressed by brittle fracturing along cleavage planes. Fractures are typically oriented at high angle to the foliation, with opening direction in the lineation direction, in a boudinage fashion (Figure 2). The fractures are commonly filled with plagioclase or sericite (from alteration of plagioclase). In cases, this fracturing leads to the development of bookshelf structures, with significant sliding along the fractures, consistent with a synthetic shear direction (Figure 2-3). Development of such microstructures suggest that at some point during the evolution of the gabbros, the CPx switch from ductile (undulose extinction/bent cleavage/porphyroclasts) behavior to brittle (fracturing/boudinage), while plagioclase was still ductile to allow for the development of CPx porphyroclasts and bookshelf sliding.

The brittle-ductile transition in pyroxene occurs where its behavior typically shifts from fracturing to plastic deformation, typically triggered by high temperatures (~700–900°C) (Boland and Tullis, 1986; Maitre et al., 2024; Ueda et al., 2020). Because of the presence of several metamorphic minerals (glaucophane, chlorite, etc.) in the pressure shadows of CPx porphyroclasts, that do not show evidence of such high temperature conditions, it is suggested that the ductile and brittle microstructures preserved in the CPx record the microstructural evolution of the gabbro prior to subduction, rather than strain accumulation near the ridge.

6.2.Tectonic evolution of the Queyras gabbros

Epidote grains forming within pressure shadows of CPx porphyroclasts as well as shear bands (Figures 3A/B & 5B/D) suggesting that the gabbros experienced a period of hydrothermal alteration. Reaction fronts can be seen around CPx grains where dissolution occurred and provided the necessary Ca, Al, Si, and Fe^{3+} to mix with H_2O and form epidote, causing the CPx to retrogress into ferro-actinolite (Figures 6-8). The association of epidote and shear bands suggest that these textures may have grown during prograde blueschist to greenschist facies metamorphism due to a need for high stress/pressure and moderate temperature conditions. Additionally, the presence of chlorite and glaucophane also supports a period of hydrothermal alteration. These two minerals commonly coexist and are typical of blueschist and greenschist metamorphism of mafic rocks. The appearance of chlorite likely tracks the transition from blueschist to greenschist conditions during prograde metamorphism. The chlorite and glaucophane are shown to have formed around pressure shadows of the clinopyroxene or next to CPx grains (Figures 4 G/H & 5H). Fe-Ti oxide grains (ilmenite, titanite, rutile) are often accompanying the CPx grains that are large and intact, although some relic fragments can be observed spread out along foliation (Figure 4). Pressure shadows are easily identifiable surrounding most oxide grains (Figure 5B-E) and are often replaced by a mixture of glaucophane and chlorite. Chemical alteration from titanite to ilmenite can be seen within large oxide grains (Figure 5B, E), which is supported by SEM/EDS findings showing a lack of Ca in areas that have been affected.

Altogether, this metamorphic overprint seems to be tracking the prograde blueschist to greenschist metamorphic conditions. The gabbros are devoid of any indication of eclogite facies metamorphism (garnet, omphacite, kyanite, phengite), suggesting that they did not go very far in the subduction channel, and must have been obducted early and rapidly during the Alpine Orogeny.

6.3.Origin of the Queyras metagabbros

With the observations and interpolations gathered on the Queyras gabbro sample set, a petrogenesis of the gabbro can be theorized with estimated times for each deformation event based on evidence supported by other research on the area. It is estimated that the opening of the Piedmont-Ligurian ocean and following subduction in Jurassic-Cretaceous, suggesting a date of around 165-155 Ma (Yegorova et al., 2023). It is expected that this gabbro originated from a slow-spreading ridge due to the presence of shear banding, major deformation of CPx, and epidote/chlorite hydration. These all indicate a tectonically active environment with significant fluid infiltration that conforms with a typical slow-spreading oceanic ridge. Following this event, subduction occurs and allows for the gabbro to enter prograde blueschist conditions. The formation of the observed shear bands and brittle deformation mechanisms occur at this point before exhumation of Tethys occurs, leading to retrograde syn-tectonic greenschist conditions. It is theorized that before the exhumation of Tethys, this gabbro experienced brief Amphibolite conditions due to the minor presence of Hornblende (Figure 4C), which require such conditions to chemically alter Clinopyroxene. Fluid is introduced into the system during exhumation before ending in the Alpine Orogeny (Figure 11). The introduction of fluid during exhumation allows hydrothermal alteration to take place and form the observed Epidote in addition to partial chemical alteration of glaucophane to chlorite.

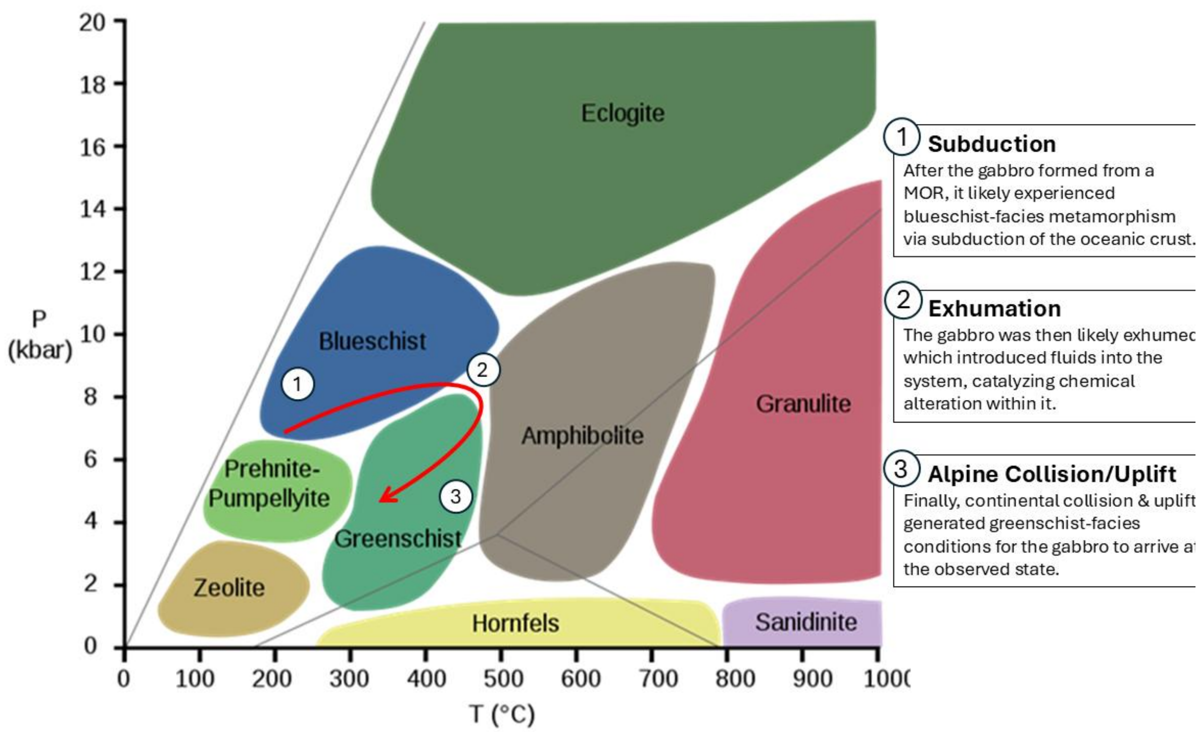

Figure 11: Approximate pressure-temperature-time metamorphic path (P-T-t) of the Queyras gabbro. Points 1-3 indicate a rough estimate for the petrogenesis and timeline of the Queyras gabbro.

7. CONCLUSIONS

This study provides new constraints on the rheology, deformation mechanisms, and tectonic and metamorphic evolution of gabbros from the Queyras ophiolites (Western Alps), that have been interpreted to form at a slow-spreading ridge. By combining petrography, SEM-EDS, and μXRCT, documentation of a complex interplay among mineralogy, deformation is available, and fluid-assisted metamorphism that governs strain localization in the lower oceanic crust.

Microstructural observations reveal that clinopyroxene accommodates both ductile and brittle deformation, recording a transition across the brittle–ductile regime likely initiated under near-ridge, high-temperature conditions. The development of porphyroclasts, undulose extinction, and bend cleavage, followed by fracturing and bookshelf sliding, indicates a progressive evolution of deformation mechanisms during cooling and tectonic exhumation. Plagioclase forms a fine-grained, dynamically recrystallized matrix that accommodates strain, while metamorphic reactions (e.g., uralitization and sericitization) further modify its mechanical behavior.

A key result of this study is the spatial and mechanical association between deformation and Fe–Ti oxides. These phases are consistently localized within pressure shadows and along foliation, and their presence correlates with zones of enhanced strain. This relationship suggests that even minor proportions of weak phases can exert a first-order control on strain localization and effectively reduce the bulk strength of gabbroic aggregates. Although μXRCT analyses did not resolve large-scale preferred distributions, they confirm the close spatial coupling between oxides and major silicate phases observed in thin section.

The metamorphic assemblages (glaucophane, chlorite, epidote, actinolite) and associated reaction textures record a prograde to retrograde evolution from blueschist- to greenschist-facies conditions, driven by fluid infiltration during subduction and exhumation. The absence of eclogite-facies minerals indicates that these rocks did not reach significant depths within the subduction channel and were likely exhumed relatively early. Altogether, the data supports a multi-stage tectonic history involving (1) deformation and hydrothermal alteration at or near a slow-spreading ridge, (2) subduction-related metamorphism and continued strain localization, and (3) fluid-assisted retrogression during exhumation in the Alpine orogeny.

These findings have important implications for models of lower crustal rheology and plate boundary processes. They highlight the critical role of phase mixing, fluid-rock interaction, and minor weak constituents in promoting strain localization in mafic rocks. In particular, the influence of Fe–Ti oxides on weakening suggests that commonly overlooked accessory phases may significantly impact the mechanical behavior of the oceanic lithosphere. This work therefore provides a microstructural framework to inform geodynamic models and experimental studies aimed at understanding deformation in multiphase systems.

Future work should focus on quantifying the rheological impact of oxide-bearing assemblages through experimental deformation studies and extending similar integrated analyses to other ophiolitic and oceanic crustal sections. Such efforts will be essential for refining the understanding of strain partitioning, lithospheric strength, and the dynamics of slow-spreading ridge systems and subduction zones.

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