Diffusive reactive percolation and impregnation processes in the Oman peridotites

A multidisciplinary and multiscale investigation

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INTRODUCTION

The Oman ophiolite exposes one of the best preserved and complete section of oceanic lithosphere worldwide. The ophiolite sequence is made up of several massifs, each exposing a complete stratigraphic sequence, offering the opportunity to study the genesis and structure of the lithosphere formed beneath a fast-spreading oceanic ridge (Nicolas & Boudier, 2015) as well as the processes that characterize the supra-subduction lithosphere (Agard et al., 2016; Ambrose et al., 2018). Despite its importance, the large-scale tectonic settings in which the Oman ophiolite formed, and its geodynamic evolution are still matter of debate. Only few studies have been centered on the evolution of the uppermost lithospheric mantle with no detailed petro-chemical work available to date. This study aims at constraining the magmatic processes (*i.e.*, pervasive reactive porous melt flow and shallow melt impregnation) which contributed to shape and modify the Oman lithospheric mantle during its accretion into the lithosphere and evolution within the oceanic environment. Investigations were conducted on the Wadi Tayin massif, located in the southern part of the ophiolite, where the magmatic features related to the oceanic accretion of the lithosphere in a ridge environment are best preserved and least overprinted by subduction related processes.

METHODS

I used a multidisciplinary methodology including field work and new sampling, detailed microstructural investigations, minerals *in situ* major and trace elements analyses, and geochemical modelling. This analytical procedure addresses the studied mantle rocks from petrographic, structural, thermometric, and geochemical perspectives, and allow *i*) the understanding of the petrological processes that affected the residual mantle after its partial melting history, and *ii*) the definition of the mantle petro-structural evolution within the complex and discussed geodynamic framework of the Oman ophiolite.

The field work was performed within the Wadi Tayin massif, in the northern part of the Wadi Zeeb and Wadi Nassif rivers where the ophiolite crust-mantle transition and the upper mantle section are best exposed. Representative rock samples were collected during two field campaigns (January 2020 and February 2024) along the Wadi Nassif and during the core logging procedures, aboard of the Chikyu vessel in 2018, after the drilling of the CM1A and CM2B boreholes (CM Sites), in the Wadi Zeeb, during the Oman Drilling Project (Kelemen et al., 2020; *https://omandrilling.ac.uk*). The crust-mantle contact in the Wadi Zeeb and Wadi Nassif dips southwards at constant inclination of 30°. I considered the true depth that of the samples collected from the CM1A relative to the crust-mantle boundary. Consequently, I estimated the other sample depths in function of the local strike and dip of the crust-mantle boundary, together with their distance from it.

The entire sample set consists of spinel harzburgites and spinel pyroxenites (ranging from websterite to orthopyroxenite in composition), plagioclase-bearing impregnated harzburgites and impregnated dunites. Thin sections were prepared normal to the foliation and/or layering and parallel to the mineralogical lineation. When no layering, foliation, or lineation was observed, samples were oriented relative to the general orientation of the foliation and/or layering measured on the field. Sample sections were prepared at the "Rocks and Minerals" laboratory of DISTAV - University of Genova, both as 30 µm- and 100 µm-thick polished sections. The former allowing for petrographic investigations, the latter for both microstructural and geochemical analyses on the same section. A petrographic study of all studied samples was first realized to describe textural variability and relationships between minerals, and their degree of alteration. The most preserved and representative samples were thus selected for *in situ* major element analyses by the Electron Probe Micro-Analyzer (EMPA), microstructural detailed investigations with the Electron Back Scattered Diffraction (EBSD) technique, and *in situ* trace element analyses performed with the Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry.

In situ minerals major elements compositions were determined using the Electron Probe Micro-Analyzer (EPMA) at the Department of Earth Sciences "Ardito Desio", University of Milano. Minerals point analyses were performed by JEOL JXA 8200 Super probe equipped with five wavelength-dispersive (WDS) spectrometers and an energy dispersive (EDS) spectrometer. The analyses of all elements were performed with a 30-seconds counting time. Additionally, EDS maps were carried out for petrographic purposes. Minerals areal analyses were realized using the TESCAN Vega-3 electron microscope, equipped with an energy-dispersive detector (EDS), at the University of Genova – DISTAV.

Microstructural analyses were realized by the Electron Back-Scattered Diffraction (EBSD) technique. In those samples showing a clear mantle foliation and lineation, EBSD analyses were performed on thin sections cut parallel to the lineation and normal to the foliation, the other samples were analyzed on a plane normal to the weak foliation plane at an unknown angle to the lineation. I used a JEOL JSM 5600 and a Cam scan Crystal Probe X500FE scanning electron microscope equipped with an EBSD Symmetry detector running with, respectively, 17 kV and 20 kV acceleration voltage, both operating at Géosciences Montpellier, University of Montpellier (France). Analyses were performed with a working distance of ~ 25 mm and a step size depending on the alteration and grain size of crystals. The EBSD patterns were processed and indexed in terms of crystal phase and orientation using the Aztec software from Oxford Instruments. Post-acquisition data processing was first realized using the CHANNEL5 software suite and then was performed using the MATLAB MTEX toolbox, version 5.5.2 (Hielscher & Schaeben, 2008; Mainprice et al., 2015).

In situ minerals trace elements compositions were determined by Laser Ablation-Inductively Coupled Plasma Mass Spectrometry at the Hydropolis Centre, University of Montpellier (France). Analyses were performed with a Thermo Scientific Element XR (eXtended Range) high resolution ICP-MS. The ICP-MS was coupled to a laser ablation system consisting of a Geolas Q+ automated platform with a 193 nm Excimer laser Compex 102 from Lambda Physik. Analyses were performed using an in-house modified 30 cm^3 ablation cell with a helium atmosphere to enhance sensitivity and reduce inter-element fractionation (Günther & Heinrich, 1999). Helium gas and ablated sample material were mixed with argon gas before entering the ICP-MS. The laser fluence was set to 4 J cm^{-2} at a frequency of 8 Hz and the beam size was set to 110 μm. NIST 612 and BIR1-G were analyzed as internal standards, and data were processed with the GLITTER software package (Van Achterbergh et al., 2001), using the linear fit to ratio method. Data were filtered for spikes on an element-by-element basis, and the standardization for clinopyroxene and plagioclase was done using ^{43}Ca, whereas that for olivine and orthopyroxene was done using ^{29}Si.

RESULTS

Pervasive reactive porous melt flow

All results presented in this section are from Battifora et al. (2026).

On the field, spinel harzburgites display a weak foliation defined by the shape preferred orientation of slightly elongated orthopyroxene and spinel, comparable with the orientation of mantle foliation in drill-cores (Kelemen et al., 2020). Spinel pyroxenite layers are 1 to 10 cm-thick, dominantly concordant to the harzburgite foliation, and occasionally displaying open folds with axial plane parallel to the harzburgite foliation (Kelemen et al., 2020). Spinel harzburgites exhibit a porphyroclastic texture of olivine (Ol), orthopyroxene (Opx), and minor clinopyroxene (Cpx) and spinel (Spl). Ol was observed both as coarse-grained and deformed porphyroclasts, displaying undulous extinction and well-defined subgrains (Ol_p), and as fine-grained and not deformed crystals with interstitial shape (Ol_i). On the other hand, Opx occurs as coarse-grained and kinked porphyroclasts (Opx_p), partially replaced by granoblastic aggregates composed of undeformed and fine-grained pyroxene crystals (Opx_g and Cpx_g). Notably, Opx_p and Opx_g often show concave/lobate and irregular boundaries at the contact with Ol_i. The same textural features and petrographic relationships were also observed and best visible within spinel pyroxenite layers. Moreover, pyroxenites often display irregular contacts with the host spinel harzburgite, where Ol_i is abundant.

Notably, Ol_p and Ol_i do not show variations of Fo (= [Mg/ (Mg + Fe) x100] mol%) and are in Fe-Mg exchange equilibrium with Opx_p and Opx_g. Mn and Ni contents of Ol_p and Ol_i mostly overlap and are consistent with those of porphyroclastic harzburgite from different Oman massifs from north to south (Takazawa et al., 2003; Monnier et al., 2006; Khedr et al., 2014; Yoshikawa et al., 2015). Nevertheless, Ol_i Mn contents are on average higher than those of Ol_p. Spinel major element chemistry reveals high mantle melting degrees (15 – 17%) consistent with those documented by Godard et al. (2000) and Dygert et al. (2017) for the Oman harzburgites. Different generation of Opx and Cpx do not show variations in their mineral major element compositions, which result consistent with those of spinel harzburgites analyzed from different Oman massifs (e.g. Khedr et al., 2014; Akizawa et al., 2016; Dygert et al., 2017). Because Opx and Cpx are heavily exsolved, areal chemical analyses best reflect the pyroxenes composition pre-exsolution. Equilibrium temperatures were estimated using 2-Px geothermometers (Brey & Köhler, 1990; Taylor, 1998) that yield a general and progressive temperature decrease (1150°C > *T* > 900°C) from the porphyroclastic to the granoblastic pyroxenes association.

Spinel harzburgites are also characterized by variable Ol_i/Ol_{tot} modal ratios (10% to 47%) correlated with the

olivine variable Crystallographic Preferred Orientation (CPO) showing systematic co-variations in intensity and symmetry. This striking correlation allowed the distinction of three main harzburgite groups. High BA-index associated with high J-index indicates orthorhombic CPO with a tendency for axial- [100] in harzburgites with less modal olivine. Intermediate BA-index displays the lowest J-index and denotes olivine CPO with intermediate symmetry, resulting from the coexistence of the two types of olivine (*i.e.*, Ol_p and Ol_i). In the latter samples, Ol_p CPO preserves well-defined orthorhombic symmetry, whereas the Ol_i CPO tends towards an axial-[010] symmetry. By contrast, low BA-index and high J-index are indicative of a progressively well-defined axial- [010] Ol_{tot} symmetry in olivine-rich harzburgites. Differently from olivine, Opx in all samples preserves the same CPO symmetry, coherent with that of Ol_p and consistent with a high-*T* deformation, suggesting that Opx fabrics were not modified by the static granoblastic recrystallization event (Hidas et al., 2007).

Shallow melt impregnation

Impregnated harzburgites and impregnated dunites are constituted by variable modal proportions of newly crystallized and magmatic clinopyroxene (Cpx), plagioclase (Plag), and orthopyroxene (Opx), partially replacing the preexisting porphyroclastic matrix of spinel harzburgite (Ol_p + Opx_p + Spl_p) and dunite (Ol_p + Spl_p). Magmatic Plag and Cpx, within impregnated harzburgites, exhibit interstitial texture. By contrast, in impregnated dunites, Plag, Cpx and Opx occur either as poikilitic grains including rounded Ol_p and Spl_p or as interstitial crystals. In impregnated harzburgites, the total modal amount of magmatic Plag + Px varies from 2 vol.% to 10 vol.%, whereas in impregnated dunites it ranges from 15 vol.% to 34 vol.%. Impregnated harzburgites preserve their high-temperature mantle texture (previously observed in spinel harzburgites), which is marked by variations in olivine CPO symmetry from pure axial- [100] (BA index = 0.88) to intermediate (BA index = 0.35). Such olivine CPO variation is not correlated to the total modal abundance of Plag + Cpx, likely reflecting the CPO heterogeneity in precursor spinel harzburgites. Among impregnated dunites, those with low total modal amounts of Plag + Px exhibit partially dissolved olivine crystals that still preserve their mantle texture with a well-defined olivine CPO symmetry. Conversely, impregnated dunites with high amounts of Plag + Px display disaggregated olivine crystals with isotropic CPO.

In all samples, Ol_p and magmatic pyroxene grains are in Fe-Mg exchange equilibrium. Also, Cpx and Plag show Ca-Na exchange equilibrium. Spl_p Cr# (= [Cr/ (Cr + Al) x100] mol%) is ~ 55 mol% and its TiO_2 content varies from 0.06 wt.% in impregnated harzburgites to 0.74 wt.% in impregnated dunites, indicating a progressive modification by successive melt-rock interaction processes (Seyler et al., 2007; Warren, 2016; Sani et al., 2020). Cpx Mg# (= [Mg/ (Mg + Fe) x100] mol%) varies through samples from 90 mol% to 93 mol%. At constant Mg#, Cpx crystals show significant variation in Na_2O contents, which allows the identification of two main groups. The first group shows Na_2O values ranging from 0.26 wt.% in impregnated dunites to 0.43 wt.% in impregnated harzburgites and is hereafter referred to as 'high Na_2O Cpx'. The second group exhibits lower Na_2O abundances (hereafter 'low Na_2O Cpx') ranging from 0.01 wt.% in impregnated dunites to 0.22 wt.% in impregnated harzburgites. Notably, high Na_2O Cpx is associated with Plag having lower An (= [Ca/ (Ca + Na) x100] mol%) (~ 87 mol%), whereas low Na_2O Cpx coexists with Plag crystals having high An contents (~ 97 mol%). High Na_2O Cpx in impregnated harzburgites and dunites is characterized by almost flat Heavy- (H-) to Middle- (M-) Rare Earth Element (REE) and slightly depleted Light- (L-) REE on C1-normalized trace element patterns, comparable with those of Cpx previously reported in impregnated dunites from the Wadi Tayin Moho Transition Zone (MTZ; Kelemen et al., 1997; Koga et al., 2001; Basch et al., 2025), and partially overlap those of Cpx from most depleted lower crustal gabbros in the same area (Müller et al., 2022). On the other hand, low Na_2O Cpx within both impregnated harzburgites and dunites show strongly depleted L-REE contents and fractionated L- to H-REE and L- to M-REE patterns (C1-normalized). These patterns are subparallel to those of porphyroclastic Cpx analyzed in spinel harzburgites, although at higher absolute concentrations.

In summary, based on microstructures and minerals chemistry we identified two groups of impregnated mantle rocks. Within each group, magmatic Cpx crystallized in impregnated dunites shows the lowest Na_2O values and the most fractionated trace element pattern compared with those in impregnated harzburgites.

DISCUSSION

Pervasive reactive porous melt flow

Data discussed in this section are from Battifora et al. (2026).

The harzburgite porphyroclastic association shows evidence of intracrystalline plastic deformation and records high equilibrium temperatures (up to 1150°C). CPOs of the porphyroclastic association are consistent with those typically documented for high-*T* deformation of the upper mantle at dry conditions (e.g. Ismaïl & Mainprice, 1998; Tommasi et al., 1999). Within spinel harzburgites and pyroxenites, Opx_p are partially replaced by granoblastic aggregates of Opx_g and Cpx_g, which record sub-solidus temperatures (950°C - 1050°C) suggesting a static recrystallization process in response to the progressive cooling during incorporation of the mantle section into the lithosphere. The lobate grain boundaries of Opx_p and Opx_g against the newly formed Ol_i corroborate the inferred process of dissolution of a partially cooled mantle by an olivine-saturated melt as

previously proposed by Basch et al. (2023) and documented in the Wadi Tayin mantle overall (e.g. Kelemen et al., 1995; Godard et al., 1995, 2000; Hanghoj et al., 2010; Kourim et al., 2022). Ol_i is interstitial, rims orthopyroxene grains, and presents an axial- [010] CPO, different from that of the residual Ol_p, which displays orthorhombic CPO. Notably, Ol_i crystals are fine-grained, indicating that nucleation was more efficient than crystal growth during their crystallization. Their formation most likely occurs in a low-temperature system in which nucleation is the dominant crystallization mechanism, suggesting that Ol_i crystallization occurred in a cooling environment, most likely within the Thermal Boundary Layer (TBL), hot enough to allow for pervasive melt percolation and melt-rock reaction. Moreover, the transition of the bulk olivine CPO from orthorhombic to axial-[010] is correlated to an increase of modal proportion of Ol_i indicates a process of deformation in the presence of melt and reflects the increasing melt/rock ratio integrated over time. Fe-Mg partitioning between the residual harzburgite minerals and the interstitial olivine indicates chemical equilibrium. However, variations in Mn contents among olivine support the reactive origin of Ol_i crystals.

Shallow melt impregnation

Studied impregnation structures consist of various proportions of interstitial Plag, Cpx, and Opx in a dunitic or harzburgitic host rock, forming impregnated dunites and harzburgites, respectively. The interstitial texture of Plag and Px, as well as high TiO_2 contents in spinel of impregnated dunites and harzburgites, indicate subsequent melt/rock interaction of dunites and harzburgites, and the crystallization of Plag and Px from a melt during impregnation of the host residual mantle. The crystallization of interstitial Plag and Px at the expense of the porphyroclastic and granoblastic associations of the harzburgitic host rock point towards Plag and Px formation in a previously cooled system. Furthermore, the transition of the bulk olivine CPO from orthorhombic to axial- [010], in impregnated harzburgites, unrelated to the impregnation event, suggests that melt impregnation does not microstructurally affect the pre-existing harzburgitic matrix, and the heterogeneity of olivine CPO was inherited from the previous history of reactive porous melt flow recorded by spinel harzburgites, before melt impregnation, thus definitely placing the impregnation event after the evolution of the lithospheric mantle under spinel-facies conditions.

The general high Mg# in Cpx and An in coexisting Plag highlights a general depleted geochemical signature of all impregnating melts. Nevertheless, the major and trace element compositions of associated Cpx and Plag allowed the distinction of impregnated lithotypes into two groups. The high Na_2O Cpx group shows Cpx geochemistry comparable with Cpx in the most primitive layered gabbro from the Wadi Tayin lower oceanic crust. The low Na_2O Cpx group displays Cpx similar, in terms of L- to M-REE and L- to H-REE fractionations, to porphyroclastic Cpx residual in studied spinel harzburgites, and completely different from those in the Wadi Tayin MTZ and/or oceanic crust. Such geochemical heterogeneity indicates a significant variability of melts migrating in the Wadi Tayin lithospheric mantle, which is not equally represented in the overlying oceanic crust, and is likely a function of different degrees of melt/harzburgite interaction. In this context, impregnated dunites either reflect a melt-dominated system where magmatic Cpx still preserves the geochemical signature of the impregnating melt (*i.e.* high Na_2O Cpx group), or a mantle-dominated system where Cpx presents a geochemical composition influenced and strongly equilibrated with the host refractory mantle rock (*i.e.* low Na_2O Cpx group). Melts formed by these two types of melt/harzburgite interaction processes subsequently percolated throughout the mantle and formed the two types of impregnated harzburgites. Assimilation-fractional crystallization (AFC) models reveal that the crystallization of melts modified during the formation of impregnated dunites can reproduce the chemical heterogeneity of magmatic phases in impregnated harzburgites, through different degrees of melt/rock interactions. Overall, melts forming the impregnated lithologies lack geochemical affinity with Oman V2 lavas that are related to the subduction phase, instead are comparable with the Oman V1 magmatism showing, however, variable trace element depletion signature. This result agrees with the geodynamic record of the southern Oman ophiolites, largely preserving the mid-ocean ridge evolution.

CONCLUSIONS / FINAL REMARKS

The oceanic lithosphere exposed in the Oman ophiolite records a complex history of melt migration and magmatic accretion, involving melts with various geochemical affinities. Reactive porous melt flow and melt-rock interaction are fundamental processes in the evolution of the oceanic lithospheric mantle.

Melt migration through reactive porous flow in the Oman ophiolite has been extensively studied in the context of focused melt flow, leading to the formation of dunite channels and the MTZ. On the other hand, pervasive and reactive melt percolation within the Oman lithospheric mantle remains poorly constrained. Slight differences in olivine minor element compositions are the only marker to chemically infer the occurrence of the reactive melt porous flow in the studied Wadi Tayin mantle portion. The textural and microstructural identification of the pre-existing olivine porphyroclasts Ol_p, different from the newly formed interstitial olivine Ol_i, thus constitutes the fundamental and missing evidence to properly describe pervasive melt percolation and melt-rock interaction of an olivine-saturated melt throughout the lithospheric mantle.

Moreover, several studies focused on documenting the magmatic records in the layered oceanic crust and MTZ of the Oman ophiolite, whereas detailed microstructural and geochemical investigations of melt migration and impregnation features in the Oman upper lithospheric mantle section are still very limited. The trace element compositions of computed melts in equilibrium with Cpx from impregnated lithotypes show variable L-REE depletion. Indeed, some computed melts exhibit very low L-/H-REE, evidencing a significant depletion in highly incompatible trace elements. Impregnating melts characterized by different geochemical signatures (from MORB-types to incompatible elements-depleted) are genetically correlated and their geochemical heterogeneity reflects different extents of melt/rock interaction between MORB-type melts and the host residual mantle, rather than the occurrence of unaggregated melts characterized by primary depletion in incompatible trace elements. This in turn indicates that melt-rock interaction is a powerful tool that can modify the melt geochemical signature, generating highly depleted melts.

Finally, the observed mantle microstructural history points to a magmatic overprinting during the progressive cooling and lithospheric accretion of the Wadi Tayin upper mantle, in turn indicating a mantle high-temperature deformation history partially overprinted by a melt-assisted deformation event. Moreover, deciphering such reactive percolation and impregnation processes will shed light on the latest magmatic events recorded in the Wadi Tayin residual mantle and the role of migrating melts in the geochemical budget of the overlying MTZ and oceanic crust, thus adding an important piece to the complex accretional history of the Oman oceanic lithosphere.

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