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Master thesis:

**PETROGRAPHIC AND GEOCHEMICAL FEATURES OF
MANTLE PERIDOTITE – GABBRO CONTACTS
FROM IODP HOLE U1601C
(ATLANTIS MASSIF, MID-ATLANTIC RIDGE)**

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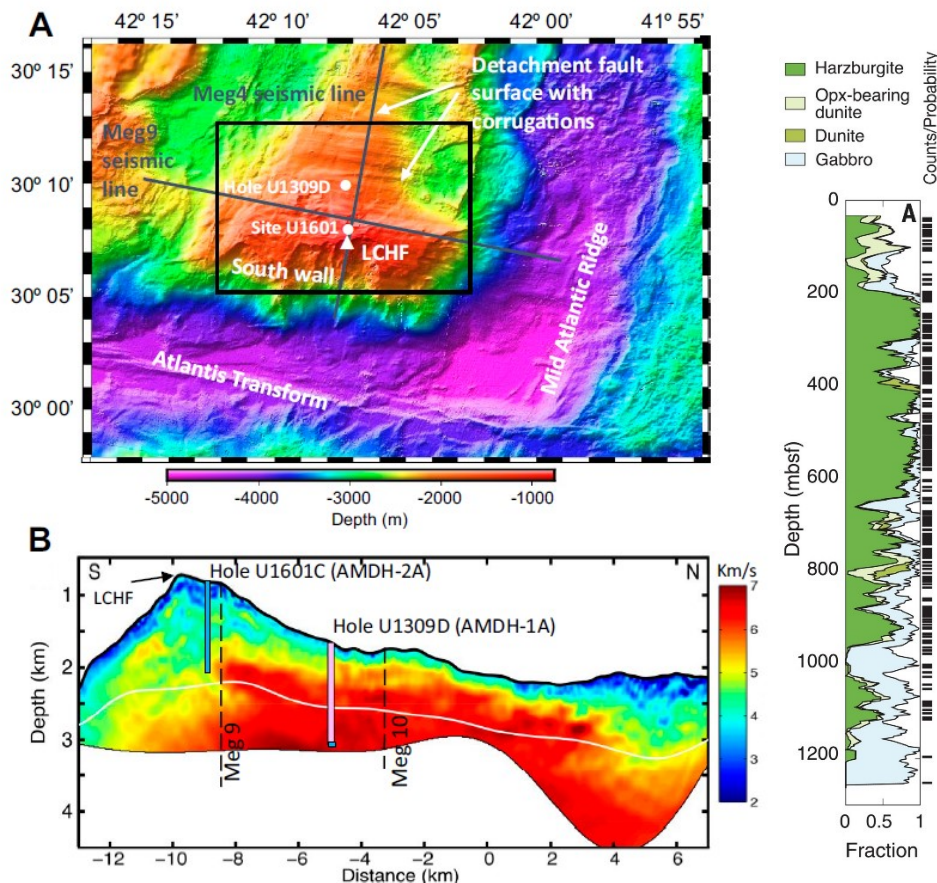
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ABSTRACT

Oceanic lithosphere formation occurs at mid-ocean ridges, where melts migrate through the lithosphere and crystallize to form the lower oceanic crust. At slow-spreading ridges, crustal accretion is characterized by strong lithological and structural heterogeneity, and gabbroic intrusions commonly occur within serpentinized mantle peridotites. IODP Expedition 399 drilled Hole U1601C at the Atlantis Massif, Mid-Atlantic Ridge (30°N), which displays these features.



From *McCaig et al. (2023)* and *Lissenberg et al. (2024)*. Location of Atlantis Massif oceanic core complex and of IODP Hole U1601C.

A total of 22 thin sections recovered from Hole U1601C cores, representing different types of gabbro–mantle contacts and contact-related lithologies were investigated. The studied samples include several different contacts and contact-related lithologies consisting of: contacts between coarse-grained gabbro and serpentinized peridotite with either magmatic percolation in the mantle or olivine occurrence in gabbro; thin (< 1 cm) olivine-rich troctolite, and thick (5–60 cm) olivine-rich troctolites.

Petrographic observations performed in Università di Pavia were integrated with major-element analyses of magmatic silicates and sulphides by electron probe micro-analysis (EPMA) during a two

months Erasmus+ Traineeship in Institut des Sciences de la Terre, in Orléans (France). LA-ICP-MS technique has been carried out in CNR-GEO Pavia for trace-element analyses of clinopyroxene.

The investigated contacts display strong textural and compositional variability indicative of mantle-rock reaction. Olivine along the contacts commonly occurs with resorbed textures or as rounded crystals enclosed within plagioclase and clinopyroxene, exhibiting reaction with the melt. Geochemical data further confirm the occurrence of the mantle-melt reaction. High-Mg# clinopyroxene occurs within contact-related troctolites and displays compositions and textural relationships consistent with crystallization during melt-rock reaction rather than simple fractional crystallization. Olivine compositions also vary according to the extent of melt infiltration and re-equilibration, with lower Fo# values associated with lithologies affected by higher melt/rock ratios that re-equilibrate with the percolating melt.

A fundamental feature of the contact-related lithologies is magmatic sulphides abundancy. The observed phases are pyrrhotite, pentlandite, and chalcopyrite, which occurrence indicates strong enrichment in sulphur and chalcophile elements during mantle-melt interaction. Thus, we can conclude that the S budget of the section is entirely dominated by mantle-melt reactions, which govern sulphur saturation in the melt and the availability of chalcophile elements that constitute sulphide aggregates.

These relationships, together with the occurrence of magmatic phases penetrating the mantle, indicate that the contact-related rocks record open-system interaction between percolating MORB-type melts and a pre-existing olivine-rich mantle matrix. The results indicate that the studied serpentinized peridotite-gabbro contacts represent hybrid zones generated by the interaction between mantle rocks and migrating melts, that control mineral assemblages and element distributions.

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1. INTRODUCTION

Mid-ocean ridges are divergent plate boundaries, where deep mantle material upwells, promoting partial melting which generates basaltic magmatism. Successive batches of primitive, high-MgO melts sourced from the partially molten asthenosphere contribute to the accretion of new oceanic lithosphere through a combination of magmatic addition and tectonic processes. Magma may be transferred into the overlying lithosphere where it accumulates and crystallizes near the petrological Moho or intrude the lower crust as plutonic bodies and crystal mushes. Repeated intrusions of hot magma diffuse heat to the host rock, which may induce partial melting of the previously crystallized lithologies to various degrees (Leuthold *et al.*, 2018).

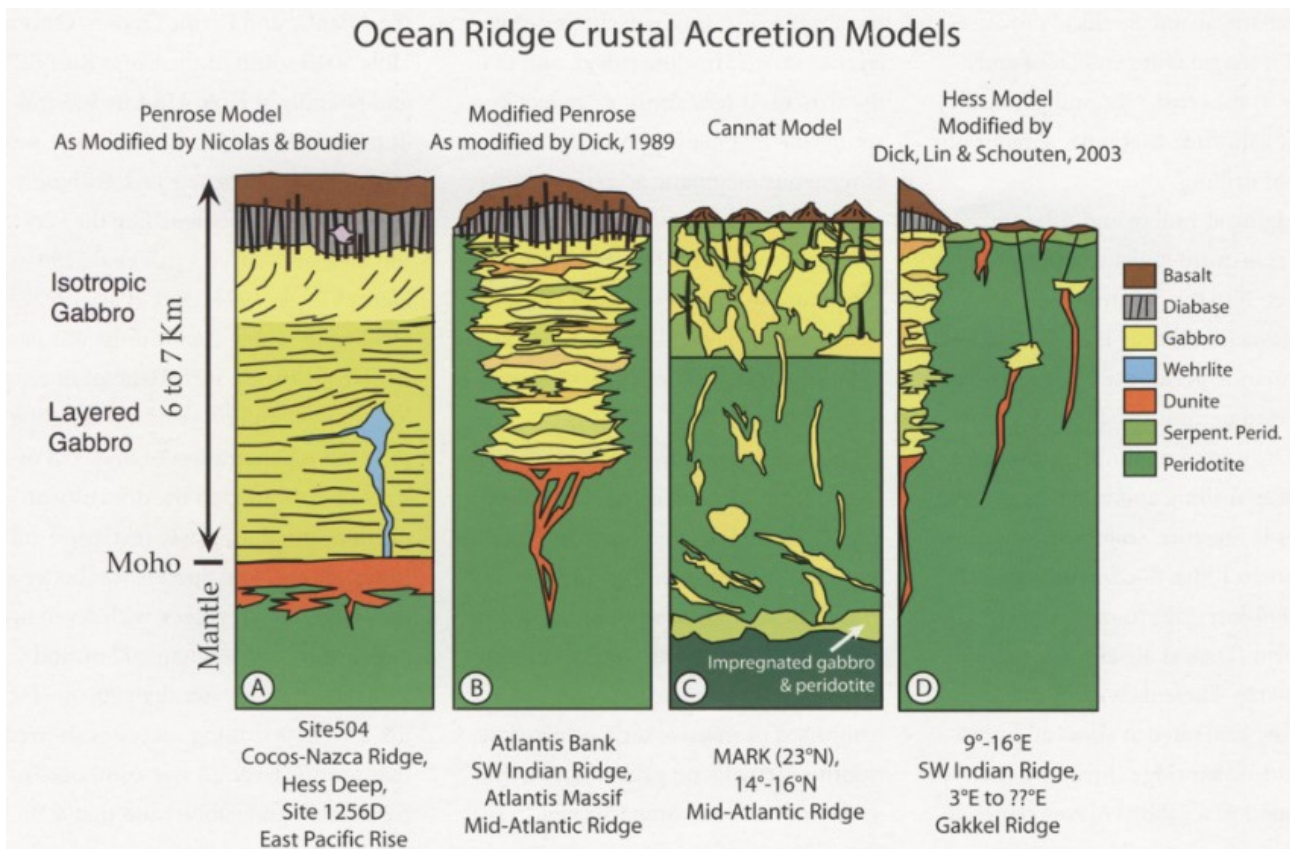


Fig 1. From Dick *et al.* (2006). Models for crustal accretion at ocean ridges. A. Classic interpretation of the Penrose Model for a fast-spreading ridge based on the Oman Ophiolite. B. Penrose model as modified for slow-spreading ridges based on the abundance of peridotite and frequent absence of gabbro at transforms following focused melt-flow models. C. Model for the anomalous 14°-16°N area of the Mid-Atlantic Ridge. D. Model for magmatic and amagmatic accretionary segments at ultra-slow spreading ridges. It is unknown how far Hess type crust extends along Gakkel Ridge as the ridge is unsurveyed east of 85°E.

Oceanic crust generated at mid-ocean ridges may develop a continuous stratified architecture consistent with the Penrose-type model, reaching up to 6 km in thickness, in mainly magmatic ridge environments (Lissenberg & Dick, 2008; Lissenberg *et al.*, 2019; Basch *et al.*, 2025; Liao *et al.*, 2025). However, the architecture and mechanisms of crustal accretion vary substantially with

spreading rate. Fast-spreading ridges are generally characterized by relatively high and continuous magma supply (*Liao et al., 2025*), while slow-spreading ridges, such as the Mid-Atlantic Ridge (MAR), are characterized by broader structural and lithological heterogeneity, with widespread gabbroic intrusions within serpentinitized peridotite (*Drouin et al., 2009*).

The formation of the lower oceanic crust is related to the migration, crystallization and reaction of melts within crystal-dominated magmatic systems. Rather than being transported exclusively through focused and episodic extractions, melts may migrate through a porous flow within a crystal-dominated matrix. Such diffuse melt migration produces prolonged interaction between migrating melts and the surrounding crystal framework, promoting reactive processes that can modify the composition of both melts and crystallizing lithologies (*Basch et al., 2025*). Melt migration and melt–rock reactions are therefore important processes in the lowermost oceanic crust and underlying sub-ridge mantle (*Lissenberg et al., 2019*). Additionally, mantle-derived lithologies may become variably hybridized and incorporated into the crustal sequence, highlighting the relevance of interactions between mantle rocks and crustal melts during oceanic crust accretion (*Basch et al., 2025*).

The architecture of the magmatic bodies beneath the ridge axis is thus fundamental to understanding how the lower oceanic crust is assembled. Classical models suggest crustal magma chambers as reservoirs where primitive melts crystallize and differentiate. However, the lack of clear geophysical evidence for large, long-lasting crustal magma chambers beneath slow-spreading ridges, associated with the occurrence of relatively small and isolated magmatic bodies, questions the applicability of such models to these environments (*Sinha et al., 1998; Leuthold et al. 2018*). Instead, melt flow may concentrate into localized magmatic centers within individual ridge segments. *Dick et al. (2008)* propose that such centers may migrate in space and time rather than remaining fixed at an axial position, with igneous complexes developing incrementally through the continuous emplacement and crystallization of successive sills and dikes.

Therefore, the interaction between these intrusive melts and their surrounding mantle host rocks can provide constraints on the processes guiding the generation and modification of the lower oceanic crust. In particular, contacts between gabbroic intrusions and mantle-derived lithologies may record the physical and chemical effects of melt emplacement and migration, as well as melt–rock interaction.

This Thesis studies in detail the contact zone and the interaction between circulating fluids and melts with the host serpentinitized mantle. These processes can promote the enrichment of trace elements, particularly sulfur, leading to anomalous sulphide crystallization along the contact zones.

2. SLOW-SPREADING RIDGES

Slow-spreading ridges are characterized by spreading rates generally lower than 50 mm/yr and represent a major component of the global mid-ocean ridge system. Approximately half of the global mid-ocean ridges are characterized by slow spreading, including the Mid-Atlantic Ridge. Compared with fast-spreading ridges, they exhibit a more heterogeneous crustal architecture and a different seafloor morphology, reflecting the variable contribution of magmatic accretion, tectonic extension and mantle exhumation (*Sinha et al., 1998; Dick et al., 2008; Blackman et al., 2011*).

A characteristic feature of slow-spreading systems is the occurrence of oceanic core complexes (OCCs). These structures are located where plate divergence is accommodated by detachment faults. Sustained slip along these faults, typically lasting 1-2 Myr, leads to the exhumation onto the seafloor of deep crustal and mantle rocks, consequently providing direct access to lithologies that would otherwise remain buried beneath the seafloor. Oceanic spreading involving oceanic detachment faults, recognized as a distinct mode of oceanic accretion, is inherently asymmetric and widespread both at slow and ultraslow spreading ridges (*Blackman et al., 2011; Escartin et al., 2017*).

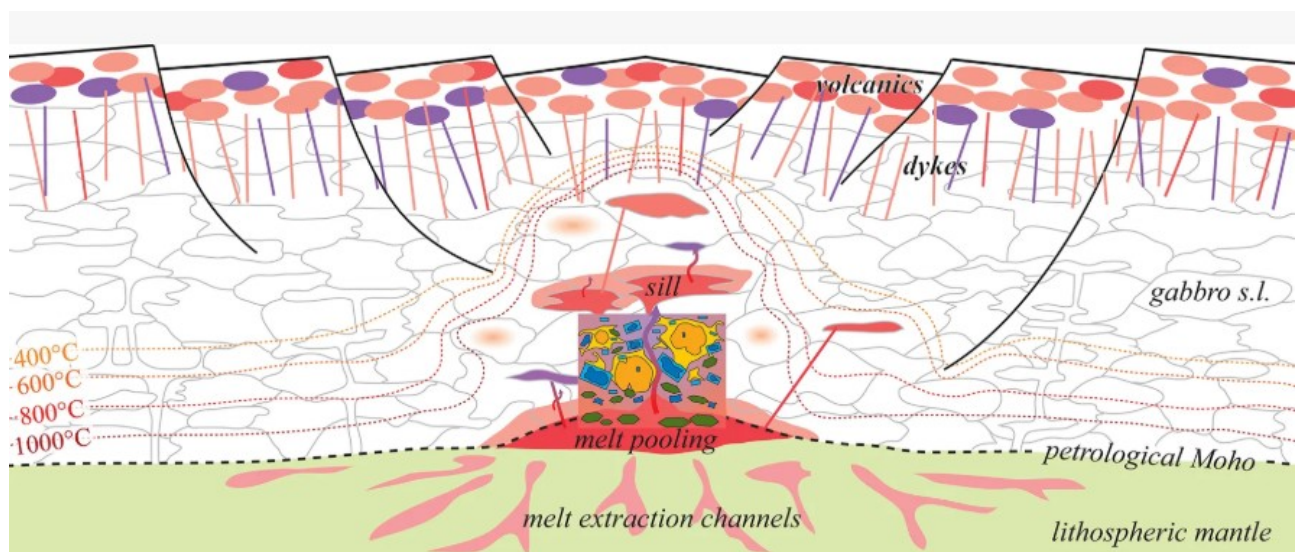


Fig 2. Leuthold et al. (2018). Cross-section of slow-spreading ridges, showing the different occurrences of melt in the oceanic crust. Gabbro s.l. includes troctolite, olivine-gabbro, gabbro, gabbro-norite and ferrogabbro. Also, dunite occurs along the Moho. Young hot crustal gabbro reacts (i.e., partial melting, hybridization, recrystallization) with invading primitive mantle-derived melt. Crystals, rocks and melt chemistry and texture are modified.

The architecture of slow-spreading oceanic lithosphere is therefore strongly heterogeneous. Magma intrudes and interacts with relatively cool serpentinized peridotites. This allows direct access to the relationship between mantle rocks and circulating melts, since the contacts between gabbroic intrusions and their mantle host may preserve evidence of modification of melts within the lithosphere

during emplacement and circulation, which produce intrusive rocks and magmatic veins, including olivine-rich troctolites which display interstitial clinopyroxene.

Tectonic exhumation produces the exposure of deep lithologies, that makes slow-spreading ridges extremely suitable for investigating the architecture of the oceanic lithosphere. In particular, the Mid-Atlantic Ridge provides several examples of oceanic core complexes, including the Atlantis Massif at approximately 30°N.

2.1 MID-ATLANTIC RIDGE

The Mid-Atlantic Ridge (MAR) is a divergent plate tectonic boundary that extends for over 12,000 km from Iceland to the Bouvet Triple Junction in the South Atlantic. Spreading rates are commonly below 50 mm/yr, classifying it as a slow-spreading ridge. Its axial region consists of a median valley, typically 5-15 km wide and bordered by steep walls, whose morphology varies along the ridge as a function of the relative contributions of magmatic and tectonic processes (*Sempéré et al., 1990; Smith & Cann. 1993; Sinha et al. 1998*).

High-resolution mapping shows that MAR spreading centers are not continuous, but organized into discrete accretionary segments, separated by axial discontinuities, a segmentation that is a global and fundamental feature of mid-ocean ridges, reflecting the three-dimensional nature of accretionary processes at divergent plate boundaries. Within each segment, the rift valley reaches its minimum width and the shallowest depth near the spreading center, widening by up to 10-15 km and deepening by 400-1200 m close to the bounding discontinuities. The rift valley cross-section is frequently asymmetric, with one flank marked by steep escarpments exposing relatively undisturbed sections of oceanic crust, and the opposite flank characterized by gentler slopes. Adjacent ridge segments are offset from one another by major transform faults (*Sempéré et al., 1990*), and it is at the inside corners where ridge segments meet these transform boundaries that oceanic core complexes commonly develop.

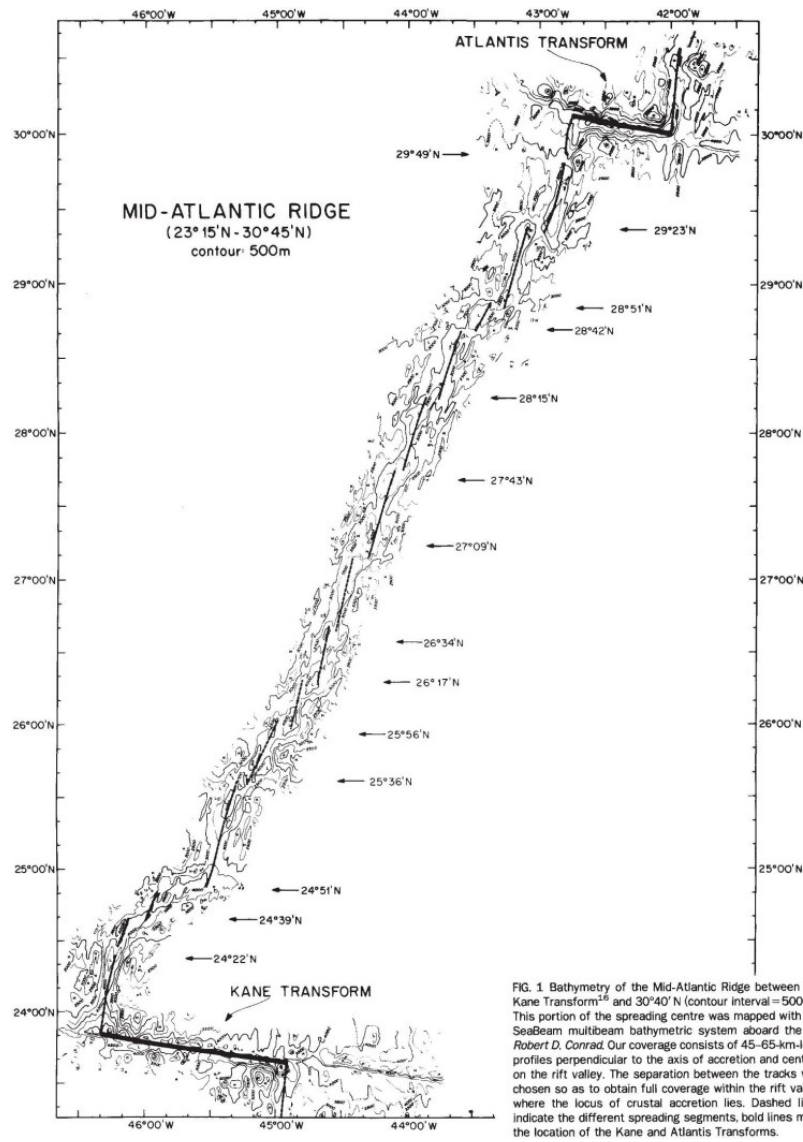


Fig 3. From Sempere et al. (1990). Picture description is already contained within the image.

2.2 ATLANTIS MASSIF (30°N) OCC

The Atlantis Massif oceanic core complex is located at 30°N, at the inside corner formed by the eastern intersection of the MAR with the sinistral Atlantis Transform Fault (*Drouin et al. 2009*). It is capped by a domal detachment fault bearing the typical corrugations parallel to the spreading direction, the surface expression of a long-lived, low-angle detachment fault that has exposed the massif on the seafloor, that has been active between 0.4 and 2 million years ago (*Lissenberg et al., 2024*). To the east, this detachment surface is truncated by rift valley faults. Massif's shallowest point (<700 mbsl) lies at the top of the south wall, from where the fault surface slopes north toward the central massif (*Delacour et al., 2008; McCaig et al., 2023*). Beneath the outcropping detachment zone, the massif's interior consists of serpentinized peridotite volumes intruded by gabbroic bodies (*Blackman et al. 2011*).

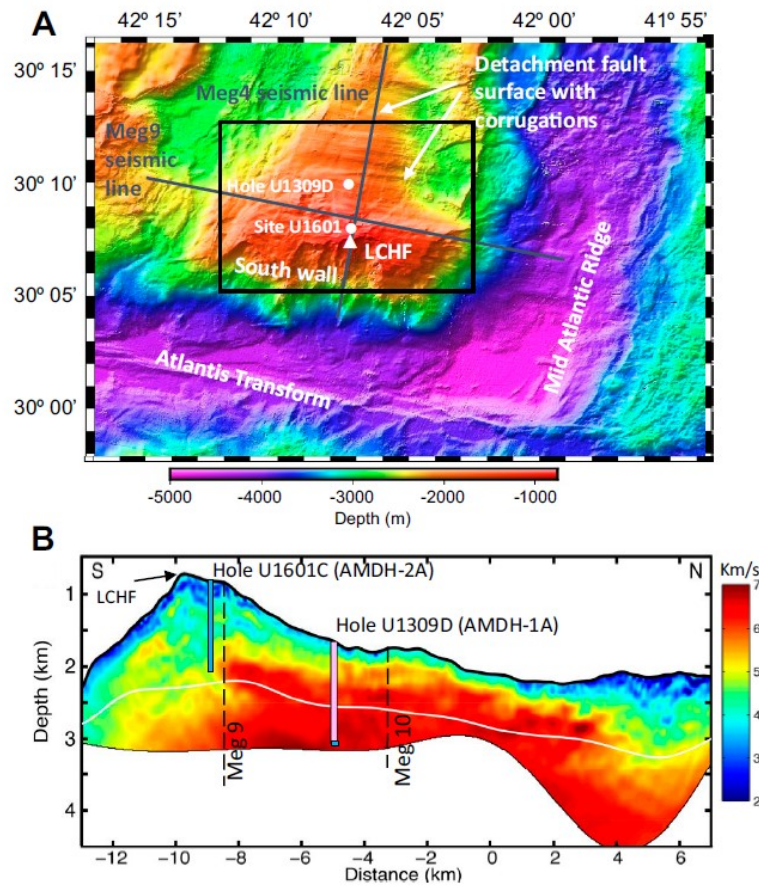


Fig 4. McCaig et al. (2023). A) Atlantis Massif showing main structural features, location of LCHF (Lost City Hydrothermal Field), Hole U1309D, and Site U1601 (core recovered in Holes U1601A and U1601C). Bathymetry was collected during Expedition 357. B) Full waveform inversion of Seismic Line Meg 4 and locations of Holes U1309D and U1601C, with proposed site numbers. Blue = new core recovered during Expedition 399, pink = core from Expedition 304/305.

Rocks recovered during IODP Expedition 399 (Hole U1601C and Hole U1309D, the latter deepened to 1498 mbsf) together with Expedition 357 (shallow holes) provide by far the most comprehensive dataset on the life cycle of a typical mafic/ultramafic OCC. This life cycle begins with mantle rocks uplifted by corner flow in the spreading environment and affected by high temperature partial melting and porous melt flow, processes recorded by the presence of dunite and by the growth of secondary orthopyroxene in harzburgite. The products of partial melting at deeper levels intrude the section as a complex network of more than 400 gabbroic bodies cored in Hole U1601C, while melt-rock reaction textures preserved in the gabbroic pluton of Hole U1309D further attest the complexity of melting and intrusion processes within the Atlantic Massif (McCaig et al., 2023; Lang et al., 2025).

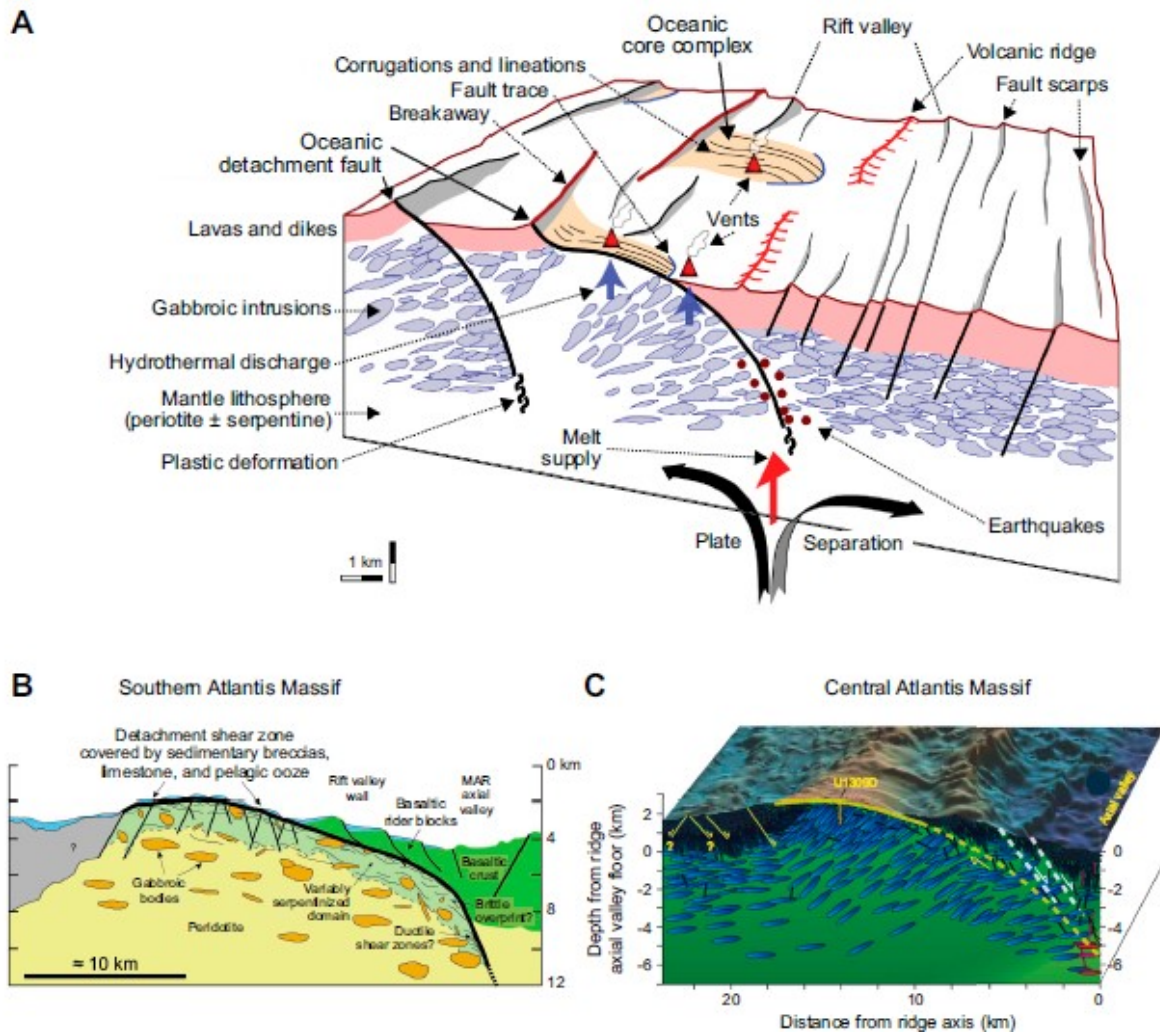


Fig. 5. From McCaig et al. (2023). Conceptual sketches of tectonomagmatic evolution of heterogeneous lithosphere and denudation of mantle rocks as detachment faulting progresses (Früh-Green et al., 2016). A. Generic “detachment mode” seafloor (Escartín and Canales, 2011). B. Southern wall of Atlantis Massif is dominated by variably altered peridotites with gabbroic lenses (Boschi et al., 2006). 100 m thick detachment fault zone containing talc-tremolite-chlorite metasomatic schists is at the summit (Karson et al., 2006). MAR = Mid-Atlantic Ridge. C. In contrast, major gabbroic intrusions dominate the central dome (Grimes et al., 2008).

Further unroofing at subsolidus temperatures was accommodated by deformation and hydrothermal alteration under waning temperature conditions, with additional hydration reactions occurring at amphibolite- and greenschist-facies conditions in gabbroic rocks, particularly close to contacts with ultramafic rocks. The most pervasive alteration is serpentinization of peridotite, most likely occurring at 200°–350°C, probably prior to complete unroofing of the massif by detachment faulting. The final phase in the life cycle of the Atlantis Massif comprises the uplift of the unroofed massif, hydrothermal circulation forming the Lost City Hydrothermal Field (LCHF), and low temperature alteration and subsea weathering (McCaig et al., 2023).

Ocean drilling across various oceanic core complexes has provided access to gabbroic rocks emplaced within this heterogeneous lithosphere, with serpentinization mainly occurring in the uppermost 3 to 4 km, at temperatures below 350°C, within the rolling hinge of downward-concave detachment faults.

2.3 IODP U1601C

Site U1601 lies in the southern zone of the Atlantis Massif, not distant from the Atlantis Transform, on a flat region at a water depth of 850 meters, about 800 m north of the LCHF. The site was originally established during International Ocean Discovery Program (IODP) Expeditions 304 and 305 (2004-2005), when the two main Holes U1309B and U1309D were drilled, while the preliminary holes at U1601 were drilled during Expedition 357 (McCaig *et al.* 2023; Lang *et al.* 2025).

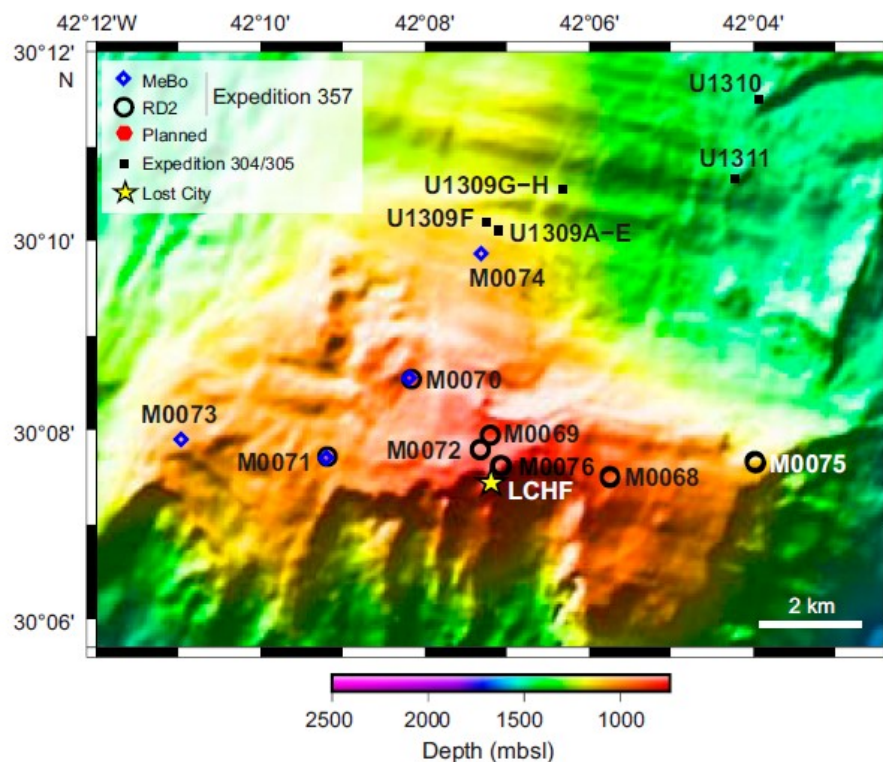


Fig 6. From McCaig *et al.* (2020). Location of previous drilling during Expeditions 304/305 and 357 (modified after Fröh-Green *et al.*, 2016). MeBo = Meeresboden-Bohrgerät 200 drill, RD2 = RockDrill2 drill. Expedition 399 sites are at Site U1309 (Hole U1309D; labeled U1309A–E) and between Sites M0069 and M0072 (Site U1601).

Site U1601 was selected in part based on the success of earlier drilling results in the region during IODP Expedition 357. Its scientific objectives were initially designed to complement the goal of deepening Hole U1309D by targeting a zone with thermal and geochemical conditions more favorable to microbial activity and to potential abiotic synthesis of organic molecules. The high recovery and fast progress while drilling Hole U1601C, however, created the opportunity to expand the initial

objectives to those originally intended for Hole U1309D. The unexpected depth reached also opened the possibility to reconstruct large-scale structural, igneous, and alteration relationships across a long section of serpentinized peridotite, and to sample material representative of the hydrothermal reaction zone feeding the Lost City hydrothermal system. The site was thus primarily chosen to access an actively serpentinizing environment (*Lang et al., 2025*).

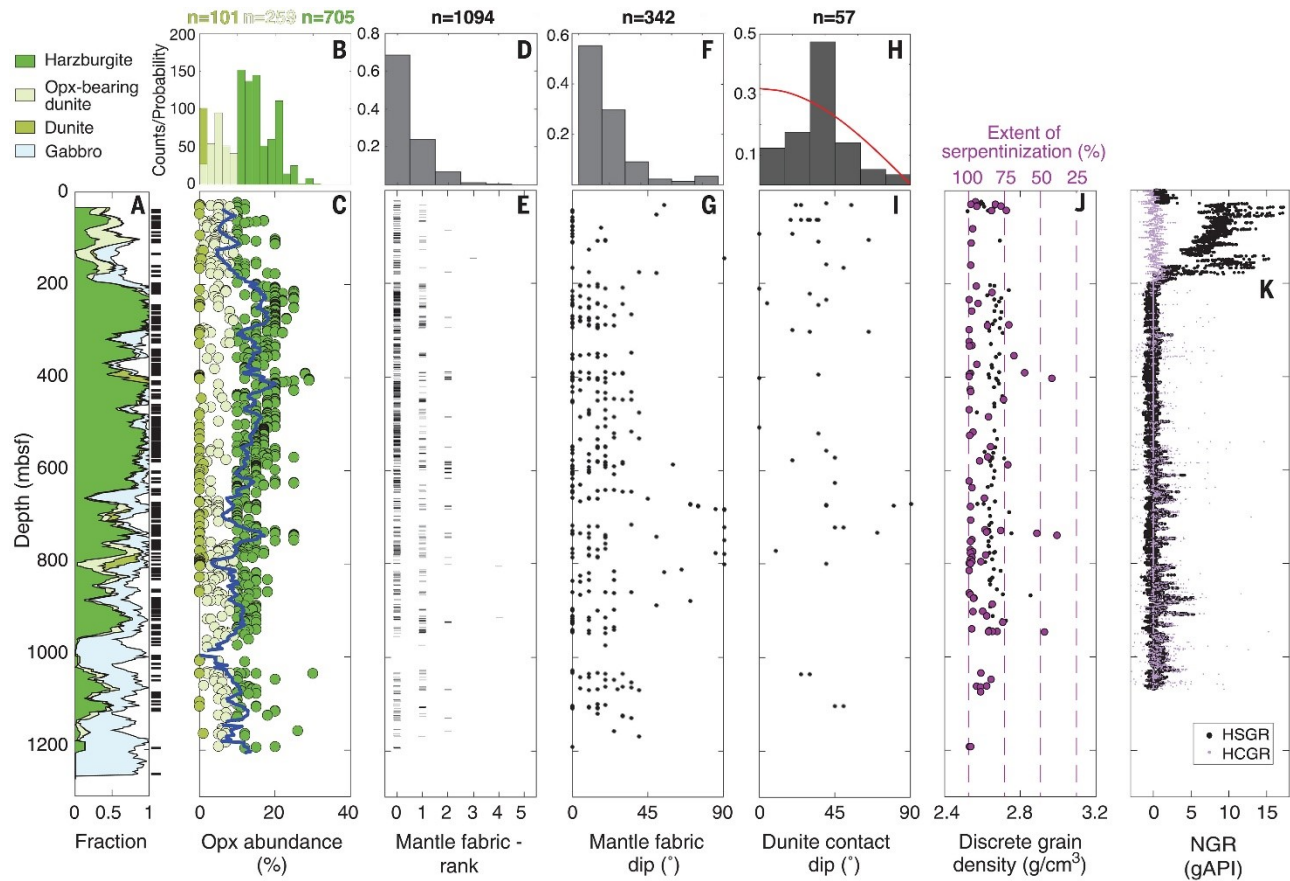


Fig. 7. U1601C observations from Lissenberg et al. (2024). (A) U1601C downhole distribution of recovered rock types (20-m running average of harzburgite, opx-bearing dunite, dunite, and gabbro). White represents no recovery, horizontal black lines mark carbonate occurrence. (B and C) Histogram and downhole variations of modal percent opx in peridotite, with a 20-m running average downhole (blue line) superimposed. (D and E) Histogram and downhole variations of mantle fabric intensity in peridotites [0 = protogranular; 1 = porphyroclastic (weak foliation); 2 = porphyroclastic (strong foliation); 3 = protomylonitic; 4 = mylonitic; 5 = ultramylonitic]. (F and G) Histogram and downhole variations of dip of peridotite fabrics (dip direction is not measured in drill core). (H) Histogram of dip of dunite-harzburgite contacts, along with the distribution predicted for randomly orientated planes in drill core in red ([50](#)). (I) Downhole variations of dunite-harzburgite contact dip. (J) Extent of serpentinization derived from downhole shipboard density measurements of discrete peridotite samples (black) and from thin section observations (purple). (K) Wireline natural gamma ray (NGR) data including the total signal (HSGR) and the computed signal without the uranium component (HCGR).

The southern wall of Atlantis Massif is dominated by variably altered peridotite with intermittent mafic plutonic intrusions (*McCaig et al. 2023; Lang et al. 2025*). Hole U1601C is a 1268 meters

section through serpentinized mantle rocks containing several “lower crustal” gabbroic intrusions, while Hole U1309D sampled a continuous sequence of gabbroic rocks – troctolite and olivine-rich troctolite, olivine gabbros, oxide gabbros, and rare leucocratic intrusions – together with minor harzburgite in the upper 300 meters of the section. The uppermost 120 meters of this sequence consists of about 40% basalt/diabase intrusions with chilled margins, and numerous igneous contacts are preserved throughout (McCaig *et al.*, 2023).

The dominant lithology in Hole U1601C is serpentinized peridotite, which constitutes 68% of the recovered rock types, and is represented by harzburgite (82%), orthopyroxene-bearing dunite (1-10% opx; 13%), and dunite (<1% opx; 5%). The peridotites are depleted, and many samples lack clinopyroxene altogether. Within the harzburgite and, more frequently, the opx-bearing dunite, dunite occurs as zones that are typically tens of centimeters thick (Lissenberg *et al.* 2024). The harzburgites have also been variably altered to magnetite-bearing serpentinite, suggesting H₂ formation and reducing conditions. Elevated concentrations of hydrogen and methane were detected in fluids recovered by the borehole samplers, indicating serpentinization may be active and ongoing, although the possibility that volatile-rich fluid pockets were released during drilling cannot be excluded. The relationship between volatile distributions, depth, temperature, lithology, and other processes may thus provide insights into the processes responsible for their formation (McCaig *et al.*, 2023).

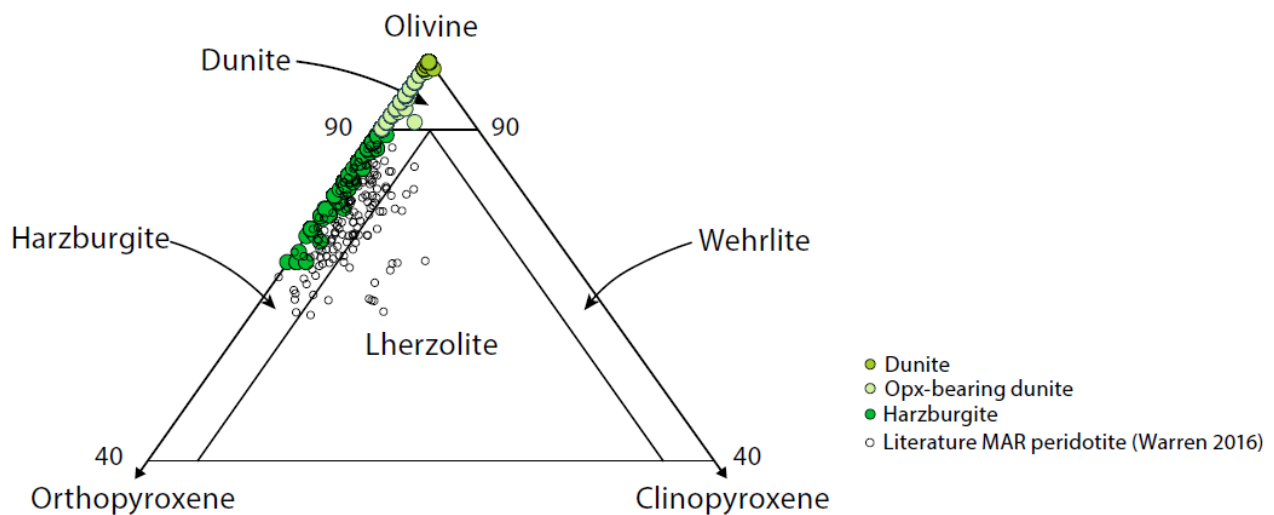


Fig 8. From Lang *et al.* (2025). Modal proportions of ultramafic rocks, Hole U1601C. Data for MAR abyssal peridotite (Warren, 2016) is shown for comparison.

Other than the dominant peridotitic lithologies, gabbroic bodies and veins account for 31% of the recovered core and are concentrated toward the bottom of the section, below 950 mbsf. Gabbroic

rocks are dominated by gabbro, with less gabbro-norite and olivine gabbro. Their generally sutured contacts with the host peridotites are indicative of emplacement into relatively warm lithospheric mantle. Notably, plagioclase peridotites are only observed at immediate contacts with gabbro. Approximately 80% of the logged gabbroic units occur as veins less than 1 m thick, with many of millimetric to centimetric thickness, with progressively few intrusions at the 1- to 10-m and over 10-m scales. Their dips are highly variable, although steep orientations dominate and shallow ones are relatively rare. The combination of predominant small intrusion sizes and highly variable orientation indicates that the gabbroic intrusions form a net vein complex (*Lissenberg et al. 2024*).

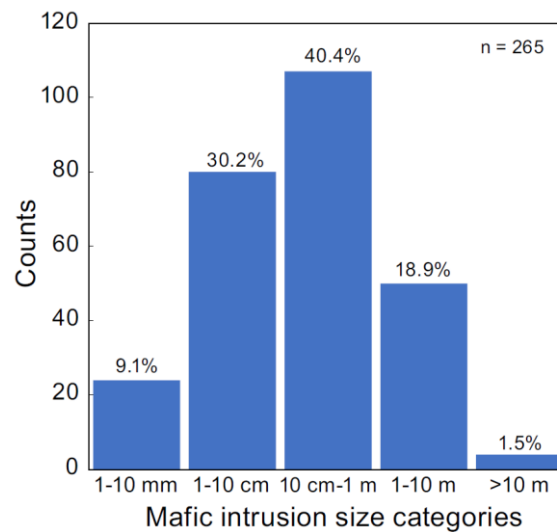


Fig 9. From Lang et al. (2025). Size distribution of gabbroic intervals recovered, Hole U1601C.

Hole U1601C offers a long, largely peridotitic section, intruded by numerous gabbroic bodies, together with evidence of active serpentinization. These characteristics make it a favorable target for analyzing peridotite – gabbro contacts and their trace element enrichments in detail.

3. SELECTED SAMPLES

The studied samples were collected during the IODP Expedition 399 from Site U1309C at the Atlantis Massif (30°N), Mid-Atlantic Ridge. Several works, including *McCaig et al. (2023)*, *Lissenberg et al. (2024)* and *Lang et al. (2025)* already investigated the 1267.8 m drilled during the expedition. The aim of this study is to characterize the different families of lithological contacts and to investigate melt-rock interactions and the petrological and geochemical features that melt percolation through the host mantle generates. Thus, the selected cores represent lithological contacts and lithologies between gabbroic intrusions/veins and the host serpentinized mantle.

The rock collection spreads throughout the entire section and covers the lithological and petrological variability observed in Atlantis Massif gabbro – peridotite contacts and contact-related lithologies.

3.1 CORES

Each core is characterized by approximately 150 cm of vertically recovered rock. Most of the sampled rocks consist of serpentinized peridotites, locally crosscut by gabbroic veins and/or small intrusions. No large gabbroic intrusion is present. The recovered rock is strongly fractured in some intervals, while other sections are well preserved and continuous.

The cores have been characterized during and immediately after Expedition 399 by the scientific crew members based on their depth, magnetic susceptibility (IU), lithology, primary mineralogy (%), average grain size (mm), deformation, fabric, serpentine quantity, structures, vein density, and alteration intensity.

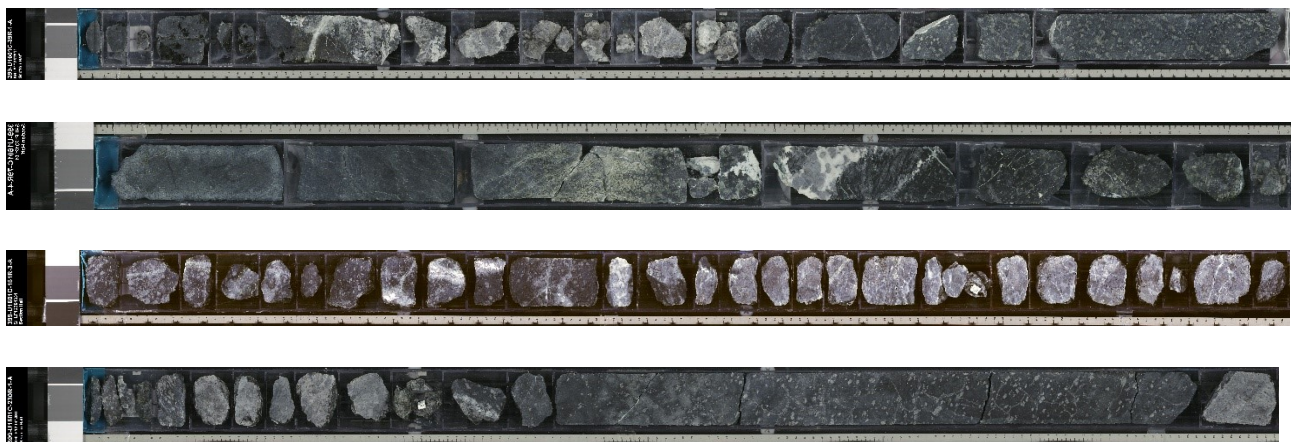


Fig 10. Cores number 39-1; 79-4; 181-3; 230-1.

From some of the hundreds of recovered cores, a selection 22 either gabbro – peridotite contact or contact-related lithology along these cores have been made for the thin section fabrication. The selected rock portions are representative of the entire spectrum of possible lithological contacts at Hole U1601C. The gabbroic vein and intrusion types are macroscopically distinguished based on their lithology, grain size, thickness and contact with the host peridotite. The following classification is based on core-scale observations, and it is strictly linked to that proposed by *Lang et al. (2025)*.

3.1.1 COARSE-GRAINED GABBRO CONTACT

Sufficiently wide intrusions consistently display coarse-grained gabbro cores characterized by centimeter-scale plagioclase and clinopyroxene crystals with no strong magmatic foliation (*McCaig et al., 2023*). Contacts are assigned to this group when the coarse-grained gabbro is in direct contact with the serpentinized peridotite and only a small reduction in grain size is observed toward the lithological boundary. Plagioclase and clinopyroxene keep their coarse grain size up to the contact where they occur as medium-grained crystals, defining a direct, sutured lithological boundary between the intrusion and the serpentinized peridotite.

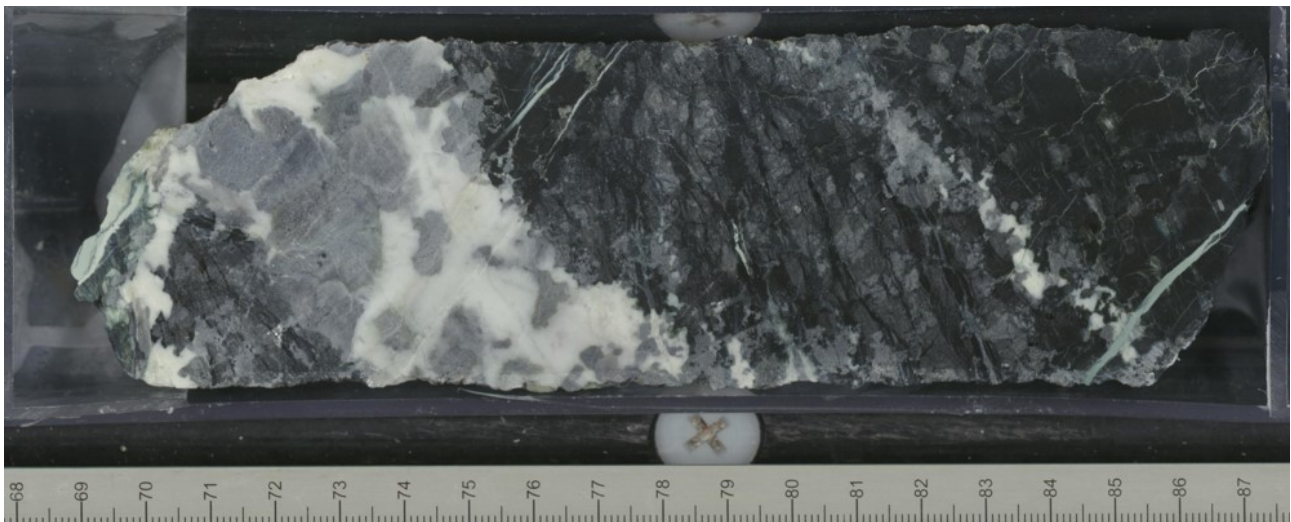


Fig 11. Hole 399-U1601C-79R-4. Coarse-grained gabbro contact with medium-intensity percolation. No grain size reduction is observed at the lithological contact.

These contacts are additionally characterized by melt percolation into the mantle host rock. The process is macroscopically expressed by the occurrence of medium-grained magmatic crystals that penetrate the peridotite along multiple, narrow pathways developing from the main intrusion.

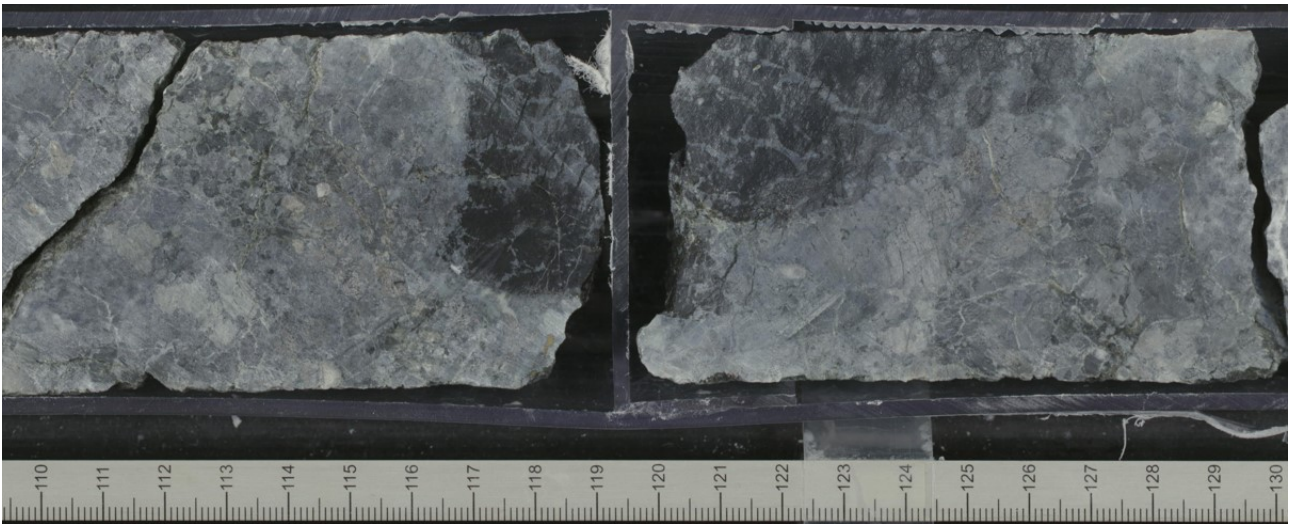


Fig 12. Hole 399-U1601C-116R-1. Coarse-grained gabbro contact with high-intensity percolation.

The intensity of melt percolation, however, varies among the samples. In samples characterized by intense percolation, olivine is not observed either within the intrusive core or along the contact.

Conversely, olivine occurs as an interstitial phase in the few coarse-grained gabbro contacts where no clear core-scale evidence of melt percolation is observed, or where percolation is present but occurs at lower intensity.

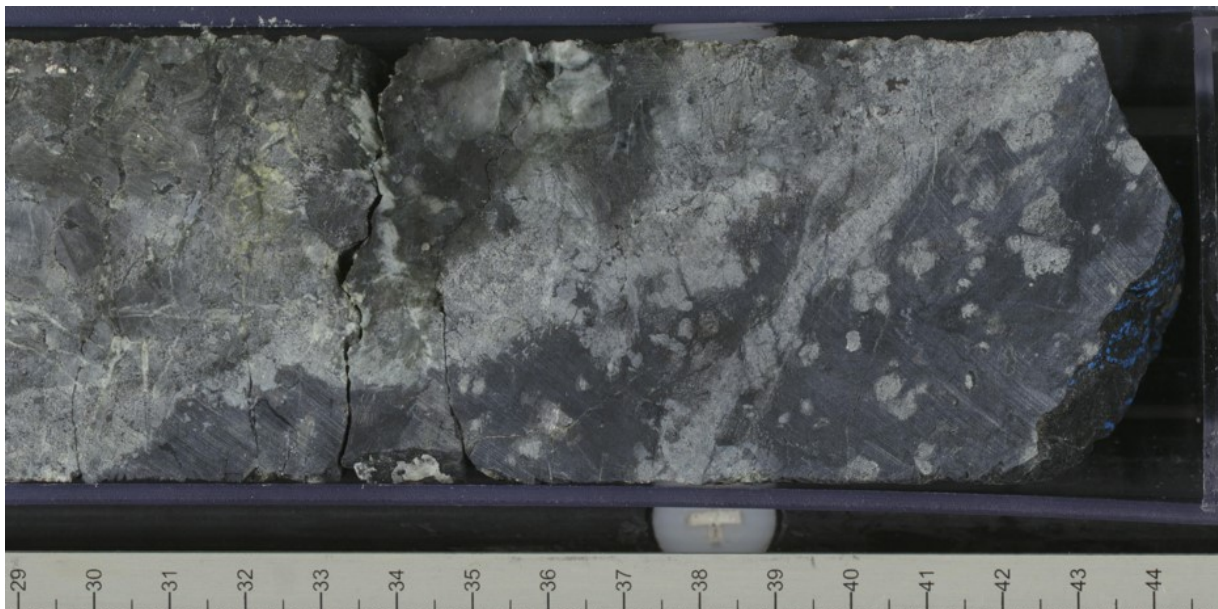


Fig 13. Hole 399-U1601C-218R-2. Coarse-grained gabbro contact with low-intensity percolation and a vein crosscutting the mantle. This sample shows a more evident grain-size reduction with respect to the others present in this category.

This contact type is relatively common throughout the recovered cores, and it represents one of the most abundant among the samples present in this Thesis.

3.1.2 TROCTOLITE/OL-GABBRO WIDE CONTACT ZONE

The peculiarity of this group of samples is that coarse-grained gabbro and serpentinized peridotite are not in direct contact. Instead, a decimeter-wide zone of medium-grained, contact-related troctolite or olivine-gabbro occurs between the intrusion and the serpentinized mantle, consistently with the observations of *Lang et al. (2025)*.



Fig 14. Hole 399-U1601C-41R-1. Contact-related olivine-rich troctolite/olivine-gabbro wide zone. The zone is about 20 cm wide.

The zone is referred to as “wide” because the thickness of the contact-related lithology is greater than that typically observed throughout Hole U1601C.

This contact-related lithology is characterized by abundant olivine, locally reaching up to 60-70% of bulk rock. At the hand-sample scale, olivine crystals appear generally rounded and are locally enclosed within poikilitic clinopyroxene and plagioclase. Based on their modal mineralogy, the contact-related rocks can be subdivided into olivine-rich troctolite, troctolite, and olivine-gabbro zones.



Fig 15. Hole 399-U1601C-139R-2. Contact-related olivine-rich troctolite/olivine-gabbro wide zone. The zone is wider than 20 cm. Sets of fractures crosscut the intrusion, and olivine crystals become concentrate along them.

When the rock is crosscut by sets of fractures perpendicular to the contact with serpentinized mantle, olivine tends to become concentrated along the fracture networks. In these areas, the surrounding rock may locally evolve into a medium-grained gabbro containing accessory olivine (>5%).

3.1.3 OLIVINE-RICH TROCTOLITE NARROW CONTACT ZONE

This category comprises narrow, medium-grained, contact-related lithologies that occur between coarse-grained gabbroic intrusions and the serpentinized peridotite. These rocks are mostly troctolite and, more rarely, olivine-gabbro, and typically form a zone no more than 5 cm thick separating the two main lithologies. Milky-white plagioclase is strongly concentrated along both boundaries of the contact-related zone, occurring particularly abundantly at the interfaces with the serpentinized peridotite and the coarse-grained gabbro. Olivine locally constitutes up to 60-70% of the rock and can occur as an interstitial anhedral phase or as rounded crystals.

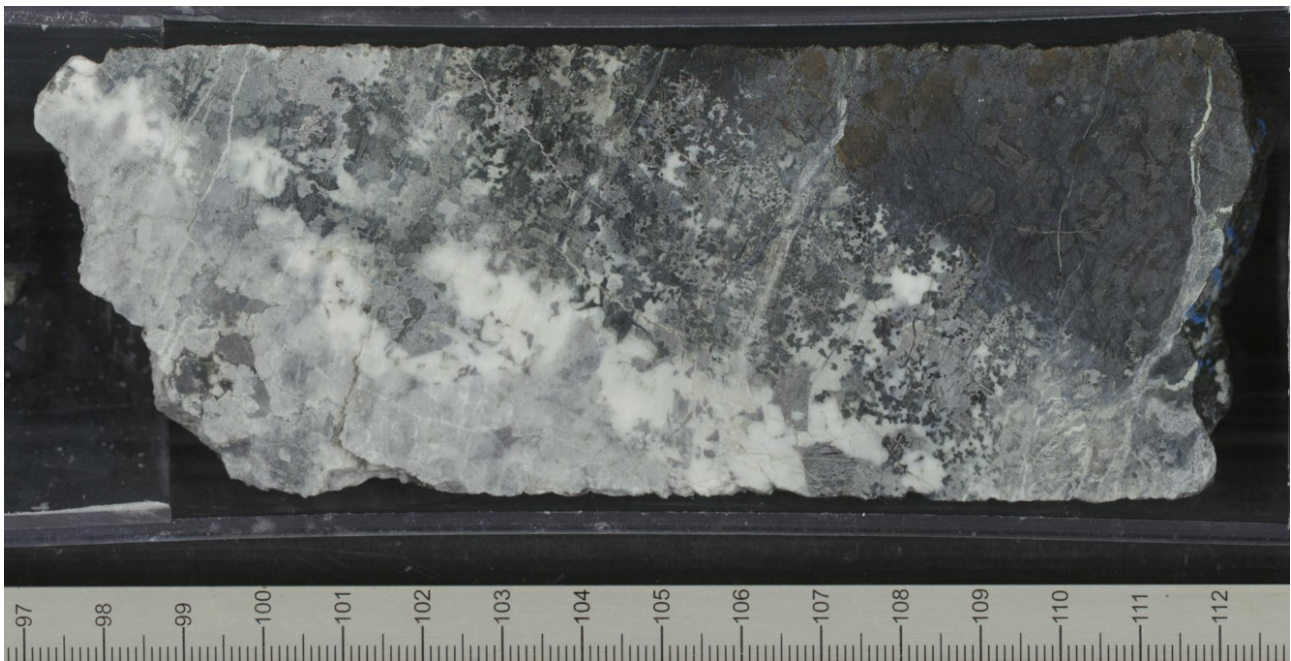


Fig 16. Hole 399-U1601C-41R-1. Contact-related olivine-rich troctolite/olivine-gabbro narrow zone, which shows a diffuse contact with the coarse-grained gabbro and a sharp one with the serpentinized harzburgite. Olivine occurs as rounded crystals.

At this hand-sample scale, the narrow contact-related lithology occurs restricted to the interface between the gabbroic intrusion and the serpentinized mantle and is therefore not observed elsewhere within the recovered cores. Its occurrence is characterized by an abrupt reduction in grain size compared to that of the adjacent coarse-grained gabbro, accompanied by increasing olivine abundance toward the mantle. The contact between the contact-related lithology and the serpentinized

mantle is commonly sharp at the macroscopic scale, while the boundary with the coarse-grained gabbro is generally more diffuse.

Sets of fracture oriented perpendicular to the mantle contact are commonly observed within the contact zone. The combination of abrupt grain-size reduction, olivine enrichment, and its occurrence exclusively at the gabbro-mantle interface distinguishes this narrow contact-related zone from the surrounding coarse-grained gabbro intrusions.

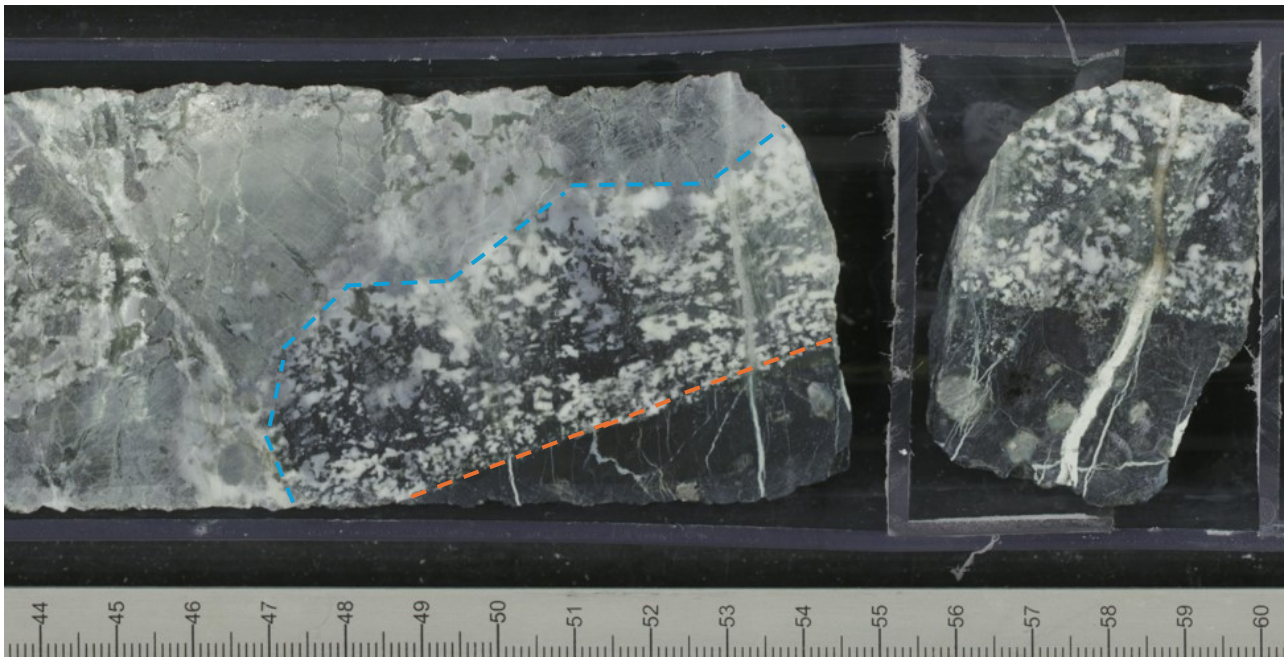


Fig 17. Hole 399-U1601C-113R-4. Contact-related olivine-rich troctolite narrow zone, which shows diffuse contact (blue dashed line) with the coarse-grained gabbro and a sharp one (orange dashed line) with the serpentinized harzburgite. Olivine occurs as interstitial crystals. Almost no clinopyroxene is visible at hand-sample scale.

3.1.4 VEINS

Among the selected samples, a few medium-grained gabbro veins, less than 1 cm thick, were also observed crosscutting the serpentinized mantle. These veins may be associated with larger, nearby coarse-grained gabbroic intrusions, and have similar gabbroic composition. Compared with the more than 1 cm-thick coarse-grained gabbroic intrusions, these veins are relatively uncommon, with only two of the selected samples containing them.

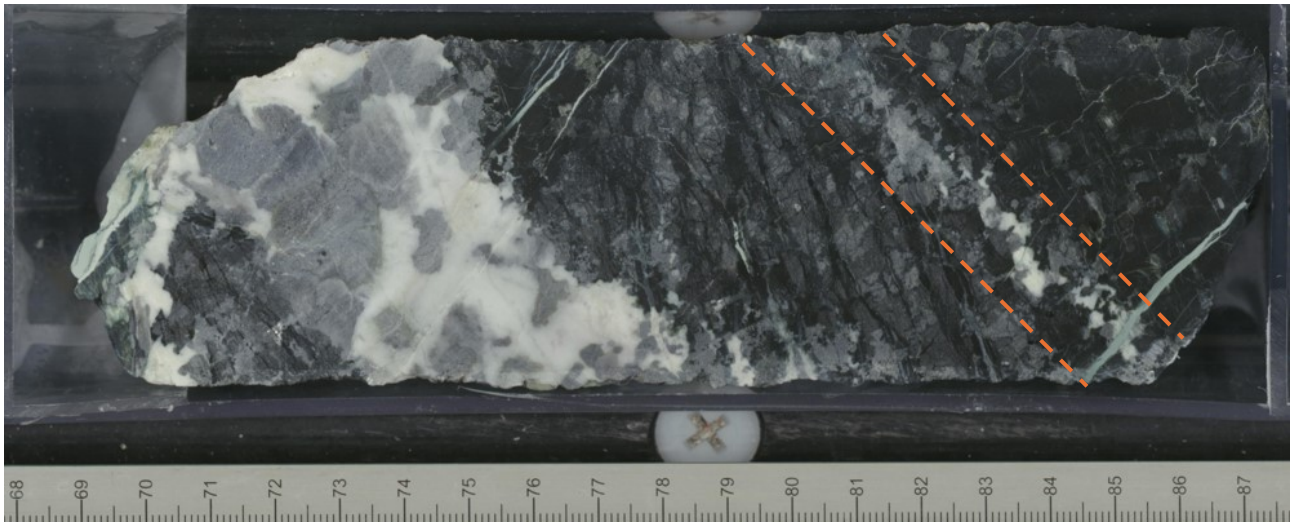


Fig 18. Hole 399-U1601C-79R-4. Left: coarse-grained gabbro contact. Right: gabbroic vein into the serpentinized peridotite occur within the area enclosed into the two orange dashed lines.

The veins locally show lateral melt percolation into the surrounding serpentinized mantle, extending approximately 1-2 cm beyond the vein margins. Interstitial olivine can occur within the veins.



Fig 19. Hole 399-U1601C-230R-1. 2 cm-thick gabbroic vein crossing the serpentinized harzburgite.

4. PETROGRAPHY

Samples representing mantle – intrusion contacts or contact-related lithologies have been selected among the recovered core samples. A total of 22 thin sections and their features will be discussed in the following sections.

Each thin section included within this work is identified by a specific code relative to the following information:

- IODP Expedition number (399);
- Hole (U1601C);
- Core number;
- Position of the top of the thin section, in centimeters below the top of the core.

For example, thin section 399-U1601C-39R-1-32 corresponds to IODP Expedition number 399, Hole U1601C, Core 39-1, with the top of the thin section located 32 centimeters below the top of the core. Since every thin section belongs to expedition 399 and Hole U1601C, they will hereafter be referred to using only the core number and top of the section. Therefore, the previous sample will be named 39-1-32.

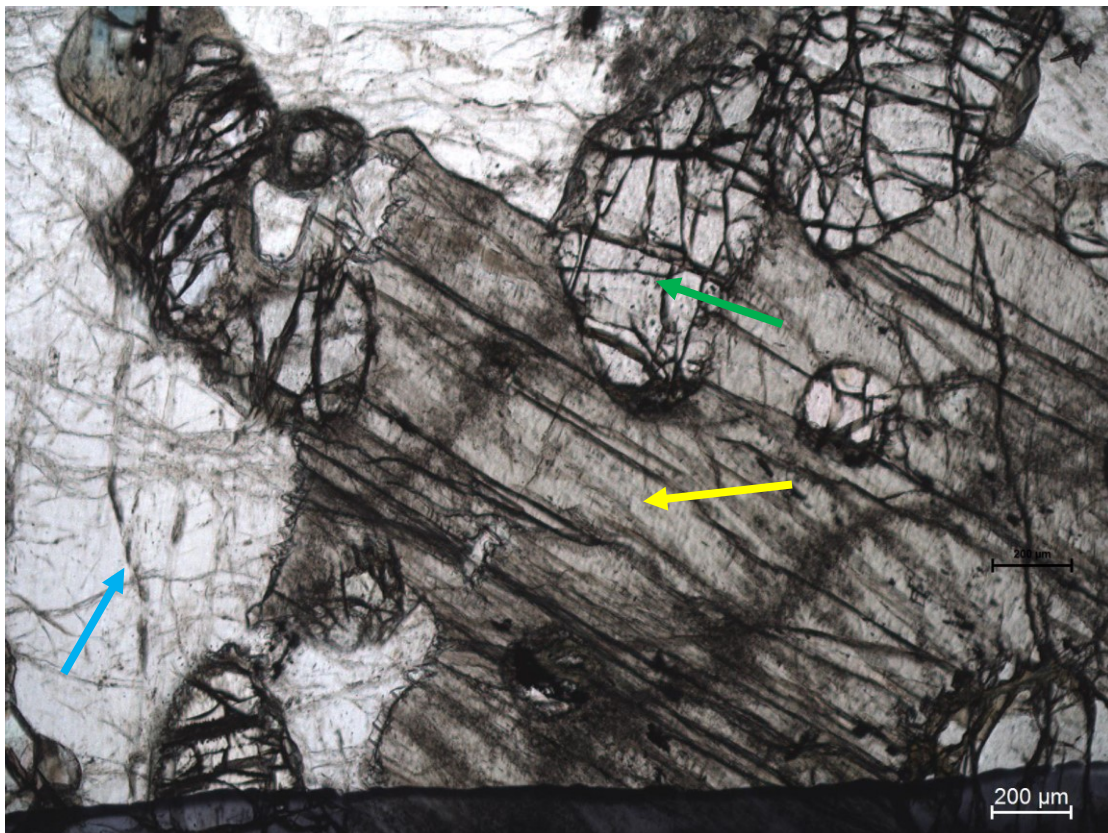


Fig 20. Preserved olivine-gabbro contact-related wide zone. Blue arrow points to plagioclase, yellow arrow to clinopyroxene, and green arrow to olivine. Section 41-1-44B.

This chapter describes the petrological characteristics of the rocks recovered from Hole U1601C. Accordingly, every thin section is assigned to one of the contact groups defined in Chapter 3. The thin sections may also contain coarse-grained gabbro, serpentinized peridotite, or both, along with either the contact or the contact-related lithology (olivine-rich troctolite – troctolite – olivine-gabbro) when present.

The petrographic descriptions of the gabbroic intrusions, host serpentinized peridotite, lithological contacts, and contact-related rocks are based on the thin sections in which these lithologies are observed.

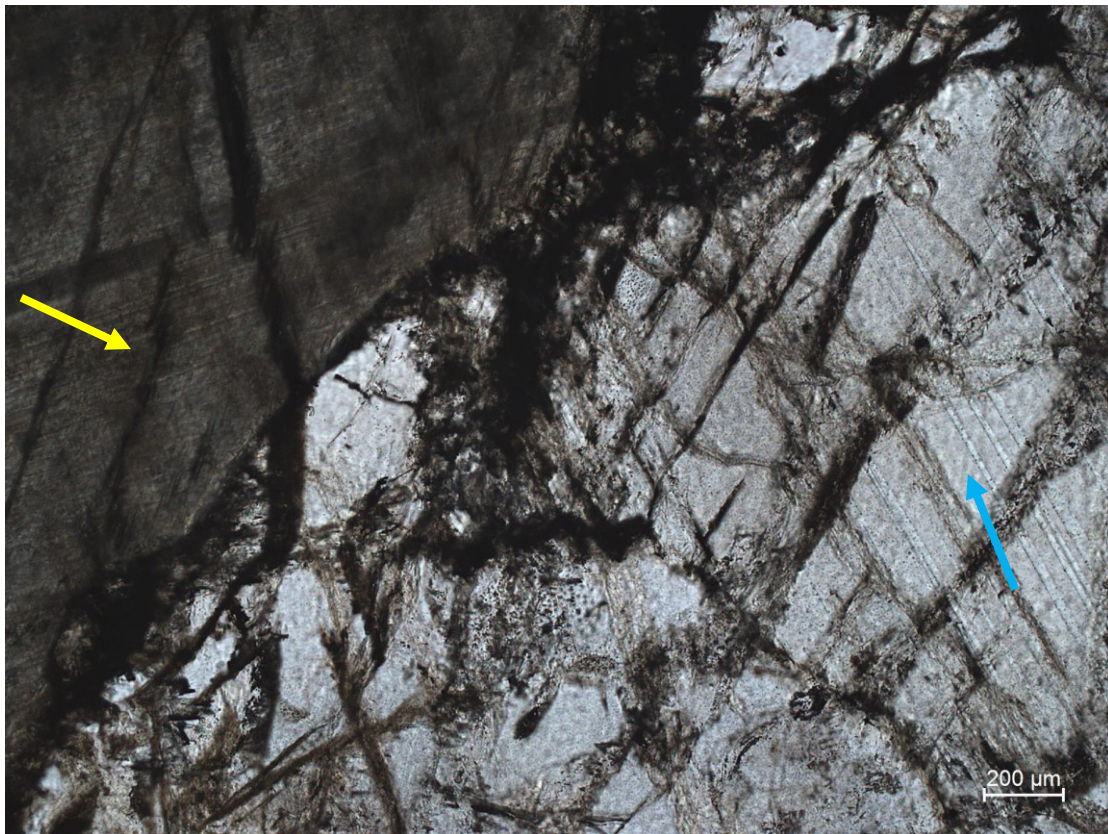


Fig 21. Slightly altered coarse-grained gabbro in section 91-1-24. Blue arrow points to plagioclase and yellow arrow to clinopyroxene.

The primary magmatic phases in the coarse-grained gabbro intrusions are clinopyroxene and plagioclase (Fig. 21), whereas the contact-related lithologies additionally contain olivine (Fig. 20), with accessory magmatic orthopyroxene and/or brown amphibole locally present. Crystals located along the contact zones, either along the contact itself or within the contact-related lithology, are commonly moderately to strongly altered, as contacts are generally considered zones of weakness that favor fluid circulation (*Blackman et al. 2011; Lang et al. 2025*).

The main hydrothermal alteration phases are diverse. Green amphibole typically occurs along the rims of plagioclase, clinopyroxene, and olivine crystals and locally replaces clinopyroxene and

plagioclase. Plagioclase alteration occurs at different stages, ranging from prehnite to chlorite and hydrothermal garnet (Fig. 22), reflecting an increasing degree of hydrothermal alteration of the protolith. Olivine is the most alteration-prone mineral and commonly undergoes extensive serpentinization, that causes the replacement of the mineral by serpentine-group minerals, magnetite, and brucite. The extent of alteration varies among the different stages of serpentinization, resulting in significant differences in the preservation and appearance of olivine relicts from one thin section to another. Clinopyroxene is generally less affected by hydrothermal alteration than olivine and plagioclase and is commonly preserved in its cores, while alteration to green amphibole is mainly concentrated along the crystal rims.

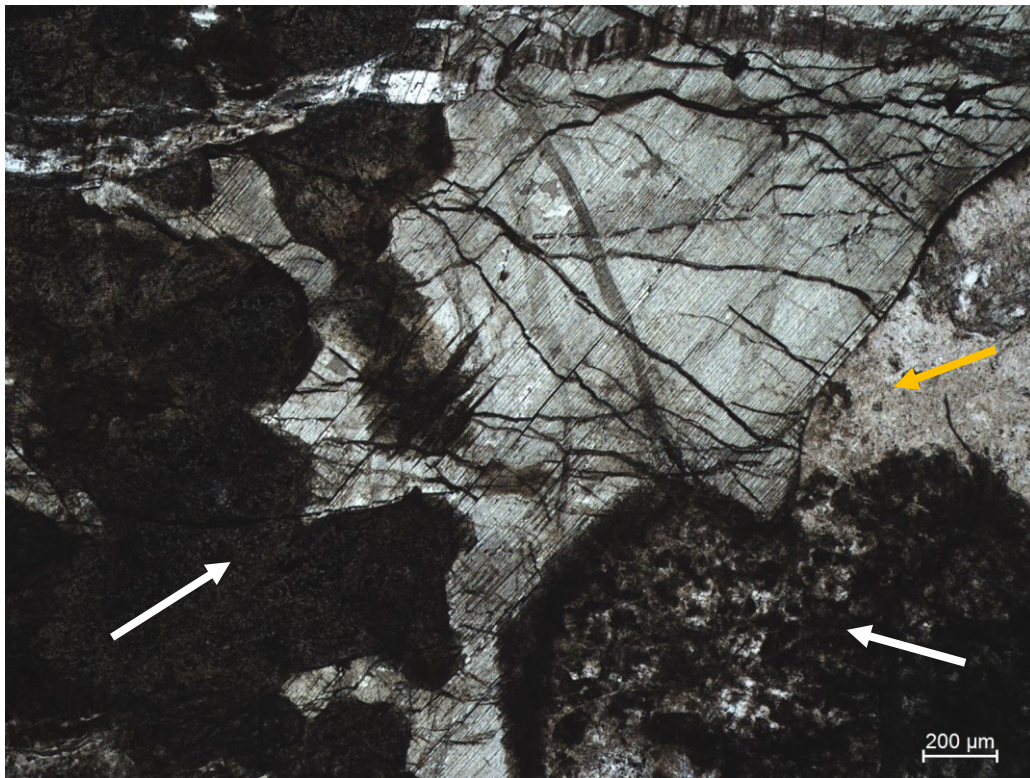


Fig 22. Gabbroic lithology with clinopyroxene ranging from euhedral (on the right) to interstitial (on the left) in section 113-4-43. Plagioclase is completely replaced by a dark phase, which is hydrothermal garnet (indicated by the white arrows). Clinopyroxene is almost entirely preserved and fractured, also showing a strong cleavage. The orange arrow indicates plagioclase alteration to prehnite.

The relative susceptibility of the silicate phases to alteration is consistent with the observations of olivine being more readily altered than plagioclase, and especially clinopyroxene (*Baker & Haggerty, 1967*). Therefore, completely serpentinized olivine, partially to extensively altered plagioclase with only small, preserved cores, and relatively fresh to slightly, altered clinopyroxene are commonly observed. However, alteration degree is highly variable (Fig. 23-24), and sections with all three phases are relatively well preserved or, on the contrary, strongly altered are also common.

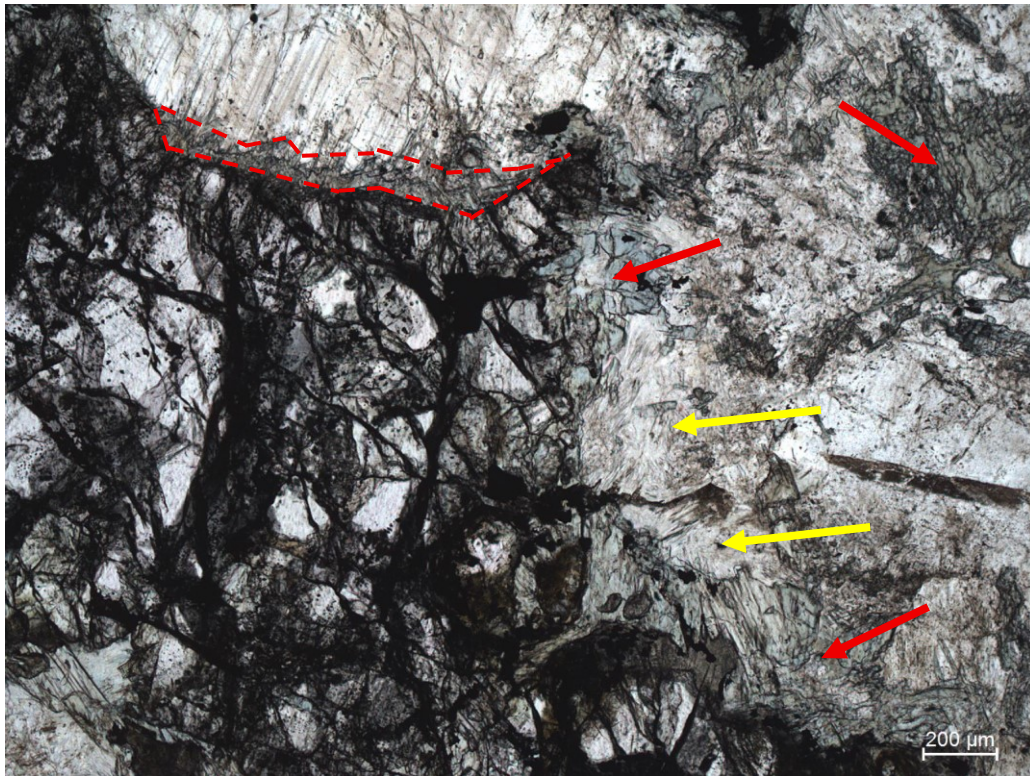


Fig 23. Olivine – plagioclase contacts composed of interstitial green amphibole in troctolite in Section 139-2-45. Plagioclase is almost entirely replaced by chlorite along the rims, while clinopyroxene rims by amphibole and locally talc. Mineral phase within the dashed area and pointed by red arrows is green amphibole tremolite; yellow arrows point to chlorite.

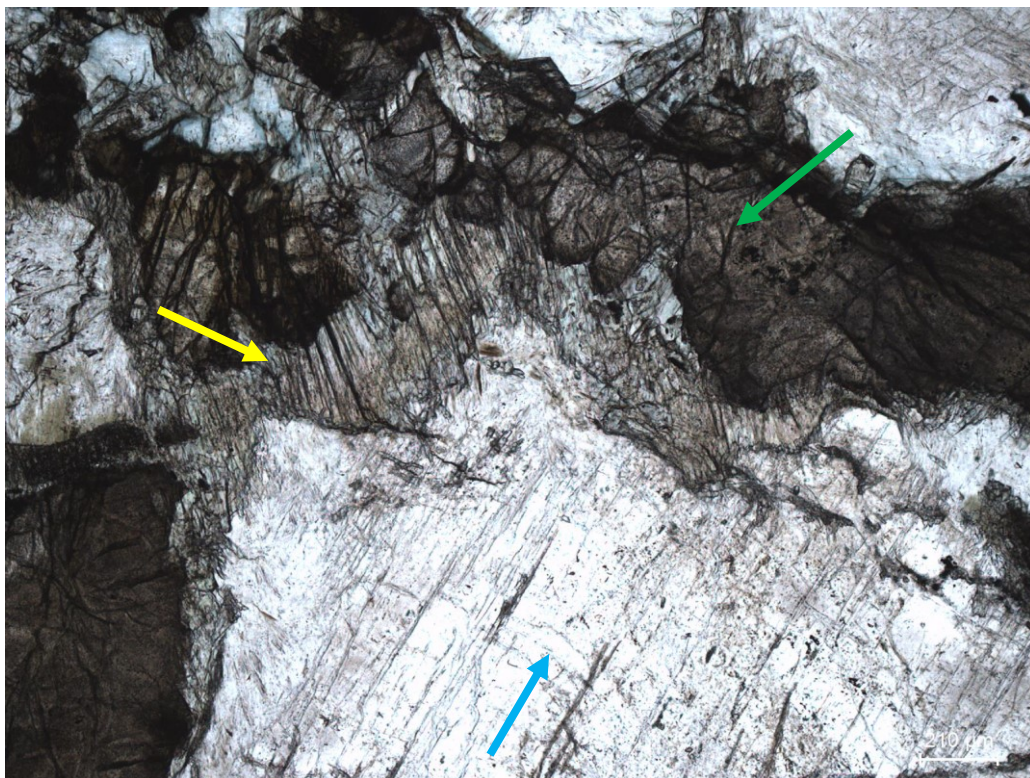


Fig 24. Preserved white plagioclase (blue arrow) and strongly serpentinized olivine (green arrow) in a troctolite from a wide contact zone. Interstitial clinopyroxene (yellow arrow) occurs along the interface between plagioclase and olivine. Section 139-2-49A.

McCaig *et al.* (2023) suggest that the mineral assemblages and crosscutting relationships observed among alteration assemblages and hydrothermal veins indicate that the rocks at Site U1601C underwent a sequence of alteration under conditions ranging from amphibolite- through greenschist- to prehnite-pumpellyite-facies conditions.

In addition to silicates, sulphides occur throughout the 22 thin sections and are characterized by either magmatic or hydrothermal origin. In the coarse-grained gabbro intrusions, primary magmatic sulphides are generally rare and, where present, are typically too small to be identified confidently under the optical microscope. The only magmatic sulphide phase found in the gabbroic intrusions is pyrrhotite (Fe_{1-x}S), which occurs along clinopyroxene cleavage planes and at the boundaries between plagioclase and clinopyroxene crystals.

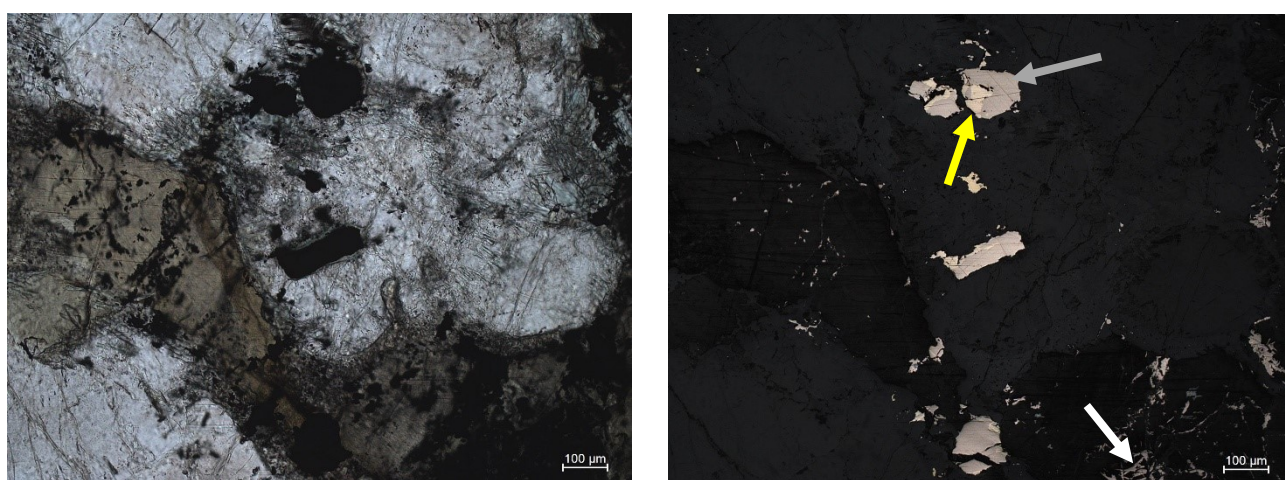


Fig 25. Opaque pyrrhotite and pentlandite in olivine-rich troctolite from the wide contact zone in section 139-2-45. Olivine is strongly altered to serpentine + magnetite (opaque phase). On the left: under transmitted light, opaque sulphide grains are observed enclosed within plagioclase, while the opaque phase occurring in serpentinized olivine is magnetite. On the right: reflected-light observations show grayish sulphide grains displaying cleavage, identified as pyrrhotite, while the associated yellowish sulphide is pentlandite. Yellow arrow: pentlandite; grey arrow: pyrrhotite; white arrow: magnetite.

Magmatic sulphides are significantly more abundant in the contact-related lithologies, where pyrrhotite, pentlandite ($[\text{Fe,Ni}]_9\text{S}_8$) and chalcopyrite (CuFeS_2) represent the totality of the primary magmatic sulphides (Fig. 25). These phases occur as large grains compared to those found in coarse-grained gabbro intrusions and are widespread in the troctolites and olivine-gabbros. Primary sulphides are uncommon in the serpentinized mantle, but when present, they consist of pentlandite.

A few hydrothermal sulphides are also locally observed. These phases preferentially occur along fracture networks, particularly within strongly altered portions of the rocks, and are spatially associated with hydrothermally altered silicates. In reflected light, they typically display greenish to blueish rims surrounding cores with variable optical characteristics (Fig. 26). Hydrothermal sulphides are mainly concentrated within the contact-related lithologies, where fractures provide pathways for

hydrothermal fluid circulation. The identified phases include horomanite ($\text{Fe}_6\text{Ni}_3\text{S}_8$) and heazlewoodite (Ni_3S_2) as the most observed.

The preferential occurrence of magmatic sulphides within the contact-related lithologies may suggest that these rocks formed from, or were affected by, a relatively sulphur-enriched melt compared to that responsible for the crystallization of the coarse-grained gabbro intrusions. This hypothesis is further evaluated in the following chapter through geochemical data.

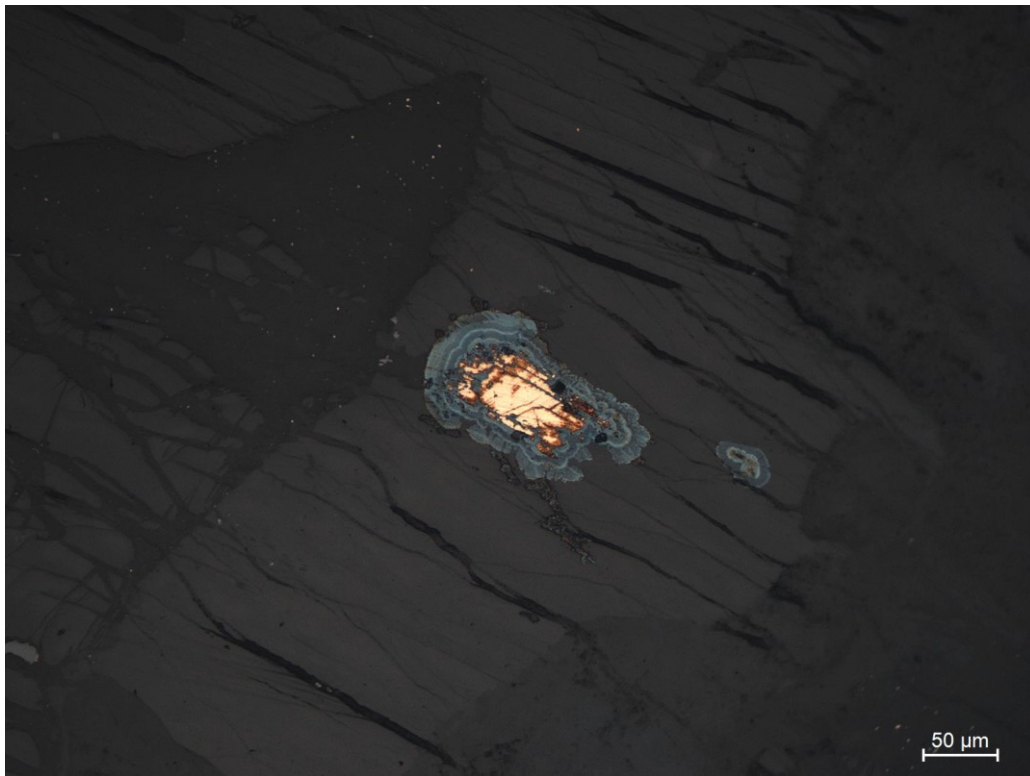


Fig 26. Sulphide in clinopyroxene. The core is magmatic, while the rim has been altered to a hydrothermal sulphide phase, due to hydrothermal fluid circulation. Section 230-1-41.

4.1 GABBRO INTRUSIONS

The coarse-grained mafic intrusions crosscutting the serpentinized mantle of the Atlantis Massif OCC derive from a source melt whose infiltration is likely related to upwelling and melting of the underlying asthenospheric mantle, induced by lithospheric extension (*Rampone et al., 2016*).

Coarse-grained gabbro intrusions generally show a holocrystalline, phaneritic, and idiomorphic texture, characterized by centimetric magmatic crystals. The intrusions rarely exceed 1 m in thickness and consistently display a strictly gabbroic composition (Fig. 27), with plagioclase and clinopyroxene as the dominant mineral phases, each accounting approximately for 50% of the rock. Accessory primary orthopyroxene and amphibole are locally observed.

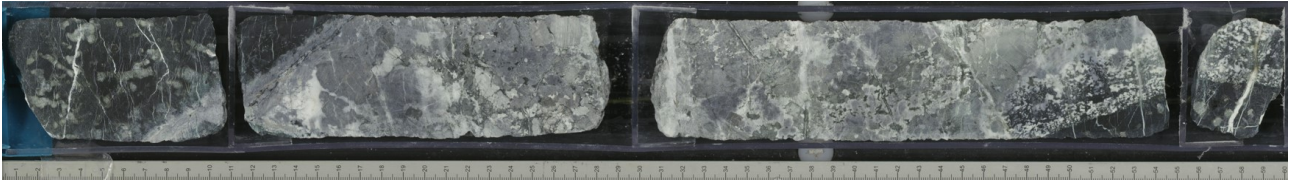


Fig 27. Core 113-4. A 50 cm-wide coarse-grained gabbroic intrusion.

Thin sections containing coarse-grained gabbro intrusions are 6 out of 22 and always include a rock portion that is relatively close to the contact with serpentinized peridotite or with a contact-related lithology. Therefore, no thin section represents the central core of a gabbroic intrusion. No magmatic olivine or other primary magmatic phases are found within the core of gabbroic lithology, away from the contact with the host serpentinized mantle.

Magmatic evolution

Clinopyroxene

Clinopyroxene occurs as centimeter-sized crystals ranging from euhedral to subhedral, locally developing anhedral rims. Crystals are typically slightly fractured and show well-developed cleavage. Twinning is observed in one thin section. Contacts with plagioclase are commonly straight or subhedral (Fig. 28), while locally lobate boundaries are observed, reflecting equilibrium and disequilibrium crystallization, respectively.

Plagioclase

Like clinopyroxene, plagioclase occurs as centimeter-sized and generally shows a subhedral habit. Alteration is widespread, but when preserved, plagioclase is uncolored and displays its typical polysynthetic twinning. It never occurs as an interstitial phase. In portions of the coarse-grained gabbro relatively close to the contact with the mantle, small plagioclase chadacrysts may locally occur enclosed within centimetric clinopyroxene crystals (Fig. 29).

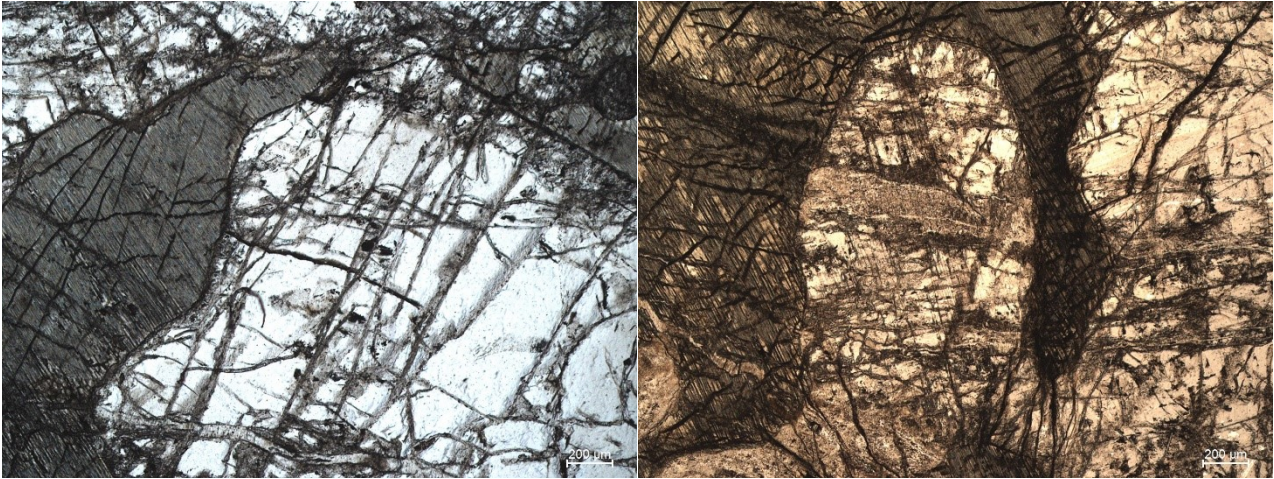


Fig 28. On the left: straight plagioclase – clinopyroxene contact. On the right: clinopyroxene interstitial habit. Boundary with plagioclase is strongly lobate.

Sulphides

Although accessory sulphide phases are concentrated close to the contacts with the host mantle, a few coarse-grained gabbros contain rare magmatic sulphides, represented by pyrrhotite grains smaller than 50 micrometers. Micrometric pyrrhotite may be found along clinopyroxene cleavage planes, but only close to the mantle or to contact-related rocks. Distancing from the contact and towards the core of the intrusion, pyrrhotite grains are absent, similarly to olivine crystals.



Fig 29. Both images showing small (altered) plagioclase chadacrysts (blue arrows) enclosed in centimetric clinopyroxenes. In both cases this happens in coarse-grained gabbro close to contact-related lithology. This does not occur in gabbroic intrusions cores.

Textural relationships provide insights into the crystallization sequence of the main mineral phases. Plagioclase crystals are occasionally enclosed within large clinopyroxene grains as chadacrysts, and their contacts with the surrounding clinopyroxene are lobate. Moreover, clinopyroxene locally shows

interstitial portions. Nevertheless, other portions of the gabbro display planar contacts between clinopyroxene and plagioclase crystals.

These relationships suggest a local earlier crystallization of plagioclase with respect to clinopyroxene, followed by crystallization under disequilibrium conditions. Conversely, other portions are characterized by simultaneous equilibrium crystallization of the two main magmatic minerals.

Hydrothermal evolution

Coarse-grained gabbro is consistently sampled along contacts with serpentinized peridotite. Since lithological contacts represent preferential pathways for fluid circulation, the gabbro samples are commonly moderately to pervasively altered by hydrothermal fluids (Fig. 30). Sets of fractures generally crosscut the rocks approximately perpendicular to lithological contacts. Portions of the rock characterized by higher fracture density typically display more intense alteration than less fractured portions. In addition, with increasing distance from a set of fractures, magmatic minerals are typically less altered and may retain unaltered their magmatic core.

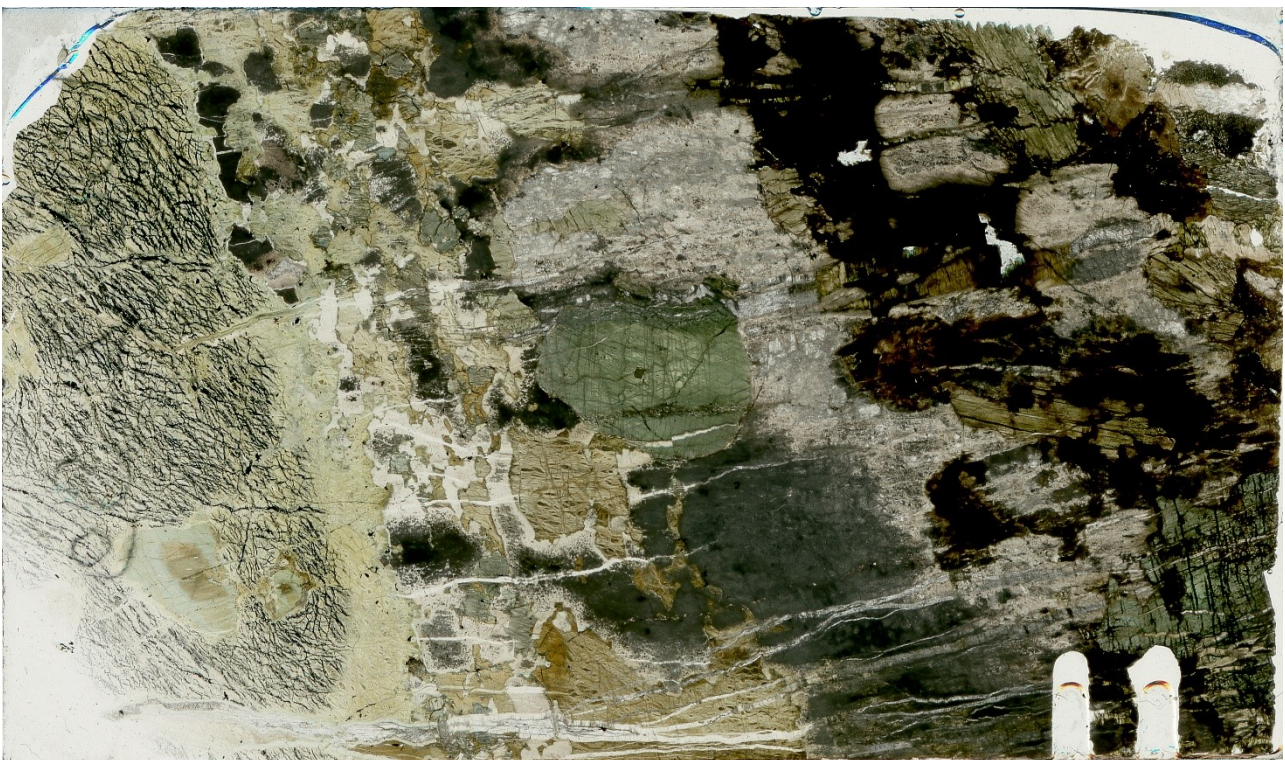


Fig 30. Thin section 166-2-99 scan. One of the most altered samples recovered. From the left to the right: serpentinized harzburgite – millimetric altered troctolite zone – extremely altered coarse-grained gabbro. The bottom part of gabbro is more altered than the upper part, due to higher fractures density.

The term of sets of fractures refers to macroscopic fractures sharing the same orientation and crosscutting entire portions of the rock and multiple crystals, rather than intracrystalline fractures,

which may occur within perfectly hydrothermally unaltered magmatic crystals, particularly plagioclase. Fractureless portions of gabbro intrusions appear preserved to moderately altered.

These observations are consistent with *McCaig et al. (2023)*, which reported that gabbro is more extensively altered in intervals characterized by a high degree of ductile and brittle deformation, a high density of hydrothermal veins, and contacts with serpentinite.

Plagioclase frequently undergoes alteration resulting in the crystallization of fine-grained prehnite, a clayish mineral typical of plagioclase alteration. In some cases, plagioclase cores remain preserved despite the occurrence of alteration closer to the rims. When such alteration is observed in thin section, the corresponding plagioclase appears milky white in the core samples. Associated with fractures, where hydrothermal fluid circulation is strongly concentrated, plagioclase may also be replaced by black hydrothermal garnet, chlorite, epidote, talc, and sericite.

Clinopyroxene is generally less inclined to alteration than plagioclase, although alteration still occurs. In such cases, clinopyroxene may display greenish colors, while in other cases it shows weaker birefringence colors associated with crystal turbidity. It can be replaced by green amphibole (tremolite) along the brims and chlorite, as well as locally by talc.

4.2 HOST PERIDOTITE

The mantle rocks only appear as serpentized peridotites, with mostly recovered harzburgite downhole, but dunite is also present. Only a few thin sections contain the host serpentized peridotite.

Along the gabbro intrusion – mantle contacts, harzburgite is associated with thin troctolite zones, while dunite is associated with thick contact-related lithologies where on the contact, there is impregnated dunite and progressive olivine abundance decrease with plagioclase and clinopyroxene increasing while distancing from the mantle lithology, entering the olivine-rich troctolite.

From core observations, it is evident how mantle rocks that do not show percolating melts along coarse-grained gabbro contact are residual serpentized harzburgites showing coarse-grained mantle orthopyroxene. Where thick (centimetric-wide) olivine-rich troctolite contacts take place the mantle lithology may be either dunite or spinel-harzburgite (Fig. 32). Typically, when MORB melt-mantle rock reaction occurs, harzburgite orthopyroxene is the first mineral to be dissolved and olivine-rich troctolites can be reproduced by assimilation of an orthopyroxene-bearing peridotite until the last phases of the assimilation-fractional crystallization (AFC) processes (*Sanfilippo et al., 2015*).

When magmatic percolation is still visible within the mantle lithology (Fig. 31), clinopyroxene and plagioclase typically refertilized the mantle harzburgite and may be associated with along with local, residual orthopyroxene crystals.

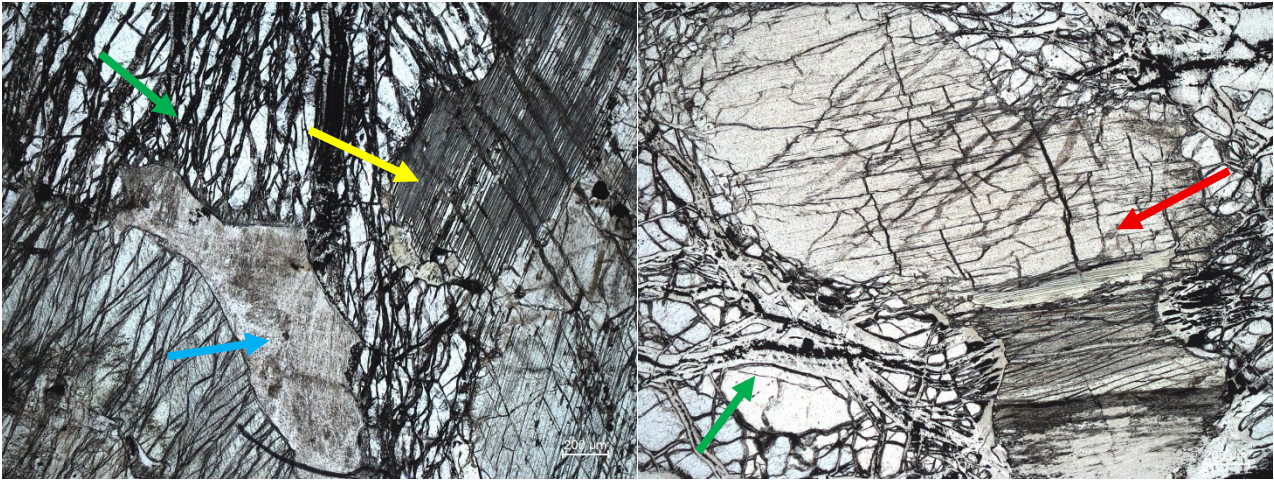


Fig 31. On the left: refertilized mantle (olivine green arrow) with clinopyroxene (yellow arrow) and plagioclase (blue arrow) crystallization. On the right: preserved residual harzburgite, constituted by olivine (green arrow) and orthopyroxene (red arrow).

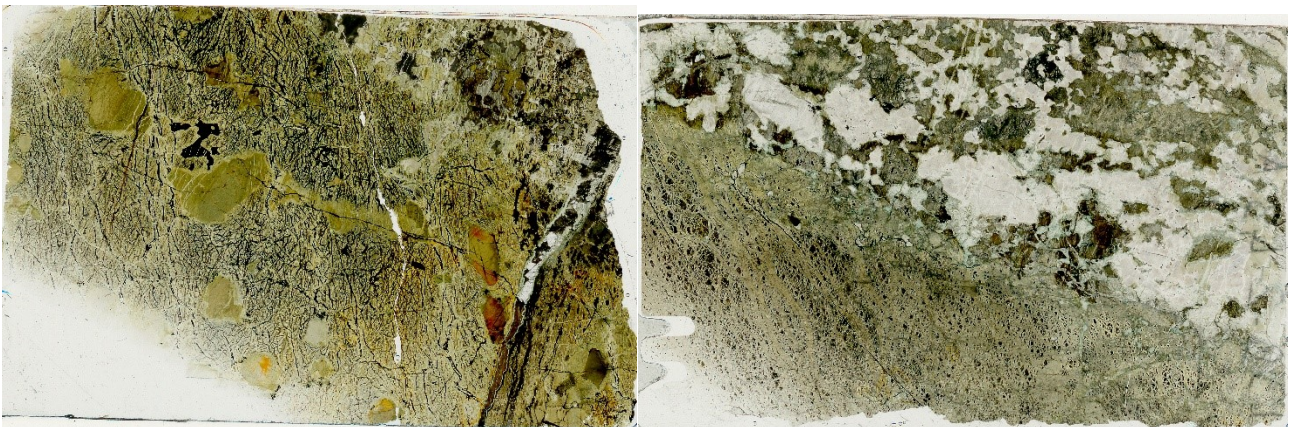


Fig 32. Thin sections 41-1-100A and 139-2-49A. Both show the contact-related (olivine-rich) troctolite associated with the mantle. On the left spinel harzburgite, while on the right dunite occurs.

4.3 CONTACTS AND CONTACT-RELATED LITHOLOGIES

This section describes the characteristics of the contacts and contact-related lithologies. Gabbro and serpentinized peridotite have already been described in the previous paragraphs and are therefore not further discussed here.

The subdivision of the contact families follows a lithological textural scheme that generally is comparable to the scheme adopted in the previous chapter, as the cores show features that can be correlated with those observed in the thin sections.

4.3.1 COARSE-GRAINED GABBRO CONTACT

This category includes the direct contact between the mantle rocks and the coarse-grained gabbro intrusions. Approaching the mantle lithology, gabbro intrusions may either retain their original grain-size or experience grain-size reduction, that results in medium-grained clinopyroxene and plagioclase close to the contact. Furthermore, magmatic phases may percolate into the ultramafic rocks, a feature that is particularly evident under the optical microscope. The intensity of this percolation varies among the samples, ranging from pervasive and widespread infiltration to its complete absence, with several intermediate stages.

Magmatic evolution

Clinopyroxene

It occurs either as a coarse- or medium-grained phase along contacts with serpentized peridotite. It may be found in euhedral and subhedral habits, although locally it can occur with interstitial crystal portions. Contacts with plagioclase may be planar and lobate (Fig. 33), but also lobate contacts with olivine, where present, are observed. Centimeter-scale, isolated clinopyroxene crystals are found along the contacts, generally much larger than the associated plagioclase crystals. These large clinopyroxene crystals show a poikilitic texture, enclosing small plagioclase chadacrysts. Where well preserved, clinopyroxene is greyish to pale green and displays its typical well-developed cleavage and second-order interference colors.

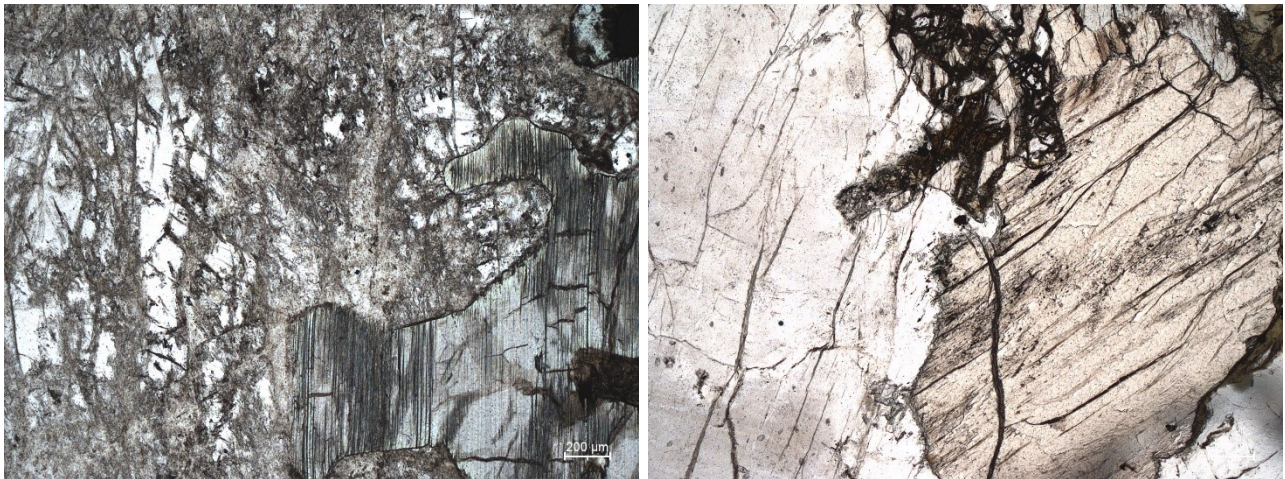


Fig 33. On the left: slightly altered clinopyroxene and moderately altered plagioclase. The contact is lobate and clinopyroxene is interstitial. Zooming out, this is only a small part of a large clinopyroxene oikocryst, which encloses plagioclase chadacrysts. On the right: almost straight contact between preserved plagioclase and clinopyroxene. Sections 91-1-24 and 229-1-120.

With increasing alteration, the mineral becomes progressively turbid. In a few samples, pervasive magmatic percolation into the mantle is observed, with clinopyroxene representing the dominant

magmatic phase, that can locally display exsolution textures. Clinopyroxenes located in between mantle altered olivine grains in such context are likely indicative of a magmatic impregnation texture (Rajeevan *et al.*, 2026).

Plagioclase

Plagioclase is extensively altered, although locally preserved magmatic cores can still be observed along the contacts. It appears white in plane-polarized light and shows first-order interference colors together with the typical polysynthetic gemination under crossed polars. Where its original habit is preserved, plagioclase is generally subhedral, however, in most cases, its original morphology is hidden by alteration. Plagioclase is the phase most commonly occurring in contact with olivine, and their boundaries are extremely lobate, possibly indicating partial resorption of olivine (Rampono *et al.*, 2016). Plagioclase also occurs within magmatic percolations into the serpentinized mantle as an interstitial phase, despite in lower abundance than clinopyroxene (Fig. 34).

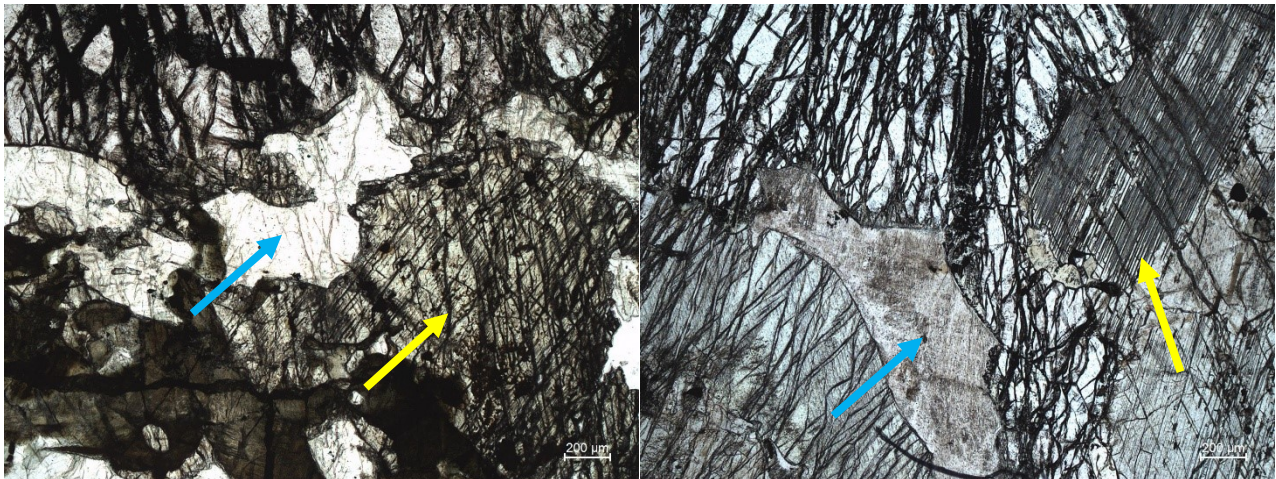


Fig 34. Both images come from Section 229-1-120 and display clinopyroxene (yellow arrows) and plagioclase (altered, blue arrows).

Olivine

When magmatic percolation is limited, olivine crystals occur close to the contact within the gabbro, and are generally well-preserved or only slightly altered (Fig. 35). They account for approximately 5% of the total gabbroic assemblage close to the contact. With increasing intensity of percolation, olivine may be restricted to small and rare chadacrysts in coarse-grained plagioclase crystals (Fig. 36). Olivine crystals are typically preserved at the contact with completely serpentinized mantle peridotite, despite the intense alteration affecting the surrounding mantle lithology.

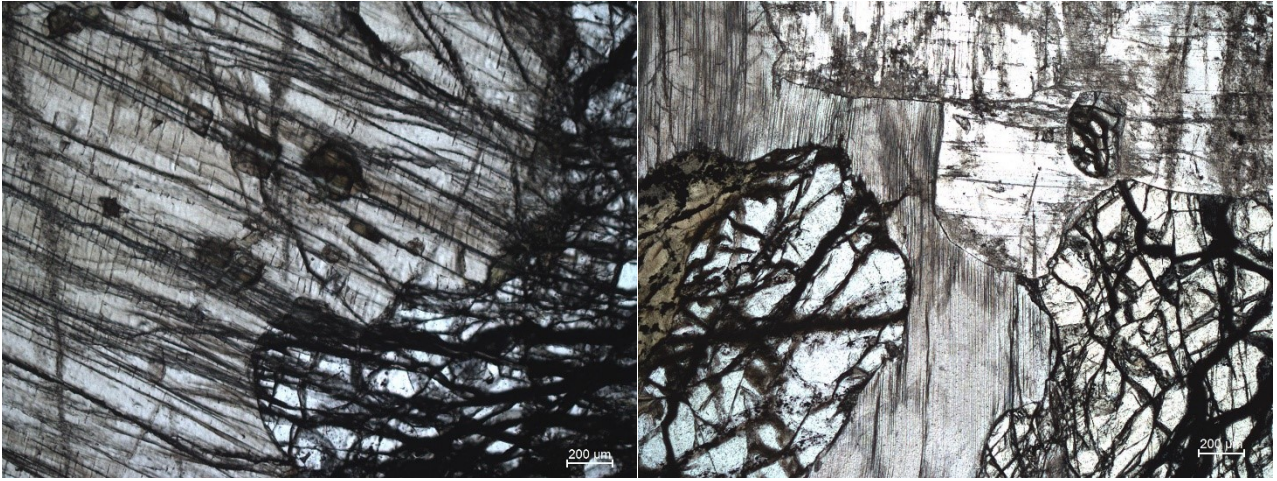


Fig 35. On the left: large well-preserved clinopyroxene bordering with an olivine crystal showing preserved cores despite heavy fracturing. On the right: moderately altered olivine crystals in contact with an interstitial portion of a centimeter-sized clinopyroxene and a plagioclase crystal. Both images represent the gabbro intrusion along the contact with the host mantle. Sections 181-3-67 and 91-1-24.

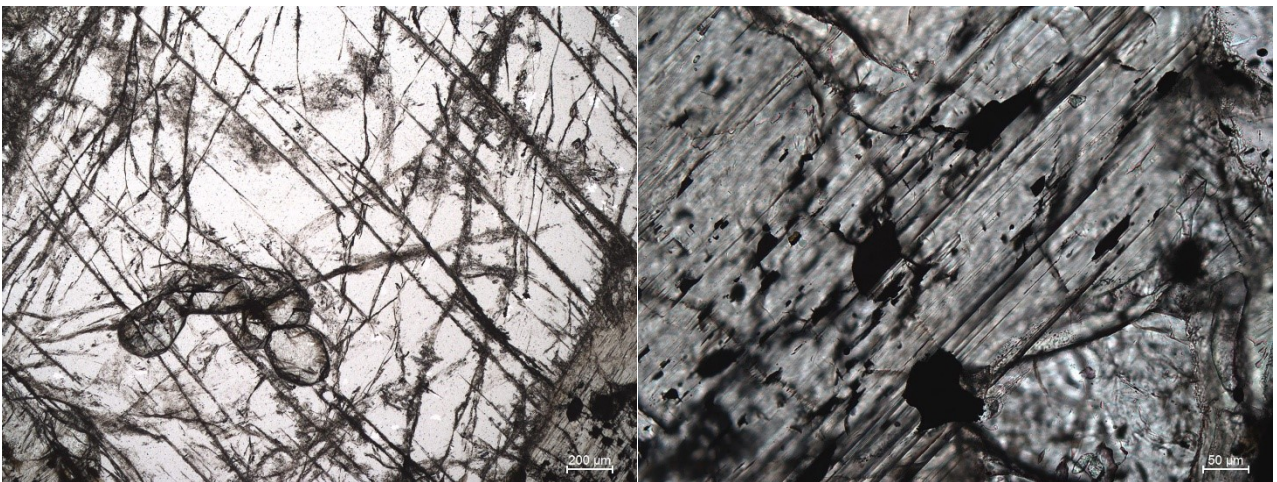


Fig 36. On the left: large well-preserved plagioclase enclosing rounded magmatic (triple junctions) olivine crystals. On the left with respect to plagioclase, peridotite-gabbro contact takes place. On the bottom right some black opaque phases take place along clinopyroxene cleavage. On the right: the same opaque phases of the left image are zoomed on, which are sulphides crystallized along clinopyroxene cleavage.

Sulphides

They are significantly less abundant than those observed in the contact-related lithologies. Pyrrhotite is by far the most common sulphide and generally occurs as single grains, but it may be locally associated with micrometric chalcopyrite and pentlandite in polysulphide grains. These two phases are not observed as isolated grains, but occur exclusively in association with pyrrhotite, that represents the dominant phase within the polysulphide aggregates.



Fig 37. On the left: several sulphides, mostly pyrrhotite, crystallized along clinopyroxene cleavage. On the right: a 70 micron-wide polysulphide grain, mainly composed of pyrrhotite (grey arrow), but also pentlandite (yellow arrow) and chalcopyrite (orange arrow). Both images were taken under reflected light.

In these contexts, sulphides occur preferentially along clinopyroxene cleavage planes, where several crystals or polysulphide aggregates may accumulate (Fig. 37). Locally, isolated pyrrhotite crystals are also observed within plagioclase. Sulphide grains associated with these lithological contacts are typically very small and do not exceed 100 microns.

Textural relationships indicate a clear crystallization sequence. When present, olivine represents the earliest crystallizing phase, as it occurs as inclusions within plagioclase, which crystallized subsequently. Plagioclase, in turn, is locally enclosed within clinopyroxene, indicating that the latter crystallized afterwards. This sequence is further supported by the locally interstitial habit of clinopyroxene, which suggests that it was the final major to crystallize within this assemblage.

Hydrothermal evolution

Although preserved magmatic cores of plagioclase are relatively common, the mineral is predominantly affected by alteration to prehnite and clayish phases. Plagioclase is partially to totally replaced by fine-grained prehnite aggregates and, locally, by opaque phases, possibly representing aggregates of hydrothermal garnet and chlorite (Fig 38).

Clinopyroxene can be partially replaced by green amphibole, especially in the vicinity of fracture networks. Overall, however, clinopyroxene is better preserved than plagioclase. Magmatic olivine is generally well-preserved throughout the thin sections.

Hydrothermal sulphides are also locally present, occurring preferentially along fracture networks. The identified phases are heazlewoodite and horomanite.

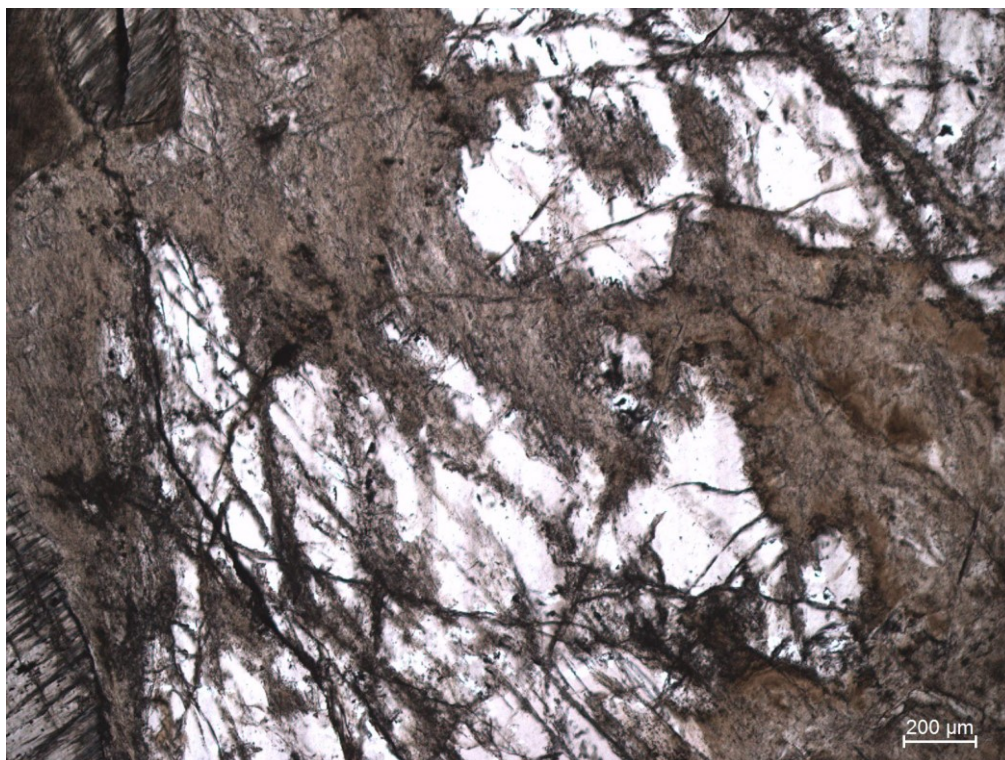


Fig 38. Partially altered plagioclase with preserved core. Section 79-4-68.

4.3.2 (OLIVINE-RICH) TROCTOLITE CONTACT ZONE

This category includes contact-related lithologies consisting of mostly medium-grained, holocrystalline, olivine-rich troctolite and troctolite occurring between the serpentinized mantle and gabbroic intrusions. These lithologies show high variable thickness which ranges from a minimum of 1 cm to a maximum of approximately 50-60 cm. Following *Rampone et al. 2016* and *Ferrando et al., 2018*, olivine-rich troctolite is defined by an olivine content exceeding 70 vol%, while according to *Drouin et al. (2009)*, olivine-rich troctolite is composed of 64 to 85% by olivine, whereas troctolite 45 to 64%. One of the samples displays a troctolite with norite/gabbro-norite domains.

Along the contact with the serpentinized mantle, olivine locally reaches up to 90 vol% of the rock and maintains the same hydrothermal alteration of the associated serpentinized mantle (Fig. 39) and is coupled with less than 10 vol% interstitial plagioclase, corresponding to an impregnated peridotite (Fig. 39-41). Distancing from the mantle, the contact-related lithology may display a continuous enrichment in plagioclase and clinopyroxene, generating a decimetric contact zone that progressively contains less olivine, turning into a troctolite. In the thicker (olivine-rich) troctolitic zones, olivine progressive decrease towards the gabbroic intrusion, and plagioclase and clinopyroxene crystals increase in size, indicate a gradual textural transition towards the gabbro. These systematic changes define a gradual textural and modal transition from troctolite to the adjacent gabbroic lithology.

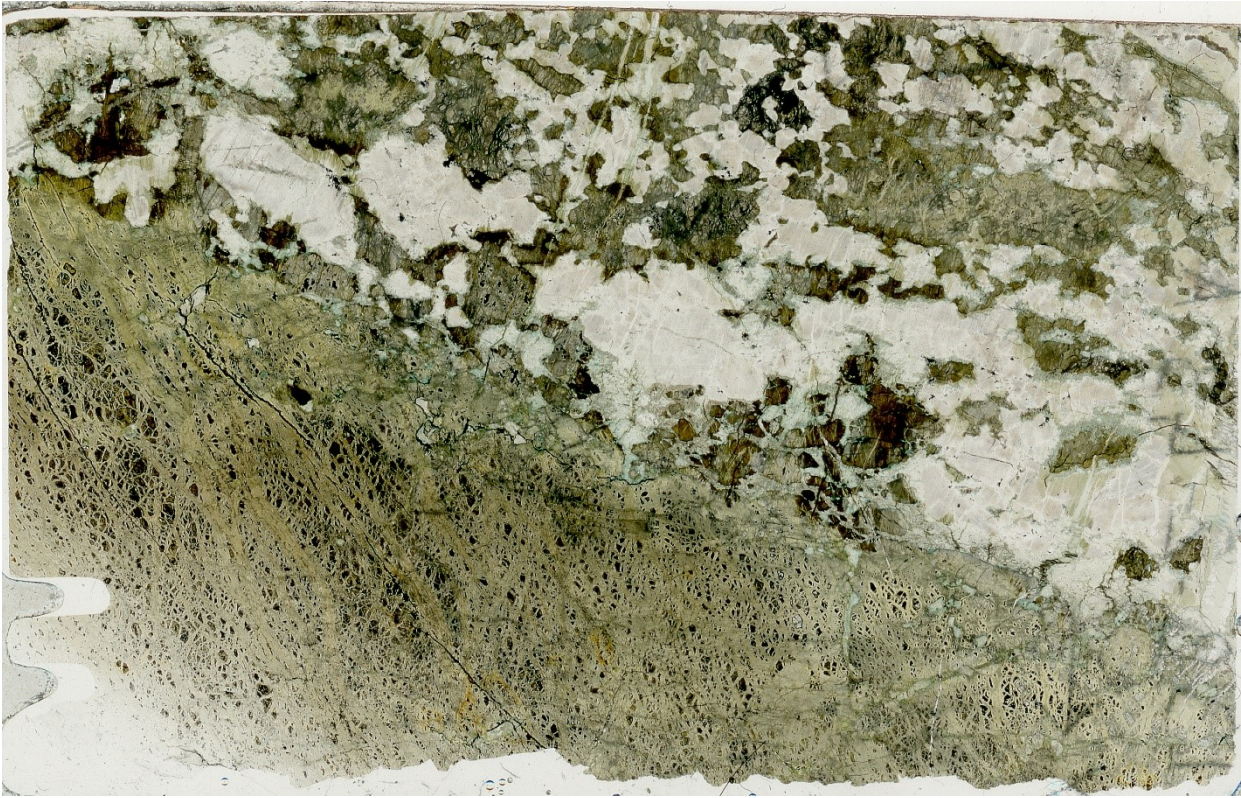


Fig 39. Section 139-2-49A represents the contact of the contact-related olivine-rich troctolite (> 30 cm) with the serpentinized mantle. On the bottom, serpentinized peridotite occurs, while medium-grained olivine-rich troctolite is on the top.

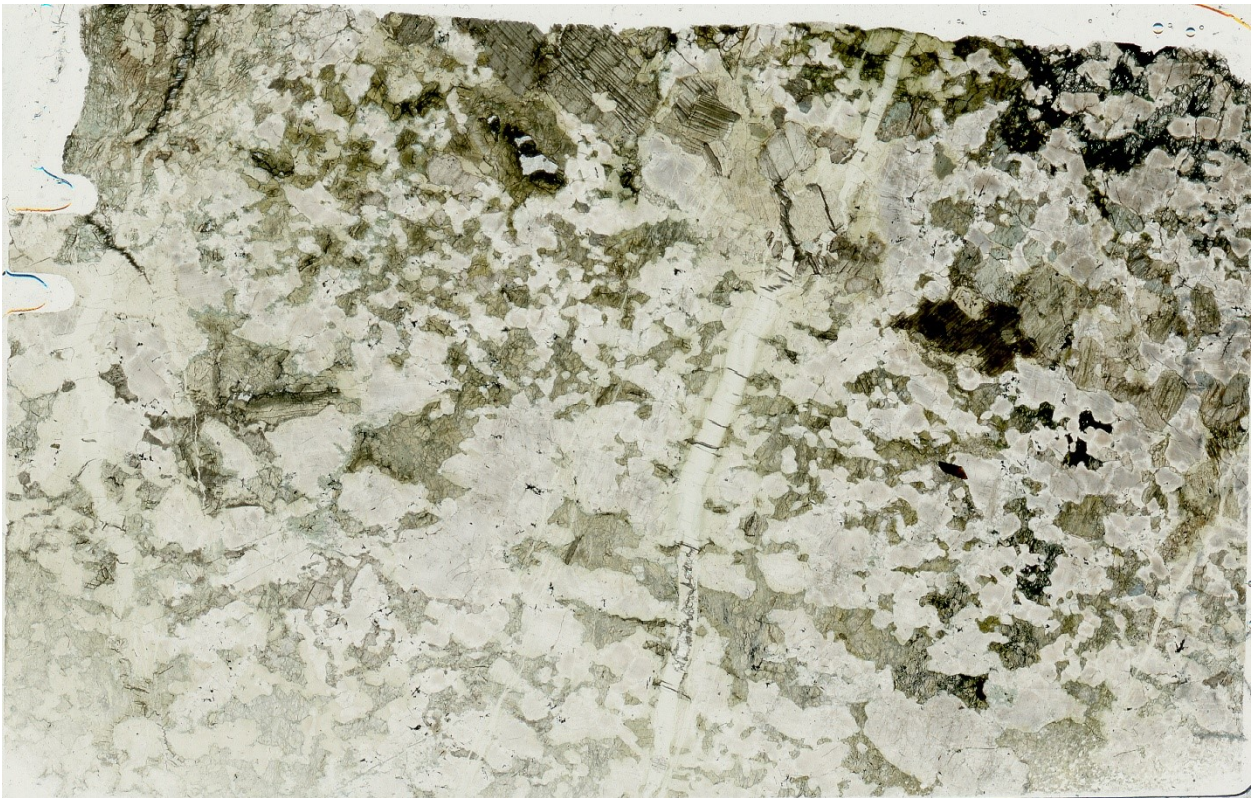


Fig 40. Section 139-2-49B represents the continuation of contact-related olivine-rich troctolite that progressively becomes a troctolite. Mantle direction is towards the bottom. Plagioclase is higher and clinopyroxene begins to crystallize as oikocrysts.

Towards the center of the contact-related lithology, olivine remains the dominant phase, but is associated with 30 to 50 vol% plagioclase, with clinopyroxene locally reaching 5-10 vol% (Fig. 40).

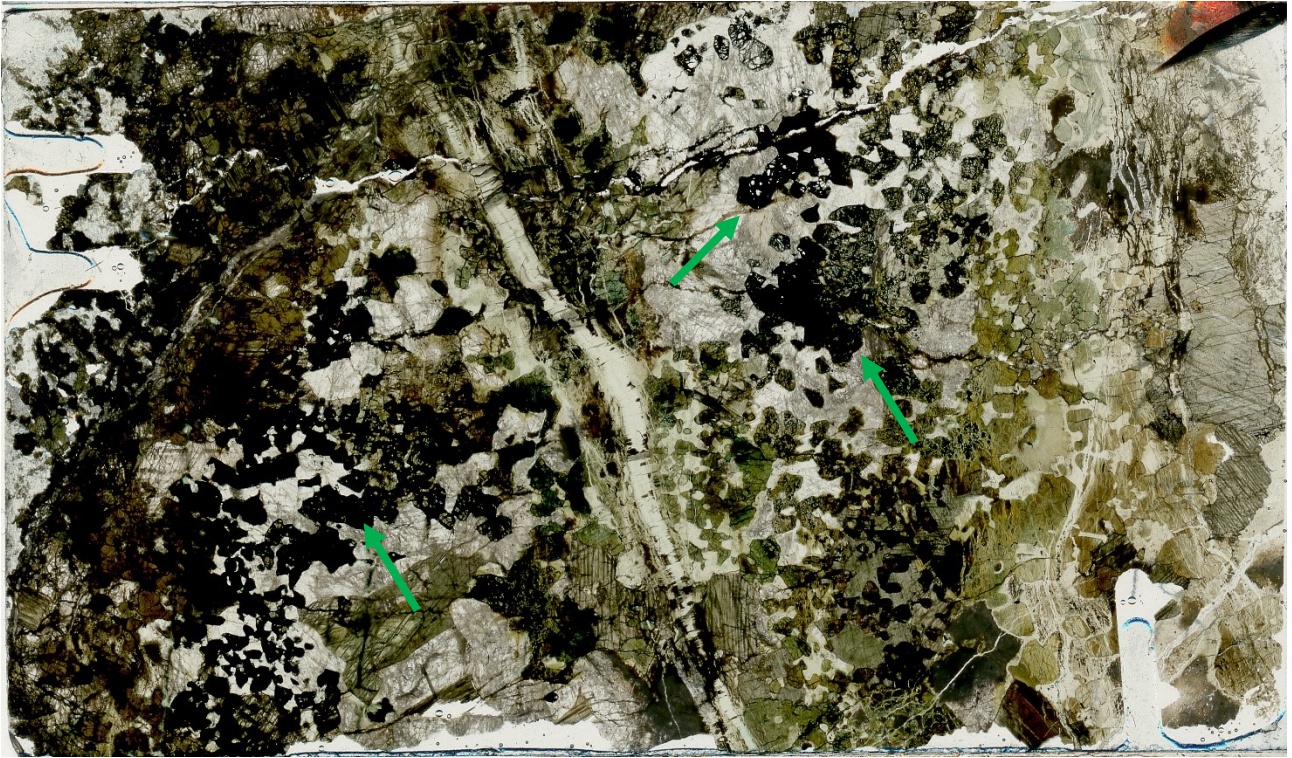


Fig 41. Section 39-1-32 represents an olivine-rich troctolite thin zone. Serpentinized mantle is present on the left of the thin section, while gabbro on the right. Altered olivine (green arrows) appears as rounded to subrounded crystals. Olivine is heavily altered.

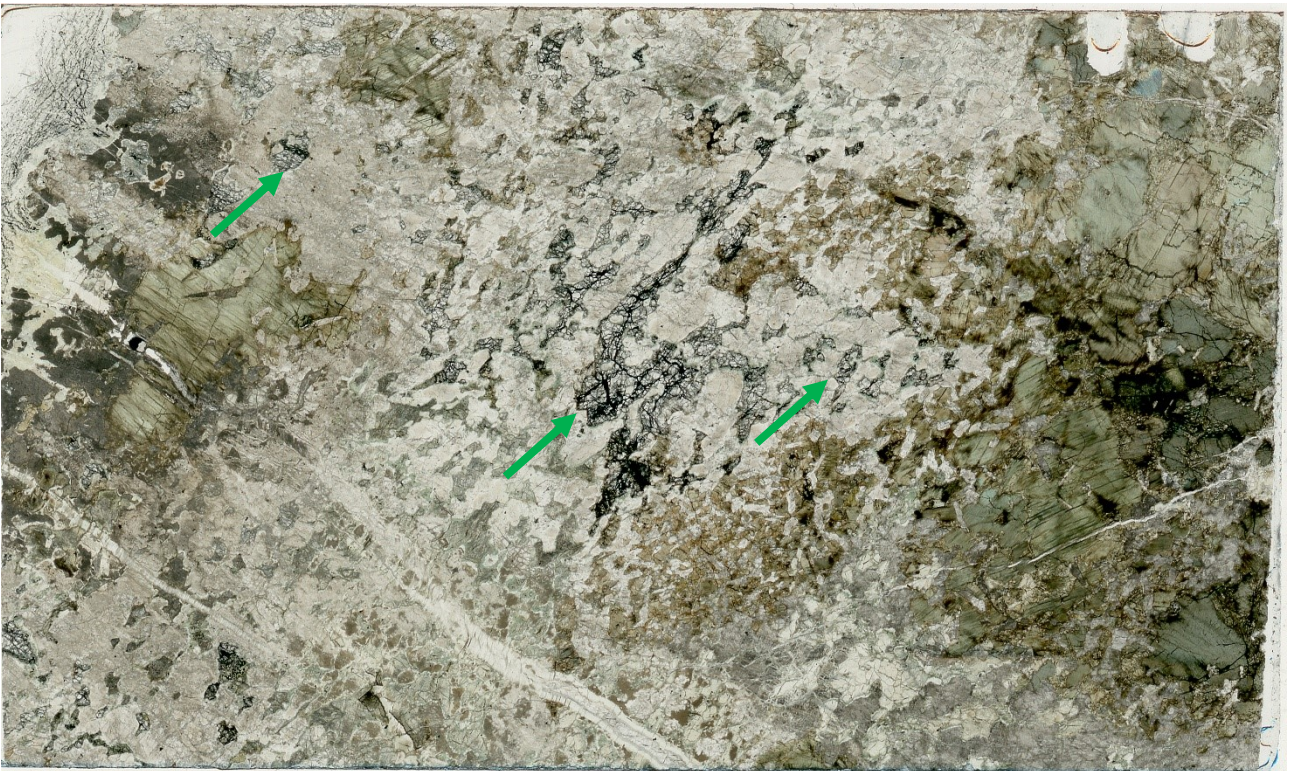


Fig 42. Section 111-2-130 represents another olivine-rich troctolite thin zone. Serpentinized mantle is present on the top left of the thin section, while coarse-grained gabbro on the right. Olivine (green arrows) appears as extremely anhedral and lobate crystals.

In contrast, moving away from the mantle, the lithology may suddenly change to coarse-grained gabbro. In this case, the contact-related olivine-rich troctolite shows a few centimeters-wide extension. Within the thin (< 10 cm) zones (Fig. 42), isolated poikilitic clinopyroxene may rarely occur.

Magmatic evolution

Olivine

It occurs with variable anhedral to rounded textures and displays a systematic textural and modal variation across the contact-related lithology. Close to mantle contact, the first olivine texture is common and occurs as subhedral to anhedral, coarse-grained crystals, generally exhibiting lobate boundaries with plagioclase (Fig. 43). The closer to the mantle contact, the highest the presence of this texture.



Fig 43. Type 1 olivine texture in olivine-rich troctolite. Altered coarse-grained olivine bordering with plagioclase.

The second texture is more abundant moving away from the mantle contact and is characterized by chains of polygonal crystals with curvilinear to lobate boundaries, although it is also observed along the contacts (Fig. 44). In this second case, clinopyroxene and especially plagioclase fill the interstitial spaces of adjacent olivine chains. This textural relationship is indicative of a partial corrosion/resorption of the coarse-grained olivine first population (Drouin *et al.*, 2009).



Fig 44. Type 2 olivine texture, that displays lobate contacts with plagioclase.

A third texture displays separated medium-grained rounded olivine occurring as chadacrysts within large plagioclase and locally clinopyroxene oikocrysts. This is typically found in troctolite far from the contact, although less common than type 2.

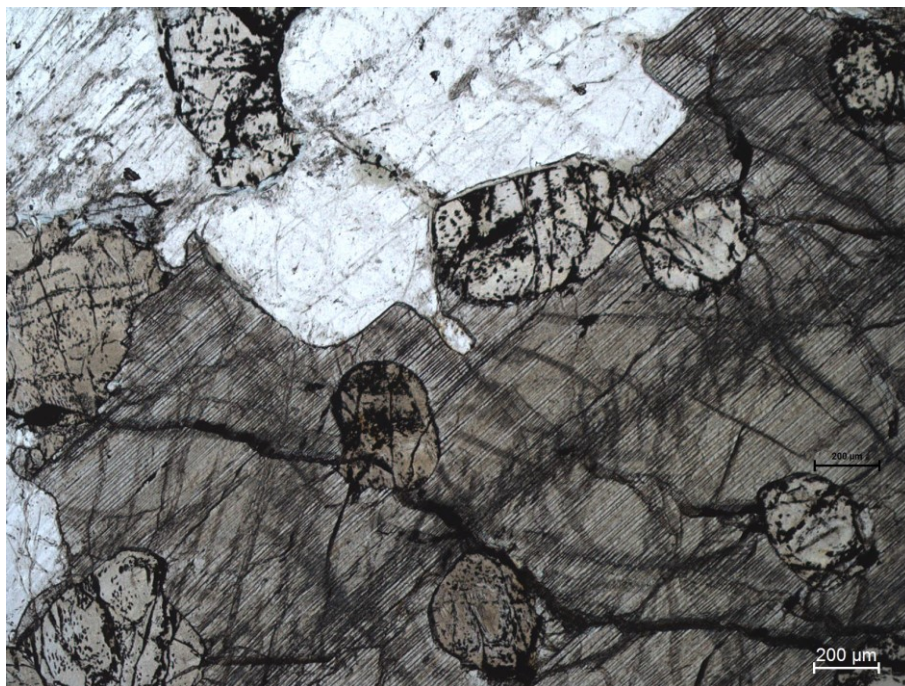


Fig 45. Type 3 serpentinized olivine texture enclosed in both clinopyroxene and plagioclase. In this case, type 2 plagioclase and type 2 clinopyroxene show a straight contact, with a small interstitial part of the plagioclase crystal.

Olivine abundance progressively decreases towards the gabbro intrusion (from up to 90 vol% to about 50 vol%), while crystals preservation improves where fracturing is less pervasive. In the same direction, plagioclase and clinopyroxene crystals progressively increase in size, indicating a gradual textural transition towards the gabbro.

Two of the samples show a 2-3 cm-wide olivine-rich troctolite to troctolite zone, where olivine can occur either with type 1 and 2 texture or as extremely lobed grains. Again, boundaries with plagioclase are strongly lobate, evidencing resorption of olivine crystals.

Plagioclase

The second most abundant silicate phase is plagioclase, accounting for approximately 10 to 50 vol% of the rock. It shows polysynthetic twinning and different textures based on the textural relationship with olivine. When associated with olivine texture type 1, plagioclase is mostly anhedral and does not form large poikilitic crystals. Instead, it displays highly lobate boundaries against olivine, suggesting possible partial resorption of olivine during plagioclase crystallization caused by reactive dissolution of olivine (*Rampone et al., 2016*). This plagioclase texture type 1 is commonly observed in the vicinity of the contact with the serpentinized mantle, and it can be characterized by coarse- to medium-grained crystals (Fig. 46).



Fig 46. Interstitial/anhedral type 1 plagioclase showing lobate crystals at the contact with altered olivine, indicative of corrosion.

A second texture is primarily observed associated with olivine texture 2 and 3. In such case, plagioclase mainly occurs as large oikocrysts partially (olivine texture type 2) or completely (olivine texture type 3) enclosing olivine crystals (Fig. 47-48-49).

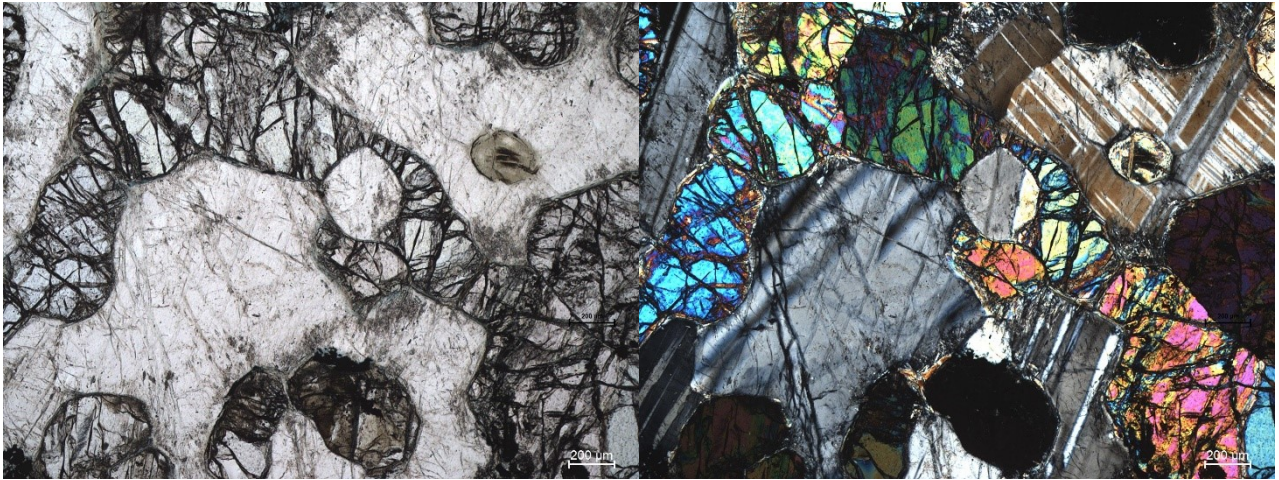


Fig 47. Plagioclase type 2 crystals partially enclosing olivine type 2. Section 41-1-44B in planar and crossed polars.



Fig 48. Plagioclase type 2 crystal associated with type 3 olivine chadacrysts and interstitial to vermicular clinopyroxene.

Plagioclase abundance progressively increases distancing from the serpentinized mantle, from as little as 5-10 vol% near the mantle contact to approximately 50 vol% within troctolite core towards the gabbroic intrusion. Clinopyroxene crystals may locally enclose small plagioclase chadacrysts, suggesting clinopyroxene crystallized after plagioclase (Fig. 48).

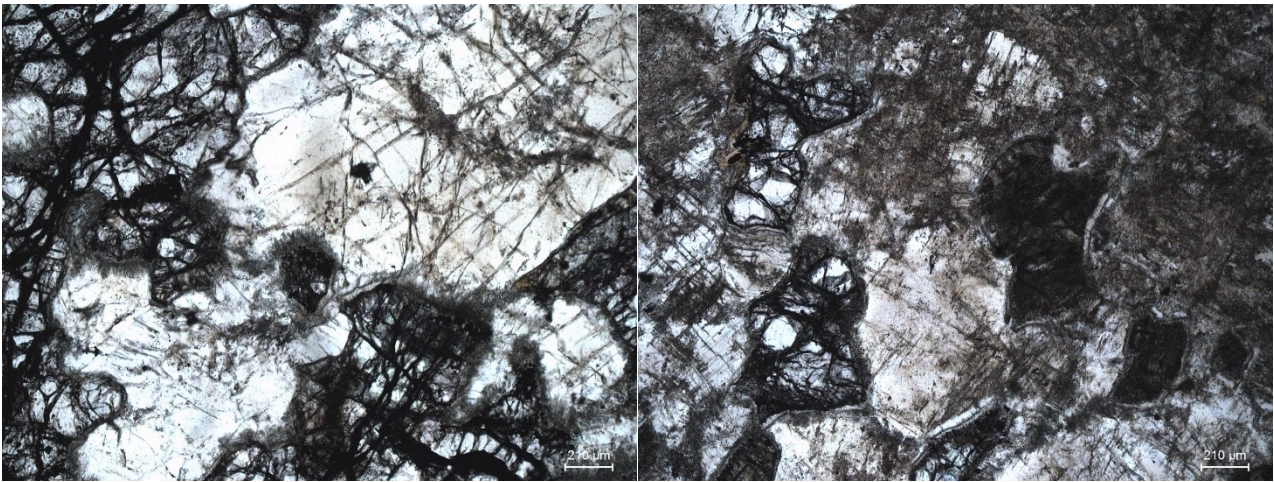


Fig 49. Lobate contacts between plagioclase type 2 and lobate olivine, which seems to display resorption textures. Section 111-2-130, thinner troctolite zone.

Clinopyroxene

Clinopyroxene represents an accessory magmatic phase close to the mantle where it only occurs as an interstitial to vermicular phase with coronas partially enclosing olivine type 1 or between olivine type 1 or 2 and plagioclase type 1. Vermicular nature of clinopyroxene (type 1) is most likely produced by the occupation of residual interstitial spaces within the olivine – plagioclase crystal mush and it is therefore the last magmatic phase that crystallizes (Fig. 50). In this context along the mantle contact, clinopyroxene may also occur as isolated oikocrysts (type 2) enclosing plagioclase chadacrysts along the contact with the mantle.

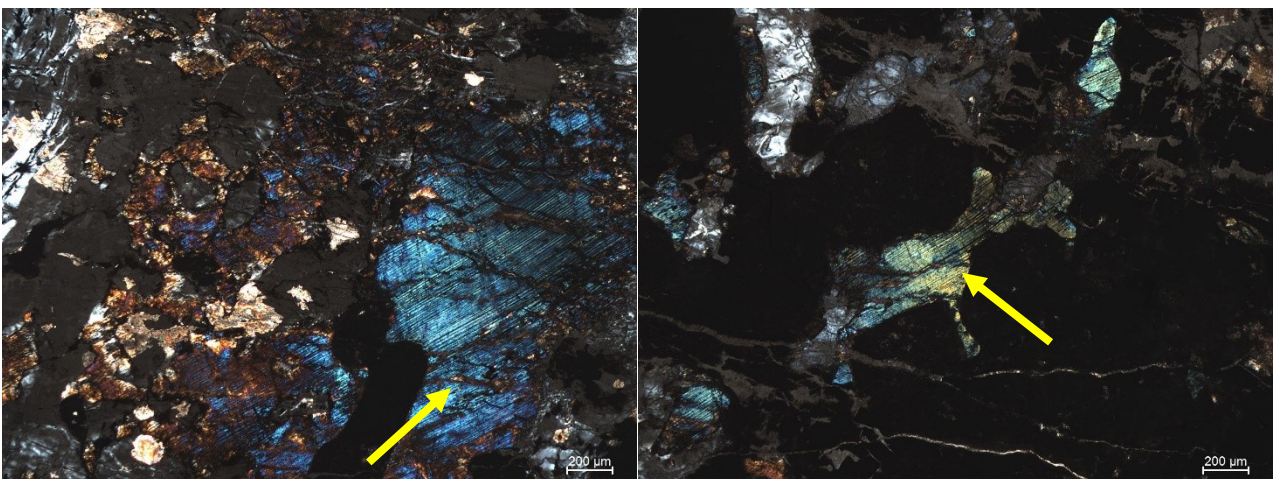


Fig 50. Both images represent a troctolite lithology visualized under crossed-polars. Interstitial clinopyroxene (yellow arrows) is clearly visible and mostly preserved, while the surrounding plagioclase is completely altered.

Distancing from the mantle, clinopyroxene primarily occurs as large poikilitic crystals (textural type 2) mostly enclosing olivine type 2 and 3, but locally small and rare plagioclase chadacrysts (Fig. 51). In this case, textural relationships with plagioclase are different, since their boundaries are locally straight, suggesting a concomitant equilibrium crystallization of the two phases. However, portions of these clinopyroxene oikocrysts result interstitial and therefore identifying those mineral portions as the last one formed.



Fig 51. On the left: type 2 clinopyroxene crystallized concomitantly with plagioclase. On the right: type 2 clinopyroxene which shows clearly irregular boundaries against plagioclase. Its interstitial portions suggest a late clinopyroxene crystallization.

Within thicker contact-related zones, large clinopyroxene type 2 oikocrysts become consistently developed at distances greater than approximately 5-10 cm from the mantle contact (Fig. 52), while thinner zones generally contain only rare, isolated clinopyroxene type 1 crystals.

Thus, clinopyroxene progressively changes from an accessory phase within the olivine-rich troctolite to a primary magmatic phase distancing from the contact in the troctolite.

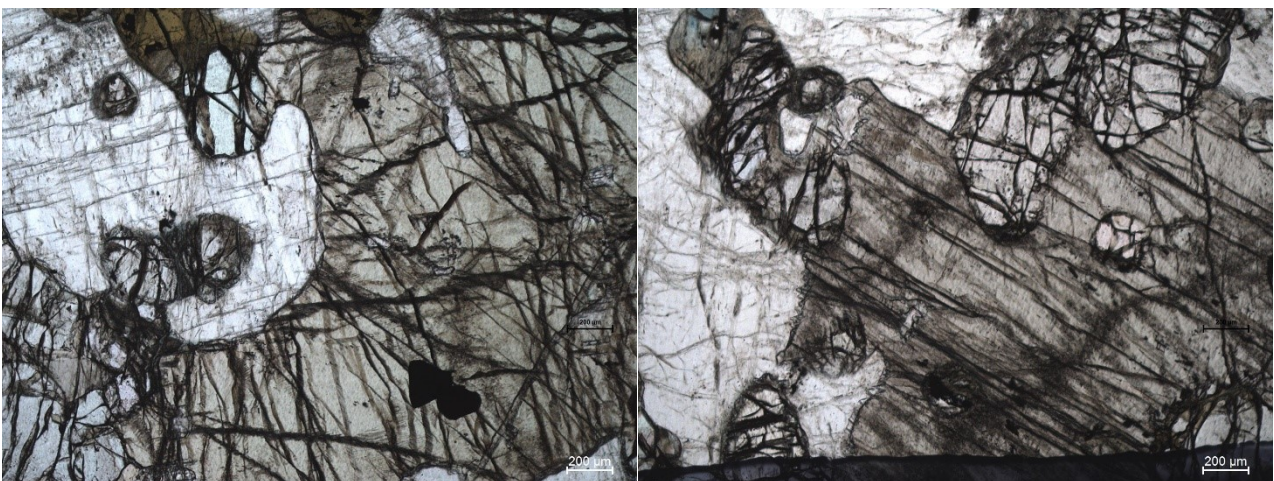


Fig 52. Clinopyroxene type 2 oikocrysts enclosing olivine type 2-3 crystals in troctolite. Lobate to straight contacts with plagioclase.

Clinopyroxene and plagioclase may show irregular to straight crystal boundaries, even within different portions of the same crystals. Straight boundaries indicate concomitant equilibrium crystallization, while when clinopyroxene encloses plagioclase or forms vermicular portions it crystallizes subsequently to plagioclase.

Sulphides

Sulphides are significantly more abundant than in coarse-grained gabbro contacts. The sulphide assemblage is dominated by pentlandite and pyrrhotite, although chalcopyrite is also widespread. Pentlandite increment is remarkable compared to coarse-grained gabbro contacts, where it is rare.

Their occurrence varies especially considering olivine textural types. Closer to the mantle in olivine-rich troctolite containing olivine type 1, polysulphide grains are characterized by pyrrhotite – pentlandite association (Fig. 53), with accessory chalcopyrite along rims (Fig. 57). In such rocks, when the polysulphide grain occur close to or within olivine, the main phase is pentlandite which can account for 50 to 70 vol% of the aggregate, which is associated with pyrrhotite 25 to 45 vol% and 5-10 vol% chalcopyrite. Sulphides occur also as aggregates within plagioclase, where the main sulphide is pyrrhotite associated with pentlandite, and chalcopyrite again as an accessory phase. Distancing from the mantle and entering troctolite with olivine type 1-2, pentlandite abundance slightly decreases, while pyrrhotite abundance increases (Fig. 54).

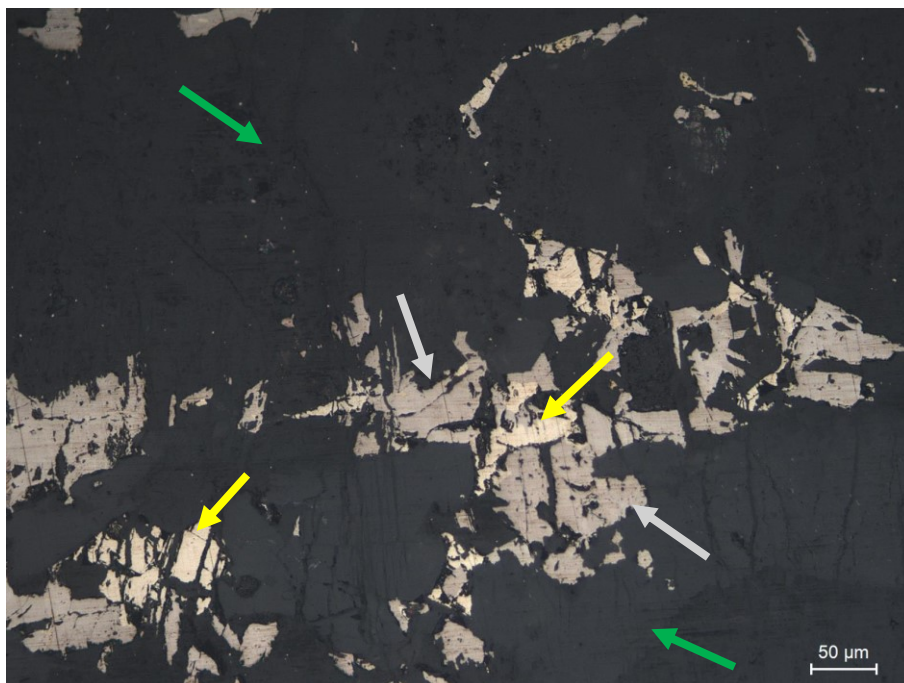


Fig 53. Polysulphide aggregates within type 1 olivine (green arrows) close to boundary with plagioclase. Approximately 60 vol% is pyrrhotite (gray arrow) and 40 vol% is pentlandite.

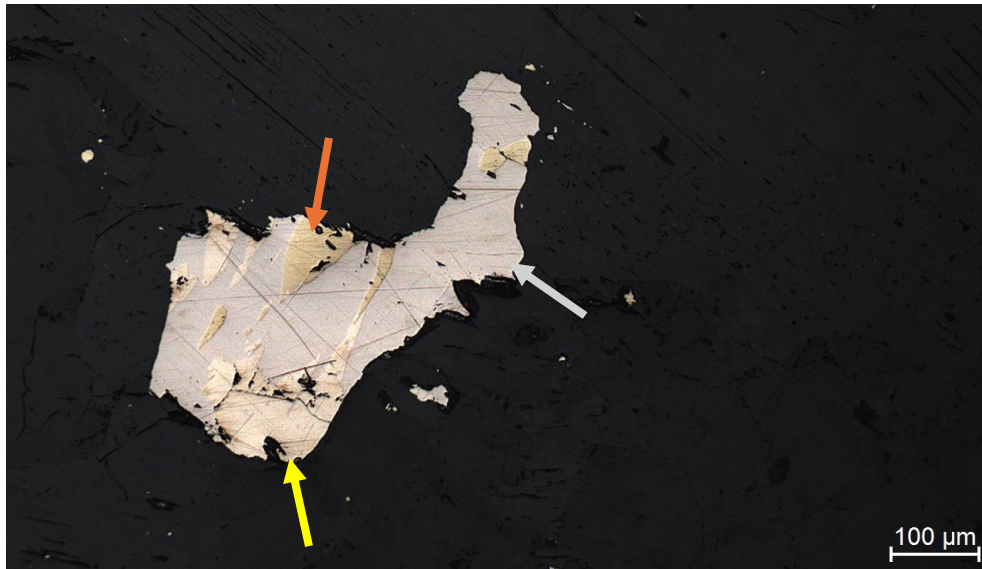


Fig. 54. Polysulphide interstitial grain comprising chalcopyrite (orange arrow), pentlandite (yellow arrow) and pyrrhotite (gray arrow).

Sulphide assemblages within olivine type 2-3 troctolite are generally dominated by pyrrhotite, with chalcopyrite and pentlandite occurring as subordinate phases, locally accounting for a combined proportion of up to 50% of the aggregate, mainly forming along the rims of the aggregate. Pentlandite accounts for at least 30-40 vol% of the aggregate only within olivine crystals. In these rocks, sulphide aggregates are observed enclosed within olivine and plagioclase (Fig. 55-56), as well as along the boundaries of the three main silicates, olivine, plagioclase, and clinopyroxene.

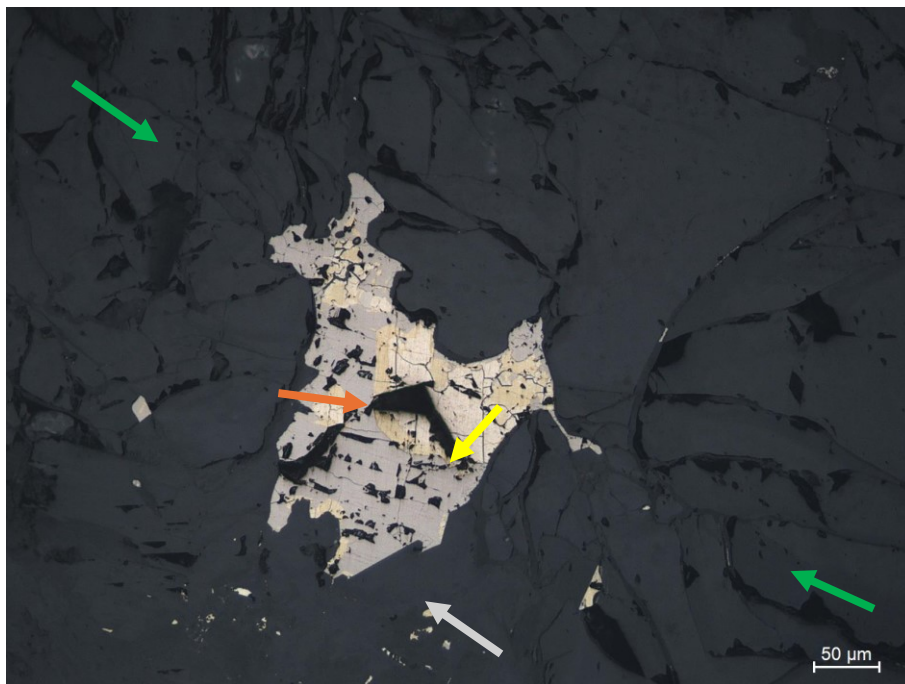


Fig 55. Polysulphide aggregate mainly composed of pyrrhotite (grey arrow), associated with chalcopyrite (orange arrow) and pentlandite (yellow arrow) at the contact between plagioclase and type 2 olivine (green arrow).

Most aggregates exceed 100 microns in size, although aggregates ranging between 50 and 100 microns are also present. Numerous smaller sulphide grains are also widely distributed throughout the thin sections. Locally, sulphide aggregates account for approximately 1 vol% of the rock.

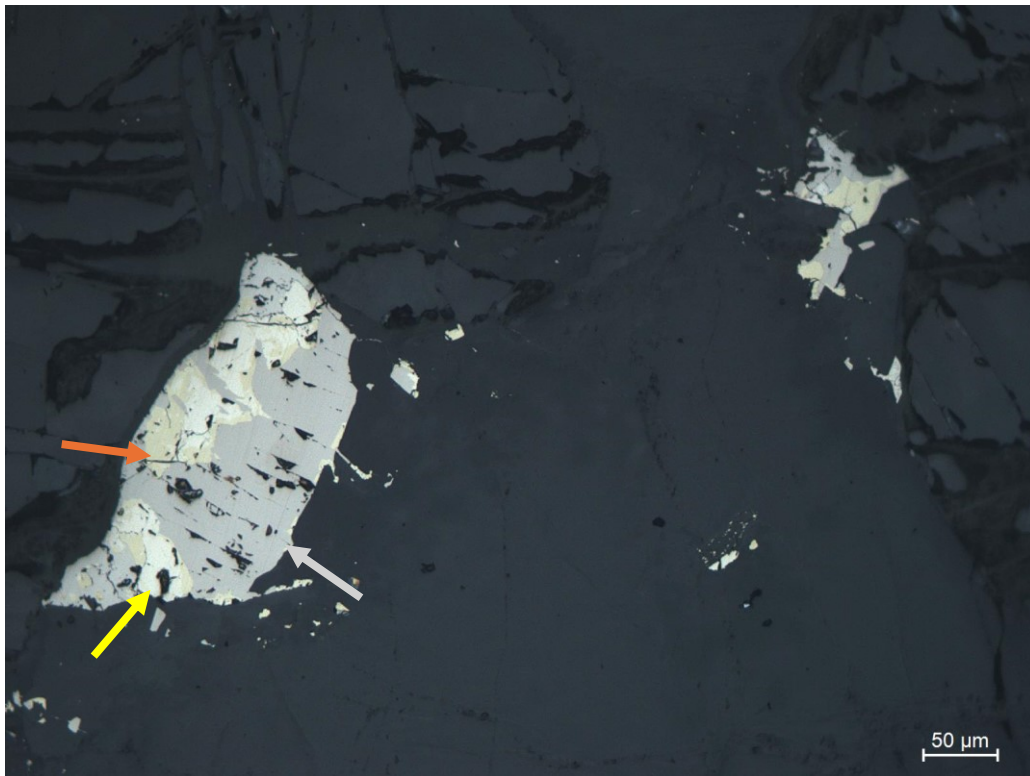


Fig 56. Polysulphide aggregate mainly composed of pyrrhotite (grey arrow), associated with chalcopyrite (orange arrow) and pentlandite (yellow arrow) at the contact between plagioclase and olivine type 2.

As observed in the coarse-grained contacts, the crystallization sequence is roughly interpreted as olivine – plagioclase – clinopyroxene. Nevertheless, the sequence may not be as precise, since plagioclase can start crystallizing while olivine is still forming, and the same concept applies to plagioclase and clinopyroxene that might locally crystallize concomitantly. This crystallization sequence is typical of low-P oceanic gabbros (*Rampone et al., 2016*). Moreover, textural relationships in troctolites suggest that clinopyroxene and especially plagioclase crystallized from a melt in chemical disequilibrium with olivine, which has been partly corroded (*Donaldson et al., 1985*).

Olivine is interpreted as the first crystallizing phase because its rounded crystals are typically enclosed within later magmatic crystals. Plagioclase crystallizes subsequently and locally forms large portions of the rock together with olivine. Clinopyroxene represents the latest magmatic silicate and occurs only as an accessory phase, commonly enclosing both olivine and plagioclase.

In contrast to the coarse-grained gabbro contacts, sulphide constitute a more prominent component of the lithology. Their occurrence is interpreted as the consequence of sulphide immiscibility within the mafic melt, resulting in the development of a distinct sulphide assemblage.

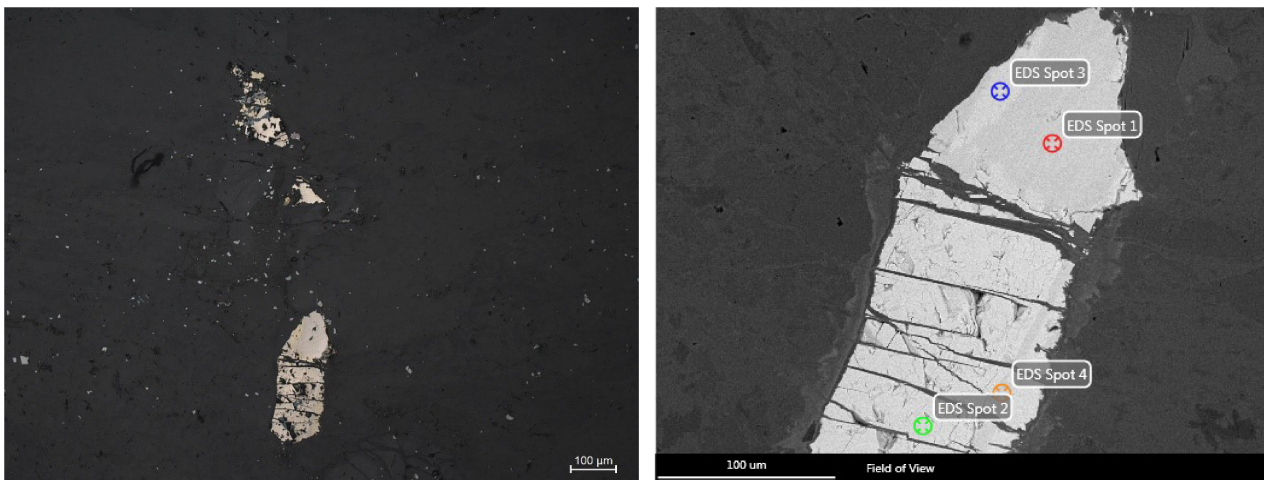


Fig 57. Relatively large (> 200 microns) polysulphide aggregates enclosed within plagioclase crystals in thin olivine-rich troctolite. On the left: reflected light image. On the right: zoomed EDS image. Spot 1 is represented by pyrrhotite, Spot 2 by strongly fractured pentlandite, Spot 3 is chalcopyrite, and Spot 4 pyrrhotite again.

Hydrothermal alteration

These rocks are generally moderately to strongly affected by hydrothermal alteration, although its intensity varies with the thickness of the contact-related zone. When the contact-related troctolite zone is thin, alteration is more diffuse and pervasive, likely reflecting the concentration of hydrothermal circulation and fracturing within the rock.

Olivine is usually completely serpentinized in the portions closest to the serpentinized mantle and along fracture networks, which represent preferential pathways for hydrothermal fluids circulation. Distancing from the contact, olivine becomes progressively less altered, with the exception of crystals crosscut by fracture networks. Serpentinization of olivine causes volume expansion and consequent fractures generation in olivine itself and in the neighboring plagioclase (Fig. 58) (*Yoshida et al., 2020*).

Plagioclase displays variable degrees of alteration, ranging from well-preserved crystals to completely altered grains. Depending on the intensity of hydrothermal alteration, plagioclase is replaced by prehnite, hydrothermal garnet, and/or other hydrothermal secondary phases.



Fig 58. Contact between serpentinized olivine type 1 and preserved plagioclase close to the mantle in troctolite. Fractures in plagioclase clearly branch out from the boundary with altered olivine. Volume increase caused by serpentinization produces this within-crystal fracture network.

Clinopyroxene is generally better preserved than olivine and plagioclase and commonly retains its typical birefringence colors and its magmatic textures and appearance. It commonly occurs as well-preserved oikocrysts or as vermicular crystals, although the rims may be locally affected by minor alteration and replaced by hydrothermal secondary phases, such as tremolite.

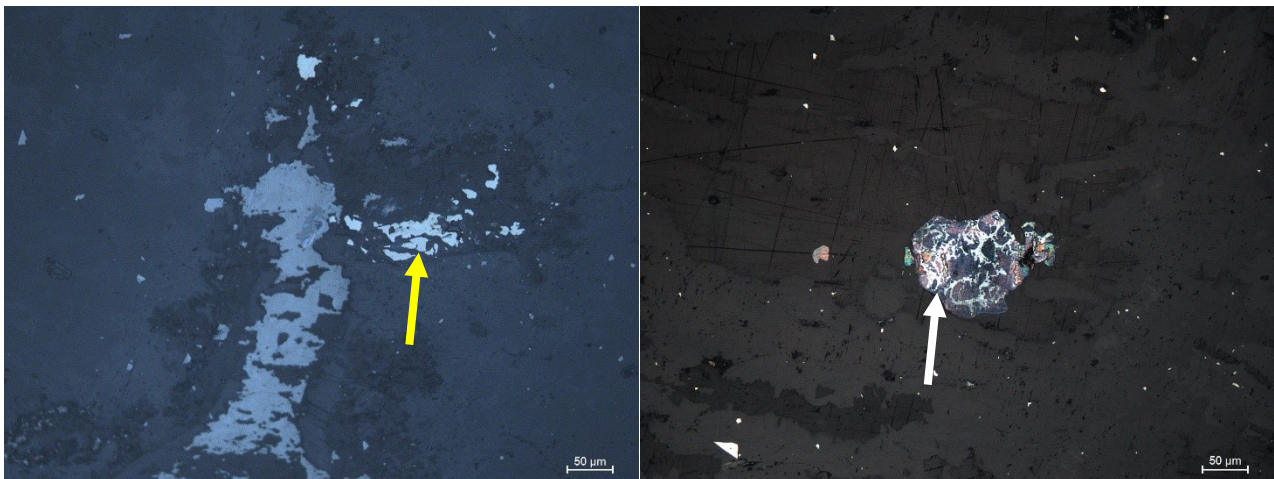


Fig 59. Hydrothermal secondary sulphides, both observed within a fracture network. On the left heazlewoodite (yellow arrow), while on the right, bornite (white arrow) occurs.

Sulphides may show variably altered rims, but their cores are generally well-preserved. Unless affected by dense fracture networks, sulphide grains retain their original composition and show little evidence of replacement by hydrothermal phases.

Primary magmatic sulphides may show variably altered rims, but their cores are generally well-preserved. A minor amount of hydrothermal sulphides occurs along fracture networks (Fig. 59). These secondary hydrothermal sulphide phases are represented by bornite, heazlewoodite, and horomanite.

5. GEOCHEMISTRY

5.1 ANALYTICAL METHODS

In addition to optical microscopy observations performed under both transmitted and reflected light, several analytical techniques were carried out to characterize mineralogical and chemical features of the samples.

A preliminary investigation of sulphide aggregates was conducted at Università di Genova using Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive Spectroscopy (EDS). SEM observations provide information on surface morphology, texture, grain size and fractures at high magnification, while EDS identifies elements present at a selected point of analysis, without providing quantitative concentrations. EDS was therefore used as a preliminary tool for compositional characterization of the sulphide aggregates.

Major elements in minerals were quantitatively analyzed at CNRS ISTO in Orléans using Electron Probe Micro-Analysis (EPMA). Two dedicated analytical programs, one for silicates and one for sulphides were employed to obtain accurate compositional data. Analyses showing total values below 98% and above 102% were removed from the database since they are considered unreliable. This criterion was not applied to hydrated phases, for which the EPMA technique cannot quantify the water content because hydrogen is too light to be measured reliably.

Trace element compositions of clinopyroxene were determined by Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) at CNR-GEO in Pavia (Italy), using a QQQ-ICP-MS Agilent Series 8900 interfaced to a GeoLas 193 nm excimer ablation system (Lambda Physik, Germany). The laser ablation system was operated at a 10 Hz repetition rate, 50 μm spot size, with a fluence of about 9 J/cm². Helium was used as carrier gas and mixed with Ar downstream of the ablation cell. NIST SRM 612 synthetic glass was used as external standard, and CaO and SiO₂ concentrations previously measured by EPMA were used as internal standard. The precision and accuracy of the trace element concentrations were assessed by repeated analyses of the BCR2-g standard and were better than $\pm 7\%$ and $\pm 10\%$, respectively. Average element abundances in synthetic glasses NIST SRM 612 were taken from *Pearce et al. (1997)*. Background and signal were measured for about 60 seconds; signal of standards and unknowns were carefully checked, and the raw data were reduced using the software package GLITTER®.

5.2 MAJOR ELEMENTS COMPOSITION

This section presents the major-element compositions of the primary magmatic and mantle minerals, with results illustrated through compositional diagrams. For clarity, the terms “troctolite 1” and “troctolite 2-3” refer to troctolites containing olivine type 1 and olivine types 2-3, respectively.

5.2.1 CLINOPYROXENE

Clinopyroxene shows variable composition among the different types of contacts, with variations related to crystal texture and lithological context. Following (*Lissenberg & Dick, 2008*), clinopyroxene is considered to have high Mg# when exceeding 86.

5.2.1.1 Clinopyroxene along coarse-grained gabbro contacts

Along coarse-grained gabbro contacts, clinopyroxene composition changes according to the extent of percolation and the presence or absence of olivine.

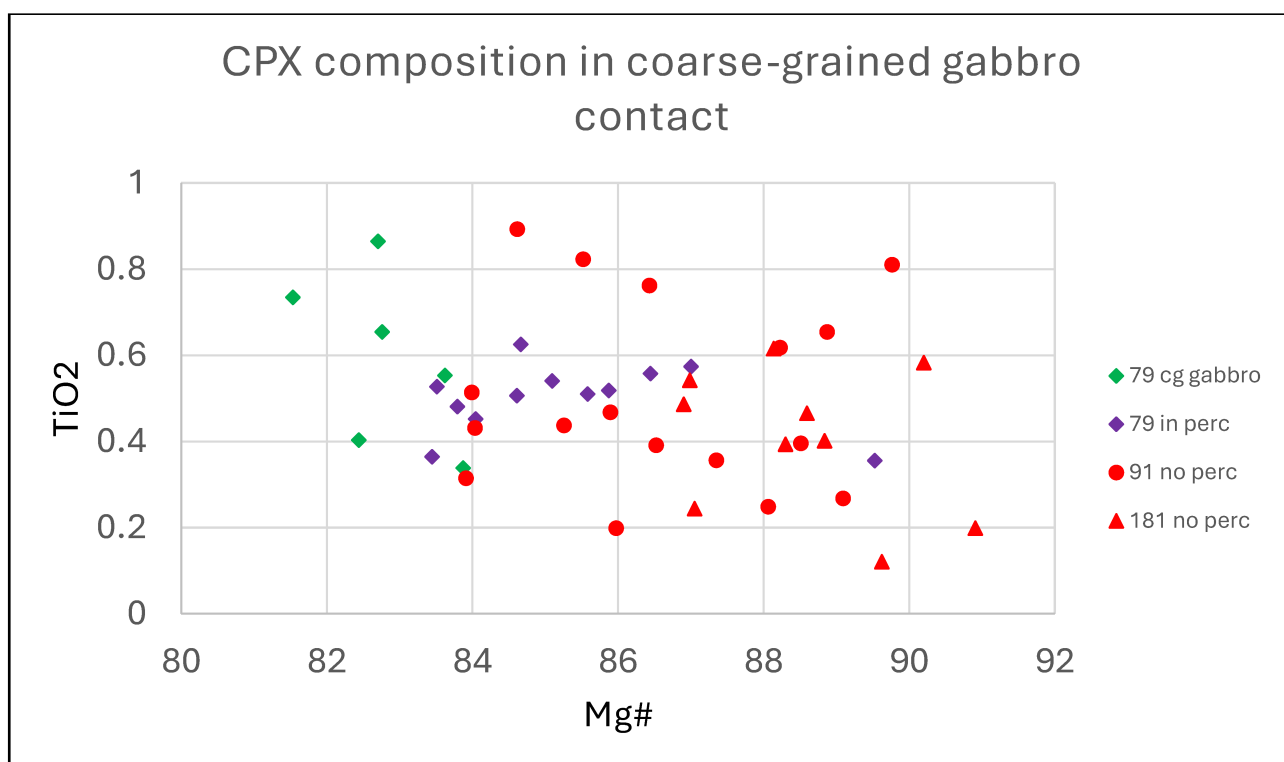


Diagram 1. Clinopyroxene composition TiO_2 vs $\text{Mg\#}$ in coarse-grained gabbro contacts. Red points (circle for section 91 and triangle for section 181) are clinopyroxene compositions for olivine-bearing coarse-grained gabbro contacts that show no percolation, while green points are related to coarse-grained gabbro contacts in section 79 with percolation into the mantle. Purple points are analyzed within magmatic percolation into the mantle also in section 79.

Diagram 1 shows $\text{Mg\#}$ vs TiO_2 for clinopyroxene from coarse-grained gabbro contacts. Data define a compositional trend related to the intensity of percolation. Olivine-bearing contacts characterized

by low percolation intensity have significantly higher Mg# values than contacts affected by pervasive percolation. Clinopyroxene with higher Mg# values, ranging from 84 to 91, occurs as medium-grained crystals to oikocrysts enclosing plagioclase chadacrysts. In contrast, clinopyroxene with lower Mg# values, between 82 and 84, occurs as coarse-grained crystals that are not associated with olivine and do not show a poikilitic texture. TiO₂ content is more variable, indeed clinopyroxene with higher Mg# contain 0.12-0.89 wt% TiO₂, whereas those with lower Mg# contain 0.34-0.73 wt%. Clinopyroxene analyzed within the percolation into the mantle have higher Mg# (83-87, with one exception of 89.5) compared with gabbro clinopyroxene within the same thin section. TiO₂ range from 0.35 to 0.6 wt%, showing no relevant difference with respect to other clinopyroxenes.

The clinopyroxene groups display only negligible core to rim variations in Mg#, while TiO₂ shows more pronounced differences. The arrows in Diagram 2 indicate the compositional evolution from core to rim and, where present, towards vermicular portions. Mg# remains nearly constant, while TiO₂ increases markedly towards the rim. This pattern is consistent with normal zoning associated with fractional crystallization. Large variations in TiO₂ are observed in the percolated contact, with the highest increase from 0.39 wt% in the core to 0.89 wt% in the rim, while in the not percolated a crystals displays 0.40 wt% within the core, 0.65 wt% in the rim, and 0.86 wt% in the vermicular portion.

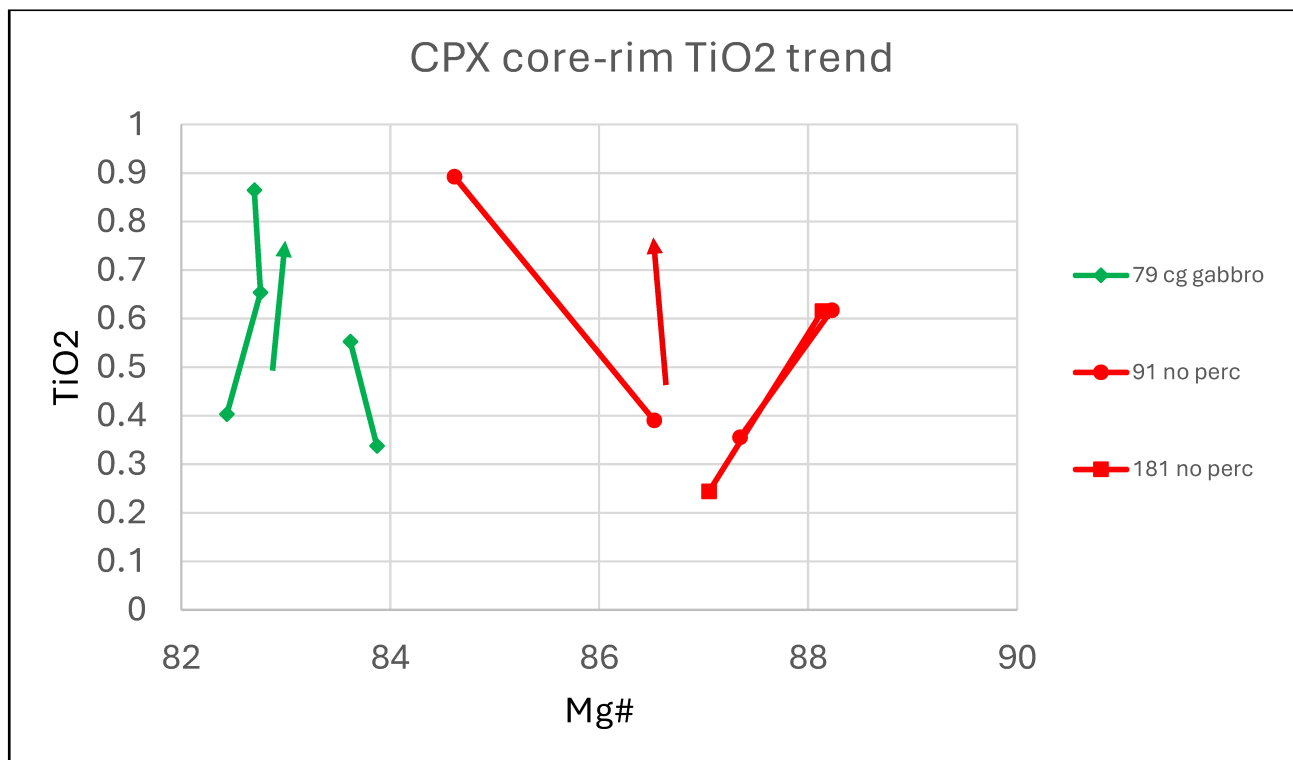


Diagram 2. Core-to-rim compositional analysis. Green points represent coarse-grained gabbro core-rim (-vermicular) analyses, while red points refer to olivine-bearing gabbro contacts. Core-to-rim enrichment in TiO₂ are observed and highlighted by arrow directions.

Diagram 3 displays the behavior of Cr_2O_3 for the same point of analysis of Diagram 1. As observed for Mg#, also Cr_2O_3 distinguishes the two types of coarse-grained rocks. The olivine-bearing gabbro contains clinopyroxene with Cr_2O_3 ranging from approximately 0.2 to 1 wt%. In the other type of contact, Cr_2O_3 does not exceed 0.3 wt%. An enrichment in Cr_2O_3 with increasing Mg# is also evident, whereas no comparable relationship is observed for TiO_2 . Clinopyroxene in percolation shows values of Mg# ranging from 83.5 to 87 (with 89.5 as one exception), and it is slightly enriched in Cr_2O_3 (0.2-0.45 wt%) compared with coarse-grained gabbro, although is lower than olivine-bearing contacts.

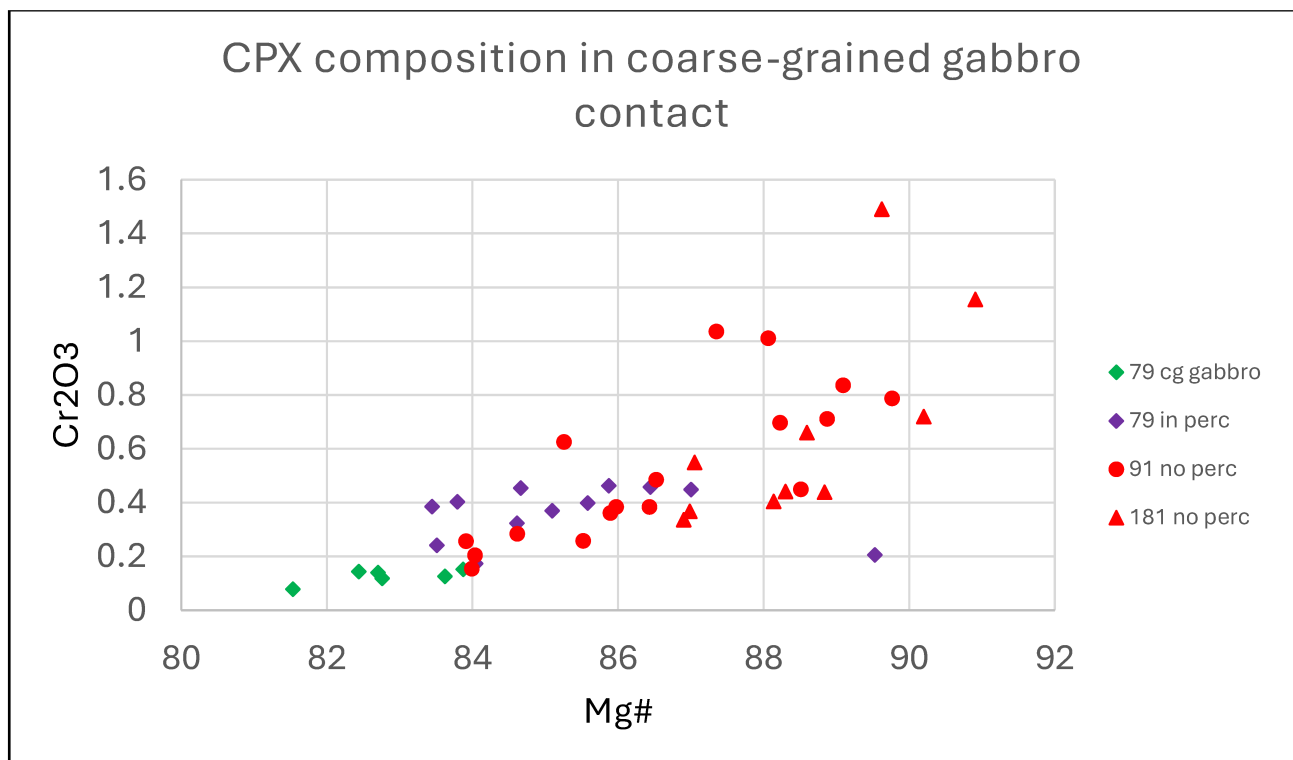


Diagram 3. Cr_2O_3 vs Mg# compositional plot. Cr_2O_3 displays stronger differences compared with TiO_2 . The legend is the same used in Diagram 1.

Clinopyroxene cores are slightly enriched in Cr_2O_3 relative to the rims, with differences of up to 0.20 wt%. This distribution is consistent with the compatible behavior of chromium.

In contacts affected by percolation, Al_2O_3 contents are consistently stable ranging from 2 and 2.8 wt%, with negligible core-to-rim differences and no significant variations in vermicular portions. In the olivine-bearing contacts, Al_2O_3 ranges from 2.2 to 4.8 wt%, with values locally reaching 5-6 wt% within the cores of clinopyroxene oikocrysts.

Transects from the mantle towards the coarse-grained gabbro also reveal systematic geochemical patterns, especially along olivine-bearing contacts (Fig. 60).

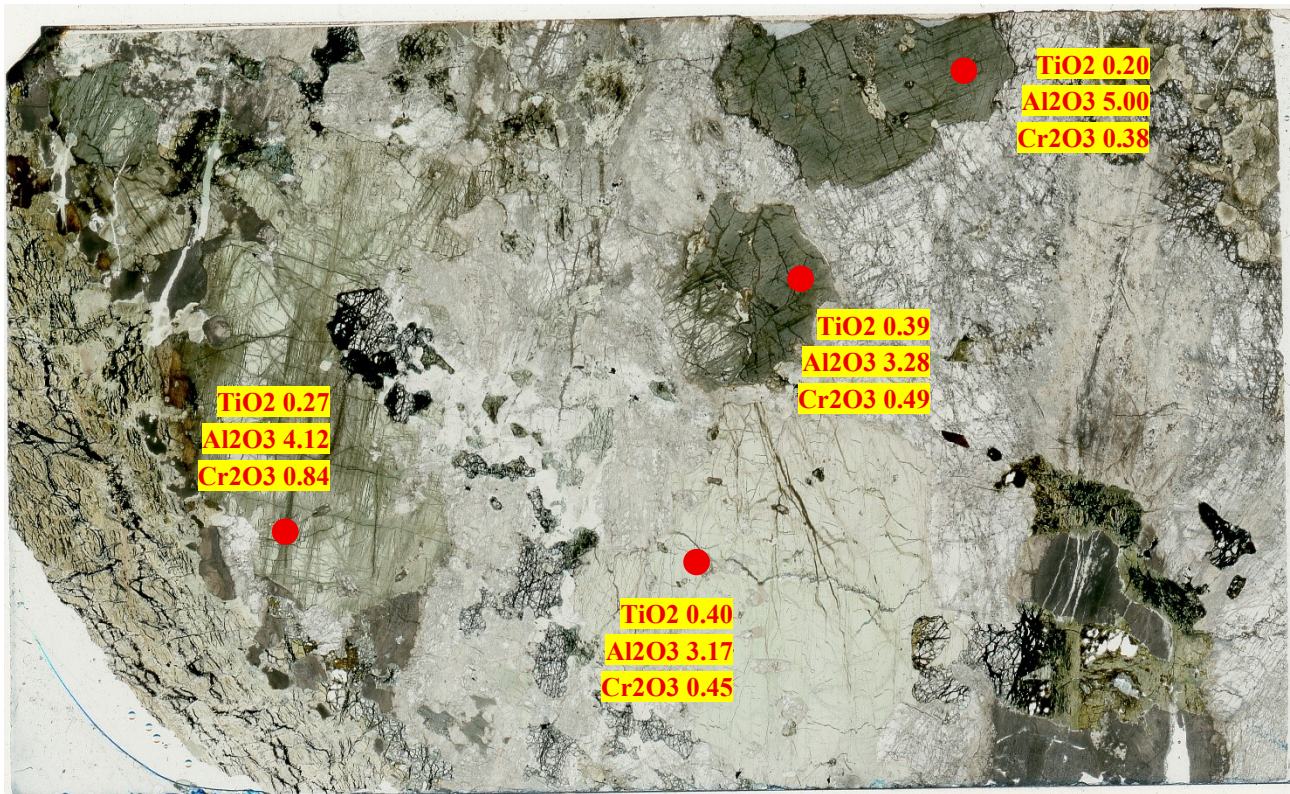


Fig 60. Transect from mantle to coarse-grained gabbro intrusion left-to-right oriented. Chromium shows systematic decrease moving away from the mantle.

In the coarse-grained olivine-bearing gabbro contact shown in Fig. 60, the red points indicate the EPMA analytical locations used to determine the reported oxide concentrations. The leftmost part of the section corresponds to the serpentinized mantle, while the points towards the right represent increasing distance from the mantle contact. Cr₂O₃ progressively decreases with increasing distance from the mantle, indicating a direct relationship between Cr₂O₃ content and proximity to the mantle. This relationship is not observed for Al₂O₃ and TiO₂, which instead show the largest variations between cores and rims of big crystals.

5.2.1.2 *Clinopyroxene in olivine-rich troctolite zones*

The contact zones are characterized by two main geometries. In some cases, a thin olivine-rich troctolite zone occurs between the mantle and gabbro and grades into coarse-grained gabbro within a few centimeters or less. In other cases, the olivine-rich troctolite develops for tens of centimeters and progressively changes towards a troctolitic composition with increasing distance from the contact. In these zones, clinopyroxene becomes a primary magmatic phase a few centimeters from the mantle and occurs with different textures. Close to the mantle, it predominantly shows a vermicular habit (type 1), while farther from contact, it progressively forms larger oikocrysts (type 2) that enclose

olivine. These textural differences are accompanied by compositional variations, which are related both to distance from the mantle and to the textural relationship with olivine.

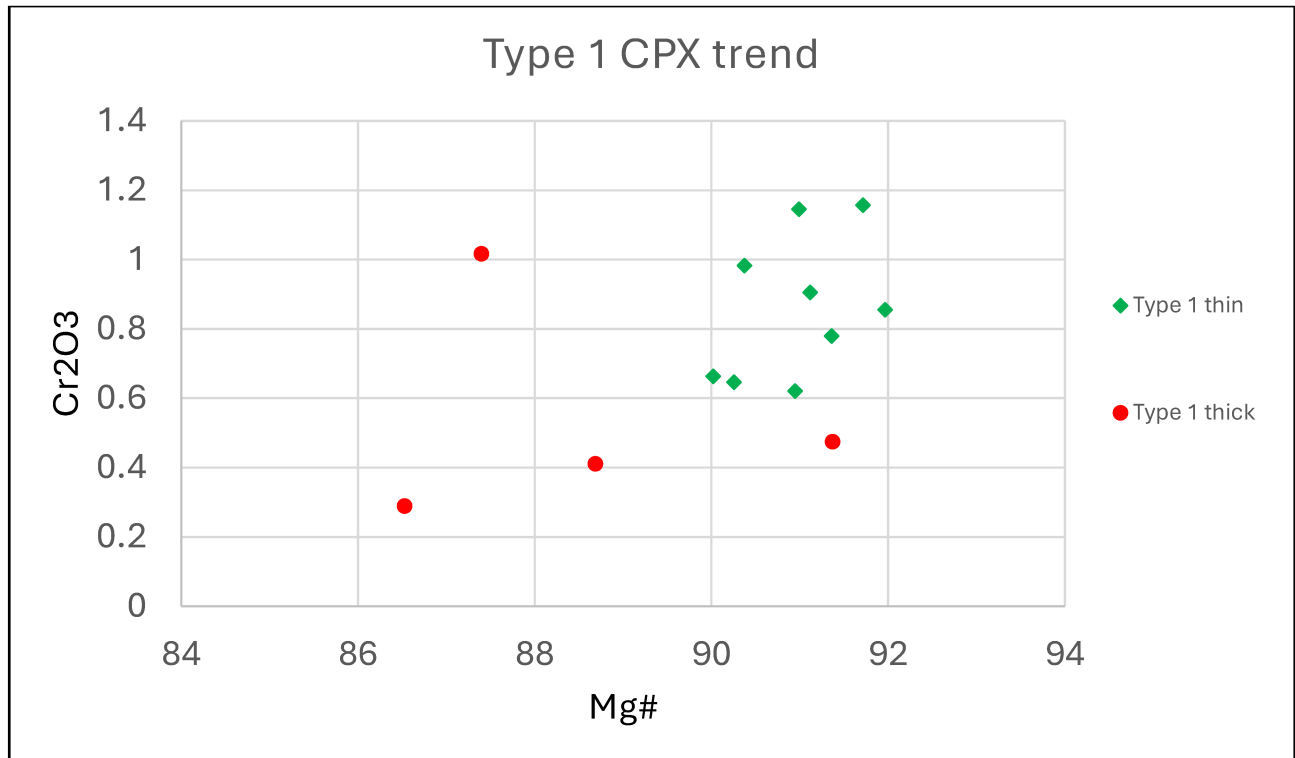


Diagram 4. Comparison Cr_2O_3 vs $\text{Mg\#}$ between clinopyroxene with texture type 1 in thin (green points) and thick (red) troctolite. Thin troctolite is higher in both Cr_2O_3 and $\text{Mg\#}$.

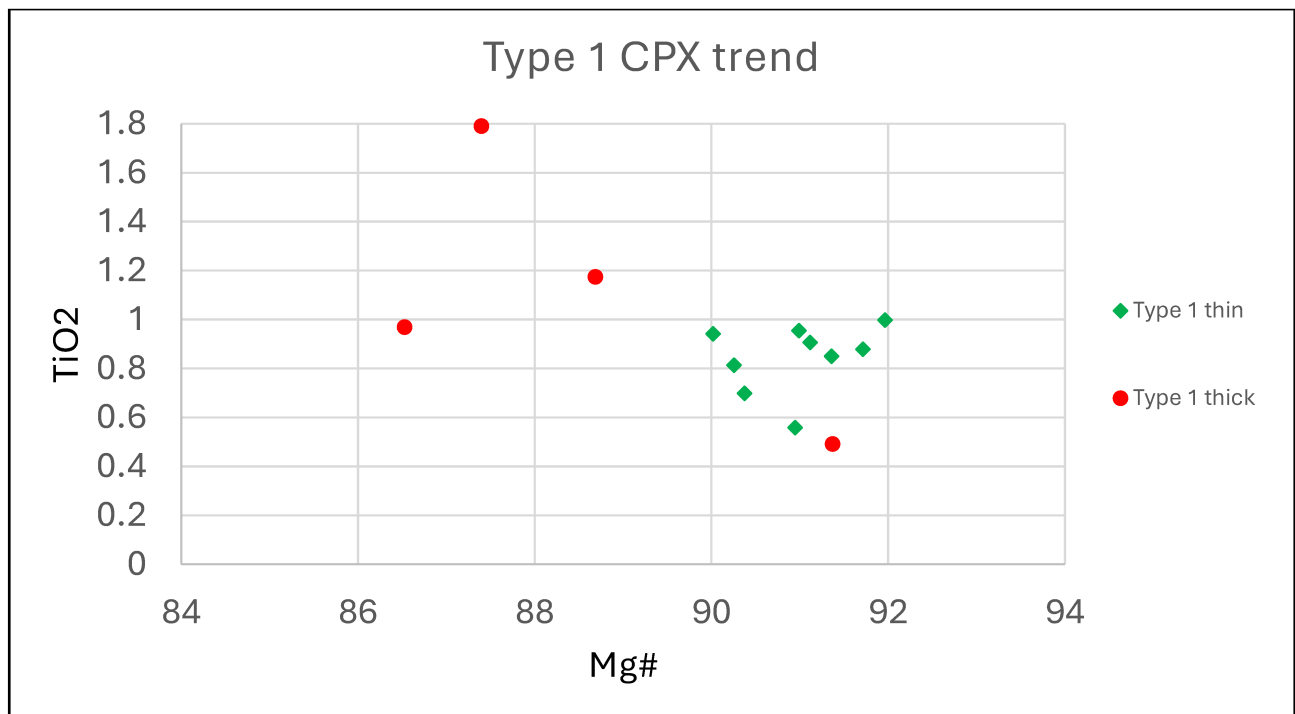


Diagram 5. Same comparison of Diagram 4, but TiO_2 replaces Cr_2O_3 .

The type 1 vermicular clinopyroxenes from thin and thick zones have clear compositional differences shown in Diagram 4. In both cases, clinopyroxene occurs close to the mantle contact. The main distinction is that the thick zone progressively changes from olivine-rich troctolite to troctolite and then gabbro, while the thin zone forms a narrow, approximately 1 cm-wide interval separating serpentinized mantle from gabbro. As shown in Diagram 4, the thin zone is enriched in both Mg# and Cr₂O₃ compared to the thick zone.

In the same way, Diagram 5 shows the same points of analysis with respect to TiO₂ instead of Cr₂O₃, with the thick zone that is slightly more enriched than the thin zone.

Comparison with data of *Drouin et al., (2009)*, shows that the high-Mg# clinopyroxene analyzed here has Mg# values of 86-92, compared with 85-90 in their dataset. Cr₂O₃ ranges from 0.3 to 1.2 wt%, compared with 0.97-1.45 wt%, and TiO₂ from 0.5 to 1.2 wt%, with for one point reaching 1.8 wt%, compared with 0.33-0.72 wt%. In the comparison adopted here, vermicular clinopyroxene is thus characterized by high Mg#, high Cr₂O₃ in the thin zone, and low to medium Cr₂O₃ in the thicker zone, together with relatively high TiO₂ contents.

Clinopyroxene textural type 2 are oikocrysts, thus core-to-rim Cr₂O₃ vs Mg# comparison is possible as shown in Diagram 6 for thick troctolite type 2-3. Cores display higher Cr₂O₃ and slightly lower Mg# than the rims.

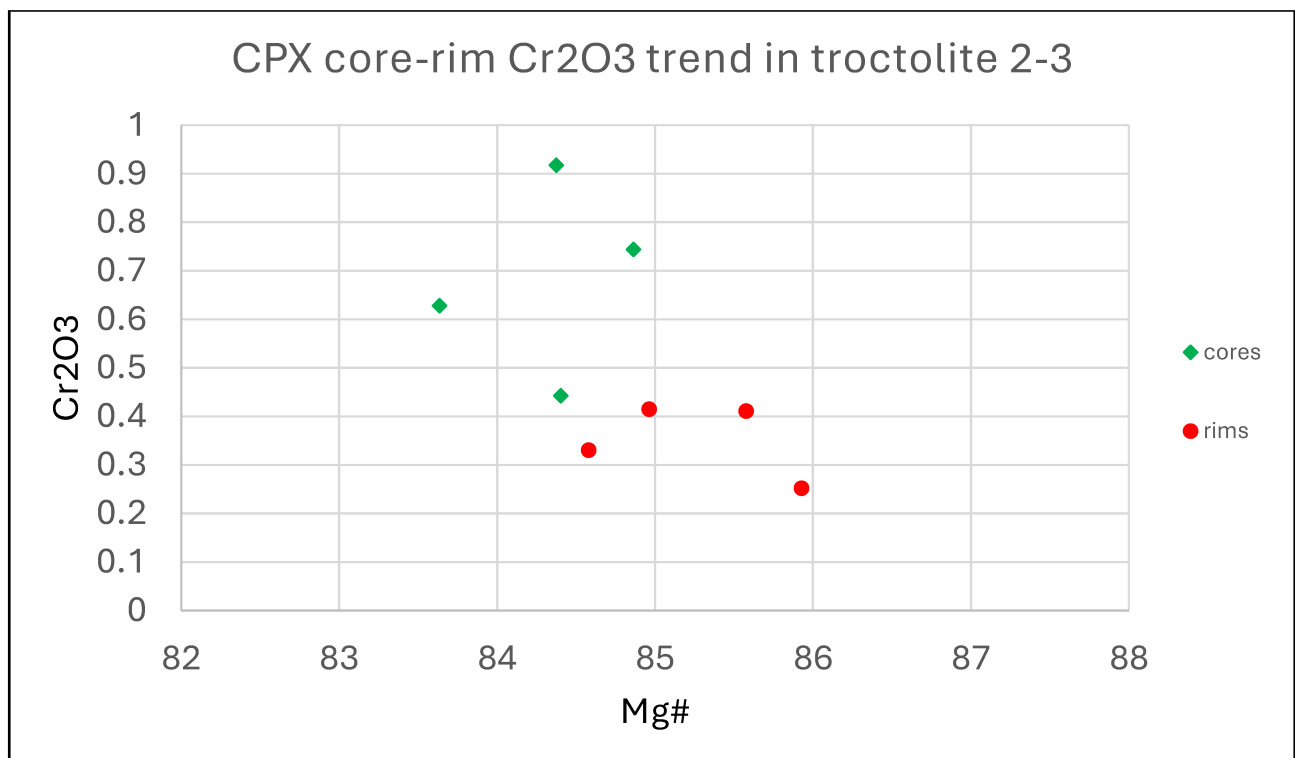


Diagram 6. Core vs rims in thick troctolite type show a trend with cores exhibiting higher Cr₂O₃ and Mg# than the rims.

A comparison between type 2 clinopyroxene oikocrysts associated with troctolite type 1 and those associated with troctolite types 2-3 shows further compositional differences, exhibited in Diagram 7. Clinopyroxenes associated with troctolite type 1 display higher Mg# than that in troctolite 2-3, but lower Cr₂O₃.

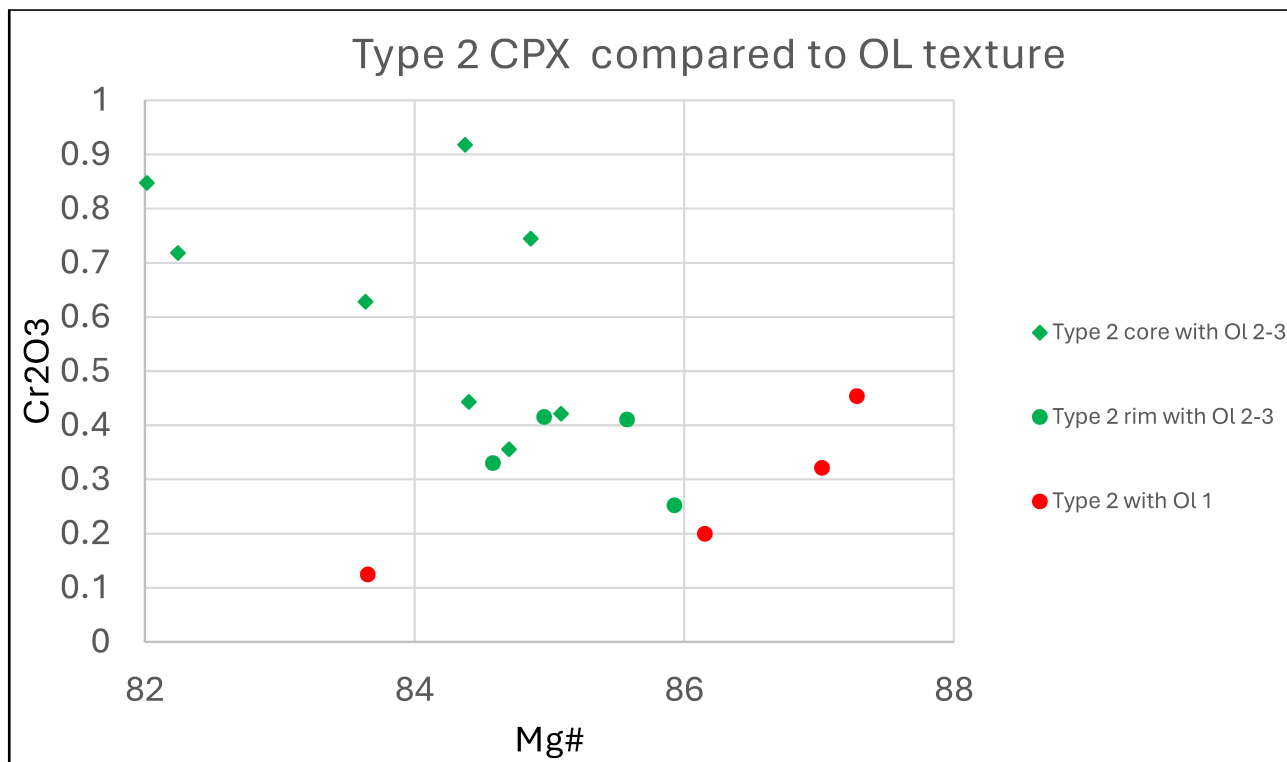


Diagram 7. Cr₂O₃ vs Mg# showing compositional variability of type 2 clinopyroxenes as a function of the textural type of olivine with which they are associated. These data highlight compositional differences among clinopyroxene oikocrysts based on the mineral texture with which they occur.

Type 2 clinopyroxene Mg# is also plotted against TiO₂ (Diagram 8) and Al₂O₃ (Diagram 9). Clinopyroxenes associated with troctolite type 1 are enriched in TiO₂ with respect to clinopyroxene in troctolite 2-3, while the exact opposite applies to Al₂O₃.

The TiO₂ contents in clinopyroxene oikocrysts (Diagram 8) are higher than those reported by *Drouin et al. (2009)*, whose values range from 0.26 to 0.54 wt%. In the present samples, TiO₂ ranges from 0.4 to 1.1 wt%. TiO₂ is slightly higher in rims (0.63-0.78 wt%) than in the cores (0.56-0.67 wt%), whereas Al₂O₃ shows the opposite trend (Diagram 9), with rims ranging from 2.4 to 3.1 wt% and cores from 3.3 to 4.0 wt%. No significant Al₂O₃ variation is observed as a function of the associated olivine texture.

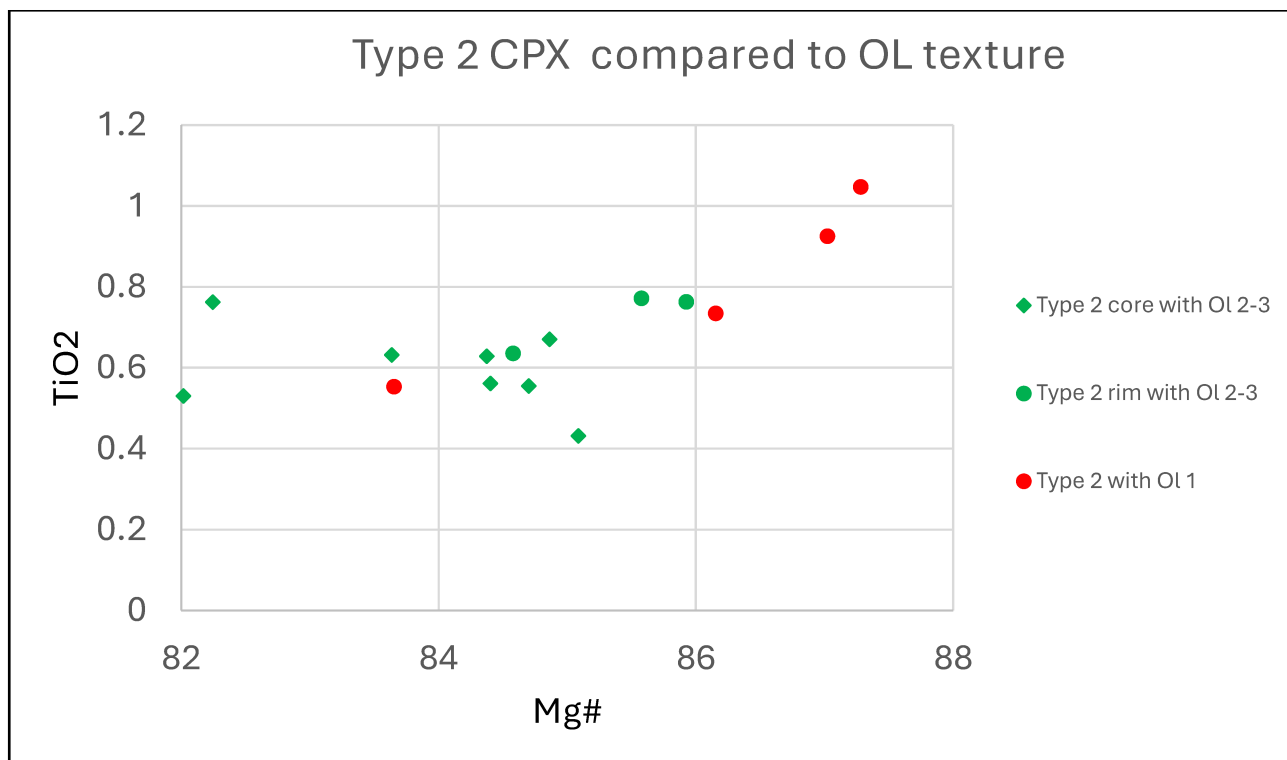


Diagram 8. As for Diagram 7, this graphic compares titanium and Mg# contents from clinopyroxene oikocrysts in troctolite 1 (red) and troctolite 2-3 (green), displaying some variability.

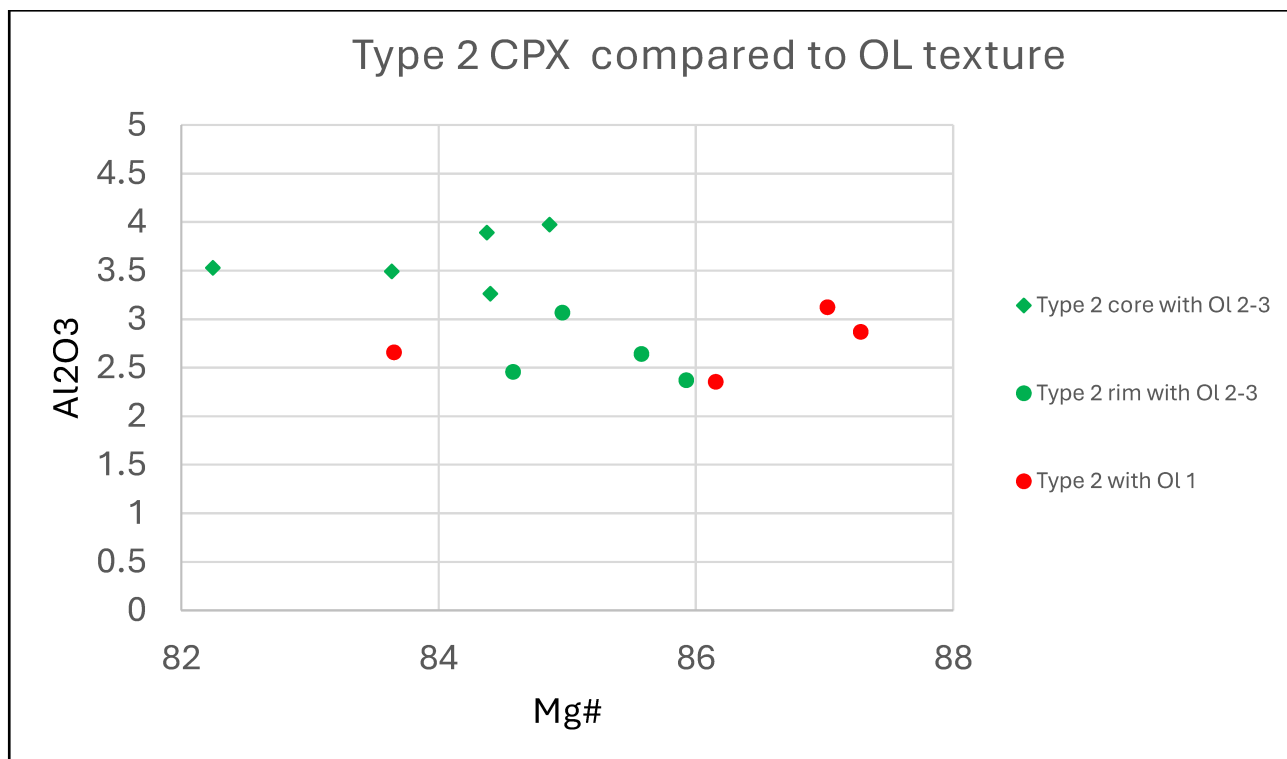


Diagram 9. Again, the plot refers to clinopyroxene oikocrysts in troctolite 1 (red) and troctolite 2-3 (green).

Cr_2O_3 is the most variable of the three oxides considered above, decreasing from 0.44-0.92 wt% in cores to 0.25-0.41 wt% in rims (Diagram 7). The core-to-rim evolution in TiO_2 , Cr_2O_3 and Al_2O_3 are interpreted as indicative of normal zoning during fractional crystallization of troctolite.

Diagram 10 shows $\text{Mg\#}$ vs Cr_2O_3 for clinopyroxene as a function of lithology and distance from the mantle. Clinopyroxene occurs close to the mantle, either as vermicular crystals (type 1) or as oikocrysts (type 2) in the thin troctolite zone, and these compositions are compared with clinopyroxene from the thicker type 1 troctolite zones close to and far from the mantle contact. $\text{Mg\#}$ is generally higher close to the mantle in troctolite 1 and in the thinner zone. Within the latter, vermicular clinopyroxene has $\text{Mg\#}$ values of 0.90-0.92, while oikocrysts range from approximately 0.88 to 0.90. In the thicker troctolite 1 zone, $\text{Mg\#}$ ranges from 0.86 to 0.91 close to the mantle and from 0.835 to 0.87 farther from it. Cr_2O_3 shows comparable spatial variations, since its values in the thin zone range from 0.6 to 1.2 wt%, and in the thicker lithology they generally remain below 0.45 wt%, with one exception of approximately 1 wt%.

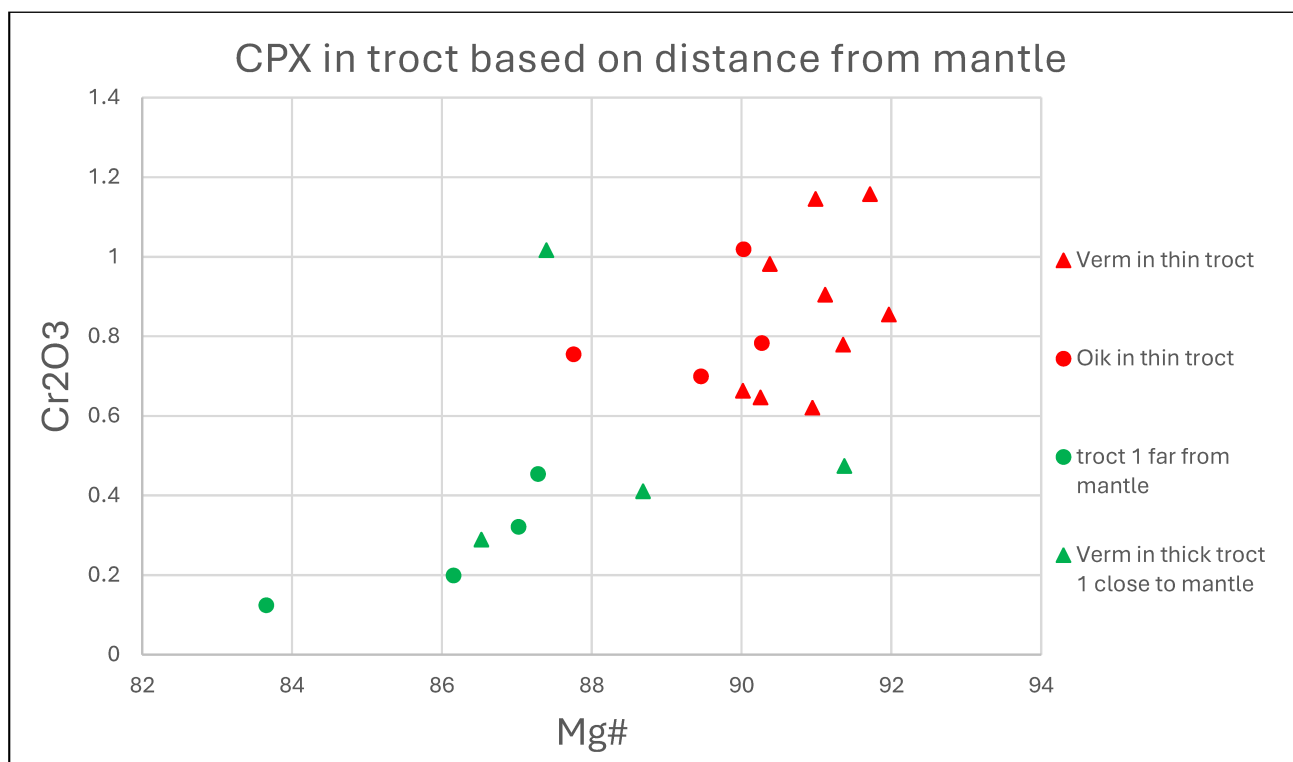


Diagram 10. Cr_2O_3 vs $\text{Mg\#}$ variations based on distance from the mantle considering thin troctolite (red) and thick troctolite type 1 (green).

5.2.1.3 Clinopyroxene comparisons

This section exposes the compositional differences observed among the clinopyroxenes from the different lithologies and textural context.

Diagram 11 reports Mg# vs Cr₂O₃ for all clinopyroxene textures identified in the samples. The symbols distinguish crystal textures: triangular for vermicular portions, circles represent cores, and diamonds for rims. Colors distinguish the lithological context: thin (olivine-rich) troctolite, thick olivine-rich troctolite/olivine-gabbro/troctolite, coarse-grained gabbro, and olivine-bearing gabbro are represented separately.

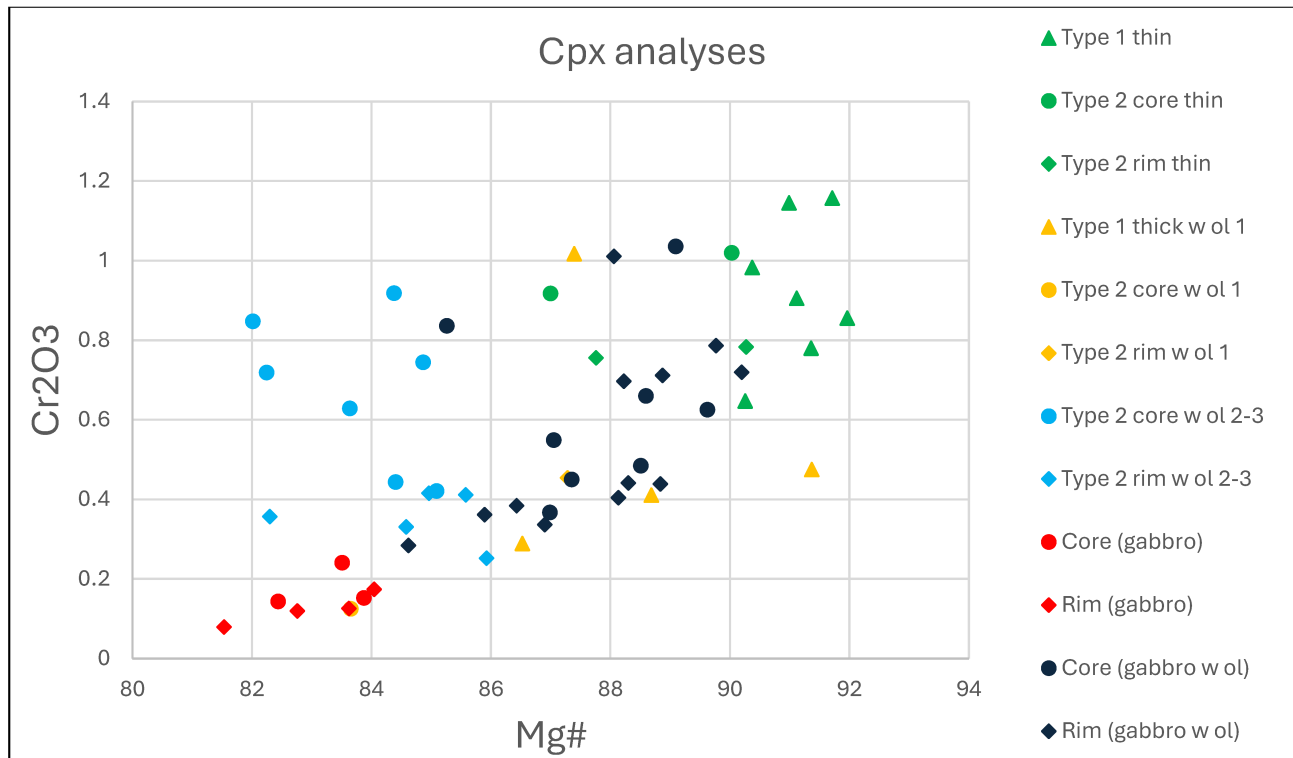


Diagram 11. Comparison Cr₂O₃ vs Mg# of all clinopyroxene textures and lithologies. Triangle indicates vermicular textures, while circle cores and diamond rims.

Clinopyroxene from the thin olivine-rich troctolite has the highest Mg# values and also shows high Cr₂O₃ content. Type 1 (vermicular) clinopyroxene olivine-rich thick troctolite also displays high Mg#, although its Cr₂O₃ content is lower. Clinopyroxene from olivine-rich thick type 2-3 troctolite has lower Mg# than the other contact-related clinopyroxenes, but its Cr₂O₃ content is equal to that of the other troctolites. Coarse-grained gabbro contain Cr₂O₃- and Mg#-depleted clinopyroxenes (0.05-0.22 wt% and 81-83, respectively), while olivine-bearing coarse-grained gabbro displays high Mg# (84-90) and Cr₂O₃ between 0.25 to 1 wt% (Diagram 11).

TiO₂ (Diagram 12) is comparatively uniform among the groups. Its content is slightly higher in thick troctolite 1 and in thin troctolite than in clinopyroxene oikocrysts in thick troctolite type 2-3.

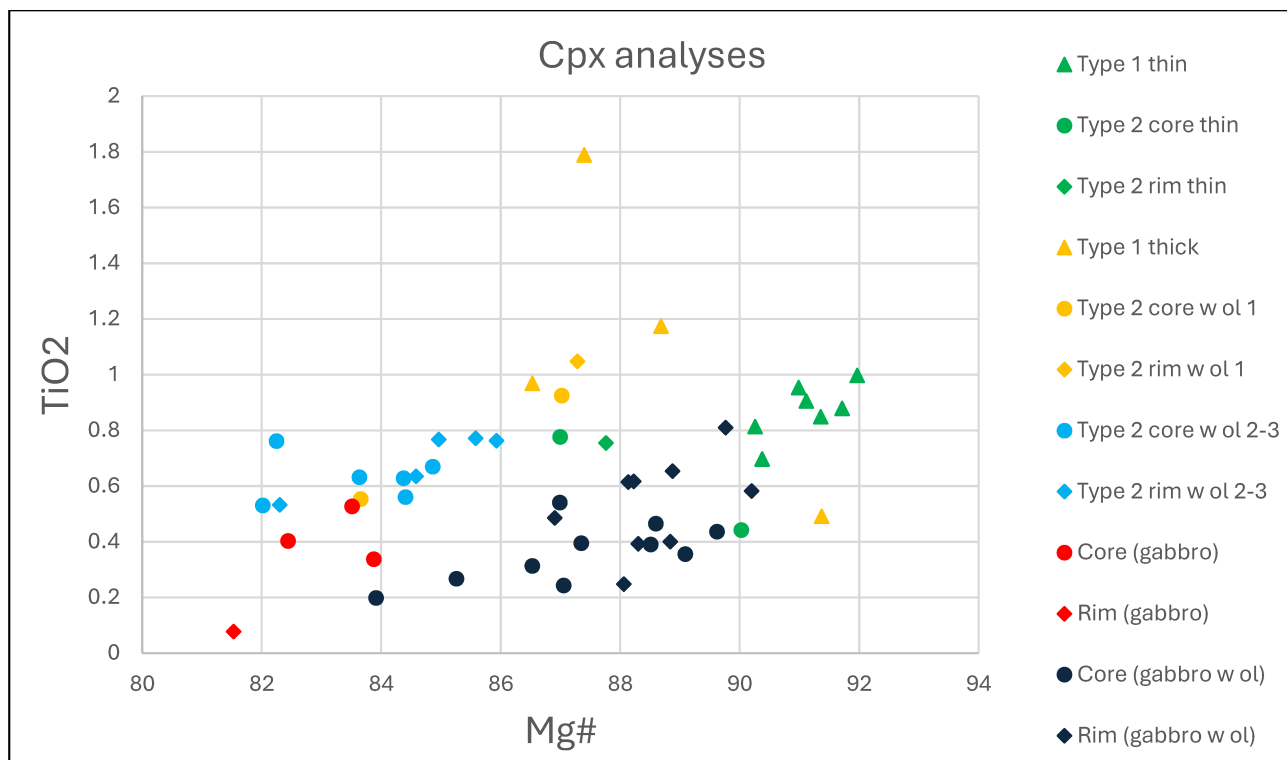


Diagram 12. TiO_2 vs $\text{Mg\#}$ comparison. This oxide shows less variability than Cr_2O_3 among the different clinopyroxene textures.

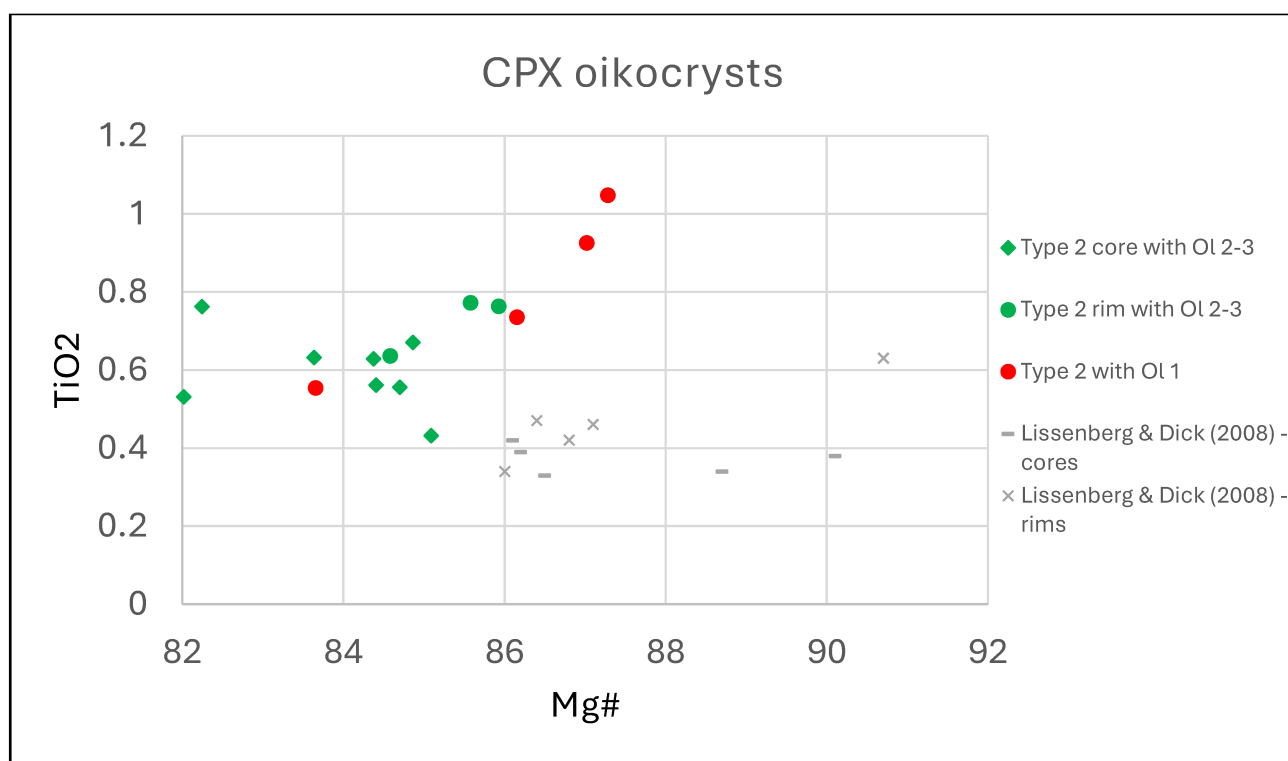


Diagram 13. TiO_2 vs $\text{Mg\#}$ of clinopyroxenes from troctolite 1 (red) and 2-3 (green) compared with clinopyroxenes in reactive troctolites from Lissenberg & Dick (2008) (grey).

The clinopyroxenes analyzed by *Lissenberg & Dick (2008)* come from a geodynamic and magmatic context considered comparable to that of the rocks of this Thesis. A comparison of core and rim compositions of type 2 clinopyroxene oikocrysts is reported in Diagram 13. The *Lissenberg & Dick (2008)* samples generally show higher Mg# values, especially relative to clinopyroxenes in troctolite 2-3. On the contrary, except for a few analyses, their clinopyroxene compositions are comparable with that observed in troctolite 1 in terms of Mg#, while TiO₂ composition is more similar to clinopyroxene oikocrysts in troctolite 2-3.

5.1.2 PLAGIOCLASE

As observed for clinopyroxene, plagioclase composition is strongly influenced by the distance from the mantle and by the presence of olivine.

The An# vs Al₂O₃ plot in Diagram 14 shows that gabbro has the lowest Al₂O₃ contents, while the highest values occur in thin troctolite. Thick troctolites 1-2-3 cover a broad range of both An# and Al₂O₃, without a clear compositional distinction based solely on lithology.



Diagram 14. Plot of every type of plagioclase of this Thesis. Both core-to-rim and lithological criteria were used to investigate the compositional variability.

The core-to-rim data for troctolites reported by *Lissenberg & Dick (2008)* show slightly higher Al₂O₃ content (32-35 wt%) than those measured in the troctolites of this Thesis (29-33.5 wt%). An# values

are widely comparable, although the published data (Diagram 15) locally reach 70-84, compared with 69-82 in the present dataset. Both datasets display slightly higher Al_2O_3 in cores than in rims, and even though the difference is slight, higher An# in cores than in rims is observed. These features are consistent with normal zoning and are indicative of higher crystallization temperatures of the cores compared to the rims, since the higher An# the higher the crystallization temperature (*Shcherbakov et al., 2010*).

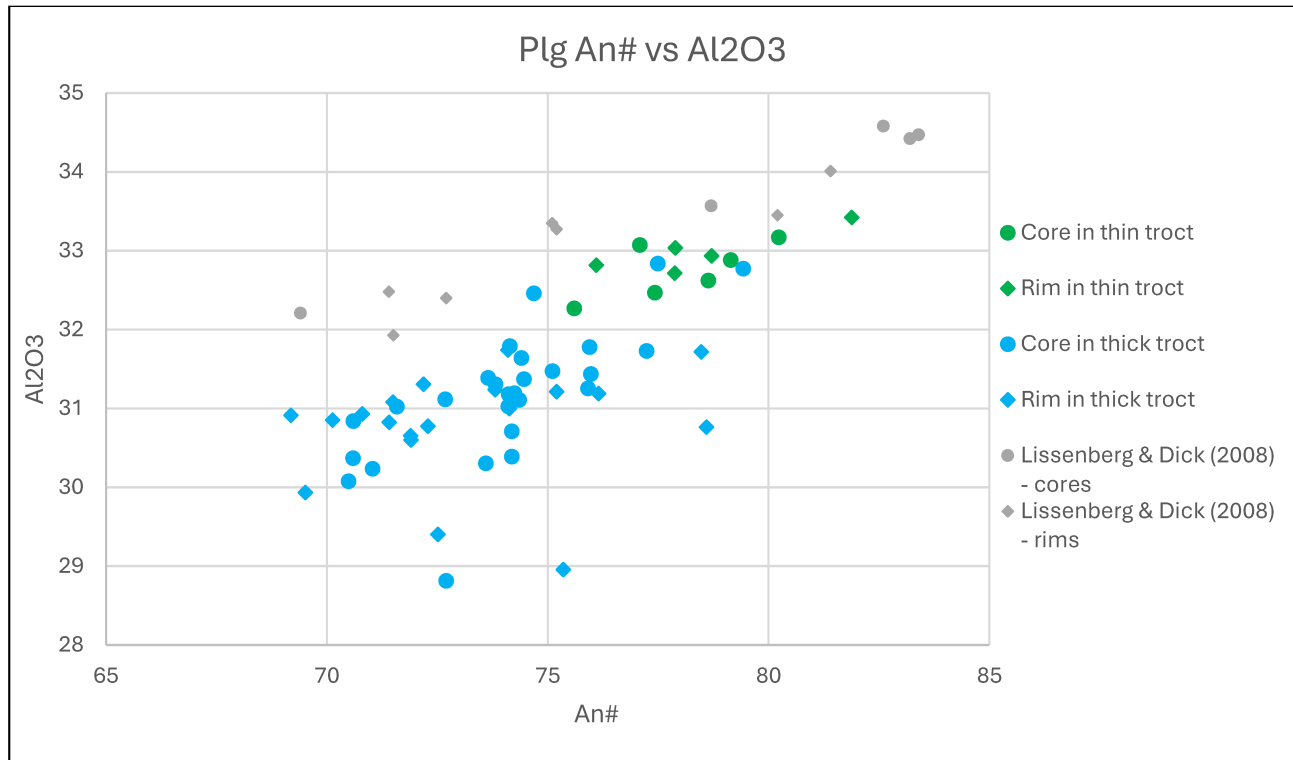


Diagram 15. Plagioclase from thin and thick troctolite (independently from troctolite 1 or 2-3) are plotted with *Lissenberg & Dick (2008)* troctolite compositions.

When the An# vs Al_2O_3 composition of contact-related troctolites is considered as a function of distance from the mantle rather than core-to-rim variations or olivine texture, a clearer trend emerges. Plagioclase closest to the mantle has the highest Al_2O_3 contents and slightly higher An# values.

Plagioclase compositions are also investigated in Diagram 16 as a function of distance from mantle and of lithology. Close to the mantle, plagioclase chemistry is broadly consistent in both thick and thin troctolite. Farther from mantle, Al_2O_3 contents are slightly lower in thick troctolite, ranging from 29 to 32 wt%, with respect to 32-34 wt% close to the contact. An# is also lower, since ranges from 69 to 79 compared with 74-82 in troctolite along the mantle contact. One exception is represented by a sample with approximately 31 wt% Al_2O_3 and An# 69 close to the contact.

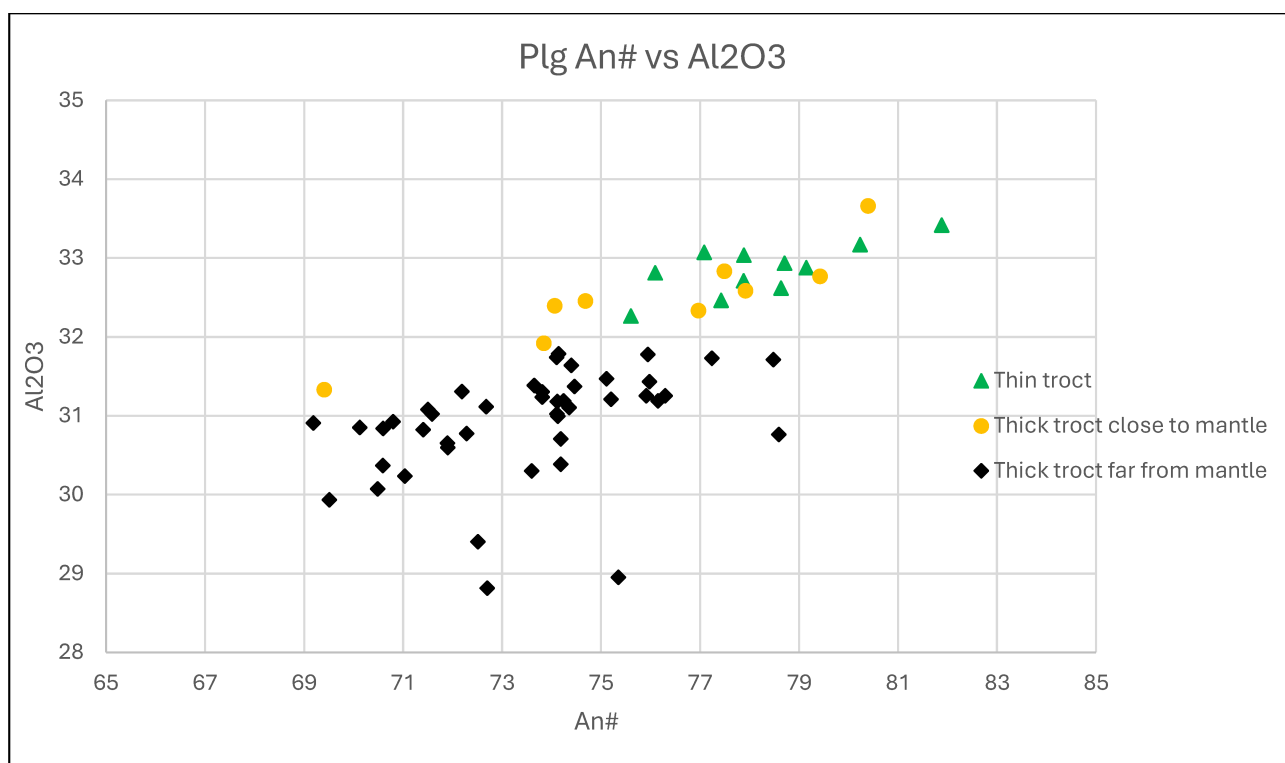


Diagram 16. Plagioclase compositions as a function of distance from the mantle and lithology. The closest to the mantle, the highest Cr_2O_3 and An#, regardless of the lithology.

5.2.3 OLIVINE

Olivine shows substantial texture and compositional variability. Crystals range from rounded to subrounded to anhedral and occur both at the contact and within the cores of contact-related lithologies.

5.2.3.1 *Olivine along coarse-grained contacts*

In coarse-grained contacts, olivine only occurs as an accessory phase where there is no pervasive percolation occurring beyond the contact with the mantle. In these contexts, it generally shows an anhedral texture. Accessory olivine from low-percolation olivine-bearing gabbroic contacts differs markedly from mantle olivine affected by strong percolation, in terms of Mg# and NiO, as Diagram 17 highlights. Where percolation occurs, preserved mantle olivine crystals may be observed close to the contact within peridotite. Locally, preserved olivine crystals outnumber the serpentinized ones. These olivines have low Fo# values, from 78 to 81 and NiO from 0.10 to 0.35 wt%. In contrast, the few olivine crystals beyond the contact in not percolated mantle have Fo# values of 88-89 and NiO contents of 0.35-0.55 wt%. Together with these preserved olivines within the mantle, olivine may also occur along coarse-grained gabbro contacts as lobate or type 1-2 crystals. In such case, Fo# is intermediate (82-88) between the percolated and not percolated mantle compositions, while NiO, falls within the same compositional range observed for percolated mantle olivine (Diagram 17).

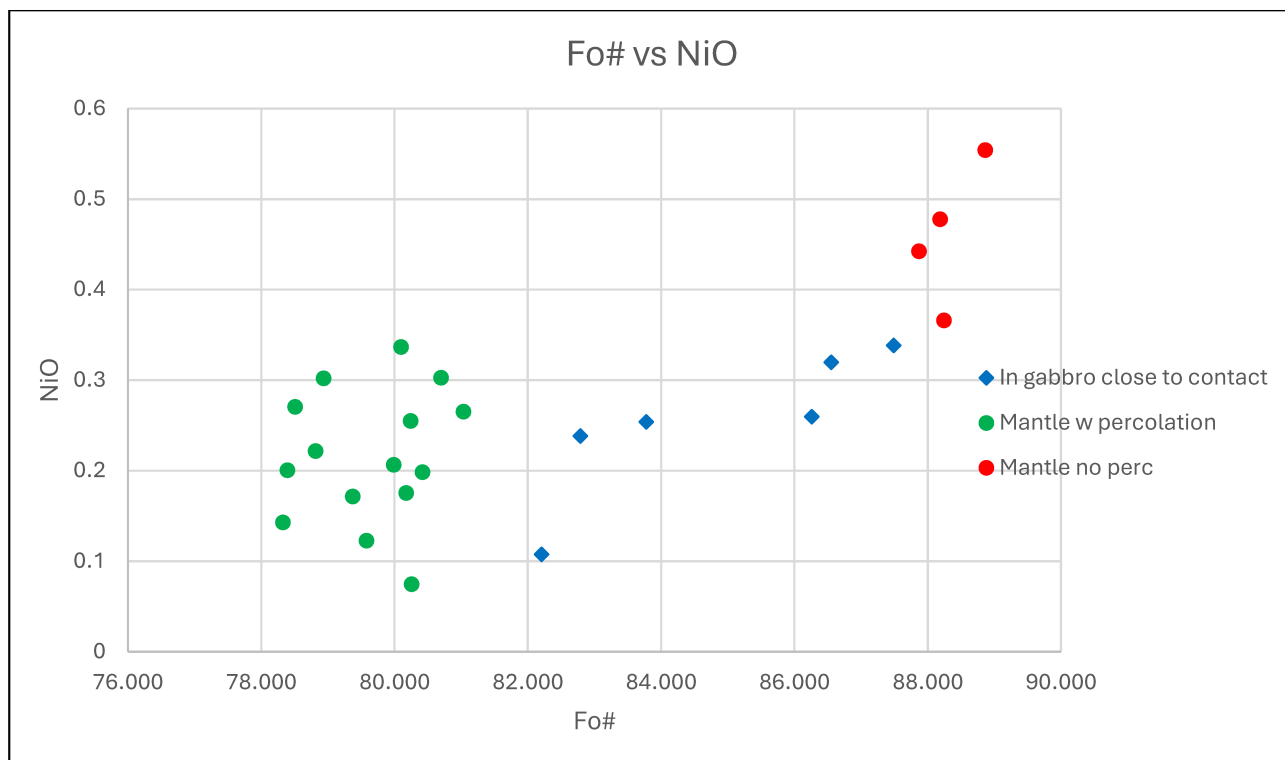


Diagram 17. Olivine compositions in mantle and along olivine-bearing gabbro contacts. Where percolation occurs, Mg# and NiO are extremely lower than preserved olivine from a non-percolated mantle. Olivine from olivine-bearing gabbro contact are compositionally in between the two.

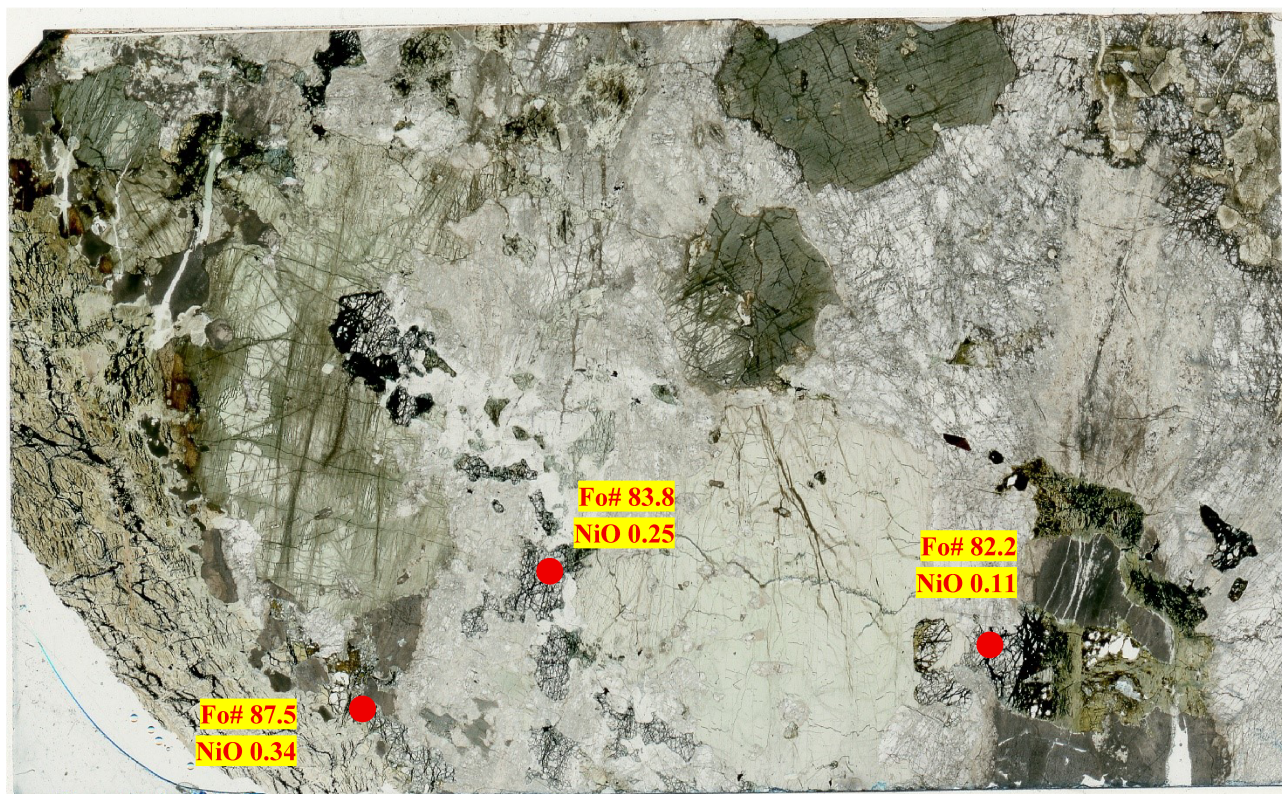


Fig 61. Transect from mantle to gabbro intrusion left-to-right oriented. Fo# and NiO show systematic decrease distancing from the mantle.

A large difference in Fo# and less marked in NiO are also observed in olivine along olivine-bearing coarse-grained gabbro contacts when comparing olivine compositions as a function of the distance from the mantle. Both Fo# and NiO show progressive decrease with increasing distance from the mantle.

5.2.3.2 Olivine in olivine-rich troctolite zones

As described in chapter 5, olivine in olivine-rich troctolite zones occurs with three main textural types. The clinopyroxene major-elements composition already highlighted the correlation between mineral composition and olivine texture.

Mg# vs NiO diagrams are used to emphasize the compositional differences among the different textural types. No type 1 olivine crystal from the thick olivine-rich troctolite zone close to the mantle has been analyzed since all such crystals are pervasively serpentinized. Nevertheless, a few analyses were obtained from resorbed olivine within the thin troctolite zone. In the cores of thick troctolite zone, several type 1 and 2-3 olivine crystals were analyzed a few centimeters away from the mantle.

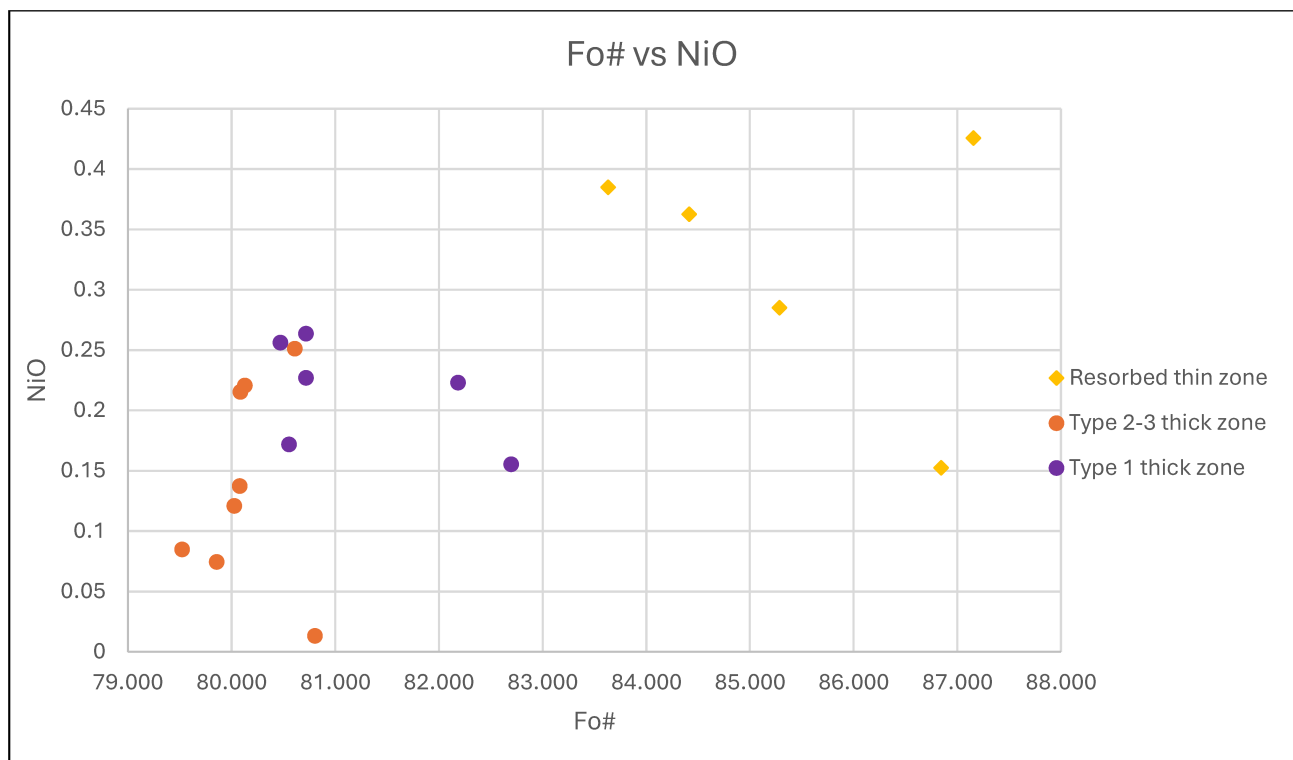


Diagram 18. Fo# vs NiO of the three olivine textures from thin and thick troctolite zones.

As displayed in Diagram 18, resorbed olivine from the thin zone has Fo# ranges from 83.5 to 87, while olivine within the core of the thin zone shows Fo# ranging from 79.5 to 81, with two exceptions

between 82 and 83. Resorbed olivine is therefore strongly enriched in Mg# compared to type 1-2-3 olivine from the wide troctolite zone and also shows a slight enrichment in nickel. Thin troctolite NiO content is 0.15-0.45%, while in thick troctolite is 0.01-0.25 wt%.

5.2.3.3 Olivine comparisons

Comparison of olivine compositions (Diagram 19) shows that not percolated mantle olivine, analyzed in harzburgite, has the highest Fo# and NiO contents. Resorbed olivine in thin zone and resorbed olivine along olivine-bearing gabbro contacts display similar Fo# values, although olivine in thin zone has slightly higher NiO. These groups differ markedly from olivine occurring in thick troctolites, where Fo# is lower than 81 (purple and orange), with two exceptions.

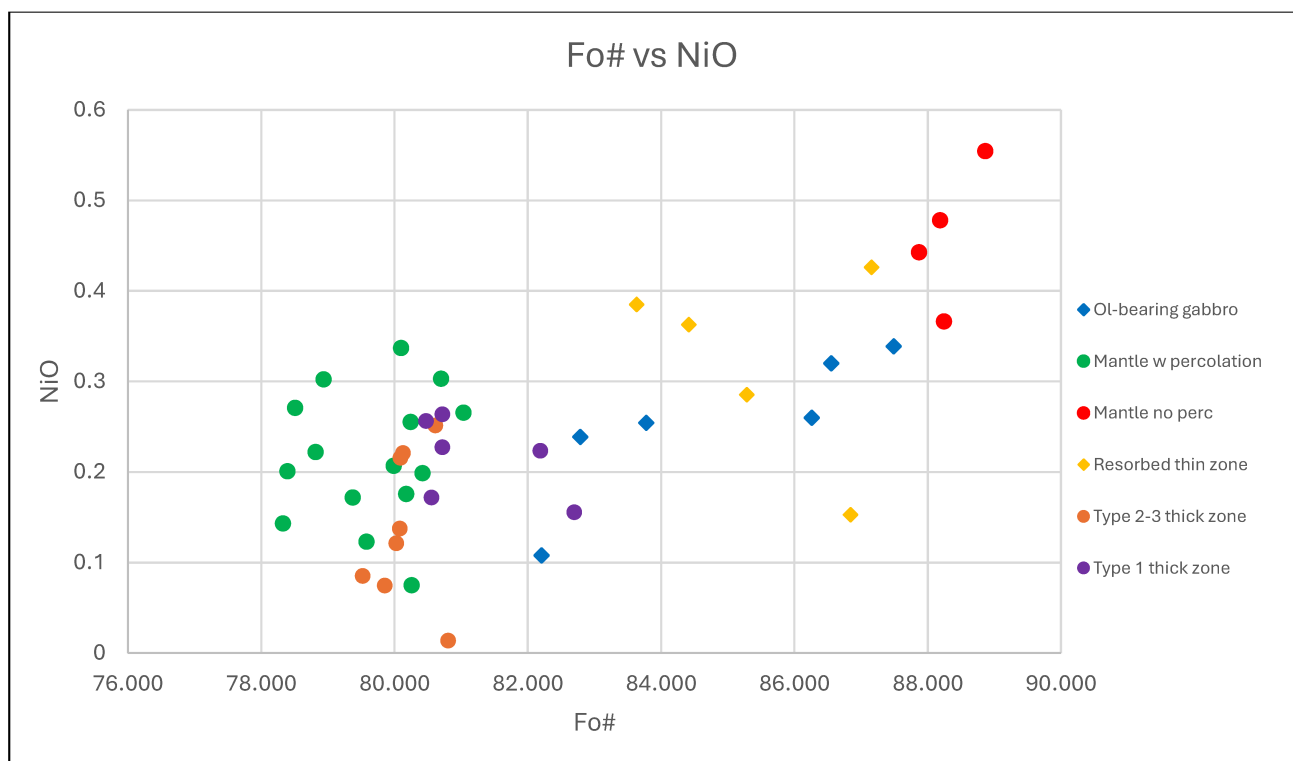


Diagram 19. Comparison NiO vs Fo# of all olivine textures and lithologies. Red indicates preserved mantle olivine not affected by percolation, which is effective in green points. Orange and purple represent troctolite cores.

In Diagram 20 the comparison of Fo# vs NiO in troctolites analyzed in this Thesis with the data of *Lissenberg & Dick (2008)* shows similar NiO contents, while olivine Fo# values reported by *Lissenberg & Dick (2008)* are higher.

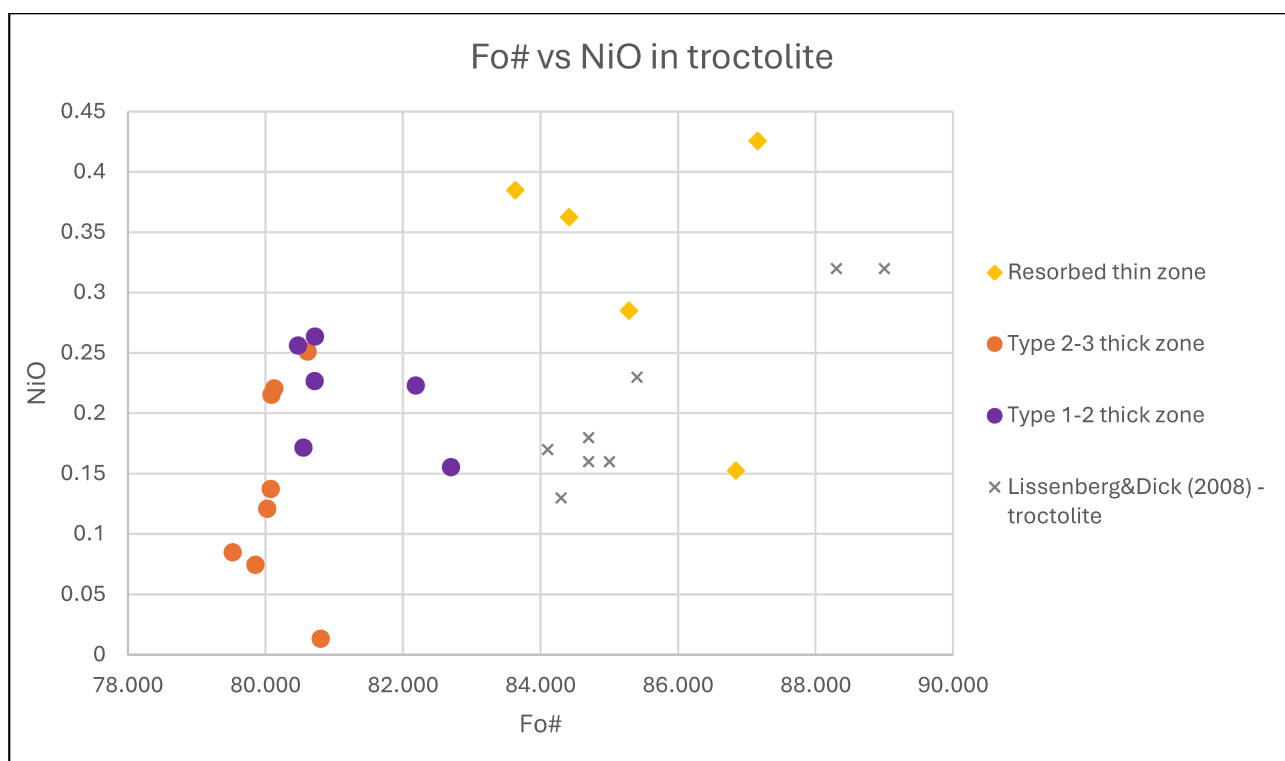


Diagram 20. Comparison of olivine composition of this Thesis with that of *Lissenberg & Dick (2008)*.

5.2.4 SULPHIDES

As described in Chapter 5, sulphides account for approximately 1 vol% of the rock within the contact-related troctolites.

5.1.4.1 *Pentlandite*

Pentlandite is the main magmatic Ni-bearing sulphide observed in the thin sections. It occurs only within the contact-related lithologies associated with either olivine or plagioclase.

Comparison among lithologies characterized by different olivine textures reveals systematic compositional differences exhibited in Diagram 21. Coarse-grained gabbro contacts and thin troctolites contain the most Co-depleted pentlandite. Ni content is variable, but no systematic differences are observed among the samples based on lithology. Co contents, in contrast, show clearer differences, since they are higher where olivine textures 2-3 occur and where olivine type 1 is present along the contact. When olivine type 1 occurs farther from the contact and is associated with pentlandite, the latter is Co-depleted compared with type 2-3 olivine association and with the same lithology closer to the contact.

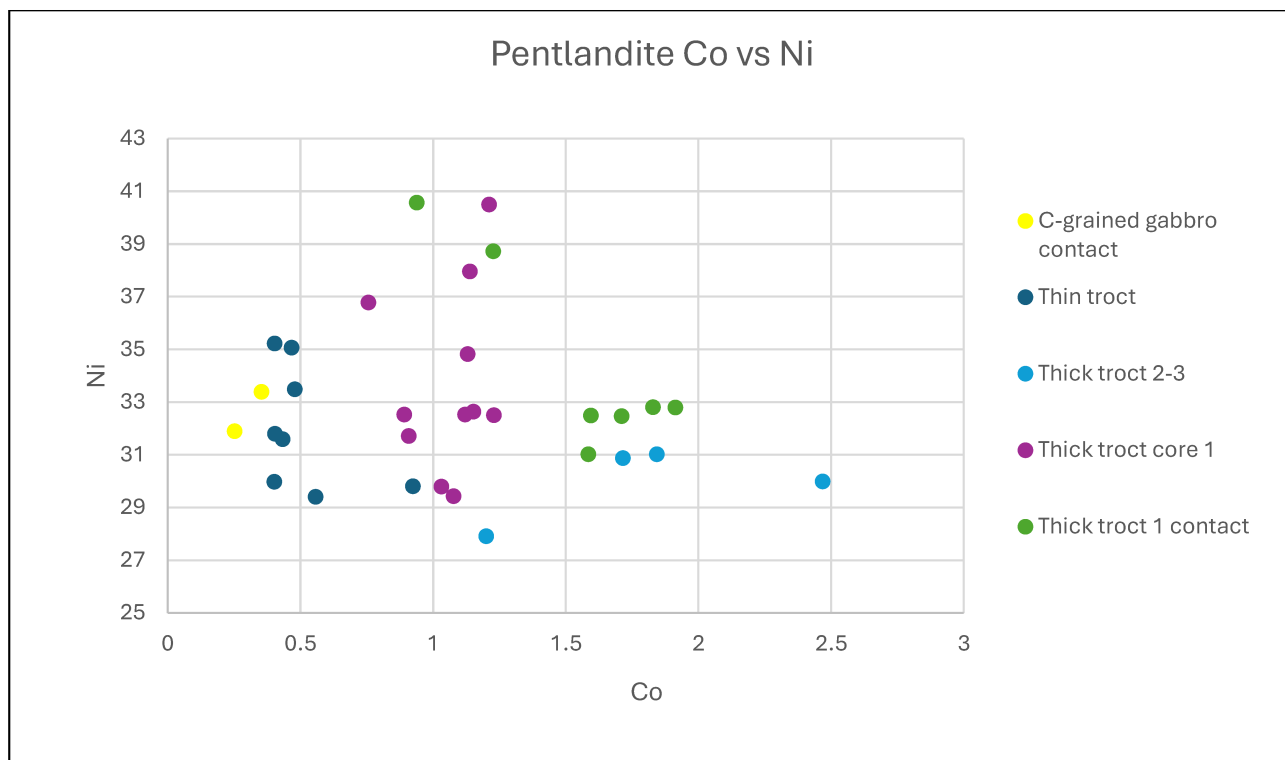


Diagram 21. Comparison Ni vs Co of all pentlandite in every lithology it is observed in. Gabbro (yellow, extremely rare) and thin troctolite show the lower Co content, while thick troctolite 2-3 core and thick troctolite 1 along the contact are the most Co-rich.

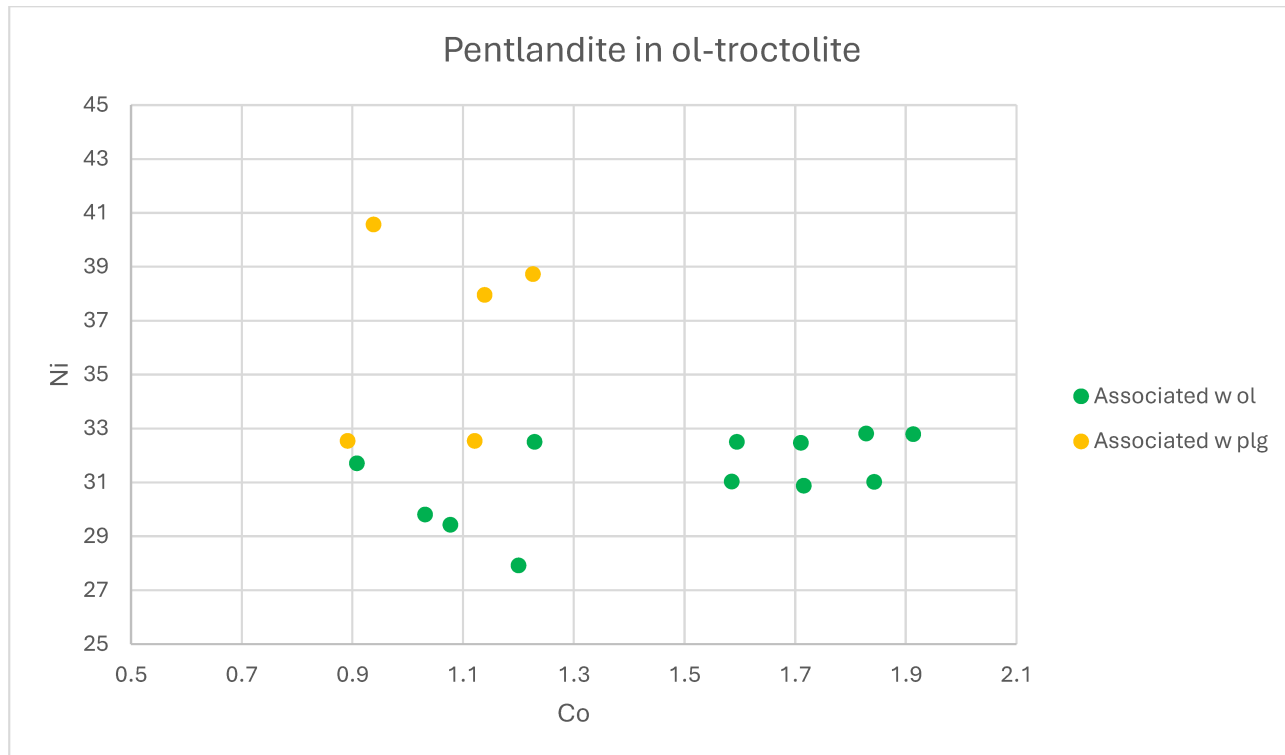


Diagram 22. Pentlandite Ni-Co composition is variable based on what mineral is associated with it.

Considering pentlandite composition in olivine-rich troctolite based on the major silicate with which it is associated reveals another clear pattern observed in Diagram 22. In this lithology, pentlandite associated with olivine, regardless of olivine texture, is strongly enriched in Co and depleted in Ni relative to pentlandite in association with plagioclase.

When considering pentlandite associated only with olivine, minor compositional differences are observed between the olivine textures in Diagram 23. Co content is approximately comparable, while Ni is slightly higher for crystals associated with olivine type 1.

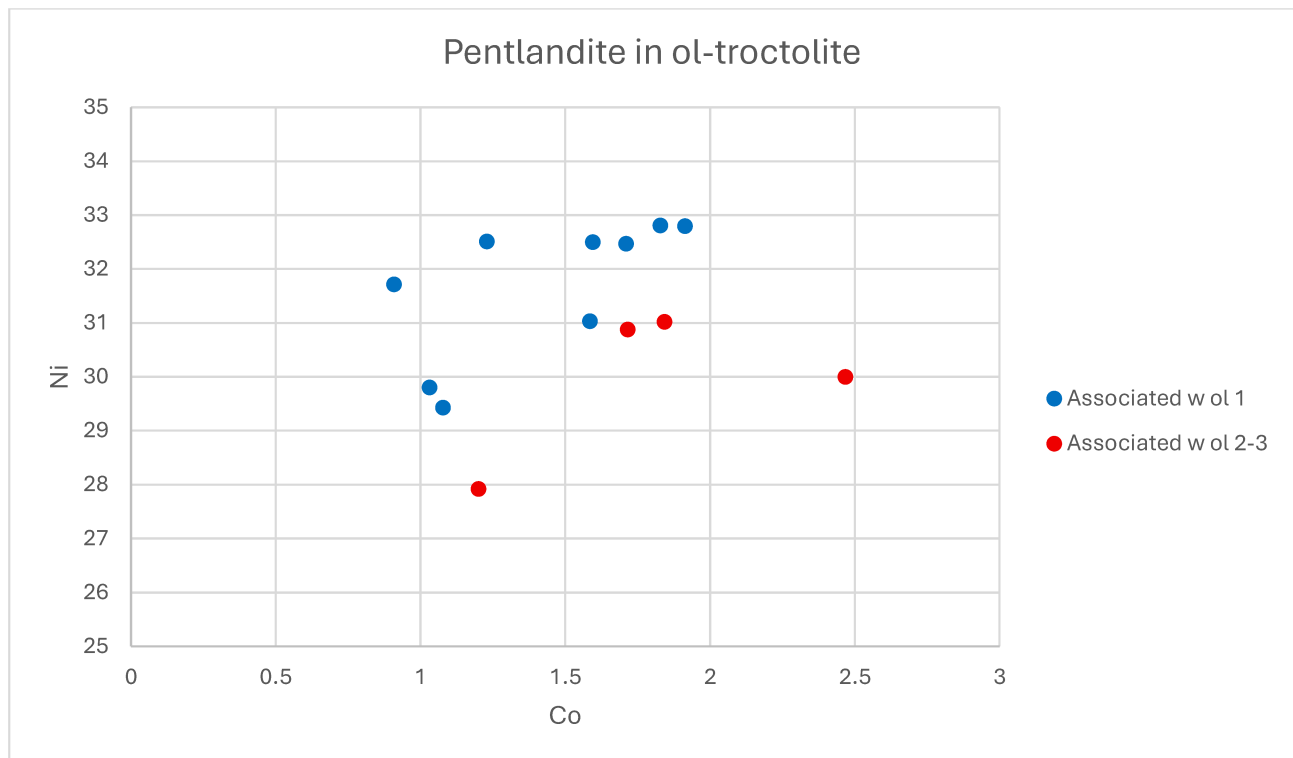


Diagram 23. Ni-Co pentlandite compositions as a function of olivine texture associated with the sulphide.

5.1.4.2 *Pyrrhotite*

Pyrrhotite is the most common sulphide throughout the samples. It is rare in thin troctolites and represents the only sulphide systematically observed in gabbro, although it is not widespread there. The metal/sulfur (M/S) ratio of pyrrhotite, displayed in Diagram 24, is higher along coarse-grained gabbro contacts, both with and without percolation, while it is evidently lower in contact-related thick olivine-rich troctolite. Thin troctolite shows an intermediate composition.

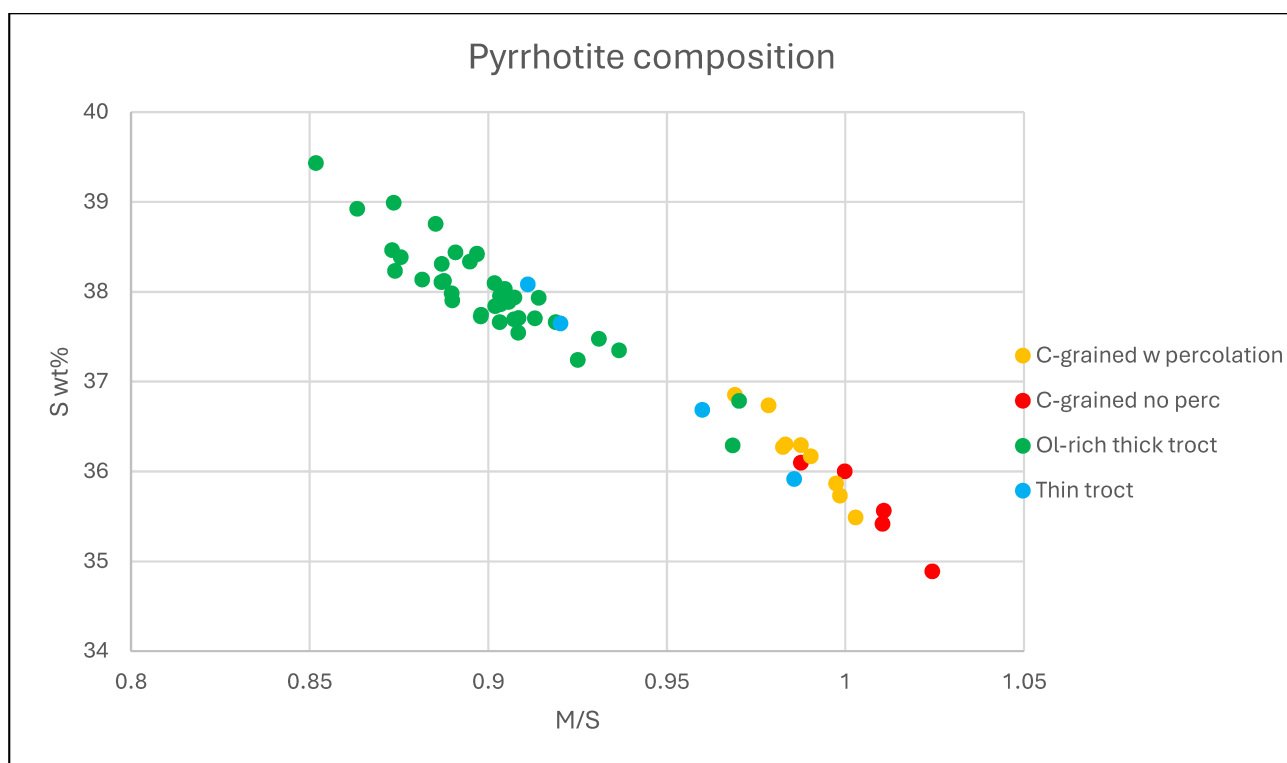


Diagram 24. Pyrrhotite M/S vs S wt% is displayed here. M/S is lower in thick troctolites and higher along gabbro contacts.

5.1.4.3 Chalcopyrite

Chalcopyrite is the least widespread primary magmatic sulphide in polysulphide aggregates. Together with pentlandite and chalcopyrite, it occurs mainly within thick olivine-rich troctolite zones, which represent the most sulphide-enriched lithology among the samples.

Chalcopyrite is absent from gabbro and only occurs in three cases along coarse-grained contact, within the magmatic percolation in the mantle. Chalcopyrite from thin troctolite is relatively Cu-enriched with respect to thick olivine-rich troctolite, while their Fe contents are similar in the two groups (Diagram 25).

Comparing M/S vs S wt% in Diagram 26, is clear how chalcopyrite from thin troctolite shows slight M/S enrichment relative to thick troctolite 1. Chalcopyrite associated with thick troctolite type 2-3 displays strongly variable S contents, locally lower than 34%.

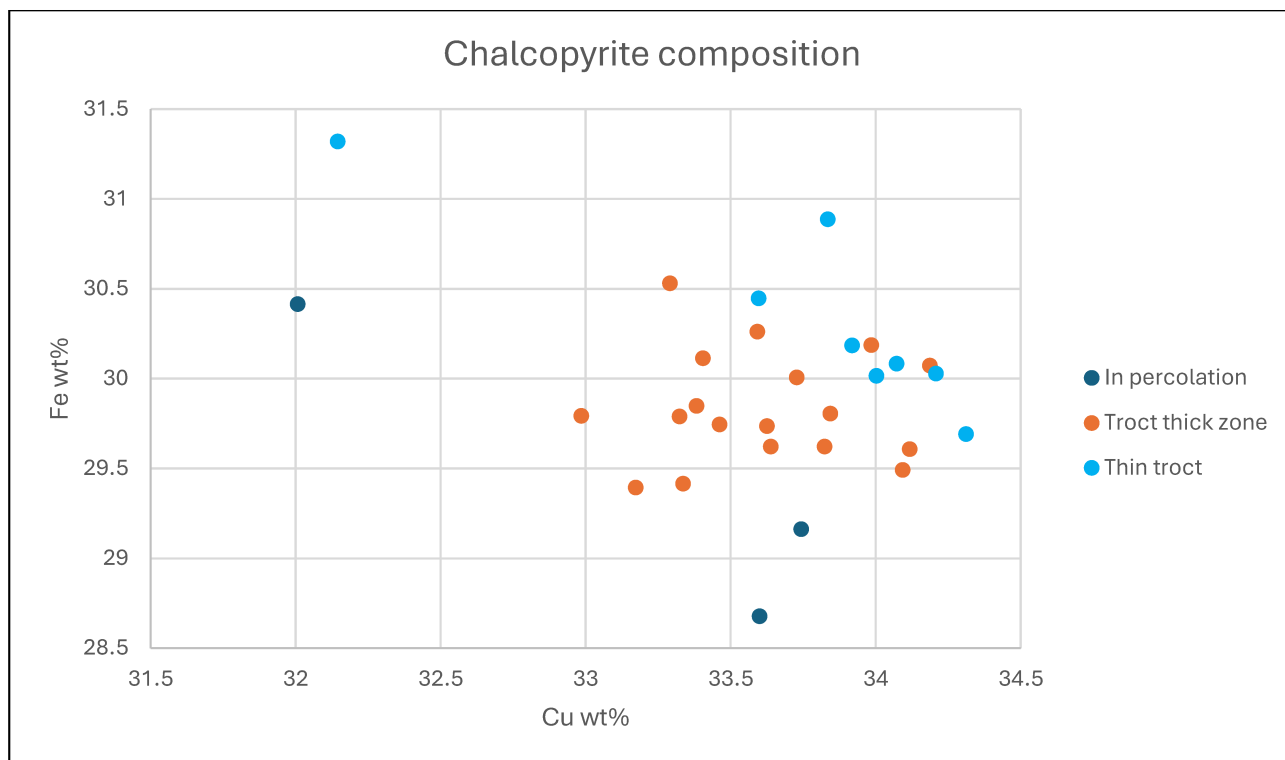


Diagram 25. Chalcopyrite compositions analyzed among the various troctolite type and in percolations in the mantle.

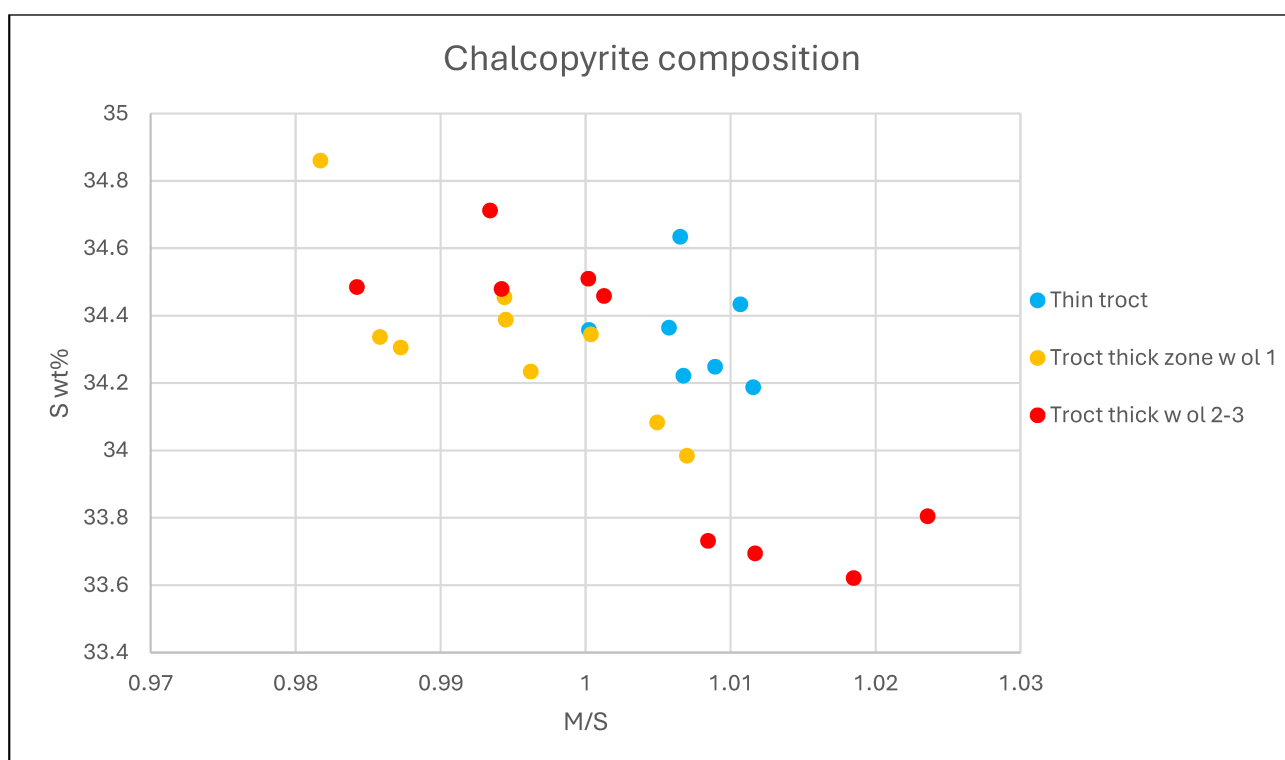


Diagram 26. In this case chalcopyrite compositions are compared among the different troctolite thicknesses and textures.

5.3 TRACE ELEMENTS COMPOSITION

The trace elements analyzed in this Thesis are limited to clinopyroxene from three thin sections. The following diagrams show chondrite-normalized rare earth element (REE) compositions on a logarithmic scale.

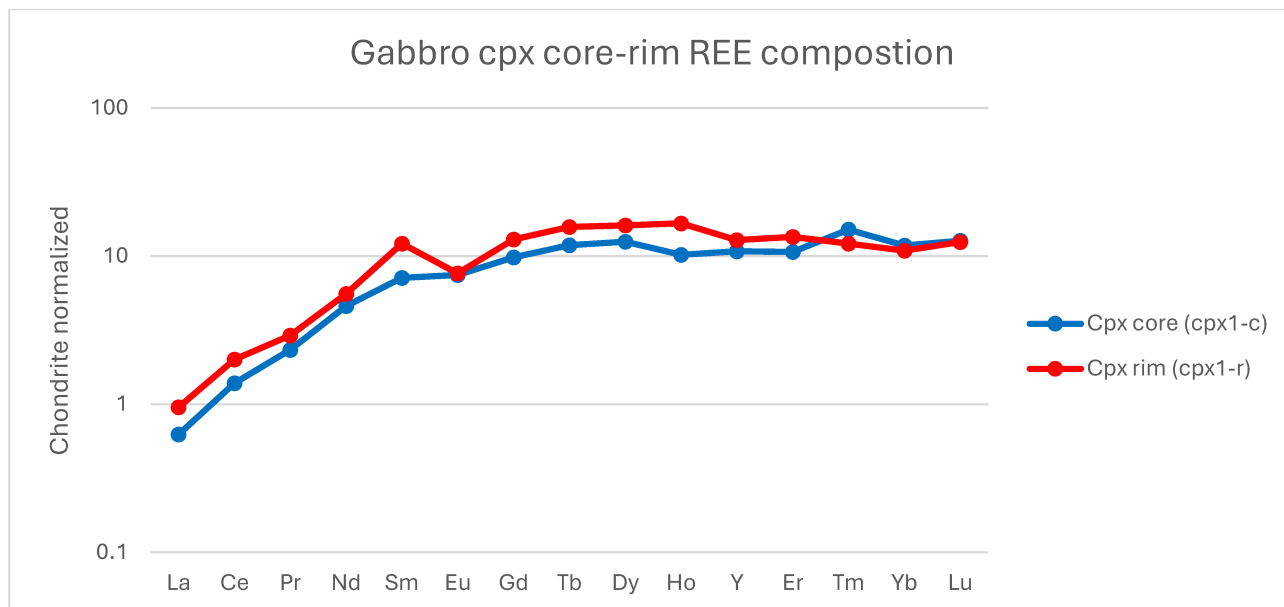


Diagram 27. Core-to-rim REE pattern comparison in a clinopyroxene from coarse-grained gabbro.

In the clinopyroxene from coarse-grained gabbro shown in Diagram 27, core and rim compositions display only minor differences in REE patterns. Eu contents are similar both in core and rim, but the rim shows a negative Eu anomaly that is absent in the core. The absence of an Eu anomaly may indicate concomitant crystallization of clinopyroxene and plagioclase, while the presence of the anomaly in the rim pattern is consistent with latter crystallization of clinopyroxene alone. In general, all the LREE and MREE are higher in the rims than in the cores, reflecting their incompatible behavior. Tm and Yb are slightly lower in rims than in cores.

In Diagram 28, no comparable core-to-rim differences are observed in clinopyroxene in coarse-grained gabbro from the same section of clinopyroxene of Diagram 27. The main difference between the two cases is their position within the intrusion, since clinopyroxene in Diagram 28 occurs along the mantle contact, while that in Diagram 27 is within the core of the gabbroic intrusion.

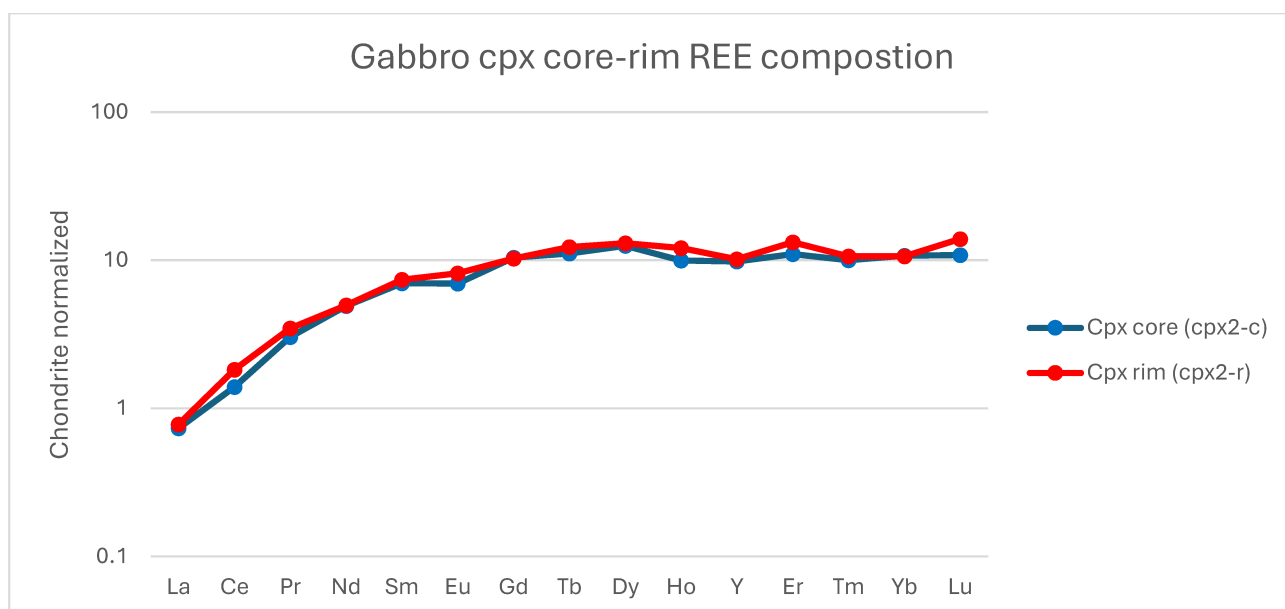


Diagram 28. Core-to-rim REE pattern of coarse-grained clinopyroxene located on the lithological contact with the mantle.

Comparison of clinopyroxene compositions from coarse-grained gabbro, from the contact with the mantle and within the percolation show no significant differences in REE pattern (Diagram 29). Eu negative anomaly is always displayed.

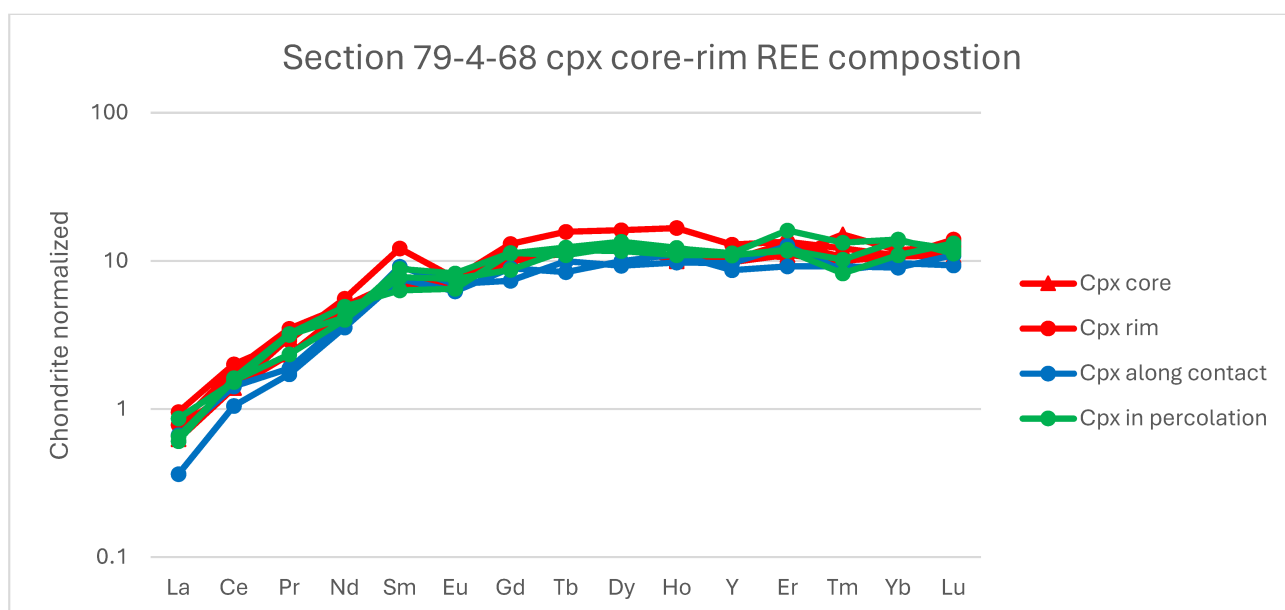


Diagram 29. REE patterns of clinopyroxenes coming from different portions of the same thin section. Red patterns display REE composition of clinopyroxene in gabbro core, blue pattern shows the composition of clinopyroxene on the contact with serpentinized olivine, and the green pattern exhibits the composition of a clinopyroxene crystal constituting the percolation into the mantle. No significant variability is observed.

Core-to-rim compositions of clinopyroxene from the core of a contact-related thick troctolite zone, displayed in Diagram 30, show no remarkable difference. The same applies to the REE composition of vermicular portions of clinopyroxene. Again, the negative Eu anomaly is observed.

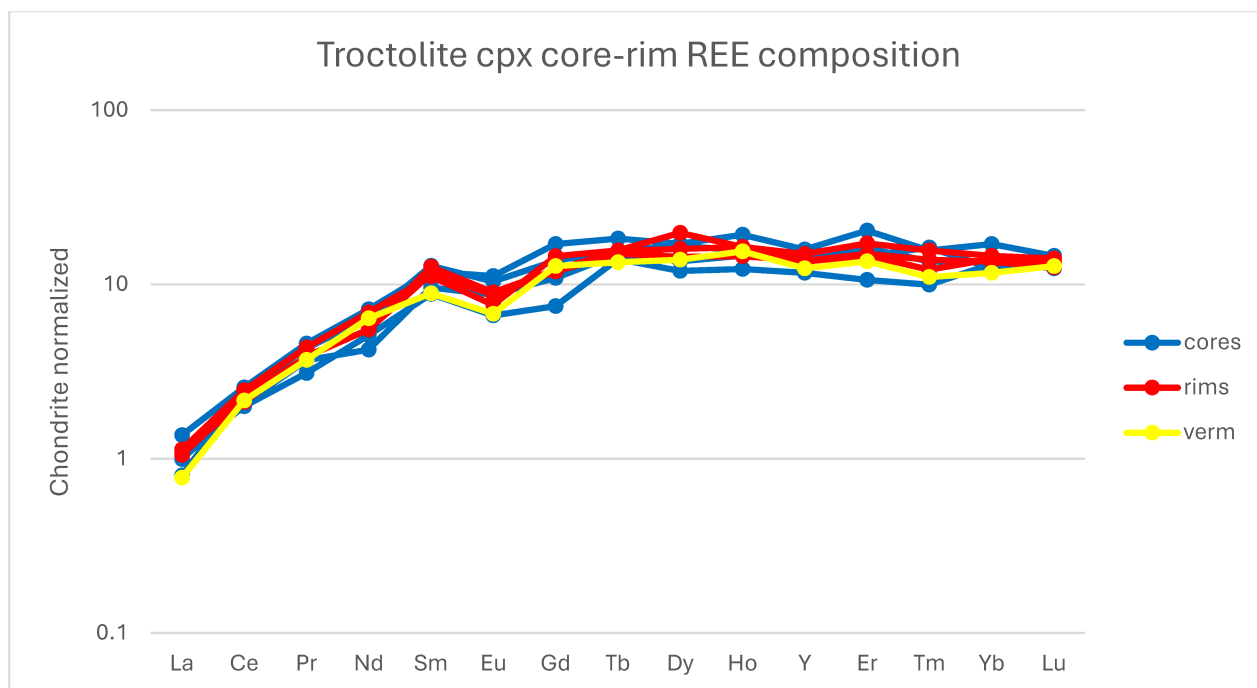


Diagram 30. REE pattern of different clinopyroxene portions from thick troctolite core.

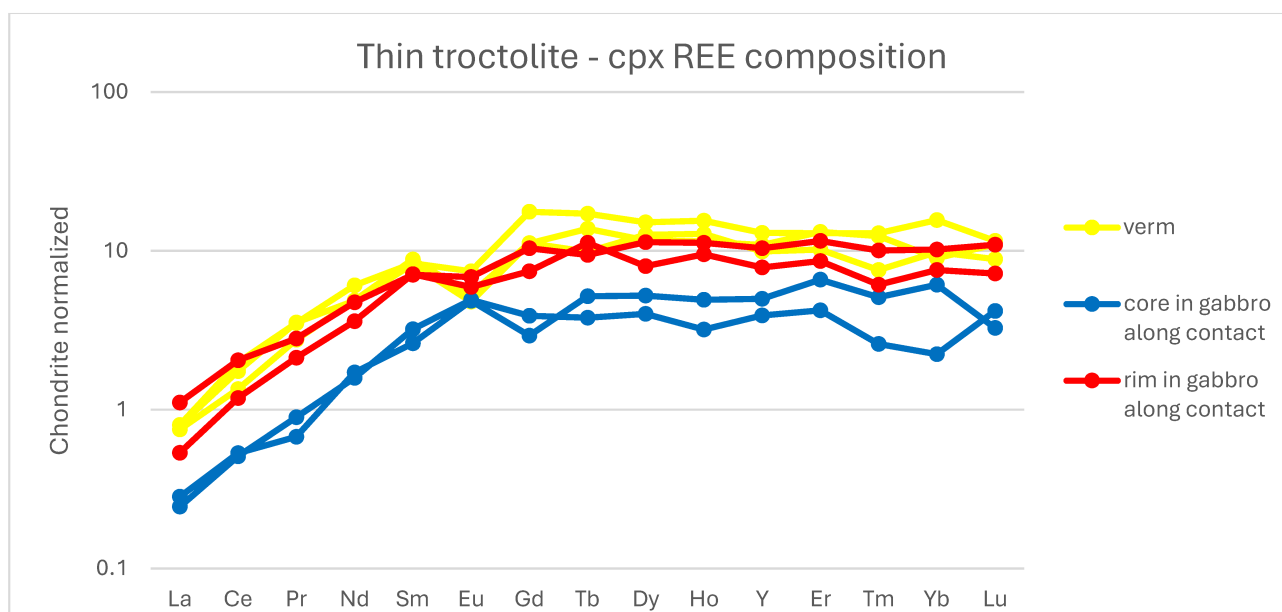


Diagram 31. Clinopyroxene showing REE differences within the same thin section, which displays a thin troctolite zone, that separates the mantle from the coarse-grained gabbro intrusion. Vermicular clinopyroxene texture is observed in the thin troctolite, while the analyzed core and rim are from coarse-grained clinopyroxene from gabbro. The vermicular texture and the gabbro show similar REE composition, while the core is strongly depleted.

The largest REE differences are observed between the vermicular clinopyroxene in thin troctolite and the coarse-grained clinopyroxene crystals in the gabbro, immediately adjacent to the thin troctolite (Diagram 31). The cores are strongly depleted in REE with respect to the rims, while the rims are themselves slightly depleted compared with the vermicular clinopyroxene occurring within the thin troctolite zone between the serpentinized mantle and the gabbroic intrusion.

Comparison between Ce chondrite normalized vs Mg# in clinopyroxene from coarse-grained gabbro and clinopyroxene occurring in percolation into the mantle is shown in Diagram 32. The common core-to-rim enrichment typical of fractional crystallization is only observed in coarse-grained gabbro. Percolated clinopyroxene does not show this systematic enrichment either in rims nor in vermicular textures. It is again clear that percolated clinopyroxene is Mg#-rich compared with gabbro clinopyroxene.

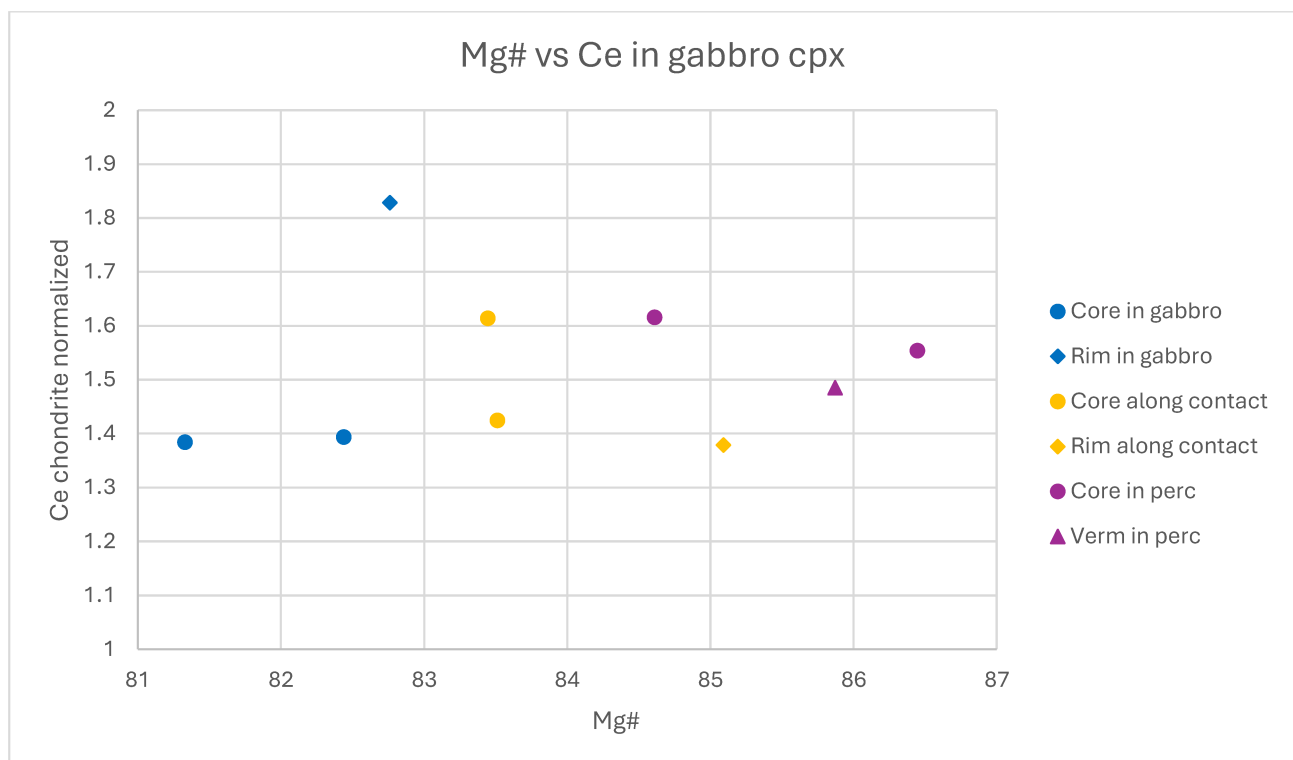


Diagram 32. Mg# vs Ce chondrite normalized comparing coarse-grained clinopyroxene from gabbro and clinopyroxene observed into the percolation in the mantle rock.

6. DISCUSSION

Several mantle-gabbroic intrusion contacts have been described and analyzed in this study. The contacts between serpentinized peridotite and coarse-grained gabbroic intrusions occur with various lithology, texture, and composition.

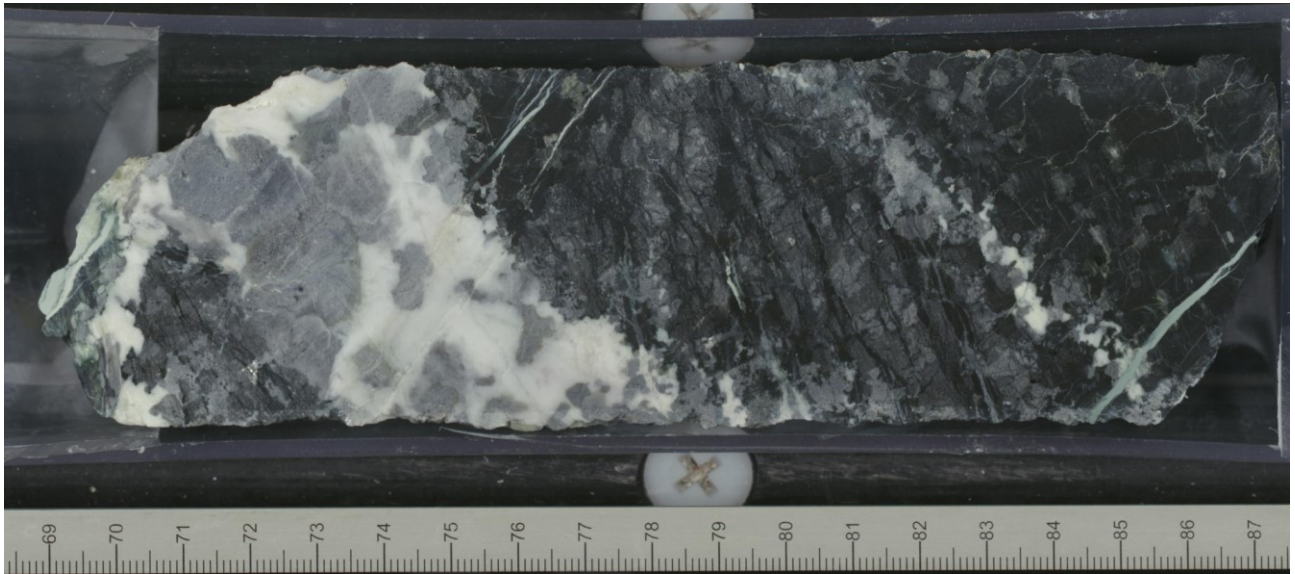


Fig. 62. Coarse-grained gabbroic intrusion core displaying refertilization of the mantle portion caused by sets of veinlets crosscutting the lithology.



Fig. 63. Contact between coarse-grained gabbro and the mantle. The latter is clearly crossed by magmatic veinlets mainly constituted by percolated clinopyroxene.

Coarse-grained gabbro and serpentinized peridotite occur adjacent along what we call coarse-grained gabbro contacts. These contacts are subdivided into two types. One type is characterized by a set of thin veinlets crossing the mantle and crystallizing clinopyroxene and minor plagioclase. Within the gabbro there are no apparent changes in texture. Fig. 62 displays an example of this contact in the core perspective, details of thin section are reported in Fig. 63. We interpret this contact as derived from melts percolating into the mantle in discrete melt channel along the contact.

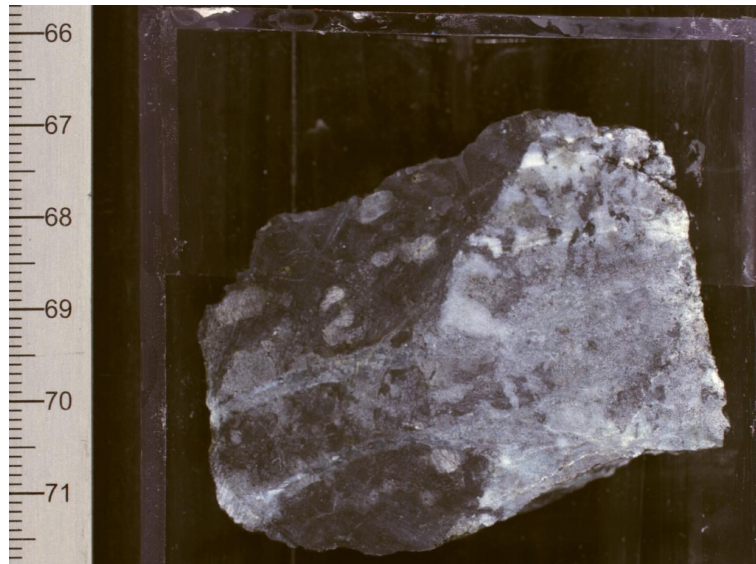


Fig. 65. Olivine-bearing gabbro contact from seen from the core scan.



Fig. 66. Olivine-bearing gabbro contact, associated with no percolation and mantle with harzburgitic composition.

The other type is called olivine-bearing gabbro contact, since gabbro on the contact reaches up to 5 vol% in olivine, which usually occurs as partially resorbed crystals. This contact type does not show any evidence of melt percolation into the host mantle harzburgite. Fig. 65 shows this type of contact in the core, while Fig. 66 in thin section.

The other samples, the majority, are represented by contact-related rocks which can occur with different compositions, lithology, and textures between the serpentized mantle and the coarse-grained gabbro intrusion. In this case, three subgroups are identified to better distinguish the various processes occurring along the contacts. The first is characterized by layers of olivine-rich troctolite to troctolite lithologies less than 2-3 cm-wide. This rock is referred to as thin troctolite and shows peculiar composition, such as high-Mg# interstitial clinopyroxene and high-Fo# partially resorbed olivine (Fig. 67 and 68 show core scan and thin section, respectively). The second and third groups are both made up of rock types developing from 5 to 60 cm from the host mantle. Olivine-rich troctolite is preponderant close to the mantle, becoming less rich in olivine far from contact. The decrease in olivine content is associated with different olivine textures. The olivine-rich troctolite is characterized by coarse-grained olivine crystals, generally exhibiting lobate boundaries with plagioclase. This olivine texture is called type 1, therefore, troctolites containing that olivine are named troctolite 1 (Fig. 69-70). In contrast, olivine texture type 2 and 3 are more abundant moving away from the mantle contact and are characterized by chains of polygonal crystals with curvilinear to lobate boundaries and by separated medium-grained rounded olivine occurring as chadacrysts within large plagioclase or clinopyroxene oikocrysts. Both olivine type 2 and type 3 are observed in troctolite 2-3 (Fig 71-72).

These textural differences can also be linked to geochemical compositional variability of the mantle-intrusion contacts, as shown in Diagram 11 and 12 for clinopyroxene, 16 for plagioclase, and 19 for olivine.

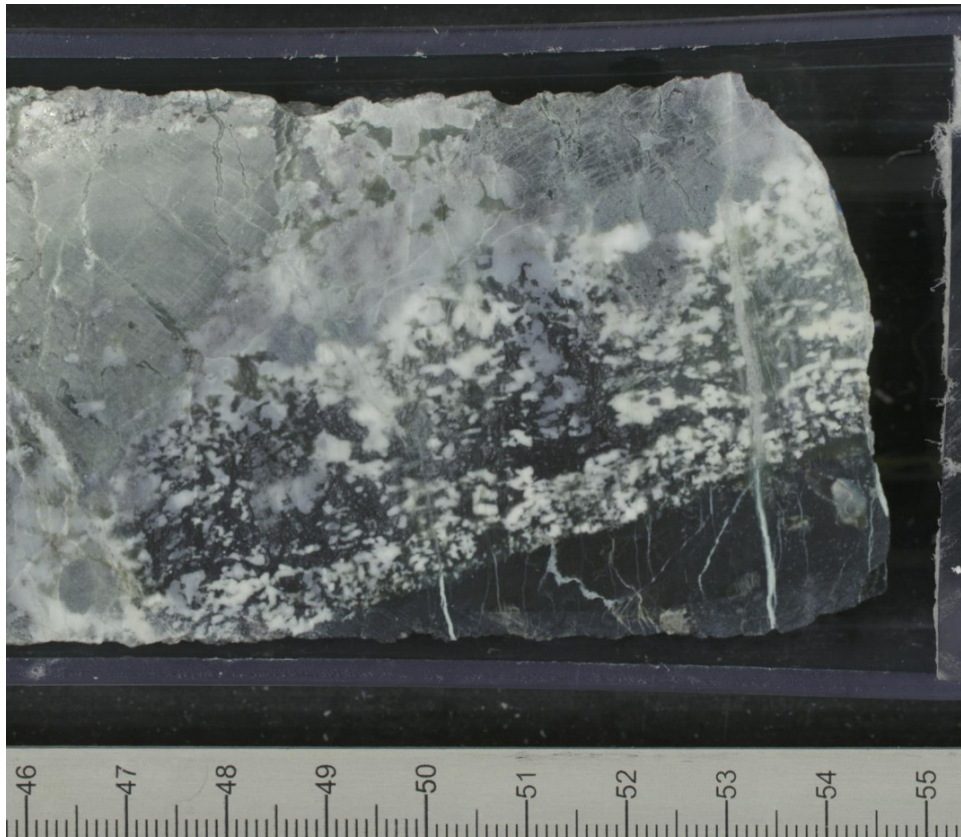


Fig. 67. Contact-related thin olivine-rich troctolite in core scan.



Fig. 68. Thin section showing from the left to right in sequence: serpentinized mantle, contact-related thin olivine-rich troctolite, and coarse-grained gabbro.

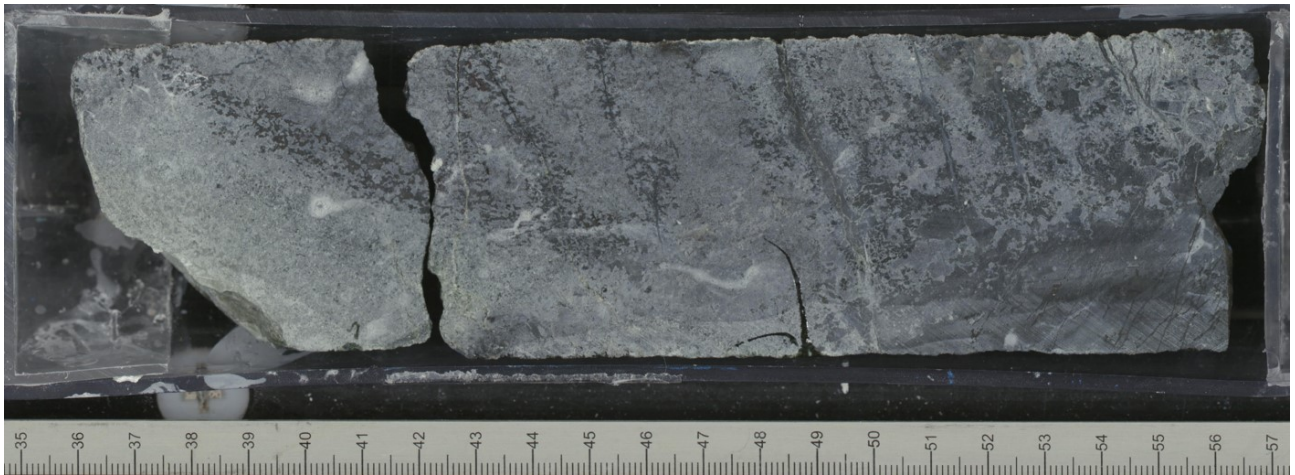


Fig 69. Thick troctolite zone type 1.

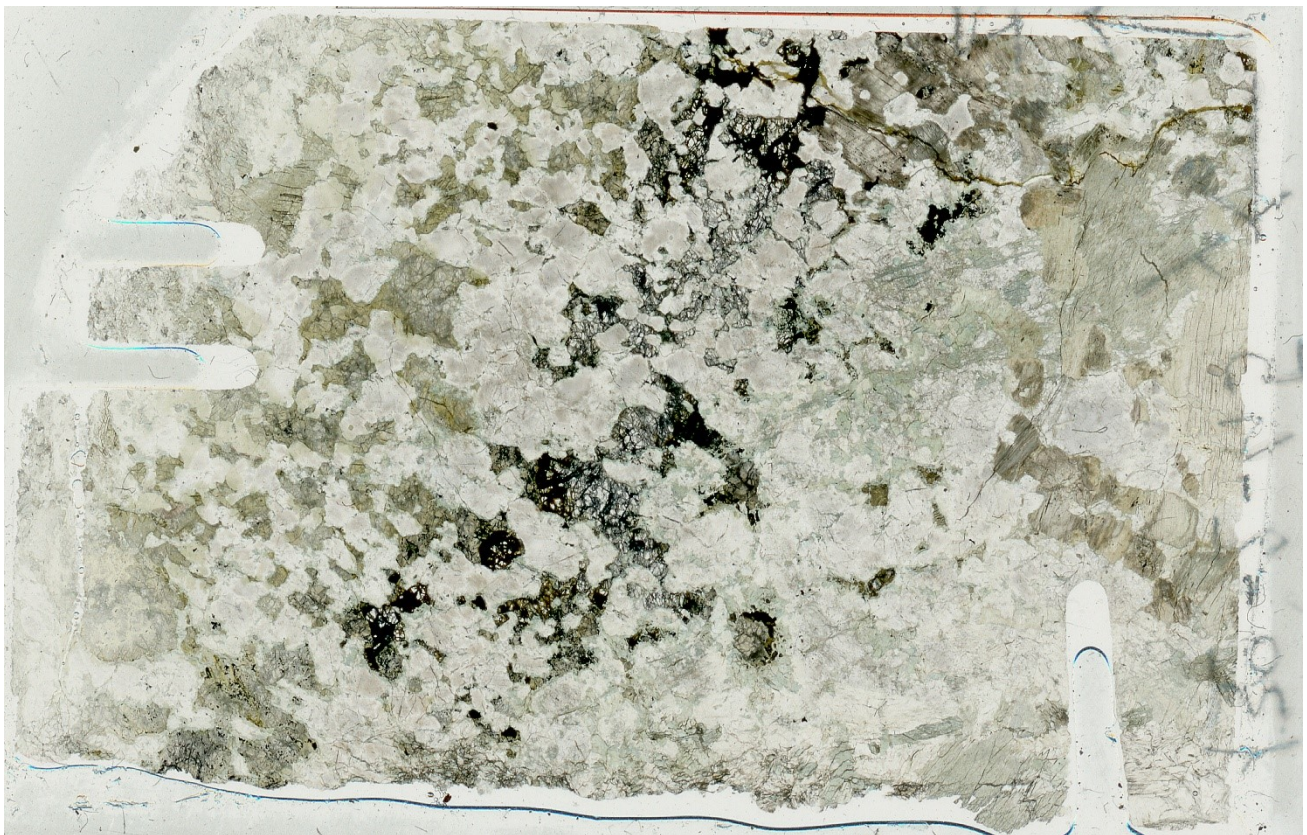


Fig 70. Thin section showing a central olivine-rich troctolite portion, with clinopyroxene oikocrysts. The other parts are made up of the only gabbro observed among the samples.



Fig 71. Olivine-rich thick troctolite type 2-3 progressively changing to coarse-grained gabbro from left to right.



Fig. 72. Central part of the thick troctolite shown in Fig. 71. Olivine textures type 2 and 3 are clearly visible here.

Since all these characteristics and lithologies of contacts are observed in the entire Hole U1601C, Atlantis Massif, chemical processes developing along the contacts are distinctive of specific interactions between the serpentinized mantle and the crystallizing gabbroic intrusion. Indeed, these lithologies systematically occur along the contacts and are not reported elsewhere, and can be considered correlated to interaction between the host mantle and the magmatic intrusions.

As already described in the IODP Expedition 399 by *McCaig et al. (2023)*, interaction between magmas and peridotites are fundamental processes occurring at Atlantis Massif OCC. Such reaction and intrusion features are consistent with assimilation of crustal melt in deep crustal hot zones, a process capable of modifying both melt and host-rock chemistry, driving crystallization of mineral phases different from a pure fractional crystallization process (*Lissenberg & Dick, 2008*).

It is thus essential assessing the occurrence of these melt-rock reactions and, by consequence, to evaluate how this process modified the compositions and textures of the contact rocks studied here and of the magmatic evolution of Atlantis Massif OCC in general.

6.1 TEXTURAL EVIDENCE FOR MELT-ROCK REACTION AT THE CONTACTS

Lissenberg & Dick (2008) inferred that melt–rock reaction is an inevitable consequence of melt transport and cumulate formation in the lower oceanic crust. In most cases, gabbroic intrusions are hot or even partially molten, promoting interaction between rising melt and preexisting mantle cumulates.

The common occurrence of disequilibrium textures along mantle-intrusion contacts suggests that much of the melt migrates by porous flow. Typically, such porous flow will lead to melt–rock reaction, since it is unlikely that percolating melts will be in equilibrium with the cumulus phases (see also *Lissenberg et al., 2013; Sanfilippo et al., 2021*). In this context, it is evident that olivine crystals that show lobate to polygonal textures (type 1) in troctolite, and in olivine-bearing gabbro contacts are produced by olivine resorption in advantage of plagioclase and clinopyroxene crystallization. In the same way, olivine texture types 2 and 3, which are enclosed in plagioclase and mostly clinopyroxene oikocrysts, are characteristic of infiltration of a melt initially saturated in plagioclase into an olivine matrix. Every single olivine texture proves chemical disequilibrium with the infiltrating melt (*Sanfilippo et al., 2013*). According to *Drouin et al., 2009*, rounded (type 2-3) olivines enclosed within plagioclase and clinopyroxene oikocrysts are formed by melts impregnating and reacting with an olivine-rich matrix, revealing large volume of infiltrating melts. These intervals can therefore represent a reaction zone where MORB-type melts migrated and crystallized via an open-system porous flow.

Following this interpretation, olivine present in the contact related lithologies is what remains of a previous olivine-rich matrix which subsequently reacted with percolating melt of gabbroic composition. *Sanfilippo et al. (2013, 2015)* interpret these troctolites as the products of partial dissolution and impregnation of an olivine $\pm$ spinel matrix, within a multistage process entailing dunitization, dissolution and crystallization of magmatic phases. Such multistage process is analyzed in depth in the following paragraphs.

In some rare cases, olivine-rich troctolites reported worldwide do not necessarily occur along the contacts with mantle (*Renna & Tribuzio, 2010; Sanfilippo & Tribuzio 2013*). Instead, pervasive percolation into the Hole U1601C mantle section formed of sets of thin (> 1 mm) veinlets occurs. These veinlets (Fig. 62-63) are exclusively constituted by clinopyroxene and interstitial plagioclase. Here, the mantle is subdivided at the contact into different zones that show pervasive magmatic percolation, evidenced by the creation pathways of magmatic crystals between mantle olivines. This texture may represent the beginning of the pervasive percolation that subsequently corrodes and assimilate mantle olivine with a mantle-melt reaction.

Deciphering the hybrid nature of olivine-rich troctolites along mantle-intrusion contacts is important to define to what extent hybridized mantle material can be a contributor to the lower crust, calling into question the assumptions that the oceanic crust reflects the composition of the melt extracted from the mantle.

6.2 CHEMICAL EVIDENCE FOR MELT-ROCK REACTION AT THE CONTACTS

6.2.1 HIGH-Mg# CLINOPYROXENE

During fractional crystallization of MORB at low pressure, clinopyroxene crystallizes after olivine + plagioclase (*Kinzler & Grove, 1992*). As a result, clinopyroxene in oceanic gabbros formed in the lower crust should have a relatively low Mg#, since the Mg# of the melt has already been lowered by olivine fractionation prior to clinopyroxene saturation (*Lissenberg & Dick, 2008*). *Kinzler & Grove (1992)* experimental data give an average Mg# for the first clinopyroxene crystallizing after olivine + plagioclase of 83. With increasing pressure, clinopyroxene stability field expands at expenses of olivine and plagioclase, leading to early saturation of clinopyroxene before fractionation has significantly lowered the Mg# of the melt. Consequently, clinopyroxenes with high Mg# (>86) are commonly found in oceanic gabbros and may be interpreted as the result of crystallization taking place at moderate to high pressures (*Lissenberg & Dick, 2008*). Nevertheless, high-Mg# clinopyroxene observed in the contact-related troctolites at IODP Hole U1601C shows several features which are inconsistent with an origin by moderate to high-pressure fractionation of a MORB.

First, high-Mg# clinopyroxenes occur as oikocrysts, that enclose earlier crystallized olivine and plagioclase, and as late interstitial/vermicular grains between olivine and plagioclase in contact-related troctolite. This indicates that melt crystallization followed the normal low-pressures fractionation trend for MORB, which are generally produced in low-pressure geodynamic systems (*Ferrando et al., 2018*).

Second, the vermicular clinopyroxene and oikocrysts have high Mg# (86-92, except for clinopyroxene in troctolite 2-3 that is 82-86, Diagram 33) coexisting with plagioclase that extends to low anorthite contents (An 82-69). This is the contrary of what expected for high-pressure crystallization, where early clinopyroxene fractionation would lower the Mg# of the melt significantly by the time it saturates in plagioclase, leading to lower clinopyroxene Mg# at a given plagioclase An# content.

Furthermore, the TiO₂ and Cr₂O₃ content of vermicular clinopyroxene and oikocrysts differ from those expected for fractionation of a MORB melt. The melt in equilibrium with these clinopyroxenes

has Cr₂O₃ concentrations (0.4-1.2 wt%, Diagram 33) too high to be in equilibrium with a typical MORB composition (*Lissenberg & Dick, 2008*). Every contact related lithology, including thin and troctolite type 1 and 2-3, and also olivine-bearing gabbro show these features and argue against fractional crystallization (*Renna & Tribuzio, 2010; Sanfilippo et al., 2013*). The only Cr₂O₃-poor clinopyroxene is that of a coarse-grained gabbro, which was formed at high melt flux far from the mantle contact.

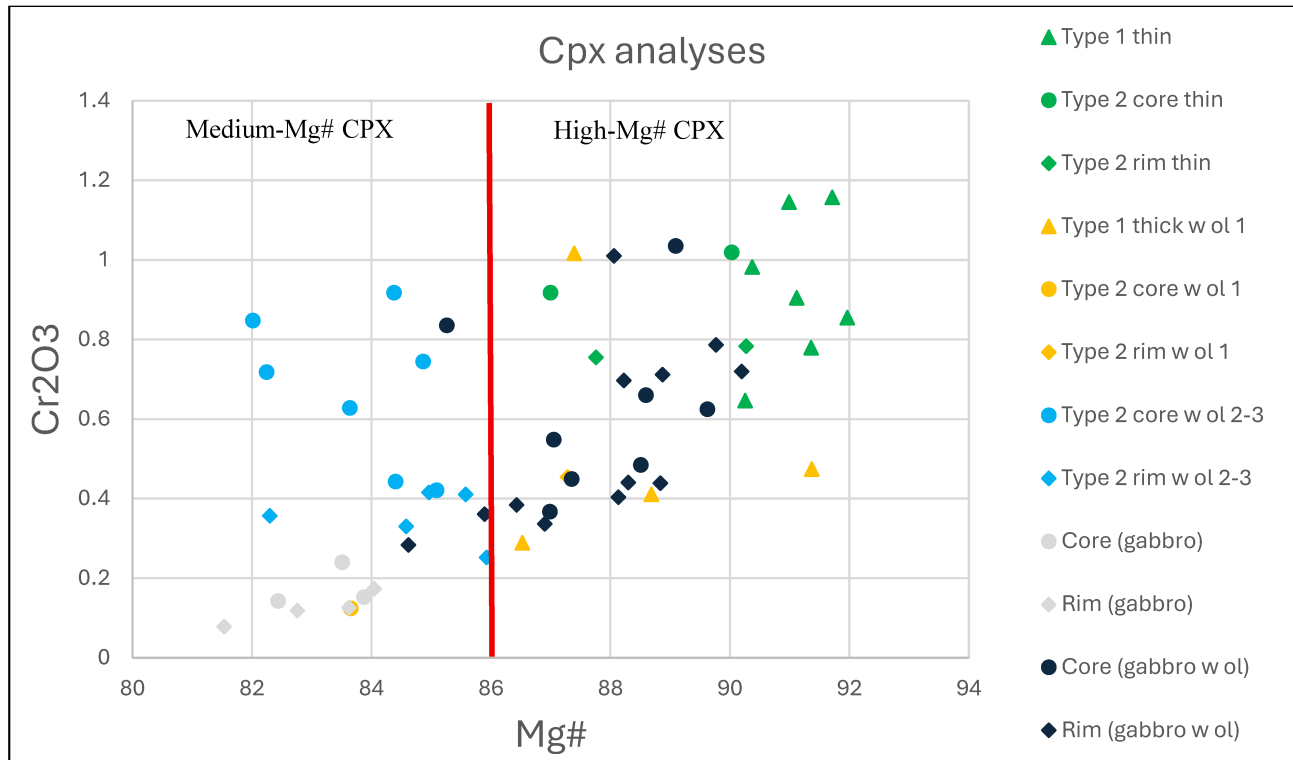


Diagram 33. Clinopyroxene textures plotted in Mg# vs Cr₂O₃. The diagram is subdivided into two fields indicating medium- and high-Mg# clinopyroxene content.

The TiO₂ contents of the melt in equilibrium with the clinopyroxenes, on the contrary, are similar to that in typical MORB from the Mid-Atlantic Ridge (1.12-1.35 wt% from *Sun & McDonough (1989)*, while TiO₂ reported here is 0.6-1.2 wt%, Diagram 12), but exceed those of melts in equilibrium with mantle peridotite (*Lissenberg & Dick 2008*). This indicates that clinopyroxene oikocrysts and vermicular grains could not have been produced by simple fractionation of a MORB magma. Some of the clinopyroxene with interstitial habits have very high TiO₂ contents (1.2 wt%), suggesting they crystallized from evolved melts with high TiO₂ contents. Such TiO₂ contents require extensive fractionation and decreases in melt mass, which would have also lowered the Mg# of the melt. The high-Ti clinopyroxenes (0.8-1.2 wt%) from the thin troctolites and from type 1 thick troctolite have Mg# ranging from 86 and 92, which is inconsistent with crystallization from an evolved MORB-type melt. Some clinopyroxene in troctolite type 2-3 has low Mg# (82-86) that can be related to high

melt/rock ratio during the interaction, as explained in Paragraph 6.3.1 for olivine composition associated with these clinopyroxenes. Instead, olivine-bearing gabbro contacts show lower TiO₂ contents in cores (0.2-0.4 wt%), and enriched rims (0.4-0.8 wt%), in agreement with a gradual evolution of the crystallizing magma.

Chakraborty (1997) suggests that the Fe-Mg exchange between melts and olivine is rapid. Therefore, a likely consequence of cumulate evolution in a crystal mush is that interstitial melt evolved through fractionation may saturate in clinopyroxene, which acquires Mg# in equilibrium with the host rock olivine. This leads to the precipitation of high-Mg# clinopyroxene enriched in incompatible elements. This explains why the oikocrysts and the vermicular clinopyroxenes are in Fe-Mg exchange equilibrium with the olivine of the host rock and indicates that clinopyroxenes from (olivine-rich) troctolites compositions are inconsistent with only fractionation trends (*Lissenberg & Dick, 2008; Sanifilippo et al., 2013; Ferrando et al., 2018*). Chemical exchanges between a pre-existing crystal matrix and exotic melts or postcumulus reactions with late-stage interstitial melts have been proposed as mechanisms able to modify the mineral chemistry of primary phases. Such reactions may in turn modify the composition of the reacting MORB-type melts (*Ferrando et al., 2018*).

Thus, high-Mg# vermicular clinopyroxene and clinopyroxene oikocrysts may record mantle-melt reaction along the interface of serpentinized peridotite and migrating gabbroic intrusions, providing the first geochemical evidence supporting the textural indications. For these reasons, fractional crystallization cannot be the only geochemical process driving melt crystallization within the U1601C mantle section. In support of this, cores of large clinopyroxene crystals are characterized by limited Eu negative anomalies indicating early clinopyroxene precipitation, before or simultaneously with plagioclase, in contrast to the expected fractional crystallization trends of MORB-type melt that predict early plagioclase crystallization (*Kinzler & Grove, 1992*).

6.2.2 SULPHIDES AT THE GABBRO-MANTLE CONTACTS

Almost the totality of sulphides analyzed in this study occurs in the contact-related troctolites. Enrichments in the chalcophile elements constituting sulphides at the crust-mantle contacts could result from both magmatic or secondary hydrothermal processes (*Ciazela et al., 2018*). The sulphides in contact-related troctolite occur as polysulphide grains of pyrrhotite as the main phase, associated with pentlandite and chalcopyrite. This systematic association occurring together with exsolution (“flame”) textures, suggests formation from a sulphide magma. Moreover, the wide Fe-Ni range of pentlandite is indicative of high-temperature crystallization from a melt (Fig. 73), further supporting their magmatic origin (*Kaneda et al., 1986; Ciazela et al., 2018*).

Magmatic pyrrhotite-pentlandite-chalcopyrite assemblages generally occur both in the melt-modified host mantle and in the residual mantle. In the latter, however, pentlandite predominates, which contrasts with polysulphide grains dominated by pyrrhotite occurring in olivine-rich troctolites. Thus, polysulphide compositions are focused mostly within crystallization in melt-modified mantle (Ciazela *et al.*, 2018). Moreover, pyrrhotite-pentlandite association is indicative of low sulfur and oxygen fugacity (Moll *et al.*, 2007). According to Naldrett (1981), in the system Fe–Ni–S the first crystallizing phase is Fe-rich and Ni-poor relative to the coexisting mafic silicate melt. Further fractional crystallization leads to Ni-enrichment in the sulfide liquid that would consequently precipitate Ni-rich sulfides such as pentlandite. This can explain why the main phase is pyrrhotite which shows pentlandite exsolutions.

The average magmatic pentlandite shows 0.6 Co wt% contents (Ciazela *et al.*, 2018). Every pentlandite from the contact-related troctolite, except for that from thin troctolite, has Co contents ranging from 0.75 to 2.45 wt%. Ciazela *et al.*, 2018 displays pentlandite average content along peridotite-intrusion contact of 1.7 wt%, which is perfectly comparable to data in the present study. These Co-rich compositions are therefore likely indicative of pentlandite formed subsequently to mantle-melt reaction (which is interpreted as a hybrid geochemical process by Sanfilippo *et al.*, 2015). that enriches the melt in Co.

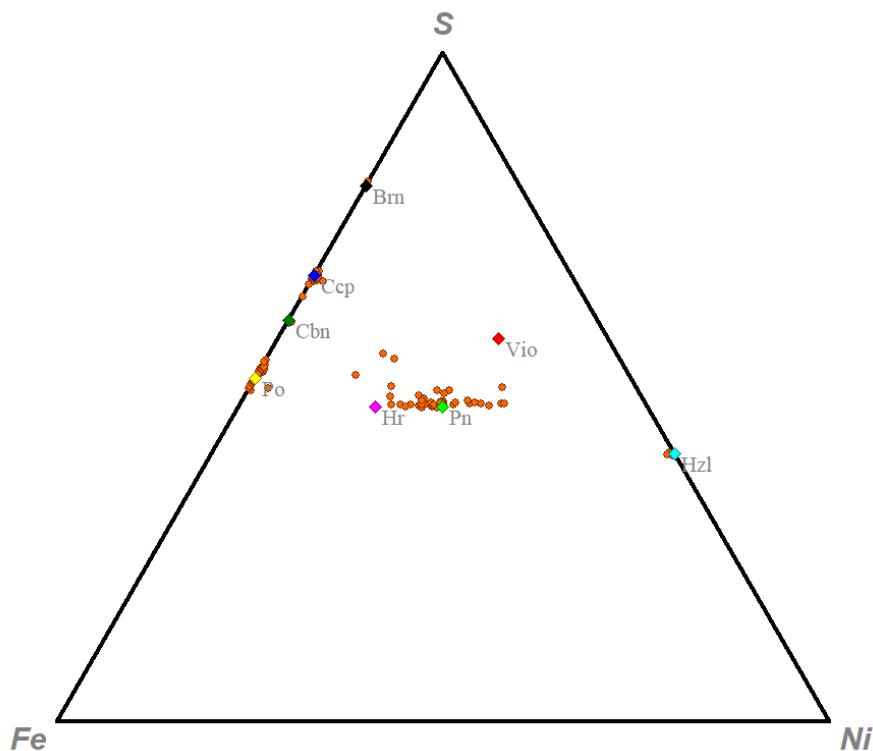


Fig. 73. Fe-Ni-S ternary diagram displaying all the sulphide compositions (orange) analyzed within this Thesis. Several sulphide compositions are shown in diverse colors to highlight the differences between the stoichiometric formula (pyrrhotite is not stoichiometric) and the actual composition analyzed. Pentlandite (light green stoichiometric composition) shows a clear Fe-Ni variable composition, typical of high-temperature magmatic crystallization and consistent with data from Miller *et al.* (2007).

Chalcopyrite only occurs in contact-related lithologies, generally as rims in polysulphide aggregates. This enrichment of chalcophile elements (Ni, Cu, Co, etc.) is also reported by *Ciazela et al. (2018)* and interpreted as a feature of the at mantle-intrusion contacts that undergo extensive melt-mantle reaction. Sulphide aggregates are partially dissolved during pervasive serpentinization of mantle rocks, but the chalcophile elements are trapped in submicron secondary sulphides, hydroxides, and native metals embedded in the silicate mantle matrix.

We argue that mantle-melt reaction is the process that causes melt enrichment in these chalcophile elements for two reasons. The first is that these elements are exclusively mobilized and incorporated into the melt due to the reaction with the mantle and its partial dissolution. The second is that decreasing Fe content in melt produces a lowering of S concentration at sulfur saturation (SCSS) and may lead to sulphide precipitation from percolating melt (*Ciazela et al., 2018*). FeO loss in melts is more efficient in narrow intrusion channels, such as those occurring in Hole U1601C, where Fe in melt is buffered by the exchange reaction with large amount of olivine and pyroxene on conduit walls (*Ciazela et al., 2018*). Again, as for high-Mg# clinopyroxene, chemical exchanges caused by the reaction between a pre-existing crystal matrix and exotic melts or postcumulus reactions with late-stage interstitial melts are the mechanisms able to modify the composition of the reacting MORB-melt (*Ferrando et al., 2018*).

Sulphide globules from MORB melts are composed of 44 wt% Fe, 11 wt% Ni, 7 wt% Cu, and 38 wt% S (*Ciazela et al., 2018*), and this iron enrichment is the reason why pyrrhotite is almost the only rare crystallizing sulphide in gabbro. Its association with pentlandite and chalcopyrite only occurring in contact-related troctolite is further evidence for melt-mantle reaction. Moreover, the presence of pentlandite in troctolite coupled with its almost entire absence in gabbro, is indicative of the dissolution of pentlandite-dominated polysulphide from residual harzburgitic mantle. This polysulphide dissolution produces Ni-enrichments in the melt that generates pyrrhotite-dominated pentlandite-bearing polysulphides in reactive troctolite.

As a whole, sulphides features and compositions are in agreement with a melt-mantle reaction that generates the troctolites.

6.3 INFLUENCE OF MELT/ROCK RATIO ON COMPOSITION OF THE CONTACT-RELATED LITHOLOGIES

Every contact-related lithology differs compositionally and texturally from coarse-grained gabbro intrusions, due to the occurrence of mantle-melt reactions. Nevertheless, within the contact-related lithologies, internal systematic compositional variability is observed.

6.3.1 OLIVINE TEXTURE AND COMPOSITION

Olivine-rich troctolites show effective chemical re-equilibration during impregnation of precursor dunites involving high instantaneous and time-integrated melt/rock ratios. This chemical modification during hybridization of the Atlantis Massif dunites is indicative of a melt dominated system, in which the matrix was re-equilibrated with the percolating melt without strong compositional modification of the latter. On the contrary, preserved and constant composition of the olivine matrix within hybridized troctolitic samples, regardless of olivine modal content, is correlated with strong compositional variability of the magmatic interstitial minerals, such as decreasing An# in plagioclase and increasing clinopyroxene Cr₂O₃ concentrations. These features suggest that hybridization occurred in a matrix-dominated magmatic system (*Rampone et al., 2016; Basch et al., 2025*).

Such homogeneous and primitive compositions of the interstitial phases that crystallized in the contact-related troctolites are the expression of the open-system character of the reactive melt migration process, during which melt dissolved only a small fraction of the percolated matrix and fractionated a small amount of its mass before being extracted from the sample and replaced by a new melt increment (*Basch et al., 2025*).

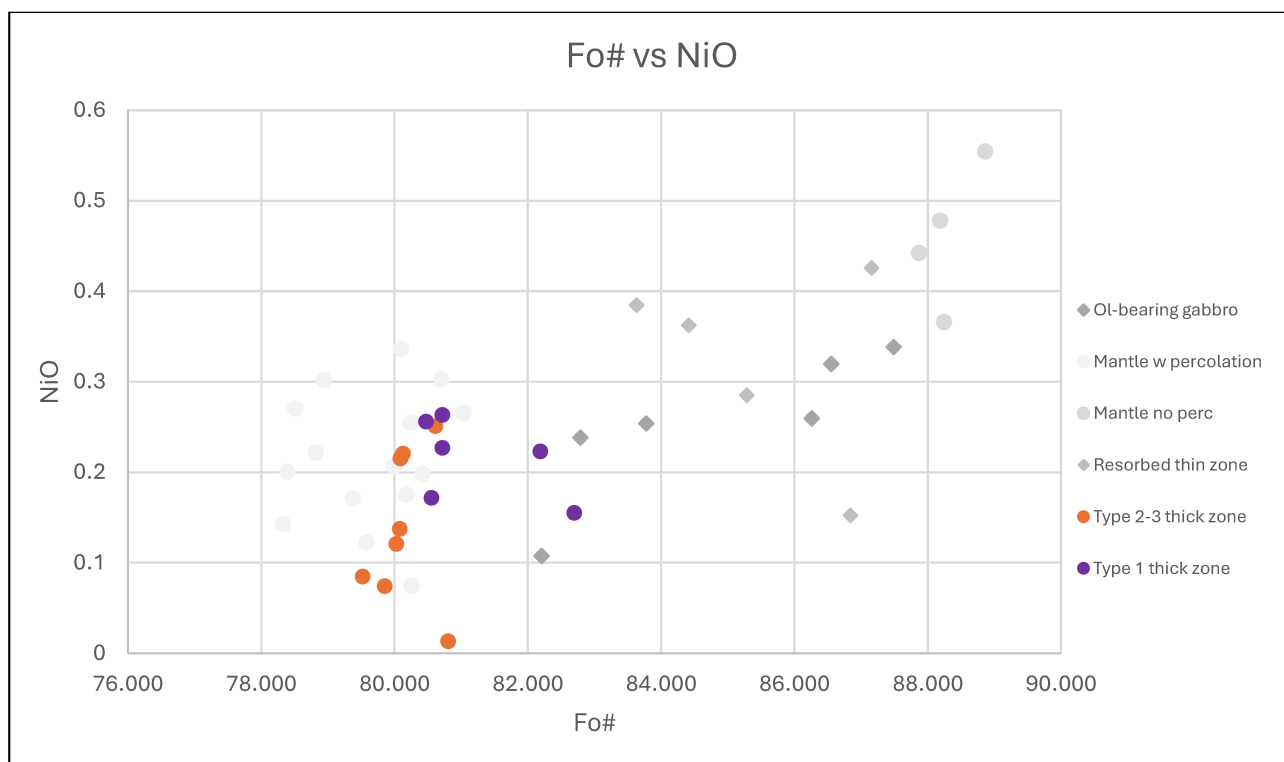


Diagram 34. Olivine Fo# vs NiO composition in thick troctolites 1 and 2-3.

In this progressive hybridization scenario, olivine in olivine-rich troctolites and in troctolites occurs with different textures and compositions which reflect the various stage of hybridization of the

samples. In the case of troctolite 2-3, where olivine is rounded to subrounded and enclosed as chadacrysts in clinopyroxene oikocrysts, Fo# is lower than 81 (Diagram 34, orange points). Within thick troctolite zone type 1, olivine is slightly enriched in Fo# compared with troctolite 2-3 (Diagram 34, purple points 80.5-82.5), but both are Fo#-poor with respect to mantle olivine along not percolated contacts, which reaches 88-89.

We argue that the olivines from thick (olivine-rich) troctolite zones did not crystallize from the percolating melt, but they partially represent the pre-existing solid matrix the was partially dissolved and after re-equilibrated during reactive percolation process. In such case, olivine recrystallizes from the percolating melt during dissolution-recrystallization process and, especially in troctolite 2-3, it is close to Mg-Fe equilibrium with clinopyroxene crystallized as late phase (*Basch et al., 2025*). As a matter of fact, Diagram 33 displays how clinopyroxene from thick troctolite 2-3 is not high-Mg# (light blue points), with troctolite 1 clinopyroxenes lying in the high-Mg#. Such cases are representative of efficiently re-equilibration of olivine with the percolating melt during continuous melt migration, explaining such low Fo# (*Basch et al., 2025*), especially in troctolite 2-3.

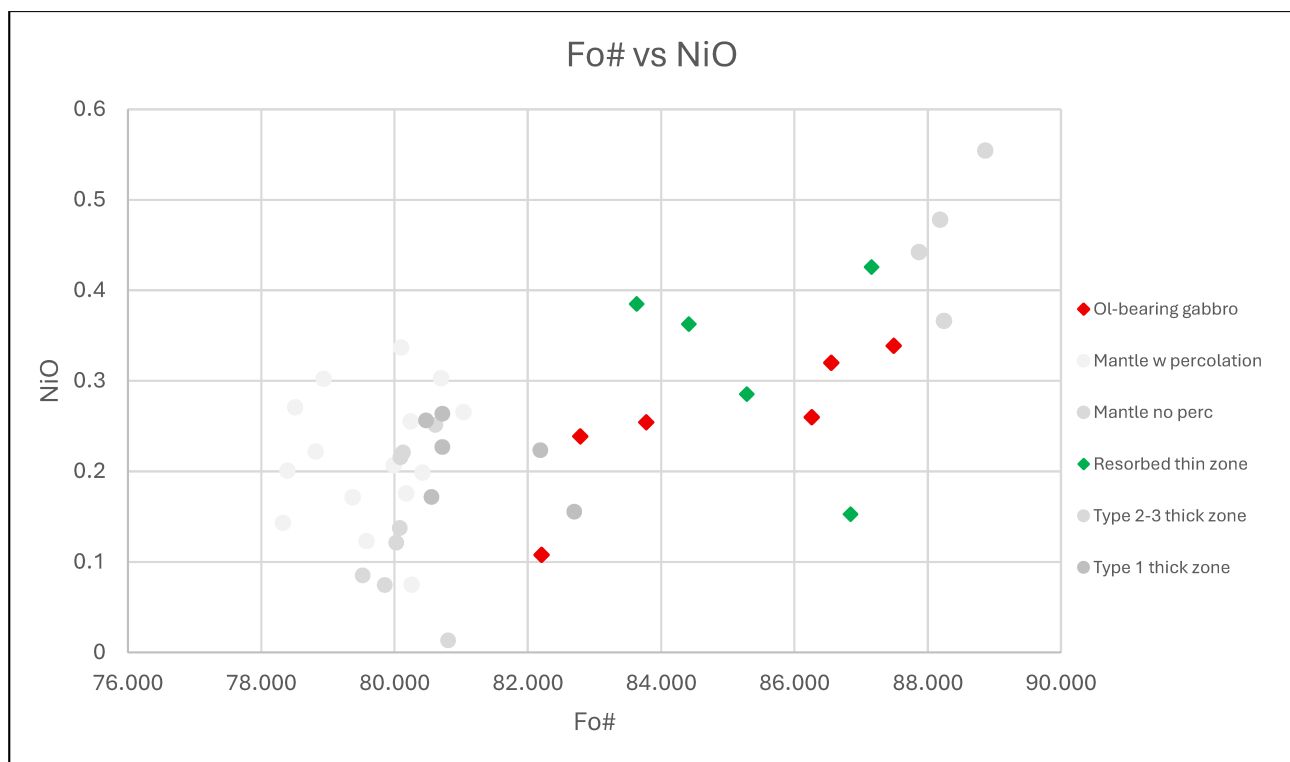


Diagram 35. Olivine Fo# vs NiO composition in thin troctolite and in olivine-bearing gabbro contact.

These features are not observed in thin olivine-rich troctolite and along olivine-bearing gabbro contacts, where olivine shows resorption texture. In thin troctolite, Fo# is always higher than 83.5 and reaches up to 87.5, which is close to olivine Fo# in harzburgite (88-89). Olivine-bearing gabbro

ranges from 82 to 87.5, although, as shown in Fig. 61, the closest to the mantle, the highest Fo# and NiO. In this case, no efficient re-equilibration of olivine is carried out by the melt. On the contrary, as Diagram 11 displays, these two lithologies contain high-Mg# clinopyroxene, which is likely representative of melt re-equilibration caused by the interaction with a matrix-rich host rock.

The last case is that corresponding to percolation into the mantle rock. Thin veinlets of plagioclase and mostly clinopyroxene cross a dunitic mantle portion (Fig.62-63). It is remarkable that olivine Fo# in such dunite is extremely low for mantle olivine, since it ranges from 78 to 81 (Diagram 35).

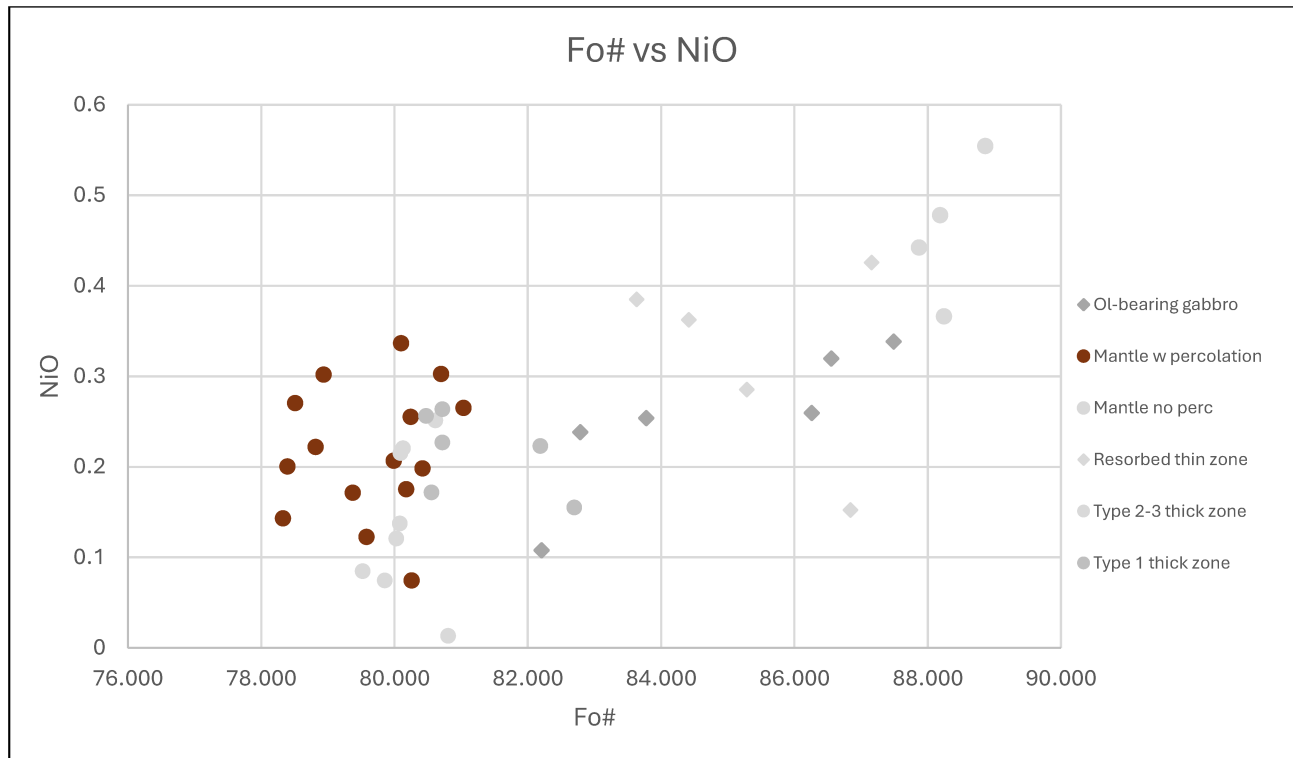


Diagram 36. Olivine composition in percolated dunite.

According to *Sanfilippo et al. (2015)*, the migration of the primitive melts in the upwelling mantle enhances the dissolution of the mantle orthopyroxene and the crystallization of olivine, which at increasing melt/rock ratio causes the formation of replacive dunite channels. When the melts cross the thermal boundary layer, which means its temperature and pressure are decreasing, the migration mechanism changes from channelized to diffuse porous flow with consequent decreases in permeability and melt velocity, conditions that enhance the assimilation of the host. Therefore, following this interpretation, percolated mantle represents the initial stage of the formation of a contact-related lithology. It represents a frozen case in which the mantle-melt migration is already in action, although the assimilation of the host is not occurring yet.

Other two data are consistent with this argument. The first is that, how shown in Diagram 29, there is no substantial difference between the clinopyroxene REE pattern in coarse-grained gabbro and within the associated percolation, since the reacting mantle is REE-poor. In contrast, clinopyroxene in percolation is Mg#-enriched compared with that of coarse-grained gabbro, indicating again mantle-melt reaction as subsequent Mg-enrichment of the melt. Also, *Ferrando et al. (2018)* state that for some elements including Fe-Mg, diffusion rates in olivine are slightly higher than dissolution rates. This may explain why percolated olivine is Fo#-poor, but no active mantle matrix dissolution is taking place.

Summarizing, in low-flux magmatic systems (low melt/rock ratio in time) such as the not re-equilibrated olivine-bearing gabbro and olivine-rich thin troctolite, the geochemical composition of the protolith is almost preserved, and melt composition is buffered by the solid matrix. This means that low-flux melt percolation is not efficient in re-equilibrating the reacting matrix with the incoming melt, but rather the contrary (*Basch et al. 2025*), as observed in thin troctolite and olivine-bearing gabbro. On the contrary, high-flux reactive melt percolation (high melt/rock ratio in time) that most likely generates the (olivine-rich) thick troctolites, leads to chemical re-equilibration of the olivine matrix, as shown by thick troctolite compositions. This is possible due to the high quantity of melt percolating that is limitedly controlled by matrix composition during the reaction. This in turn implies that only melts involved in low-flux magmatic systems can drive significant modification of the tholeiitic melts during their upwards reactive percolation, since the precursor olivine composition at decreasing modal olivine is not compatible with re-equilibration during high-flux melt percolation (*Basch et al. 2025*).

6.3.2 MANTLE-MELT REACTION

The strong textural and compositional variability observed in this study is therefore explained by the occurrence of different stages of melt-rock reaction. These reactions occur when chemical disequilibrium between the percolating melt and the olivine matrix produces partial dissolution and re-equilibration of the pre-existing olivine crystals (*Sanfilippo et al. 2015*). The process of assimilation is combined with progressive crystallization of new phases, which changes the composition of the reacting melt and of the olivine matrix. This mantle-melt interaction progressively decreases olivine modal contents and may account for an increase in MgO and Ni contents of the migrating melt (*Ferrando et al., 2018*), which is consistent with the compositions observed in not re-equilibrated low melt/rock ratio melts.

According to *Ferrando et al. (2018)*, crystallization of clinopyroxene and plagioclase is generally thought to be preceded by formation of dunites with abundant crystallization of new crystals of olivine. The most used model to reproduce chemical and modal variations in this context is the Assimilation-Fractional Crystallization (AFC) of *De Paolo, (1981)*. This model is not accurate in reproducing REE patterns, suggesting that mineral-melt exchange is not the only control on olivine-troctolite and melt compositions in a reactive system like this. These trends may be controlled also by element transport by migrating melts, which can play an important role in the re-distribution of the most incompatible elements (*Navon & Stolper, 1987*). To describe mantle-melt reaction and the behavior of the major phases and their major element compositions AFC is a reliable model.

The reaction process is triggered by a melt percolating in an olivine-rich porous matrix which controls element transport through the crystals. *Ferrando et al. (2018)* suggest that the impregnated harzburgites intruded by the magmatic veins preserve the first stages of melt impregnation in the mantle (dunitization) prior to the extensive melt percolation that formed olivine-troctolites.

Dunitization caused by percolation is the first stage of the process and produces the dissolution of orthopyroxene in the residual harzburgite, causing olivine precipitation and melt composition first change and saturates in SiO₂ (*Sanfilipo et al., 2015; Ferrando et al., 2018*). At this stage, percolated mantle-gabbro contact occurs.

A second reaction stage occurs when olivine assimilation begins. The combination of SiO₂ saturation and olivine assimilation causes progressive crystallization of olivine, followed by plagioclase and clinopyroxene. Residual olivine tends to equilibrium with the melt if the melt is sufficiently abundant, on the contrary, melt assimilates olivine and its MgO contents strongly increases.

Therefore, at this stage, low melt/rock ratio over time is insufficient to promote re-equilibration of the olivine matrix, which consequently displays high Fo#, as observed in thin troctolite and olivine-bearing gabbro. In contrast, high melt/rock ratio re-equilibrates olivine relicts and induces the precipitation of new olivine characterized by lower Fo# values than those of the assimilated olivine. Higher degrees of olivine assimilation are associated with lower olivine Fo# values. This trend is consistent with the lower Fo# values observed in olivine texture type 2-3 compared with texture type 1, which represent textures respectively more in equilibrium and disequilibrium with the melt (Diagram 34).

Fig. 74 from *Ferrando et al. (2018)* represents this reaction processes in different stages (note: rock and melt names are not consistent with the names used in this Thesis, therefore the figure is only meant to allow direct visualization of the reaction process without any name correlation). Stage a) represents the appearance of mantle residual harzburgite prior to melt percolation. Stage b): inputs of

MORB melts cause orthopyroxene dissolution and new olivine crystallization, increasing silica in the melt. Orthopyroxene-poor have therefore the lowest permeability. Stage c) and d): silica-rich melt is in disequilibrium with the olivine matrix, and olivine tend to be partially dissolved and assimilated. This reaction produces the formation of local olivine-troctolite. Zones with lower orthopyroxene record less olivine dissolution and minor crystallization of high-Mg# clinopyroxene. Then, olivine re-equilibrates with a progressively evolved melt by crystallization of interstitial phase generating the olivine-troctolite. Stage e): relatively more evolved melts crystallize in crosscutting gabbroic veins that buffer the composition of pre-existing olivine-troctolite forming thick troctolite contact.

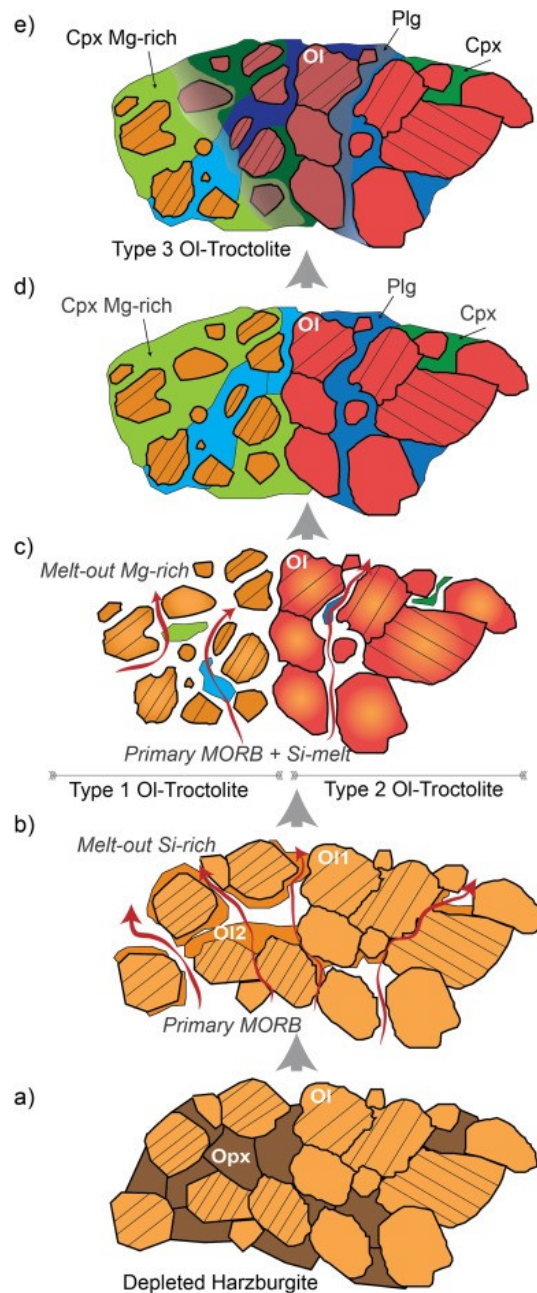


Fig. 74, from Ferrando et al. (2018).

The extent of melt-rock interactions is therefore locally controlled by the orthopyroxene distribution in the harzburgitic protolith (*Ferrando et al., 2018*). These mantle-melt interactions lead to modification of mineral compositions and create hybrid rock type, related to open-system melt impregnation of an olivine crystal framework (*Lissenberg & Dick, 2008; Rampone et al., 2016*).

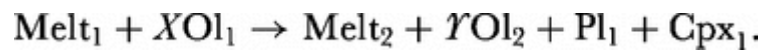


Fig. 75 from *Sanfilippo et al. (2015)*. Mantle-melt reaction that leads to olivine-rich troctolites.

7. CONCLUSIONS

Objects of this study are samples from Hole U1601C, Atlantis Massif, Mid-Atlantic Ridge. In detail, we focused on serpentinized mantle rocks crosscut by gabbroic intrusions. The contacts between the serpentinized mantle and these gabbroic intrusions display strong lithological and compositional variability, which allow us to distinguish different contact-related lithologies: gabbro percolation in the mantle, olivine-bearing gabbro, thin olivine-rich troctolite, and thick olivine-rich troctolite.

All lithologies are not the product of typical fractional crystallization processes, but rather are produced by melt-rock reactions when the magma was injected within the mantle. This process is supported by: *textural evidence*: olivine in the contact-related lithologies shows clear disequilibrium textures with respect to MORB melt-derived plagioclase and clinopyroxene; and *chemical evidence*: presence of high-Mg# and high-Cr₂O₃ clinopyroxene, similar core-rim REE patterns in clinopyroxene, and sulphide enrichment cannot be explained by fractional crystallization alone.

Moreover, the geochemistry of these lithologies is strongly governed by the melt/rock ratio during the reaction. Lower melt/rock ratios result in a stronger modification of the melt through interaction with the mantle, leading to higher Mg, Ni, Cr, elements typically hosted in mantle peridotites. These chemical features are evident in the thin contact-related troctolites and olivine-bearing gabbros. On the contrary, high melt/rock ratios are reflected by lower Fo# in olivine, as observed in thicker contact-related troctolites.

Hence, the injection of the magmas occurred in two major stages that produced the difference in texture and chemistry of the samples. The first phase involves the dunitization of the residual mantle harzburgite, as evidenced in mantle-percolated contacts. The second stage is represented by the crystallization of plagioclase and clinopyroxene, whose compositions depend on the melt/ratio. Overall, the principal factors controlling the lithology, texture, and composition of the contact-related rocks are the compositions of the mantle and melt, the melt/rock ratio, and the extent of mantle-melt reaction occurring at the lithological contact.

Finally, mantle-melt reaction envisaged here produced hybrid lithologies that were enriched in elements not commonly abundant in typical oceanic gabbros, such as sulfur. The presence of sulphide phases within fractionally crystallized gabbro intrusion is extremely rare. Isolated sulphides are only present along coarse-grained gabbro contact, and rare from the central part of the intrusion where they are represented by pyrrhotite too small to be scrutinized in detail at EPMA.

The presence of several sulphide phases, hundreds of microns in size, within the contact-related lithology provides strong evidence that the S budget of the section is entirely dominated by mantle-

melt reaction. Importantly, such reaction controls sulphur saturation in the melt and the availability of chalcophile elements that constitute sulphide aggregates.

To conclude, this study highlights that contact-related lithologies should not be regarded as purely magmatic rocks. Instead, they represent hybrid products of processes occurring specifically at the interface between the two lithologies, which may concentrate elements of critical importance.

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