

MELT-ROCK INTERACTIONS IN THE OCEANIC LITHOSPHERE: MICROSTRUCTURAL AND PETRO-GEOCHEMICAL CONSTRAINTS FROM OPHIOLITES

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INTRODUCTION: IMPORTANCE OF MELT-ROCK INTERACTIONS IN THE OCEANIC LITHOSPHERE

Melt-rock interactions have been increasingly invoked as key processes in the formation of extensive small-scale structural and geochemical heterogeneities within the percolated mantle peridotites at different depths (e.g., Dijkstra *et al.*, 2003; Lissenberg & Dick, 2008; Collier & Kelemen, 2010; Higgie & Tommasi, 2012; Tursack & Liang, 2012; Saper & Liang, 2014; Dygert *et al.*, 2016; Sanfilippo *et al.*, 2017). It has also been demonstrated that they are strongly involved in the formation and compositional evolution of the oceanic crust, from separate lines of evidence: 1) dissolution-precipitation microstructures and geochemical zoning reported in lower crustal gabbros (Lissenberg & Dick, 2008; Lissenberg *et al.*, 2013; Lissenberg & MacLeod, 2017; Ferrando *et al.*, 2018); 2) the composition of melt inclusions in lava phenocrysts (Laubier *et al.*, 2014; Coumans *et al.*, 2016); 3) peculiarities in the compositional field of mid-ocean ridge basalts (MORBs), not consistent with a process of fractional crystallization alone (Collier & Kelemen, 2010; Van den Bleeken *et al.*, 2011; Paquet *et al.*, 2016); 4) the structural and geochemical mantle inheritance inferred in olivine-rich troctolites enclosed in the lowermost oceanic crust. These olivine-rich gabbroic rocks are thought to represent the replacive product of the interaction between a dunitic matrix and a percolating tholeiitic melt undersaturated in olivine (Lissenberg & Dick, 2008; Suhr *et al.*, 2008; Drouin *et al.*, 2010; Higgie & Tommasi, 2012; Sanfilippo & Tribuzio, 2013; Sanfilippo *et al.*, 2013, 2016; Rampone *et al.*, 2016; Basch *et al.*, 2018; Ferrando *et al.*, 2018). The latter studies thus describe melt-rock interactions as a rock-forming process, leading to the incorporation of mantle slivers into the lower oceanic crust and formation of olivine-rich lithologies after multiple episodes of melt-rock interaction (Drouin *et al.*, 2010; Sanfilippo & Tribuzio, 2013; Basch *et al.*, 2018). However, during the dissolution-precipitation reaction, the texture of the olivine matrix progressively evolves towards a cumulate-like poikilitic texture of the olivine-rich gabbroic rock (Suhr *et al.*, 2008; Drouin *et al.*, 2010; Ferrando *et al.*, 2018; Basch *et al.*, 2018), thus calling for the need of strong structural and geochemical constraints to discriminate between a magmatic and a replacive origin of the lithotype.

The study presented in this thesis aims at constraining the structural and geochemical variations caused by melt-rock interaction processes. These reactions intensively occur at oceanic peridotite/gabbro transition settings and lead to the formation of replacive lithotypes (plagioclase-bearing dunites, troctolites and olivine gabbros). These processes are often described in oceanic settings (Mid-Atlantic Ridge, Southwest Indian Ridge, East Pacific Rise), where clear field associations from the mantle protolith to the end-product of the reaction are lacking, thus not allowing the direct observation of the evolution related to melt-rock interaction processes. This work has been developed through investigations on three ophiolitic case studies, fossil analogues of the oceanic lithosphere, preserving the primary association between mantle peridotites and gabbroic rocks: *i*) the Monte Maggiore peridotites and associated dunites and troctolites, in the Alpine Corsica (France; Fig. 1a), *ii*) the Erro Tobbio impregnated peridotites and associated troctolites and olivine gabbros, in the Ligurian Alps (Italy; Fig. 1a), and *iii*) the Maqsad massif Moho Transition Zone, in the Oman ophiolites (Fig. 1b). In all these ophiolites, previous studies documented a multi-stage melt-rock interaction history. In this study, we have used a multi-disciplinary and combined field, structural (EBSD analyses) and geochemical approach (mineral major and trace element analyses) to define the replacive *vs.* magmatic origin of the gabbroic lithologies and the correlation between the structural and geochemical variations induced by melt-rock interaction processes in a field-controlled petrological setting.

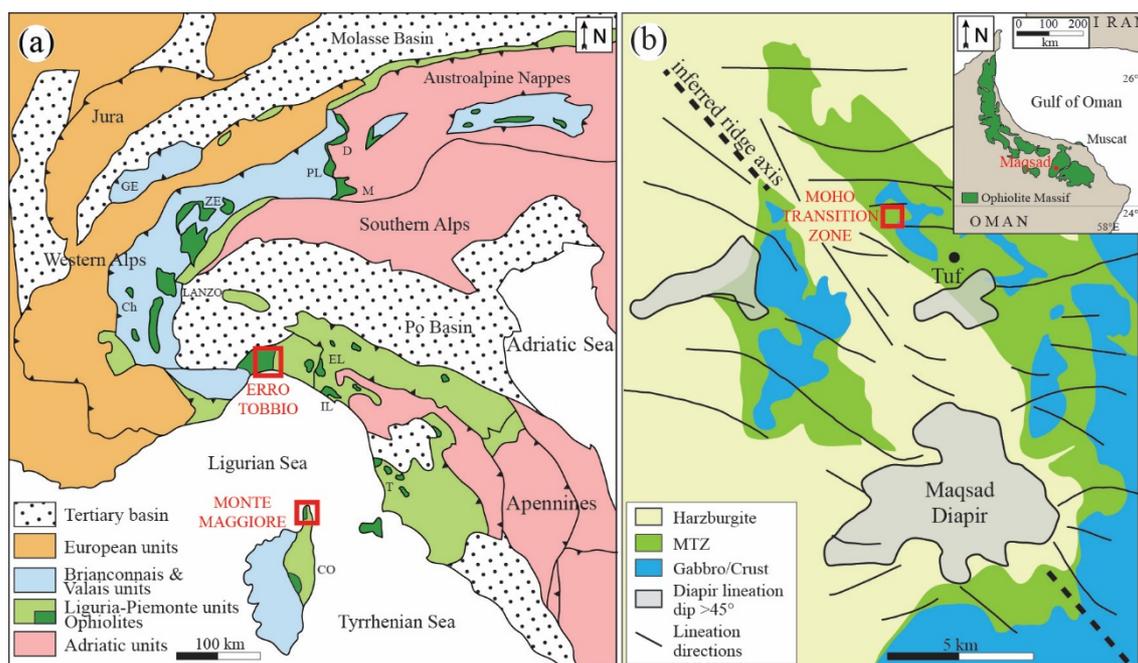


Fig. 1 - Structural context and maps of the three case studies. a): Sketch representing the structural unit forming the Northern Apennines and Western Alps; b): lithological map and location of the Maqсад diapiric structure. The three studied areas are indicated by a red square.

FROM MANTLE PERIDOTITES TO HYBRID TROCTOLITES (MONTE MAGGIORE PERIDOTITES, CORSICA, FRANCE): TEXTURAL AND CHEMICAL EVOLUTION DURING MELT-ROCK INTERACTION HISTORY

The Mt. Maggiore peridotitic body (Alpine Corsica, France) displays a clear evolution from spinel lherzolite to plagioclase-bearing lithotypes (plagioclase peridotites, olivine-rich troctolites and troctolites) (Rampone *et al.*, 1997, 2008; Müntener & Piccardo, 2003; Piccardo & Guarnieri, 2010; Basch *et al.*, 2018) during two continuous episodes of melt-rock interaction (Fig. 2). At spinel facies, the reactive melt percolation of LREE-depleted melts, likely produced by fractional melting of the underlying asthenosphere mantle, leads to the crystallization and growth of olivine and dissolution of mantle ortho- and clinopyroxenes, until the formation of spinel-bearing replacive dunites in the most reacted peridotites (Fig. 2a). As a result, metre-size dunitic lenses, composed of irregular coarse grains of olivine, are enclosed in olivine-rich reacted spinel harzburgites (Rampone *et al.*, 1997, 2008; Müntener & Piccardo, 2003; Piccardo & Guarnieri, 2010). The progressive evolution from spinel lherzolite to olivine-rich harzburgite to replacive dunite is accompanied by a change of olivine Crystallographic Preferred Orientation (CPO), from axial- $[100]$ in the lherzolite, consistent with high-temperature low-strain dislocation creep, commonly described in mantle peridotites worldwide (Tommasi *et al.*, 2000), to axial- $[010]$ olivine CPO in the most reacted harzburgite and spinel dunites, indicative of deformation in presence of melt (Le Roux *et al.*, 2008). The initial percolating melt composition is consistent with unaggregated melt increments after 6% partial melting of a depleted mantle source (Rampone *et al.*, 1997, 2008). The reactive melt percolation leads to a progressive enrichment in the melt HREE absolute concentrations, while preserving its LREE depletion (REE modelling using the Plate Model after Vernières *et al.*, 1997), consistent with the enriched analyzed HREE composition of olivine in the spinel dunite (Basch *et al.*, 2018).

At shallower plagioclase facies, the melts modified after reactive melt percolation (LREE-depleted, HREE-enriched) impregnate the spinel-facies lithotypes, leading to the crystallization of plagioclase and orthopyroxene (\pm clinopyroxene) and dissolution of olivine in the peridotites (Rampone *et al.*, 1997, 2008;

Piccardo & Guarnieri, 2010; Basch *et al.*, 2018). The impregnation stage is also observed in the associated spinel dunites and leads to the replacive formation of olivine-rich troctolites and troctolites, after crystallization of interstitial plagioclase and dissolution of the olivine matrix (Fig. 2b). The dissolution-precipitation reaction forming the replacive troctolite develops progressive textural variations well correlated with the modal content in olivine (progressively decreasing during reaction). As inferred from previous investigations of replacive olivine-rich troctolites in oceanic settings (Suhr *et al.*, 2008; Drouin *et al.*, 2010), the irregular coarse olivines from the dunite protolith are corroded and progressively disrupted by the plagioclase-crystallizing reactive melt, to form textures characterized by numerous rounded olivines embayed in poikilitic plagioclase. Therefore, during progressive impregnation, the increase in grain number is correlated with a decrease in grain area, aspect ratio, shape factor and PARIS factor of the olivine grains. The textural evolution during impregnation is not accompanied by clear variations in the olivine CPO, indicative of very low instantaneous melt/rock ratios during the impregnation process. Olivine, plagioclase and clinopyroxene REE compositions analyzed in the troctolite fit a process of impregnation with a progressive closure of the porosity (at decreasing melt mass), leading to the reactive crystallization of trapped melt and REE enrichments during the last crystallization increments (Plate Model; Vernières *et al.*, 1997; Basch *et al.*, 2018). The crystallization of small trapped melt fractions is consistent with the low instantaneous melt/rock ratio suggested by the preserved protolith olivine CPO during the impregnation process.

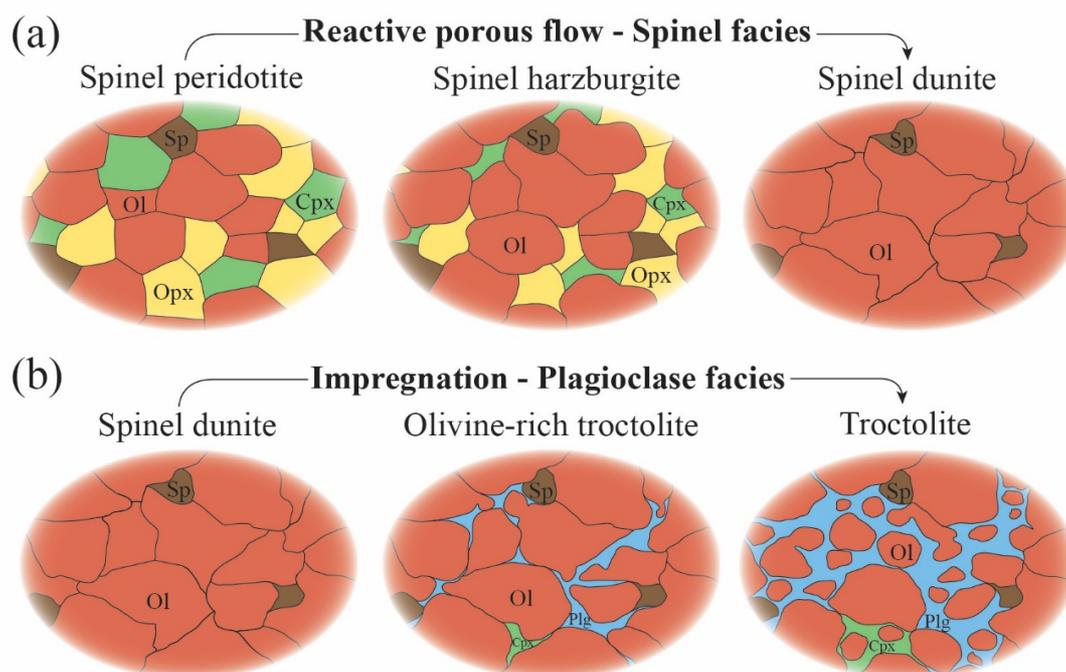


Fig. 2 - Textural evolution observed during a): spinel-facies reactive porous flow leading to the replacive formation of dunites (dissolution of mantle pyroxenes and crystallization of olivine); b): plagioclase-facies impregnation leading to the replacive formation of troctolites (dissolution of olivine and crystallization of plagioclase \pm clinopyroxene), modified after Basch *et al.* (2018).

MULTI-STAGE FORMATION OF A TROCTOLITIC BODY (ERRO-TOBBIO, LIGURIAN ALPS, ITALY): STRUCTURAL CONSTRAINTS AND GEOCHEMICAL MODELING

The Erro-Tobbio impregnated mantle peridotites are primarily associated to a hectometre-size troctolitic body and crosscutting gabbroic dikes, providing a good field control on melt-rock interaction processes and

subsequent intrusions, and constraints from both mantle and magmatic end-member. The troctolitic body exhibits high inner complexity, with a host troctolite (Troctolite A) crosscut by a second generation of troctolitic metre-size bodies (Troctolite B) (Borghini *et al.*, 2007; Rampone & Borghini, 2008; Rampone *et al.*, 2016). The host Troctolite A is characterized by two different textural types of olivine, between corroded deformed millimetre- to centimetre-size olivine and fine-grained rounded undeformed olivine, both embedded in interstitial to poikilitic plagioclase and clinopyroxene. It includes centimetre- to decimetre-size dunitic pods, surrounded by plagioclase enrichments. The Troctolite A shows melt-rock reaction microstructures indicative of formation after impregnation of dunites by an olivine-undersaturated melt (olivine being corroded by interstitial plagioclase). The textural evolution during impregnation is accompanied with a clear change of the olivine CPO, from dunitic areas bearing interstitial plagioclase preserving an axial- $[100]$ pattern, similar to the CPO analyzed in the country peridotites, to disaggregated olivine matrix embedded in poikilitic plagioclase showing a scattered orientation of the $[100]$ and $[010]$ axes of olivine and increased $[001]$ concentration (Fig. 3), indicative of the loss of cohesion of the solid matrix during impregnation at high melt/rock ratios ($> 20\text{-}40\%$; Rosenberg & Handy, 2005; Drouin *et al.*, 2010).

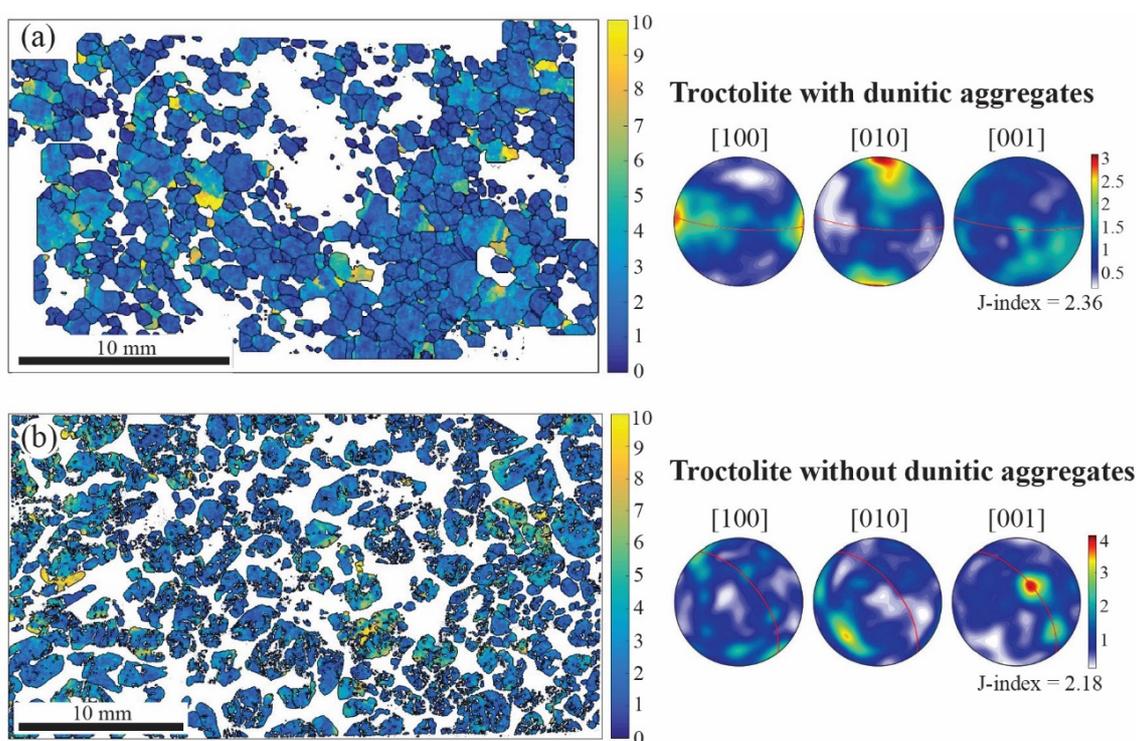


Fig. 3 - Olivine misorientation maps (left column) and CPO (right column) of Erro-Tobbio replacive troctolites. a): Troctolite sample bearing dunitic aggregates; 66 vol% olivine; b): troctolite sample without dunitic aggregates; 68 vol% olivine. One-point-per-grain equal-area, lower hemisphere stereographic projections. The colour bar is scaled to the maximum concentration of the three crystallographic axes. The foliation is indicated by the red line in oriented samples. *J-index* refers to the fabric strength.

The Troctolite A shows reactive mineral compositional trends of evolution, characterized by variable Anorthite compositions in plagioclase at constant Forsterite in the olivine matrix, indicative of the buffering of the melt composition by the assimilation of olivine during impregnation (modelling performed using the *pMELTS* thermodynamic software; Ghiorso *et al.*, 2002). The Troctolite B pseudo-tabular bodies correspond to intrusions within the pre-existing Troctolite A, showing olivine CPO indicative of a formation by magmatic flow (shape-related orientation of the crystals; Benn & Allard, 1989; Joussetin *et al.*, 2012). They are characterized by

extreme textural variations from decimetre-size dendritic to fine-grained euhedral olivines, embedded in poikilitic plagioclase. This textural variability is the result of olivine assimilation during melt-rock reaction and the related increase in the degree of undercooling of the percolating melt (increase of the melt liquidus temperature up to 65°C during olivine assimilation). Mineral compositions within the Troctolite B are similar to the ones analyzed in the Troctolite A and indicate that olivine-dissolving melt-rock interactions were still involved in the focused melt percolation (*pMELTS*; Ghiorso *et al.*, 2002). The late gabbroic intrusions crosscutting the association between mantle peridotites and the troctolitic body show mineral compositional trends of evolution consistent with the fractional crystallization of the melts modified after the olivine-dissolving reactive melt percolation related to the formation of the Troctolite A and Troctolite B (*pMELTS*; Ghiorso *et al.*, 2002). Therefore, the Erro-Tobbio troctolitic body shows a formation history related to a single thermal evolution, from diffuse reactive percolation leading to the replacive formation of the host Troctolite A, to focused reactive percolation and formation of the Troctolite B, to the intrusion and fractional crystallization of the modified melt and formation of the gabbroic dykes.

FORMATION OF REPLACIVE OLIVINE GABBROS IN THE OMAN MOHO TRANSITION ZONE: GEOCHEMICAL EVOLUTION DURING DEFORMATION-DRIVEN DUNITE IMPREGNATION

The Oman Moho Transition Zone (MTZ) is formed of a layering of interfingered dunites (*sensu lato*; >70 vol% modal olivine) and variably evolved olivine gabbros (from 10 to 70 vol% olivine; Boudier & Nicolas, 1995; Higgie & Tommasi, 2012). A recent petrological and structural study by Higgie & Tommasi (2012) demonstrated the replacive origin of the olivine gabbro layers, formed by a deformation-driven focused reactive percolation within the pre-existing dunite, corroding the olivine matrix and crystallizing interstitial clinopyroxene and plagioclase. The progressive evolution of modal compositions (decreasing modal composition of olivine) is accompanied by a change in symmetry of olivine CPO from axial- $[100]$ patterns in the dunite to axial- $[010]$ CPO in the olivine gabbro, observed over a range of olivine modal compositions from 60 to 40 vol%. Higgie & Tommasi (2012) interpreted this olivine CPO evolution as indicative of the higher cumulated strain and melt/rock ratio integrated over time in the olivine gabbro layers. The centimetre-scale at which the structural variations are observed within the dunite-olivine gabbro layering calls for a positive feedback between deformation and melt focusing in the weaker olivine gabbro layers, as previously described in melt-bearing simple shear experiments (Zimmerman *et al.*, 1999). Strong chemical discrepancies are observed between the dunite layers showing compositional trends of evolution indicative of a closed system melt impregnation, with the buffering of the melt composition by the host rock and the olivine-dissolving melt-rock interaction, and the olivine gabbro layers showing compositions dominated by the percolating melt composition (Fig. 4), consistently with the open-system reactive melt percolation previously described by Higgie & Tommasi (2012). We observed a good correlation between the transition from axial- $[100]$ in olivine-rich samples to axial- $[010]$ in more evolved olivine gabbros, and the geochemical transition from closed system (matrix-dominated) to open system (melt-dominated) mineral compositions (Fig. 4).

CONSTRAINTS ON MELT-ROCK INTERACTION PROCESSES

The results of this PhD thesis demonstrate the possible replacive origin of gabbroic rocks in field-controlled ophiolitic settings, and provide a textural, structural and geochemical methodology to constrain melt-rock interaction processes and the magmatic *vs.* replacive origin of an olivine-rich gabbroic rock. The three case studies highlight a significant control of instantaneous and cumulated melt/rock ratios, together with the percolation style on both the structural and the geochemical preservation/evolution during melt-rock interaction processes. Major variations are observed in closed systems, dominated by the melt-rock interaction processes, whereas open systems, characterized by high melt/rock ratios integrated over time, show a complete reequilibration of the mineral compositions with the percolating melt. The combination of structural and

geochemical analyses allows a detailed understanding of the melt-rock interaction processes, from large to small scale, and the related structural and geochemical evolution of the pre-existing mantle matrix and percolating melt.

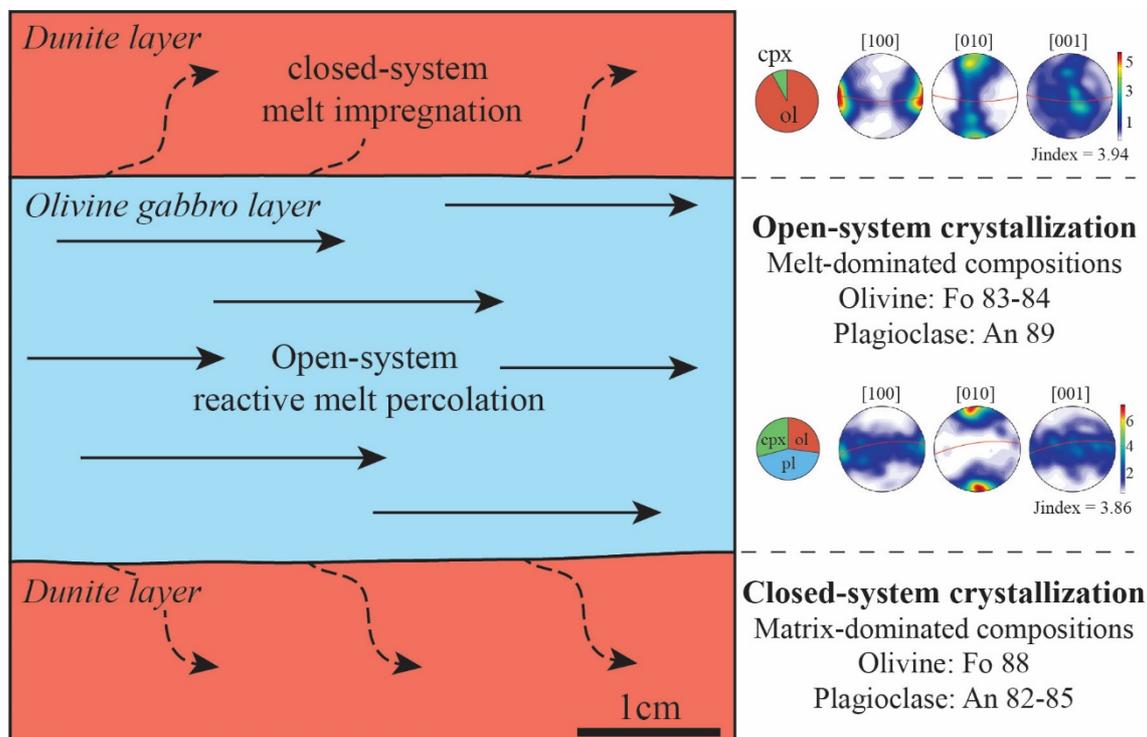


Fig. 4 - Sketch of the correlation between percolation style and structural and geochemical changes between dunitic and olivine gabbro layers. One-point-per-grain equal-area, lower hemisphere stereographic projections. The colour bar is scaled to the maximum concentration of the three crystallographic axes. The foliation is indicated by the red line in oriented samples. *J*-index refers to the fabric strength.

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