The shallow mantle as a reactive filter: a hypothesis inspired and supported by field observations

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The footprints of mafic melts travelling from the depths to the surface are abundant in the mantle section of ophiolites. They constitute an important source of information about the melt migration mechanisms and related petrological processes in the shallowest part of the mantle beneath former oceanic spreading centres. In the field, these so-called 'melt migration structures' attract attention when they consist of mineral assemblages contrasting with that of their host peridotite. They therefore record a particular moment in the migration history: when the melt becomes out of equilibrium with the peridotite and causes a reaction impacting its modal composition, and/or when a temperature drop initiates the crystallization of the melt.

The existence of cryptic effects of migration revealed by geochemical data shows that melts do not always leave a trail visible in the field. Although incomplete and patchy, the melt migration structures preserved in ophiolites are witnesses of processes that do actually occur in nature, which constitutes an invaluable support to the interpretation of geophysical data and inescapable constraints for numerical simulations and models of chemical geodynamics.

Here we show how field observations and related petrological and geochemical studies allow us to propose answers to fundamental questions such as these: At which temperature is porous flow superseded by dyking? What are the factors governing melt trajectories? What is the nature of the 'universal solvent' initiating infiltration melting and making channelized porous flow the most common mode of transport of magmas through a peridotite matrix regardless the tectonic setting?

A fundamental message delivered by ophiolites is that the shallow mantle behaves as a particularly efficient reactive filter between the depths and the surface of the Earth. Unexpectedly, the reactions occurring there are enhanced by the hybridization between mafic melts and a hydrous component, whatever its origin (*i.e.* magmatic vs. hydrothermal). This hybridization triggers out of equilibrium reactions, leading to the formation of exotic lithologies, including metallic ores, and impacting the global geochemical cycle of a whole range of chemical elements.

1. Introduction

"Few questions in geology are more important than that of the capacity of magmas to dissolve the country rocks. (…) Most geologists (…) have either not considered the problem seriously or have refrained from publishing the product of their thought concerning it." Daly (1914, p. 209).

Geologists trust in observations. As much as possible, they anchor their models in field evidence rather than in theoretical speculations. The history of geology is full of examples of paradigm shifts that resulted from the providential finding of key outcrops. The granite veins intrusive in the meta-sedimentary rocks of Glen Tilt, Scotland, brought to light in 1785 by James Hutton, played such a role at the dawn of igneous petrology: it was the field demonstration that granites do issue from molten silicates and are not necessarily the oldest rocks on Earth. As stressed by Charles Lyell (1830, p. 62), "By this important discovery (…) Hutton prepared the way for the greatest innovation on the systems of his predecessors."

Melt transport from the source to the location of solidification, and its impact on the composition of the melt itself, have always been recognized as important issues by igneous petrologists although we are far from a consensus on the topic. Melt migration involves processes initiating at the scale of a few millimeters or less, which is the size of mineral grains in the mantle source rock. It is far below the spatial resolution of current geophysical methods used to probe the inner Earth. To quote Bowen's thought about the obsessive question of the origin of magmas, "Geophysical data help very little. (…). The decision on this point would still depend principally upon geologic considerations" (Bowen, 1928, p. 319).

Geological data alone cannot solve all the issues related to melt migration in the mantle but, at least, can provide evidence of processes that do happen in nature. Here we illustrate with a few examples what has been learned about melt migration and related melt-rock reactions beneath former oceanic spreading ridges through the study of the Oman and Trinity ophiolites. We evoke the potential impact of these observations on the hypotheses subtending chemical geodynamics.

2. Field evidence of melt migration in the mantle section of ophiolites

2.1. Feeding dykes

As in the granite realm, the dykes observed in the mantle section of ophiolites (commonly referred to as 'mantle dykes') are witnesses of migration of a melt through the solid peridotite matrix, residue of one or more partial melting events. Dykes are former cracks filled with rocks of various compositions and textures (Fig. 1). They crystallized in response to decreasing temperature during the journey of their parent melt from the deep partial melting region to the surface. The contacts between these crystallization products and the host mantle, *i.e.* the dyke walls, are generally parallel to each other and knife sharp (Fig. 1a), which is the criterion to ascribe the name 'dyke' to these structures. Although dykes are emplaced at shallow depth and are not witnesses of the early stages of melt migration, they carry a wealth of precious information in their composition, mineral texture, orientation, and cross cutting relationships.

The orientation of the dykes at the outcrop or even massif scale is generally not random and is of great use to infer the stress orientation at the time of the crack generation (Nicolas and Jackson, 1982; Sleep, 1988) (Fig. 2). The cross-cutting relationships are
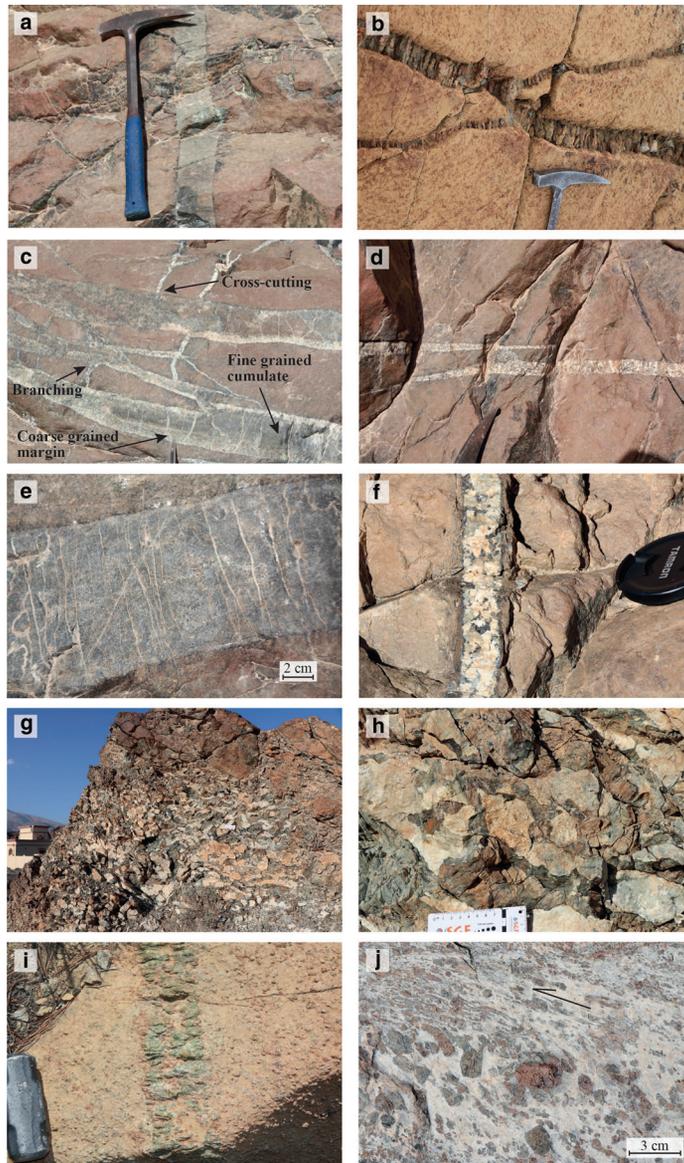
Fig. 1. Field aspect of mantle dykes in the Trinity ophiolite (panels b and i) and Oman ophiolite (other panels). (*a*) A common type of gabbro dyke. (*b*) Cross-cutting relationships between two generation of pyroxenite dykes. (*c*) Complex intersection and branching relationships between gabbro dykes. (*d*) Two overlapping gabbro dykes with dyke tips showing opposing directions of propagation. (*e*) Detail of the fine-grained texture of a gabbro dyke. (*f*) Detail on the coarse-grained texture of a gabbro dyke. (*g*) Pegmatitic dyke several metres thick. (*h*) Detail of the gabbro pegmatite. (*i*) Olivine-clinopyroxenite dyke with a crescumulate texture: the crystal growth stopped when the pyroxene crystals from facing margins met in the centre of the dykes. (*j*) Coarse-grained gabbro dyke partially affected by a mylonitic shear zone.
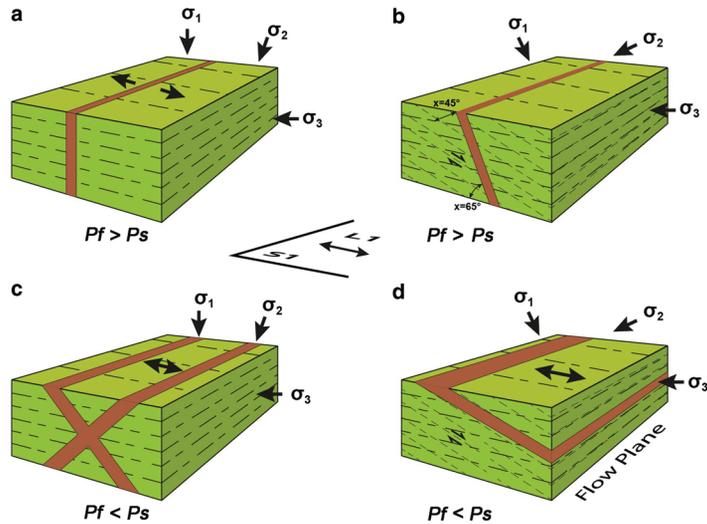
Fig. 2. Relationships between the orientation of the dykes and the stress field. Pf = melt pressure; Ps = pressure exerted by the surrounding solid; S1 and L1 are the plastic foliation and lineation related to solid-state mantle flow; σ1, σ2 and σ3 are the maximum, intermediate and minimum deviatoric stress components respectively. (**a**) Pure shear (extensional) regime with $Pf > Ps$; (**b**) simple shear regime with $Pf > Ps$; (**c**) pure shear regime with $Pf < Ps$; (**d**) simple shear regime with $Pf < Ps$. After Nicolas and Jackson (1982).

reliable indications to determine a relative chronology of injection events (Fig. 1b). Conversely, branching relationships can indicate that dykes of different orientations are coeval (Fig. 1c). The complex situation illustrated in Fig. 1c shows that the two kinds of relationships can occur on the same outcrop: the thin coarse-grained gabbro dykes (white) are cross cut almost orthogonally by thicker dykes with, locally, a coarse-grained margin of similar composition to the thin veins, and a fine-grained (darker) inner part. Cross-cutting could be interpreted in terms of change in stress direction between two injection events but the branching relationships show that the two directions of injections developed contemporaneously.

In well preserved ophiolites, the dyke orientation can be analysed in the ocean-spreading structural framework deduced from: (1) the mantle-crust boundary, proxy of the palaeo-horizontal; (2) the sheeted dyke complex, the average strike is equated with that of the former ridge axis; (3) the solid-state flow structures of the host peridotites, a record of the geometry of the asthenospheric currents; and (4) any other structural elements such as ductile shear zones and brittle faults. When observed, dyke tips indicate the direction of crack propagation (Fig. 1d) (Rubin, 1995).

The texture of the rocks filling the dyke reflects primarily the cooling rate which depends on many factors including the temperature difference between the melt and the host mantle. Apart from rare diabase dikes that were injected in a relatively cold country rock ($<\sim400°C$), most ophiolitic mantle dykes are filled with holocrystalline rocks, essentially gabbroic and pyroxenitic in composition, more rarely dunitic, dioritic,

trondjhemitic or tonalitic. The crystal size ranges from fine- to coarse-grained (Fig. 1e, f) whereas texture ranges from cumulate to pegmatitic.

Dykes with a pegmatitic texture (Fig. 1g, h) are common. Pegmatites indicate rapid, disequilibrium crystal growth, often along a preferred lattice direction, in the context of a low degree of nucleation. Pegmatites are diagnostic of a significant temperature contrast between the melt and the host rock, although not high enough to induce sudden freezing of the melt as in the case of diabase. The presence of fluids is another factor favouring pegmatite formation, as suggested by the common occurrence of magmatic amphibole overgrowing pyroxenes.

Among the dykes presenting a cumulate texture, adcumulates are the most common. A continuum exists between dykes entirely filled with pegmatites and dykes entirely filled with cumulates as attested by the frequent occurrence of dykes showing coarse crystals at their walls only ('crescumulate') (Fig. 1i) and filled with rocks with an adcumulate texture in its inner part (Fig. 1c). Finally, cumulates filling the dykes can be affected by plastic deformation, which constitutes an interesting source of information concerning the interplay between igneous and tectonic activities (Fig. 1j).

The adcumulate texture points to efficient extraction of the interstitial melt and thus to fractional crystallization and mineral accumulation in an open system (Wager *et al.*, 1960). This was confirmed by Benoit *et al.* (1996) on the basis of major and trace element analyses and mass balance calculations. Briefly, an almost perfect fit exists between the trace element concentrations and patterns measured in the bulk rock and those calculated from mineral separate analyses and modal proportions, pointing to the virtual absence of trapped melt. It is thus reasonable to suppose that most of the melt that flowed within the cracks reached crustal magma chambers after a variable but generally low degree of fractional crystallization and crystal accumulation (Ceuleneer *et al.*, 1996). Most mantle dykes in ophiolites share common parent melts with the rocks making up the crustal section (*e.g.* Lippard *et al.*, 1986; Benoit *et al.*, 1996; Python and Ceuleneer, 2003), which is an argument supporting the view that they were the former 'feeding dykes' of the overlying magma chambers.

In the absence of trapped melt, the mineral proportions and chemical compositions are straightforward to interpret in terms of cotectic assemblages crystallizing along the liquid line of descent of common mafic melts, and are of great use to infer the nature of this melt (*e.g.* Ceuleneer *et al.*, 1996; Benoit *et al.*, 1996; Varfalvy *et al.*, 1996).

The hope of the geologists who analysed mantle dykes was, initially, to find in them the crystallization products from the primary melts that fed the crustal magma chambers (*e.g.* Malpas, 1978; Boudier and Coleman, 1981; Lippard *et al.*, 1986). However, the cumulate filling the dykes appeared to be issued from melts that were already and variably evolved. Although the quest for the primary melt seems an unreachable objective, the systematic petrographic and chemical studies of mantle dykes is, as in the case of the layered cumulates, a very efficient way to determine the magma series that contributed to the igneous evolution of an ophiolite (Python and Ceuleneer, 2003; Ceuleneer and le Sueur, 2008).

Most ophiolites are characterized by the occurrence of lavas, dykes and/or plutonic rocks belonging to two or more different magma series (*e.g.* Dilek and Furnes, 2011).
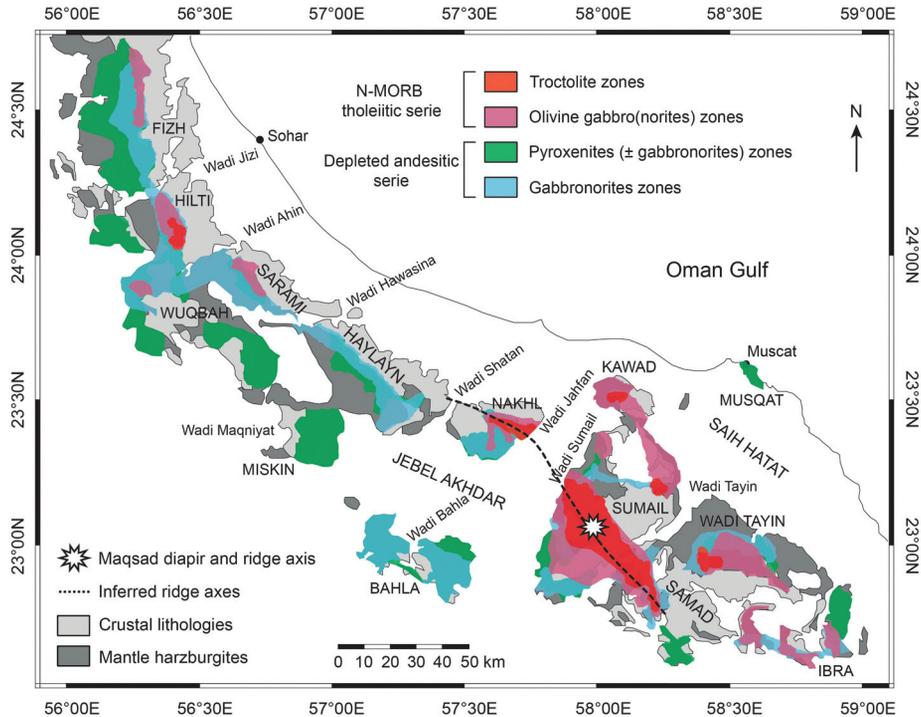
Fig. 3. Simplified map of the distribution of various lithological groups of mantle dykes and porous flow channels in the mantle section of ophiolites. Troctolites and olivine-gabbros (+rare evolved oxide-gabbronorites) are the primitive and differentiated cumulates from MORB-like olivine tholeiites, respectively; pyroxenites and opx-rich gabbronorites are the primitive and differentiated cumulates from depleted, Mg-rich andesites or high-Ca boninites, respectively. The main MORB area is an 80 km-long former ridge segment centred on the Maqsad diapir (white star). After Python and Ceuleneer (2003).

Mantle dykes appear to be a very convenient tool to map the spatial distribution of these magmatic series and to reconstruct the tectono-magmatic history of ophiolites. Figure 3 gives an example of such a distribution along the Oman ophiolite (Python and Ceuleneer, 2003). Bi-modal magmatism in Oman is generally interpreted in terms of successive episodes of melt generation and emplacement, typically a first-generation synchronous with the accretion of the ophiolite in a spreading context, mid-ocean ridge or arc-related basin, and a second one related to the emplacement events that preluded its final obduction on a continental margin (*e.g.* Belgrano *et al.*, 2019 and references therein).

However, the mapping of mantle dyke distribution revealed that the dykes of each petrological family do not crop out in the same areas (Benoit *et al.*, 1999; Python and Ceuleneer, 2003). Feeding dykes of MORB type are restricted to few districts corresponding to former ridge segments opening in a lithosphere hosting pre-existing dykes of boninitic-andesitic affinity that crystallized as pyroxenites and orthopyroxene-rich gabbronorites. These pyroxenite dykes and most of the gabbronorite dykes are restricted to the

mantle section and do not invade the overlying crust, which should be the case if they represented a late volcanic episode related to subduction. So, the existence of two magmatic series could alternatively be attributed to the cyclicity and spatial variability in the spreading processes and modes of melt production than in a succession of distinct magmatic episodes (Benoit *et al.*, 1999; Python and Ceuleneer, 2003; Nonnotte *et al.*, 2005; Clénet *et al.*, 2010).

2.2. Porous flow structures

As mentioned above, mantle dykes represent an already evolved stage of melt migration, following significant pooling of incremental melt fractions. According to experiments and to the laws of thermodynamics and solutions, partial melting of a polymineralic assemblage initiates at the junctions between different mineral phases, where the melting temperature reaches a minimum value. In the case of mantle peridotites, it will take place at the contact between olivine, pyroxenes and aluminous phases. As these multiple junctions are evenly distributed in the peridotite, at least in a simplified frame not considering lithological heterogeneities, melt droplets produced by melting will likewise be spatially uniformly distributed (*e.g.* Zhu *et al.*, 2011). The early stages of melt pooling will thus involve migration at grain boundaries, currently referred to as 'porous flow' in the petrological literature.

To seek for field structures inherited from the initiation of melt migration at the depths of the partial melting region (several tens of kilometres or even deeper) would be illusive. However, even if they are more discrete and seem less common than mantle dykes, porous flow structures formed at shallower depths are present in the mantle section of ophiolites (Fig. 4). They are quite informative about the way a melt makes its way through the solid peridotitic matrix and it is reasonable to assume that it may be extrapolated, *mutatis mutandis,* to greater depths.

2.2.1. Macroscopic evidence of porous flow: no unique interpretation

Dykes are structures recognized as such by structural geologists. What we describe as porous flow 'structures' in the field refer actually to variations, more or less subtle, in the proportions and distribution of different minerals that catch our attention, and that we interpret as the footprint of migration of interstitial melt. In other words, the preservation of macroscopic evidence of former melt migration requires: (1) that the melt was in disequilibrium with at least one mineral of the solid matrix, inducing a dissolution reaction; (2) that it migrated through a temperature gradient leading to its partial crystallization; of (3) a combination of both processes with crystallization in response to dissolution, referred as "reactive crystallization" (Collier and Kelemen, 2010). So, the porous flow structures we can observe in the field give access either to the time-integrated distribution of a melt that was "aggressive" for its host peridotite or to a snapshot of the melt distribution at the time of crystallization, corresponding to the closure of the porosity and thus to the final stage of melt migration.

Strictly speaking, where the melt comes from and where it goes can generally not be deduced from field observations, although we currently interpret our data in the frame of
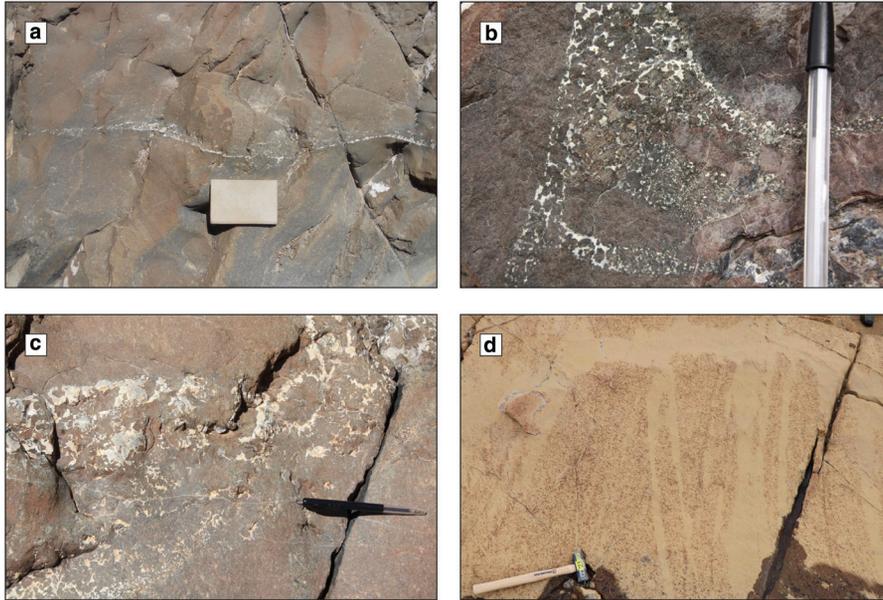
Fig. 4. Porous flow structures observed in the Oman (*a*, *b*, *c*) and Trinity (*d*) peridotites. In Oman, relics of the percolating melt are evidenced by whitish crystallization products, mostly plagioclase and, more rarely, clinopyroxene. In Trinity, former melt paths are shown by dunite (rock with a smooth surface) left after infiltration melting and dissolution of the pyroxenes from the lherzolite (rugged surface).

scenarios integrating melt trajectories and direction of flow. Field observations are objective but their interpretation is not, being anchored in assumptions (*e.g.* the melt being less dense than the country rock, it should migrate upward) and/or on petrogenetic and structural considerations. In the following, we illustrate with an example from the mantle section of the Trinity ophiolite the way how preconceived ideas may drive the interpretation.

Figure 5a shows a trail of clinopyroxene grains sandwiched symmetrically by dunite layers and then by the host lherzolite. The contacts between the different lithologies are contoured and follow the shape of the crystals, contrasting with the knife cut contacts shown by dykes. The lherzolite shows solid-state plastic deformation in high-temperature and low-stress conditions, as well as modal and chemical compositions typical of residual peridotite after a moderate degree of partial melting suggesting, thus, that this rock represents the ambient asthenospheric mantle. The clinopyroxene grains from the central trail are interstitial between olivine grains of the dunite and have a composition consistent with fractional crystallization from a primitive basaltic melt. Accordingly, this trail can reasonably be interpreted as the footprint of the melt that circulated in a percolation channel.

To determine the origin of the dunite is trickier. In theory, a dunite may be the residue of extreme degrees of decompression melting of a peridotite if the mantle potential
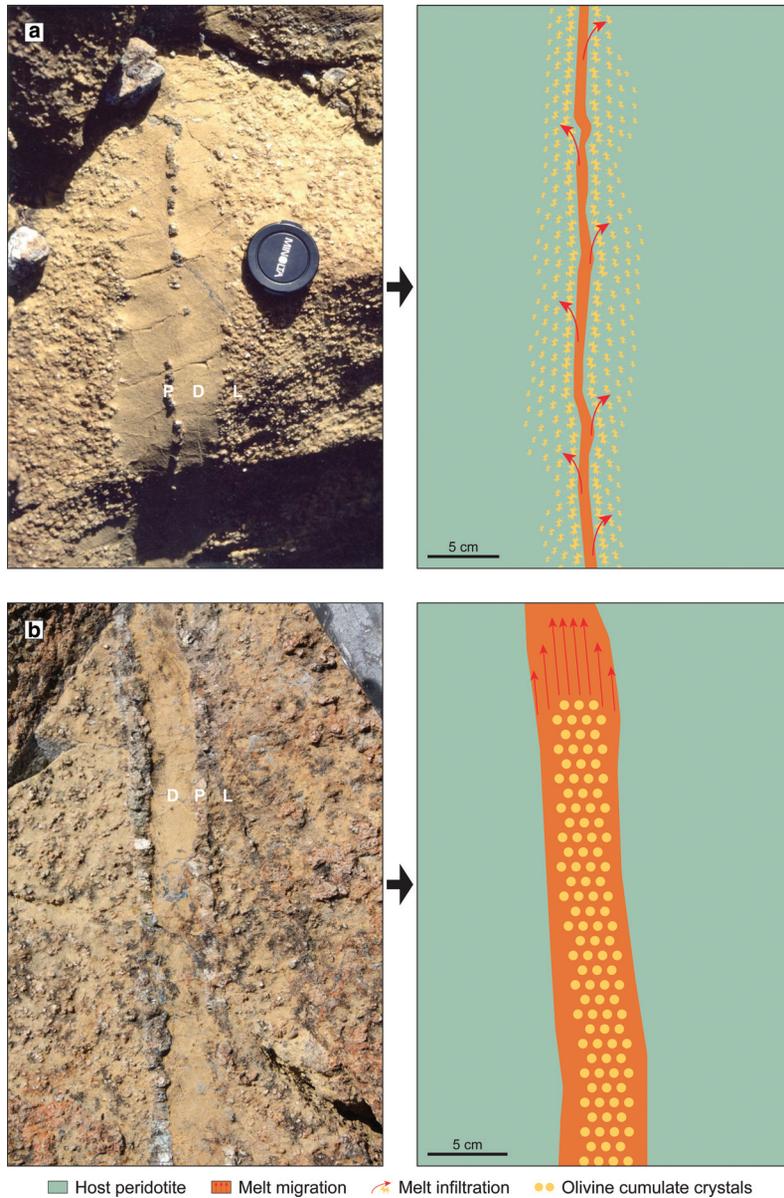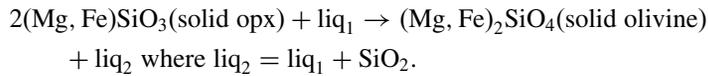
Fig. 5. Two different mutual relationships between lherzolite (L), dunite (D) and pyroxenite (P) in the Trinity ophiolite leading to different interpretations about melt migration.

temperature exceeds ~1500°C (*e.g.* Takahashi, 1986). However, this mechanism cannot account for the discrete occurrence of dunite in a host environment dominated by lherzo-lite, residue of decompression melting of a much colder mantle. The formation of both

lithologies by decompression melting would imply unrealistic temperature gradients at small scale (a few centimetres) in the asthenosphere.

Considering decompression melting alone as implausible to account for dunite formation, we are faced with two physically and petrologically possible mechanisms for the origin of the dunite in Fig. 5a: (1) fractional crystallization of olivine from a Mg-rich melt followed by accumulation in the melt conduit (*e.g.* Elthon, 1979); and (2) the by-product of a reaction between the lherzolite and a melt in disequilibrium with the pyroxene (*e.g.* Kelemen *et al.*, 1992; Braun and Kelemen, 2002); in this case, the dunite would be a mixture between primary olivine grains from the lherzolite itself and secondary olivine issued from the incongruent melting of the pyroxenes according to the reaction (written for a simplified orthopyroxene (opx) composition):

$$2(\text{Mg, Fe})\text{SiO}_3(\text{solid opx}) + \text{liq}_1 \rightarrow (\text{Mg, Fe})_2\text{SiO}_4(\text{solid olivine})$$
$$+ \text{liq}_2 \text{ where } \text{liq}_2 = \text{liq}_1 + \text{SiO}_2.$$

To resolve the two options has a strong impact on our understanding and interpretation of physical processes occurring in the shallow mantle. The cumulate hypothesis implies that the dunite represents a former channel where a large amount of primitive, Mg-rich melt circulated and differentiated and the thickness of which may be approximated by the present distance between the two facing dunite/lherzolite contacts. The second melt-rock reaction hypothesis implies dunite is a relic of a system with a much lower melt/rock ratio with melt percolating interstitially between the grains of the peridotite, the central clinopyroxene trail showing us the path taken by the last melt that circulated in the channel. In this case the dunite/lherzolite contact would correspond to the lateral extent of a reaction front, *i.e.* the distance up to which the melt responsible for the reaction did percolate within the host lherzolite away from the central vein.

Cases where dunites are symmetrically distributed around a central vein are frequently observed in the field. However, other configurations exist and to see in all dunite veins the imprint left by "infiltration melting" might be a hazardous generalisation. For example, a few hundred meters away from the outcrop shown in Fig. 5a, we can observe a different situation: here, the dunite lies in the centre of the structure and clinopyroxenite trails locate at both interfaces between the dunite and the host lherzolite (Fig. 5b). Accordingly, considering field evidence alone, infiltration melting is not really the most convincing way to explain the origin of dunite in this specific case. In turn, this structure perfectly matches the expected distribution of the solid charge carried by a melt in a pipe flow situation. The solid charge would be the olivine grains that crystallized from the flowing melt and that were preferentially concentrated in the zones of weak velocity gradient, *i.e.* in the central part of the vein, while the clinopyroxenes would have crystallize from the more evolved melt that was expelled from the compacting central part and concentrated along the vein margins. This hypothesis was favoured by Maaloe (2005) for the dunite-pyroxenite association from the Leka ophiolite.

The reactional vs. cumulate origin of dunites formed during melt migration in the mantle is still a matter of debate. Geochemical criteria are frequently ambiguous when

used alone. If interpreted with the support of other observations, mostly petrographic and structural, the answer has been shown to be non-unique, both origins can co-exist in a single section across tabular dunite (Abily and Ceuleneer, 2013). Nonetheless, geochemical and petrological studies tend to support the view that the reactional origin is the most common (Dick, 1977; Quick, 1981a,b; Kelemen *et al.*, 1992; Kelemen *et al.*, 1995; Suhr *et al.*, 2003, Dygert *et al.*, 2016). Dunites (or their olivine) showing no melt migration features observable in the field generally have slightly lower Mg# and Ni contents than in surrounding mantle peridotites. However, these values are far too high to consider such dunites as cumulates (*e.g.* Kelemen *et al.*, 1995; Godard *et al.*, 2000). They would imply a MgO-rich parent melt formed by high mantle partial melting rates that could not be reached in the modern Phanerozoic Earth. In addition, dunites share another common geochemical feature with mantle peridotites with enrichments in the most incompatible elements relative to expected partition coefficients in olivine, such as in light REE, defining U- or V-shaped REE and multi-element patterns (*e.g.* Prinzhofer and Allègre, 1985; Bodinier *et al.*, 1990; Godard *et al.*, 2000, 2008; Bouilhol *et al.*, 2009; Rospabé *et al.*, 2018) (Fig. 6). Such characteristics were either attributed to serpentinization (Gruau *et al.*, 1998) or to cryptic metasomatism, *i.e.* to the modification of the chemical composition of minerals from the peridotite under the action of migrating melts $\pm$ fluids (*e.g.* Navon and Stolper, 1987; Godard *et al.*, 1995; Vernières *et al.*, 1997).

2.2.2. Cryptic evidence for porous flow
The composition of mantle minerals is known to be deeply modified by the reactions leading to extreme modifications of the paragenetic assemblage. In the petrological
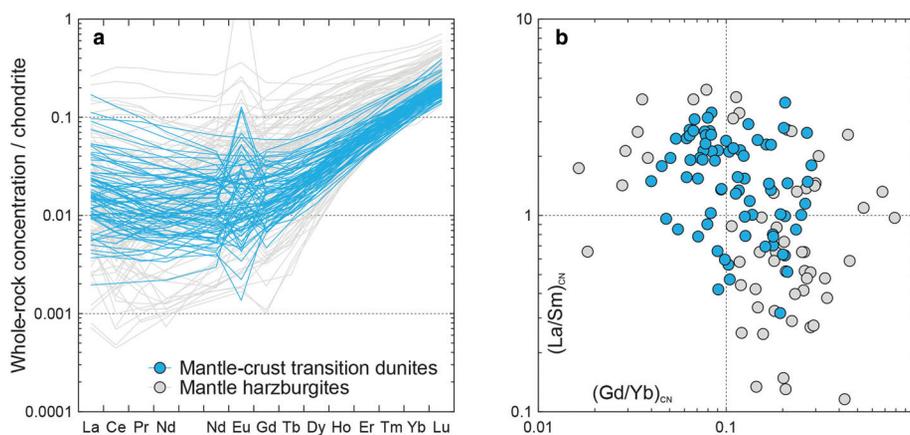

Fig. 6. Whole-rock REE patterns (*a*) and $(La/Sm)_{CN}$ *vs.* $(Gd/Yb)_{CN}$ ratios (*b*) CN for chondrite normalized) for DTZ dunites and mantle harzburgites from the Oman ophiolite. Data for DTZ dunites are from Godard *et al.* (2000), Rospabé *et al.* (2018, 2019a) and Kourim *et al.* (2022). Data for mantle harzburgites are from Godard *et al.* (2000), Gerbert-Gaillard (2002), Girardeau *et al.* (2002), Takazawa *et al.* (2003), Monnier *et al.* (2006), Hanghøj *et al.* (2010) and Kourim *et al.* (2022). Normalizing chondrite values are from Barrat *et al.* (2012).

literature devoted to melt migration, "cryptic" refers to evidence for melt-rock interaction that has no impact on the modal composition but is revealed through changes in the chemical composition of the different minerals.

We illustrate the reliability of this concept of "cryptic metasomatism" (Dawson, 1984) with an example from the Trinity ophiolite, where both modal and cryptic interactions coexist in the same outcrop. This is a different petrological context from that leading to dunite formation. In that case, the participants in the interaction were a mantle plagioclase-lherzolite and a vein of depleted, primitive, high-Ca boninitic melt that left an olivine-websterite cumulate after a small amount of fractional crystallization (Ceuleneer and le Sueur, 2008).

The sample (Fig. 7) can be described as a sandwich composed of a 16 mm-thick olivine-websterite vein surrounded by ∼5 cm-thick walls of plagioclase-free lherzolite, surrounded, in turn, by plagioclase-bearing peridotite. Boundaries between these three lithologies are rather sharp, even if not knife-cut. No significant difference in the modal proportions of olivine and pyroxenes is observed between the plagioclase-lherzolite and the plagioclase-free lherzolite at the vein walls. Accordingly, the melt migrating in the vein and invading the country rock was apparently in equilibrium with olivine and both ortho- and clinopyroxenes but not with plagioclase, which is consistent with the Al-depleted nature of primitive boninite melts.

Therefore, plagioclase consumption is the only macroscopic evidence for melt-rock interaction in this specific case. To explore the consequences of melt-mantle interaction for the chemical compositions, we performed a detailed geochemical profile across this composite sample with the electron microprobe and using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). We show representative profiles with Ti, Zr, Y and Sr in clinopyroxene (cpx).

In the specific case of the Trinity ophiolite, there were fewer incompatible element in the clinopyroxene (cpx) from the lower crustal cumulates and in the vein-filling cumulates than in residual cpx in the mantle peridotite. This unusual situation results from the fact that the mantle peridotite from Trinity is relatively fertile, having experienced a moderate degree of partial melting and was not the parental mantle of the boninitic melt, which is issued from an ultra-depleted source (Ceuleneer and le Sueur, 2008). The Trinity massif is better described as a piece of mantle peridotite eventually intruded by boninitic plutons than as a typical ophiolite where the mantle and crustal sections are petrogenetically related.

The incompatible elements (Ti, Zr and Y) define V-shaped concentration profiles centred on the vein (Fig. 7). The cpx from the peridotite at the contact with the vein has concentrations in these trace elements that equal those in cpx from the vein. This content increases linearly and symmetrically away from the vein walls and reaches plateau values at distances of ∼10 cm from them. Consequently, it happens that the thickness of the zone modified chemically by the interaction exceeds by a factor of ∼2 the thickness of the 'macroscopic' reaction zone defined by plagioclase consumption (4–5 cm).

Clinopyroxene is the main reservoir of most incompatible trace elements in the peridotite (*i.e.* greater partition coefficients, *D*, in cpx than in opx and olivine for these
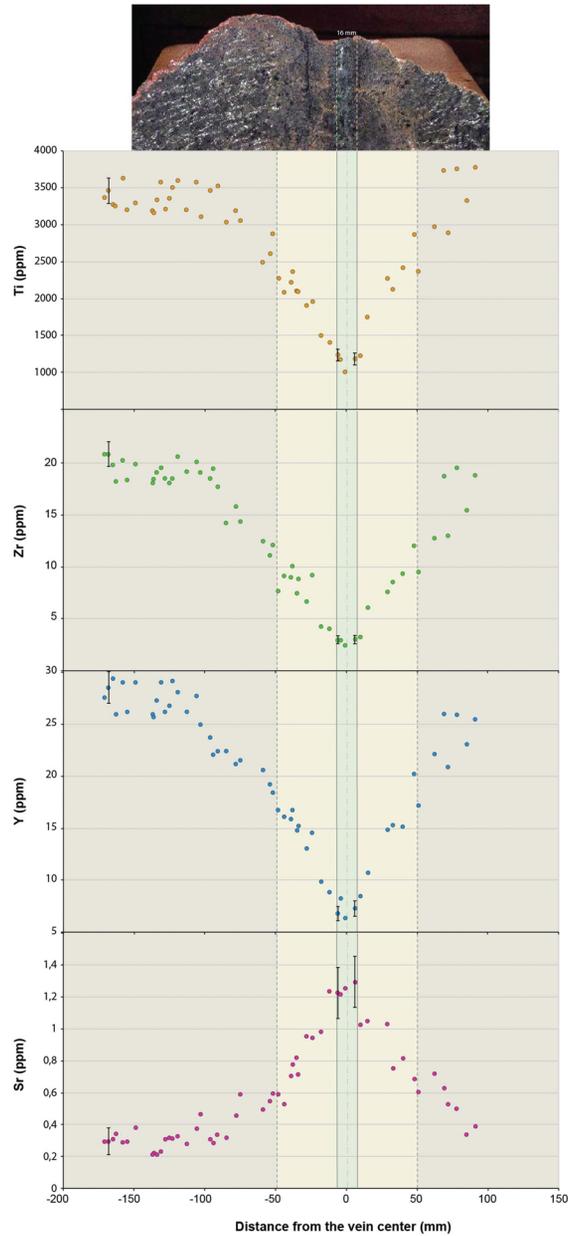
Fig. 7. Evidence for both modal and cryptic effects of melt–rock interaction in the Trinity plagioclase-lherzolite. A pyroxenite vein (pale green on the diagrams) is surrounded by lherzolite devoid of plagioclase. The cryptic impact of melt–rock interaction can be followed further away as revealed by the evolution in the content of incompatible trace elements in clinopyroxene (LA-ICP-MS unpublished data). The error bar is shown for a few analytical points.

chemical species). Accordingly, the dissolution of plagioclase had a minor effect on the concentration of these elements, and the profiles are scarcely disturbed if at all when crossing the plagioclase-out boundary. Sr shows a reverse evolution ('inverted V' profile, Fig. 7), which is consistent with the fact that its concentration in plagioclase is greater than in cpx (*i.e.* $^{plg/\text{liquid}}D_{Sr} >> {}^{cpx/\text{liquid}}D_{Sr}$) and that cpx becomes the main host for Sr where plagioclase is dissolved (*i.e.* $^{cpx/\text{liquid}}D_{Sr} > {}^{opx/\text{liquid}}D_{Sr} > {}^{olivine/\text{liquid}}D_{Sr}$).

Cpx crystals present important grain size and texture variations from coarse porphyroclasts to minute grains in the recrystallized matrix and coarse cumulate grains in the vein. Nonetheless, these textural variations have no influence on the composition of cpx that appears to depend only on the distance from the vein and on the chemical concentration contrast between the vein and the far field peridotite. The fact that plastic deformation textures are preserved in the peridotite regardless of the distance from the vein indicates that the instantaneous melt volume was not great enough to erase this texture during the interaction process. Accordingly, the progressive decrease in incompatible element concentrations in the mantle pyroxenes approaching the vein, down to magmatic values at the vein walls, may be explained if mantle residual phases re-equilibrated with a melt with the melt/rock ratio decreasing linearly away from the vein. A chromatographic process controlled by diffusion in the interstitial liquid may also be invoked but would result in parabolic rather than linear concentration profiles (Bodinier *et al.*, 1990).

These simple data demonstrate the effect of cryptic metasomatism. The contrast between cryptic metasomatism recorded by trace element concentrations in cpx and modal metasomatism recorded by the occurrence/disappearance of plagioclase can be explained by the propagation of a percolation front in tiny inter-granular melt films away from the vein. The percolating melt, given the very low melt/rock ratio, is modified rapidly by chemical re-equilibration with mantle minerals. The composition of the modified interstitial melt is reset continuously by mixing with boninite melts flowing in the vein: the closer the peridotite is from the vein, the greater is the time-integrated contribution from the boninite melt, the more Al-undersaturated is the interstitial melt. Accordingly, the conditions for plagioclase dissolution will be fulfilled up to a given distance from the vein but not to the limit reached by the percolation front. It will result in a relatively sharp plagioclase-out boundary, half-way between the vein and the percolation front as revealed by the cryptic chemical evolution, in the case documented in Fig. 7.

To determine if cryptic metasomatism is negligible or if it may have a major impact on the composition of mantle peridotite at the scale of a massif is a fundamental matter. Regional variations in Ti content of cpx in the Trinity ophiolite are shown in Fig. 8 (Ceuleneer and le Sueur, 2008). Cpx in the ultramafic cumulates from the crustal section and in websterite veins have a small Ti content ($TiO_2 < 0.4\%$) and show a trend diagnostic of fractional crystallization from a depleted, boninitic melt with a slight increase in Ti as Mg# values decrease. Clinopyroxene in mantle lherzolite away from veins have variable but always large Ti contents ($0.3 < TiO_2 < 1.0\%$) with Mg# buffered around mantle values. Cpx in the peridotites sampled close to vein walls but showing no macroscopic evidence of melt-rock reaction (Fig. 8) have TiO_2 contents intermediate between those in veins and those in far field peridotite.
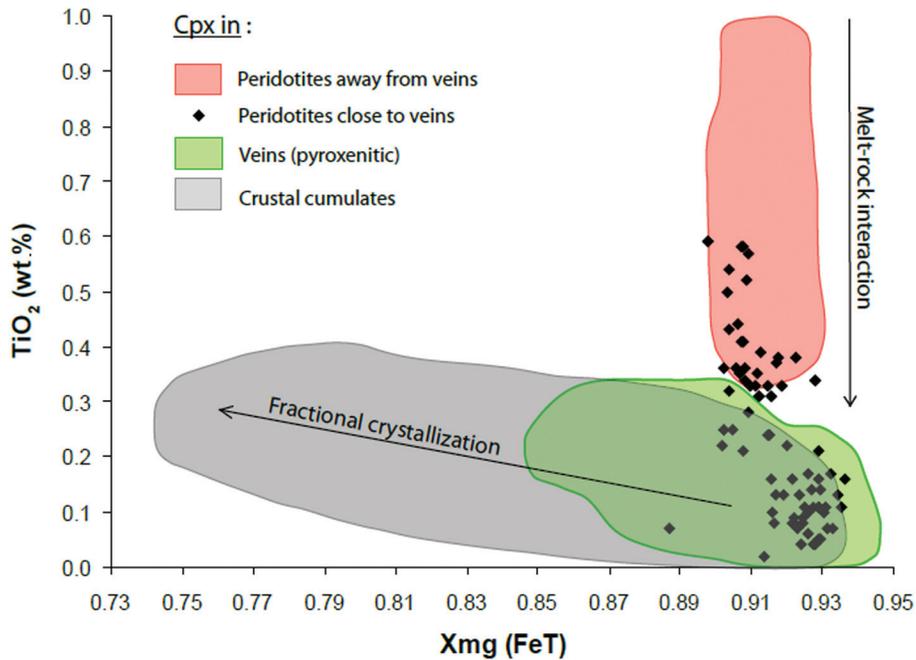
Fig. 8. Ti content *vs.* Mg# of clinopyroxenes from various lithological groups in the Trinity ophiolite. After Ceuleneer and le Sueur (2008).

The same conclusions can be deduced from the comparison of the REE patterns in cpx according to their mode of occurrence (Fig. 9). The cpx from plagioclase-lherzolite away from pyroxenite veins show a typical pattern for cpx in residues of moderate degrees of partial melting. The cpx in gabbroic segregations show the same pattern but with greater concentrations, which is consistent with the view that they represent products of low-degree melting of these lherzolites followed by *in situ* crystallization. The cpx in the crustal ultramafic cumulates show highly depleted patterns characteristic of primitive island arc andesitic-boninitic parent melts. Cpx from the pyroxenite veins show a high scatter in REE concentrations consistent with interaction between the primitive andesite and the host lherzolite.

This evidence indicates that the interaction process highlighted in the sample studied in detail is not a local feature but acted all across the Trinity massif. Peridotite described in the field as 'away from veins' also present a significant scatter in the Ti contents of their clnopyroxenes. It is likely that this also reflects variable degrees of cryptic metasomatism in situations where the percolating melt left no footprint behind it in the form of clinopyroxenite vein, or, simply, that the vein does not crop out or was eroded. We can propose that low degrees of decompression melting of the lherzolite left a rather homogeneous, Ti-rich ($\sim$1.0% TiO_2) residual cpx and that the scatter in TiO_2 concentration in cpx towards smaller values is mostly attributable to the interaction with the depleted melt,
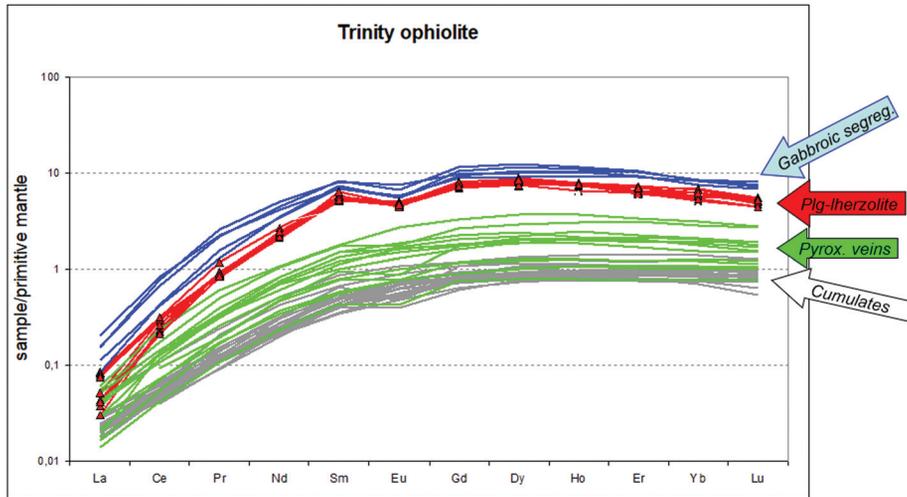
Fig. 9. REE patterns of clinopyroxenes from various lithological groups in the Trinity ophiolite (LA-ICP-MS unpublished data).

regardless of the presence of field evidence for melt percolation in the vicinity of the peridotite.

2.3. From porous flow to dyking: a major transition

Melt extraction from the mantle starts with intergranular porous flow and ends with fracturing ('dyking') according to cooling conditions. However, how, where and when the transition between these two endmembers occurs is still poorly constrained. In other words, the question is to determine if porous flow is rapidly superseded by dyking, as soon as the melt is produced (Fig. 10a) (*e.g.* Waff and Holdren, 1981; Nicolas, 1986; Sleep, 1988; Maaloe, 2003), or if dyking is restricted to shallow depths in which case porous flow would be the dominant mode of melt migration almost up to the surface (Fig. 10b) (*e.g.* Scott and Stevenson, 1986; Turcotte and Phipps Morgan, 1992; McKenzie and Bickle, 1988; Khodakovskii *et al.*, 1995; Rabinowicz *et al.* 2001; Rabinowicz and Ceuleneer, 2005). It primarily governs the composition of a magma, *i.e.* mostly inherited from the deep source with minor modification during migration, or being a blend of all the sources with mixing during its long journey to the surface. To locate where and how the transition from porous flow to dyking occurs also has an impact in the field of geophysics as it governs the mantle rheology, the electrical conductivity and the seismic wave propagation in the partial-melting region.

Dykes are not only the clearest but also the most widespread and abundant melt migration structures in the mantle section of ophiolites: an outcrop devoid of dyke is an uncommon situation, not the reverse. The preponderance of mantle dykes in the ophiolitic record, compared to the more tenuous and, apparently, less abundant porous flow
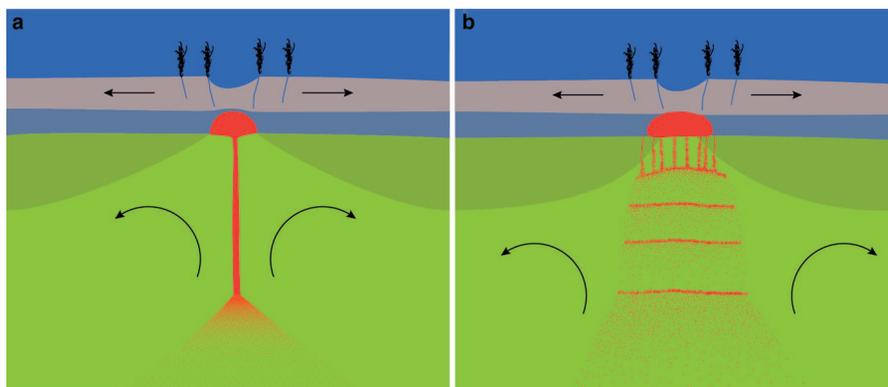
Fig. 10. Two conceptual models of melt migration in the mantle beneath oceanic spreading centres. (**a**) Dykes root directly in the partial melting region at depth and are the main avenues of melt transfer from the asthenosphere to crustal magma chamber (*e.g.* Nicolas, 1986). (**b**) Most of the melt transport occurs by porous flow. The process may imply the development of compaction waves (*e.g.* Scott and Stevenson, 1986; Khodakovskii *et al.*, 1995; Rabinowicz *et al.* 2001; Rabinowicz and Ceuleneer, 2005). Migration occurs in porous flow channels up to the axial magma chamber. Dykes are slightly off-axis features restricted to the lithospheric mantle (Ceuleneer *et al.*, 1996).

structures, has been considered as evidence of a predominantly brittle mode of melt trans-
fer from the partial melting zone to the crust, hydraulic fracturing taking over porous flow
at great depths in the asthenospheric mantle (Fig. 10a) (Nicolas, 1986). We will see below
how this evidence may be misleading.

   The interpretation of geological features can be quite tricky because an outcrop inte-
grates potentially a long history of structural, magmatic or other processes. To quote
Carol Cleland (2013), "The observational data (…) are collected in the messy, uncontrol-
lable world of nature (…)". In the particular case of the porous flow *vs.* dyking transition,
the challenge is to determine the precise structural setting and mantle temperature at the
time a melt migration feature observed in the field was active. It is generally impossible to
do. As a matter of fact, the mantle section of ophiolite is, in most cases, a remnant of the
oceanic lithosphere accreted progressively when cooling away from an ocean ridge and
thus integrates magmatic events during a relatively long, although unknown, time lapse.
Luckily, detailed mapping of the plastic flow structures in the Maqsad area of the Oman
ophiolite has revealed the existence of an exceptional situation. There, an asthenospheric
upwelling was preserved thanks to initiation of detachment of the future ophiolite in a
near-ridge context (Ceuleneer, 1986; Rabinowicz *et al.*, 1987; Ceuleneer *et al.*, 1988;
Ceuleneer, 1991). This so-called "Maqsad diapir" offers the rare opportunity to
observe as near as we get to a snapshot of the melt plumbing system below oceanic
spreading centres. It includes structures recorded before the corner flow of the astheno-
sphere and their eventual transposition in an off-axis position.

   Our survey (Ceuleneer *et al.*, 1996) has revealed that the type, orientation, texture and
composition of the melt migration features are systematically related and display a con-
centric zoning centred on the Maqsad diapir (Fig. 11). The mantle in the very centre of the
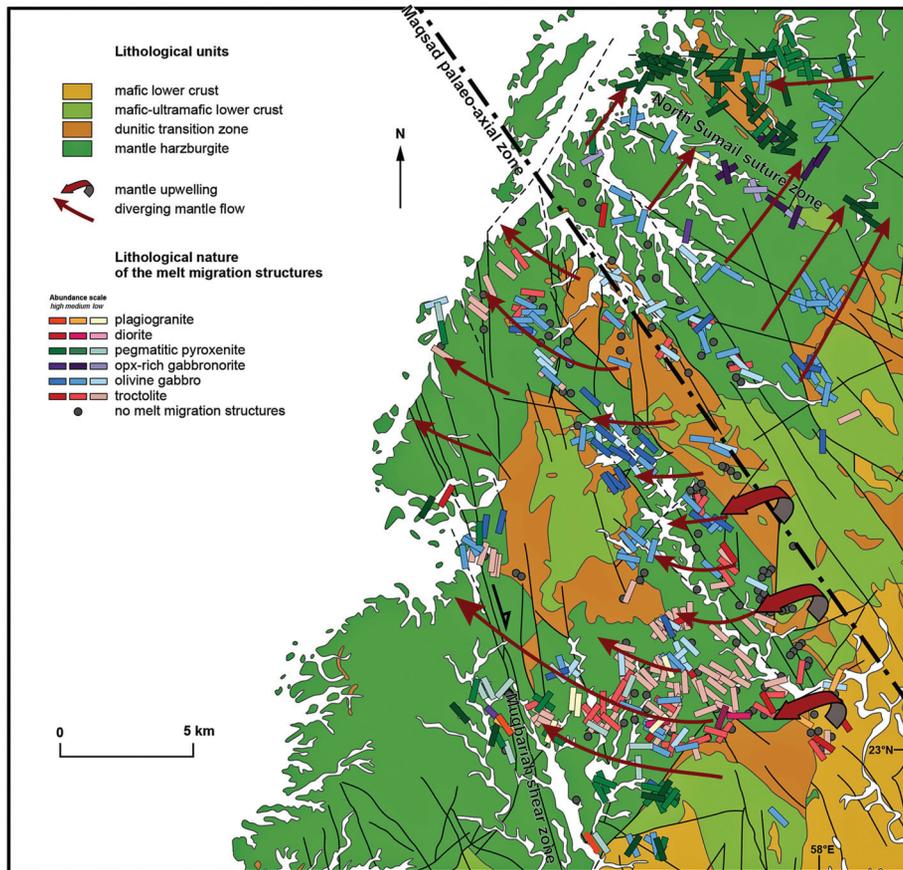
Fig. 11. Distribution of various lithologies of mantle dykes and porous flow channels in and around the Maqsad diapir. Source of the data: Ceuleneer (1991) and Ceuleneer *et al.* (1996).

upwelling contains an unusually small abundance of crystallization products from migrating melts. Only dunite channels are common as bands a few centimetres to a few decimetres thick either transposed into parallelism with the plastic foliation of the peridotite or discordant to this foliation, showing that they can predate or post-date the late stages of asthenospheric flow before the accretion of the asthenospheric mantle to the base of the lithosphere. The rare crystallization products are troctolitic in composition and are scattered in a shallow-dipping dunitic horizon discordant with respect to the foliation (Fig. 12). The contact relationships of these troctolites with their host dunite are gradational over distances of a few centimetres to a few decimetres. Away from the contact, the troctolitic segregations are typically made of 60–70% plagioclase and 30–40% olivine, corresponding to the proportions predicted on experimental grounds for the crystallization of primitive MORB along the olivine-plagioclase low pressure cotectic

(*e.g.* Grove *et al.*, 1992). The texture of these troctolites is, in most cases, recrystallized, *i. e.* a mosaic of equant grains with frequent 120° triple junctions. The geochemical data indicate that they were pure accumulates with virtually no trapped melt (Benoit *et al.*, 1996). Contacts between olivine and plagioclase are underlined by a reactional corona of orthopyroxene, clinopyroxene or hornblende (Fig. 12). These features indicate that troctolites experienced extensive solid-state grain boundary adjustment made possible by intra-crystalline diffusion at high (close to solidus) temperatures, in a slightly hydrous system. The absence of shear deformation texture in the troctolites indicates static conditions of recrystallization.

Moving away from the centre of the diapir, troctolitic segregations become increasingly abundant and adopt progressively a vertical dip but show no preferred azimuth (Fig. 13). On the other hand, their contacts with the host harzburgite become sharper, evolving to dykes (they can be described as 'proto-dykes'). This evolution goes with an increasing abundance of interstitial to poikilitic clinopyroxene. Recrystallization textures are less developed in these cpx-rich troctolites than in the troctolites devoid of clinopyroxene.

Further away from the upwelling, in the zone of diverging flow, olivine-gabbro dykes become abundant. Gabbro-filling the dykes are generally finer grained than troctolites and display adcumulate textures indicative of the simultaneous crystallization of olivine, plagioclase and clinopyroxene. Orthopyroxene, hornblende and Fe-Ti oxides, diagnostic of more evolved melts, become more and more abundant when moving away from the Maqsad diapir. In contrast with the troctolites, which are generally isolated features, olivine-gabbro dykes occur in swarms of many individuals (Fig. 12). Their azimuth is restricted to a NW-SE sector, roughly parallel to the sheeted dyke complex, and their dip is sub-vertical (Fig. 13)

To sum up, there is progressive compositional evolution of the melt migration structures from dunite to troctolites, gabbros and gabbronorites from the centre to the border of the diapir, which is correlated to an evolution in their texture, abundance and orientation. This zoning reflects the thermal structure of the diapir and of the associated melt plumbing system at the time the spreading stopped. Within the diapir, at "Moho" pressures ($\sim$0.2 GPa), the troctolites crystallized in porous flow channels at temperatures close to 1200°C assuming a MORB-like primitive olivine tholeiite parental melt. Although not quantifiable, the host mantle temperature was certainly very high also as attested by the static recrystallization textures described above. At the periphery of the diapir, clinopyroxene joined olivine and plagioclase as a cumulus phase pointing to melt temperatures of $< \sim$1150–1190°C depending on the melt composition (*e.g.* Grove *et al.*, 1992; Yang *et al.*, 1996). At this stage, the melt was channelled into dykes and crystallized as olivine-gabbros. Cross-cutting relationships between troctolitic porous flow channels and gabbroic veinlets are not common but can be observed in the transition between the centre and the periphery of the diapir; they confirm that the injection of gabbro dykes post-date the crystallization of troctolite in the dunitic porous flow channels, as expected (Fig. 12).

This case study shows that the transition between the porous flow and the brittle dyking mode of melt migration occurs, at least in the oceanic spreading centre context,
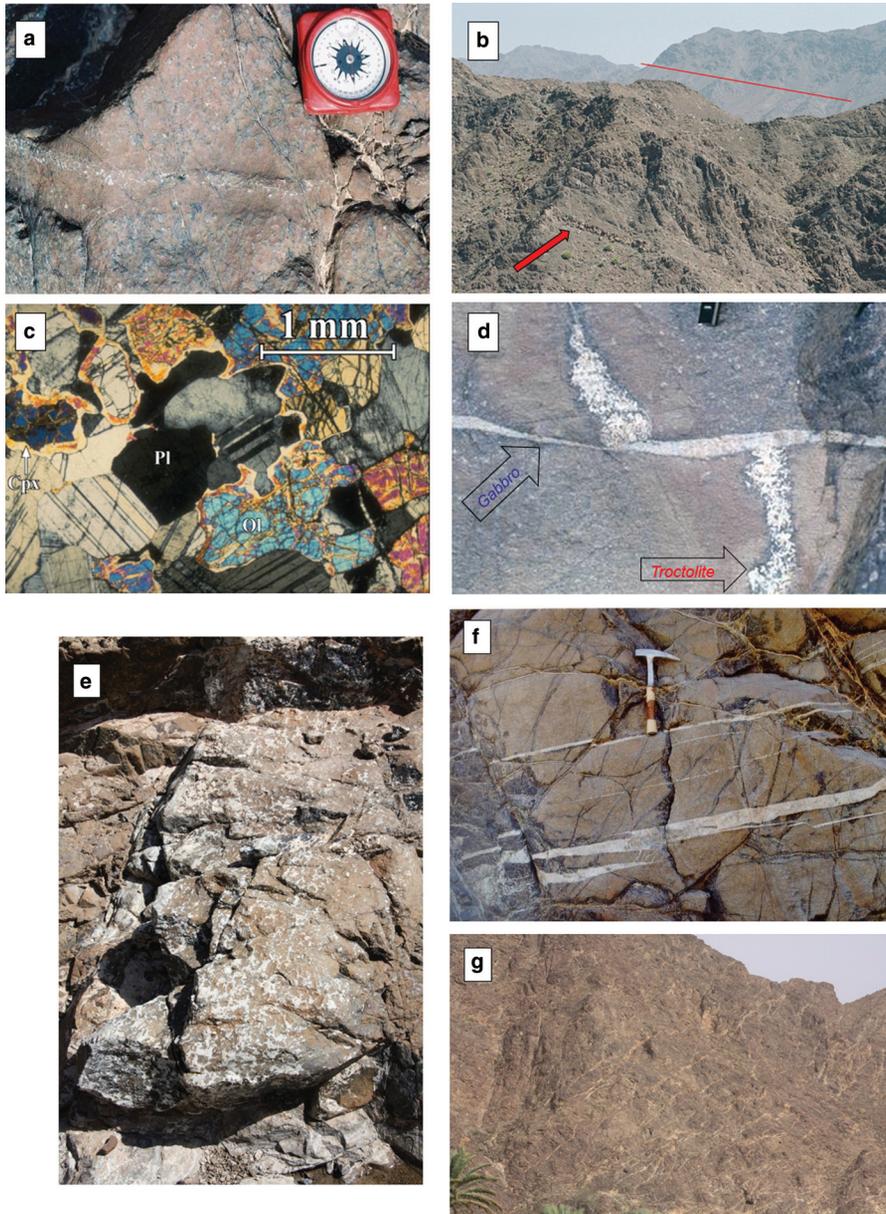
Fig. 12. Porous flow/dyking transition in the Maqsad mantle diapir, Oman ophiolite. (*a*) Typical porous flow channel from the inner part of the diapir: the troctolitic assemblage in its centre marks the location of the melt at the time of crystallization; screens of dunites separate the troctolite from the host harzburgite and attest to infiltration of a melt that induced the melting out of orthopyroxene. (*b*) Troctolite horizon ∼1 m thick (red arrow), sub-parallel to the palaeo-Moho (red line) in the harzburgites from the inner part of the diapir, possible footprint of compaction waves. (*c*) Thin section of the troctolite of part b showing evidence of static
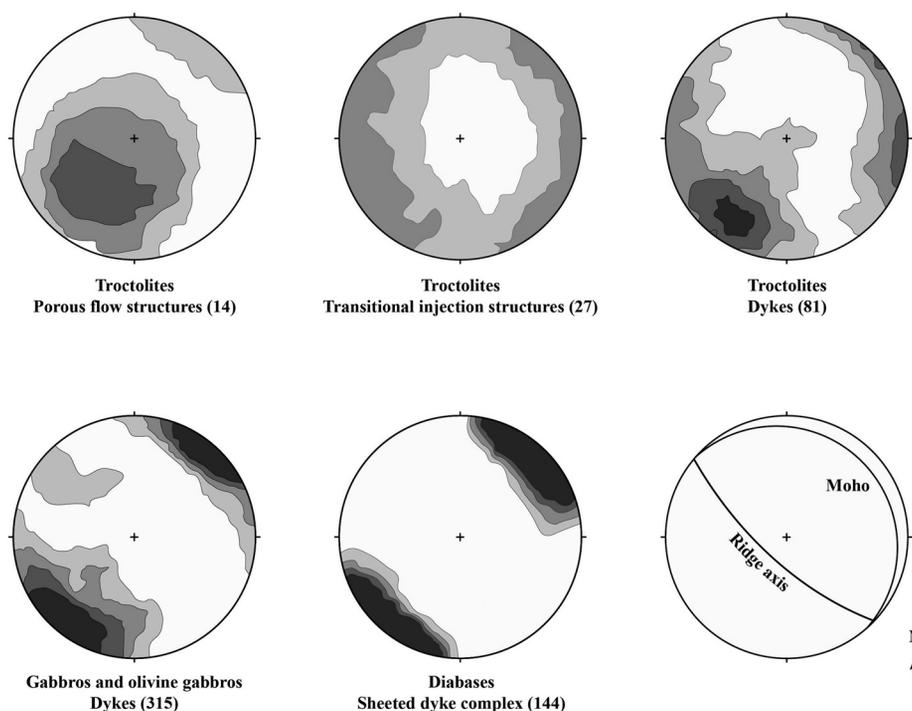
Fig. 13. Orientation of the melt migration structures within and around the Maqsad diapir. The orientation of the palaeo-Moho was measured in the field and the orientation of the palaeo-ridge axis from the mean orientation of the diabase dykes in the sheeted dyke complex. The stereonets are lower-hemisphere equal-area projection with contours at 1, 2, 3 and >4%. The number of orientation measurements is given in parentheses. For explanations, see the text. Redrawn from Ceuleneer *et al.* (1996) originally published in the journal *Nature*.

in a narrow temperature interval bracketed by the crystallization of troctolites, around 1200°C. This temperature is classically attributed by geophysicists to the base of the thermal lithosphere (Parker and Oldenburg, 1973). Therefore, we conclude that porous flow is the mode of melt migration in the asthenosphere and that the transition to dyking occurs at the base of the lithosphere. Consistently, the orientation of the melt

Fig. 12. *Continued.* recrystallization and pyroxene coronas issued from sub-solidus re-equilibration between plagioclase and olivine. (*d*) Rare intersection relationships at the periphery of the diapir between a troctolitic channel and an olivine-gabbro dyke; note the presence of dunitic reactional margins around troctolite and their absence around the olivine-gabbro dyke. The troctolite crystallized in the temperature range of 1190–1210°C and the olivine-gabbro slightly below 1190°C, which allows constraint of the temperature of the transition between the porous flow and brittle modes of melt migration at shallow depth beneath oceanic spreading centres. (*e*) Transitional structure between a porous flow channel and a dyke, filled with cpx-troctolite. The structure is ~40 cm wide in the foreground. (*f*) Olivine-gabbro dykes fracturing the harzburgite at the periphery of the diapir. (*g*) Swarm of close-spaced olivine-gabbro dykes in the same area.

migration structures presents a clear evolution according to their composition and contact relationships with the host mantle: the porous flow structures are shallow dipping, the troctolitic proto-dykes become vertical but have no preferential azimuth, the troctolite and olivine-gabbro dykes are vertical and their azimuth parallels, on average, that of the sheeted dykes complex, *i.e.* the azimuth of the former spreading ridge. This evolution reflects the increasing influence of the lithospheric stress field on the geometry of the melt plumbing system as temperature decreases.

In conclusion, the fact that dykes are the most abundant macroscopic melt migration features observed in the mantle section of ophiolites cannot be used as an evidence for dyking in the asthenosphere. It simply results from the fact that a large proportion of the volume of cumulates crystallizing from a MORB at low pressure occurs along the three phases (olivine, plagioclase, clinopyroxene) cotectic, when the melt is already focused into dykes, the volume of melt crystallizing in porous flow structures being much less.

3. Influence of lithological heterogeneities on the melt trajectory

Melt migration in the asthenosphere is governed by the laws of two-phase flow involving a ductile solid (peridotite matrix) and an interstitial silicate melt. The non-linear dependence of the bulk viscosity of this medium on the melt/rock ratio induces a positive feedback loop that will enhance any local porosity variation and hence focus and maintain the melt in porous flow channels (Scott and Stevenson, 1986; Khodakovskii *et al.*, 1995).

Field observations and numerical simulations show that the formation of these channels is triggered by infiltration melting (Aharonov *et al.*, 1995; Morgan and Liang, 2005; Rabinowicz and Ceuleneer, 2005; Pec *et al.*, 2017) resulting from the disequilibrium between the liquid and the solid phases (mostly orthopyroxene), a process that will significantly increase the porosity and the permeability. The possible origins of the disequilibrium leading to the formation of dunitic channels (the most common among the melt channels) will be discussed in the next section.

Numerical models and laboratory experiments show that the trajectory of the interstitial melt is determined by the deviatoric stress field associated with the convective flow and compaction of the solid matrix (*e.g.* Scott and Stevenson, 1986; Spiegelman and McKenzie, 1987; Rabinowicz *et al.*, 1987; Liang *et al.*, 2010; Baltzel *et al.*, 2015; Rees Jones *et al.*, 2021). Therefore, the idea that the geometry of the melt plumbing system can be predicted, governed solely by the stress field "and not by any pattern inherent in the host rock" (Holtzman *et al.*, 2003), became a common view. In contrast, the observation of melt migration structures has contributed to the view that the melt trajectory in the mantle is strongly influenced by such a pattern.

In most situations, the melt migration features we observe in the field are only small segments of a much larger melt migration network. It is exceptional to have the opportunity to follow the former melt path on distances exceeding a few meters and to observe branching relationships allowing us to better figure out the general architecture of the melt plumbing system. In this context, the discovery of a "Rosetta stone" such as
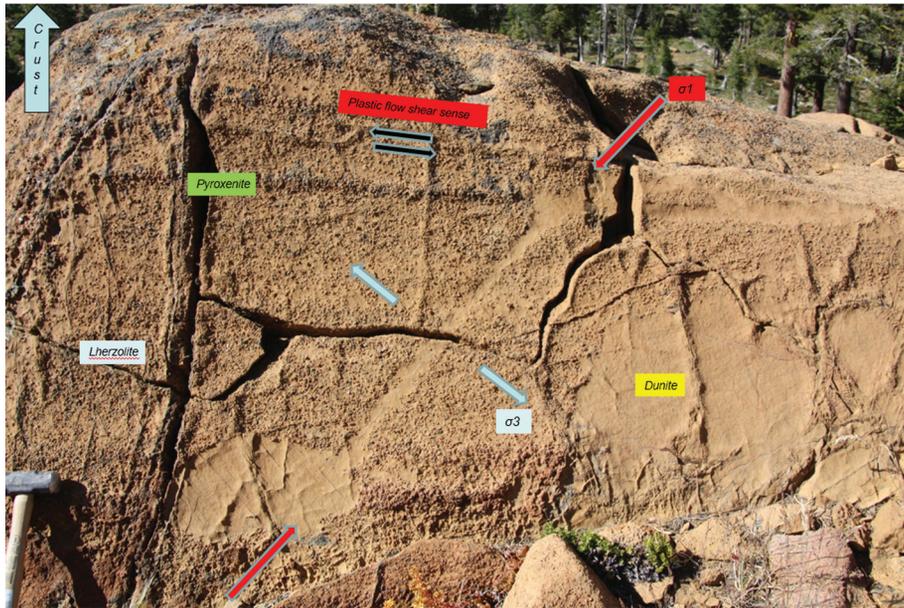
Fig. 14. Outcrop in the Trinity peridotite showing the impact of lithological heterogeneities (here pyroxenite layering) on the melt trajectories. For explanations, see the text. Redrawn from a paper by Ceuleneer *et al.* (2022), published in the journal *Geology*.

the outcrop shown in Fig. 14, where nicely preserved structures are exposed and speak by themselves, is quite exceptional.

This outcrop is located in the mantle section of the Trinity ophiolite, where the interpretation of the structures is made easier thanks to the lack of regional metamorphism and deformation and to the global preservation of the bottom-to-top polarity (Quick, 1981a; le Sueur *et al.*, 1984). Here is the message delivered by this outcrop (Ceuleneer *et al.*, 2022).

A migrating melt in disequilibrium with the lherzolite (rock with a rugged surface in Fig. 14) has locally dissolved the pyroxenes leaving a dunitic residue (rock with a smooth surface). Dunite distribution reveals the melt trajectory assuming that the general tendency of the buoyant melt was to find its way to the surface. In the lower part of the outcrop, we see that the liquid pooled in rounded structures, which may result from the self-organization of the interstitial melt in a compacting matrix (*e.g.* Rabinowicz and Ceuleneer, 2005). A thin dunitic channel highly oblique to the horizontal (∼45°) rooted in one of these pockets and drained the melt upward. The channel orientation is consistent with the stress field induced by weak sinistral shearing experienced by the lherzolite there (le Sueur *et al.*, 1984; see also Fig. 2b). The orientation of the dunitic vein changes suddenly where it reaches a sub-horizontal pyroxenite layer, becoming parallel to this layer. This behaviour is consistent with the abrupt permeability increase

caused by the dissolution of the pyroxenite layer, consisting entirely of crystals soluble in the migrating melt.

Generally, models consider a homogeneous distribution of pyroxenes in the host peridotite. Variations in the pyroxene content of the host rock have been taken into account in some simulations (Schimenz *et al.*, 2011) but they do not concern such abrupt contrasts as in the case of pyroxenite layering. As a consequence, the orientation of the high-permeability channels predicted by the models is still governed by the stress field.

The outcrop shown in Fig. 14 reveals that, in a natural situation, the melt has favoured a trajectory following the high-permeability channel it has itself generated, *i.e.* the former pyroxenite layer, as long as the disequilibrium between the melt and the pyroxenes has not been neutralized by the reaction. The outcrop reveals another interesting feature: the melt has progressed towards a single direction (to the right) which is consistent with the pressure gradient induced by the sinistral shearing. Accordingly, the stress field related to the plastic deformation did not lose control completely on the melt trajectory.

This unique preservation of a snapshot of a transient situation allowed us to understand the origin of more diffuse, partly resorbed, pyroxenite layers that are abundant in the thick tabular dunites of Trinity. They are relics of the process described above, although frozen at a later, more advanced stage of development (Ceuleneer *et al.*, 2022).

Thanks to this outcrop, we have learned that melt trajectory in the mantle is governed by the trade-off between the imposed stress field and the petrological processes. The result is the development of a network of interweaved channels. The thick horizon of tabular dunite commonly observed in ophiolites (*e.g.* Quick, 1981b) may result from the dissolution of closely spaced pyroxenite layers that are common features in mantle peridotite (*e.g.* Le Roux *et al.*, 2016; Tilhac *et al.*, 2016). One of the consequences of this double control on the melt trajectory is that the topology of the plumbing system is hard to predict, as the nature, shape, orientation and distribution of the lithological heterogeneities are inherited from a long petrological and structural history.

4. Initiation of dunitic porous flow channels: the concept of 'pioneer melts'

Returning to the petrological origin of the dunitic channels, the simplest hypothesis is that the melt responsible for the incongruent melting of pyroxenes is the melt produced in the melting region and feeding the crustal section, *i.e.* tholeiites, andesite, boninites or other magma types, depending on the tectono-magmatic setting of formation. The minerals making up the dunite (olivine, chrome spinel $\pm$ minor interstitial pyroxene and plagioclase) are broadly in chemical equilibrium with such common melts (*e.g.* Kelemen *et al.*, 1995; Suhr *et al.*, 2003; Ceuleneer and le Sueur, 2008; Abily and Ceuleneer, 2013).

Initially, a partial melt is in equilibrium with its mantle source. When the porosity exceeds a permeability threshold, which is achieved for a melt amount that does not exceed a few percent (*e.g.* Zhu *et al.*, 2011), the melt will migrate upwards at a faster

rate than the upwelling rate of its host solid mantle. Due to the pressure dependence of its multiple saturation composition, the melt becomes progressively out of equilibrium with the peridotite assemblage from which it was issued. In the case of primitive MORB (olivine tholeiites) the pressure dependence concerns essentially silica and magnesium: the lower the pressure, the greater are the SiO_2 and the lesser are the MgO concentrations in the equilibrium, multiply saturated melt (Stolper, 1980). To reach a new equilibrium, the melt will permanently readjust its composition through the incongruent melting of orthopyroxene associated with the precipitation of olivine, a process that will increase the SiO_2 concentration and reduce the MgO content of the melt and leave a solid residue made of dunite.

This hypothesis of 'self-digestion' of the mantle by its own melt is currently the favoured paradigm for the formation of dunite channels. It is a simple and elegant mechanism but recent data on mineral inclusions in chromite grains scattered in the dunites (Rospabé *et al.,* 2017, 2021; Ceuleneer *et al.*, 2022) and bulk-rock ultra-trace elements data on dunite (Rospabé *et al.*, 2018) show that the natural rocks record a more complex history, at least in the case of dunites that formed in the shallowest part of the mantle as those exposed in ophiolites.

Pyroxene has significant contents in various minor and trace elements that will be released during the incongruent melting reaction. Among these elements is chromium, the solubility of which in silicate melts is quite small (Roeder and Reynolds, 1991) and it is not well accommodated by the crystallographic network of olivine. Consequently, as soon as liberated, it will crystallize as chromite on, or close to, the site of the reaction. These neo-formed chromite grains can encapsulate tiny minerals as microliths present in the melt, and/or the melt itself, during their growth and preserve these inclusions from further modification at the contact with later percolating melts. These inclusions are thus privileged witnesses of the nature of the corrosive melt that acted at the earliest stage of formation of the dunite channels.

An exhaustive survey of these mineral inclusions in chromite from the dunites of the Oman ophiolite, in a MORB magmatic context has been performed (Rospabé *et al.*, 2017, 2018, 2019a,b, 2020, 2021), and from the Trinity ophiolite, in an andesitic-boninitic context (Ceuleneer *et al.*, 2022). Surprisingly, in both cases, the minerals included contrast significantly in nature and relative abundance with interstitial ones present in the dunitic matrix. In Oman, the minerals in inclusions are, excluding low-temperature alteration products such as serpentine and chlorite, by decreasing order of abundance, pargasitic amphibole, Mg-Fe clinopyroxene, pure magnesian diopside, micas (both sodic and potassic), olivine, orthopyroxene and much less frequently garnet, plagioclase, jadeite, nepheline, albite, chlorapatite and pectolite (Fig. 15). In Trinity, minerals included in chromite are, by decreasing abundance, pargasitic amphibole, potassic and sodic micas, clinopyroxene and pure diopside, orthopyroxene, olivine and plagioclase.

These minerals assemblages, however they were entrapped as solid inclusions, crystallized from entrapped melt, or a mixture of melt and microcrystals (*cf.* discussion by Rospabé *et al.*, 2021), cannot be considered as common crystallization products of the dominant melt that percolated through the mantle. Those authors pointed out the existence of a fluid rich in water, silica and alkali elements. The common presence of micas is
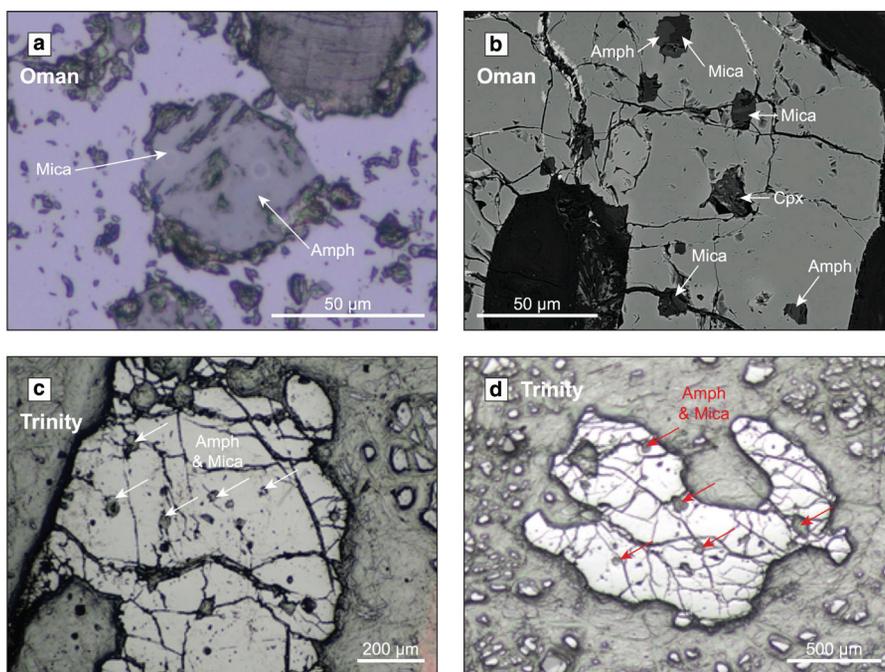
Fig. 15. Mineral inclusions in scattered chrome-spinel grains in the dunite of Oman (*a,b*) and Trinity (*c,d*). Part a is modified from Rospabé *et al.* (2020) and part b from Rospabé *et al.* (2021). Parts c and d, unpublished, are associated with the publication by Ceuleneer *et al.* (2022).

probably the most puzzling observation as these minerals are totally absent from the interstitial minerals in the host dunite and peridotite, as well as in crustal cumulates in both ophiolites. Moreover, the crystallization of potassic micas implies a K-rich source that cannot be the MORB melt or the high-Mg andesite melt, which are both strongly depleted in this element. To solve this paradox, we have proposed that the dunites are generated through the action of an "exotic agent" issued from the hybridization between a common melt and a hydrous fluid rich in alkali elements (Rospabé *et al.*, 2017).

The existence of mineral inclusions in chrome spinel pointing to the involvement of a hydrous fluid during their crystallization was well documented by a wealth of previous studies (see review by Gonzalez-Jimenez *et al.*, 2014). However, that study was considered to be specific to the chromite ore bodies while our survey has revealed that the chrome spinel scattered in reactive dunites contained the same sort, diversity and abundance of included minerals, with a significantly more variable chemical composition, and thus probably shared a common igneous origin with chromitites (Rospabé *et al.*, 2021).

For the same melt/rock ratio, a dunite has a greater permeability than a peridotite due to differences in wetting properties of olivine and pyroxenes (Toramaru and Fujii, 1986). Once formed, a dunite becomes a preferential channel for melt migration in the mantle. Accordingly, the melt forming the dunite can be considered a "pioneer melt" (Ceuleneer

et al., 2022) opening the gates to the eventual migration of the volumetrically dominant, basaltic or andesitic magmas formed in the deeper partial melting regions. Consequently, the mineral composition of dunite will be permanently readjusted during this long history of melt percolation (*i.e.* interstitial minerals crystallize or re-equilibrate with the last migrating melt fraction), although inclusions protected in chrome spinel will maintain the memory of the initial stage of dunite genesis, hence the difficulty in determining their origin.

The pioneer melt may be considered a 'universal solvent' that can be produced in various settings, based on the similar nature and composition of inclusions encapsulated in chrome spinel in contrasting Oman and Trinity ophiolites, as discussed above. The condition needed for its formation is an environment favourable to the hybridization between a mafic melt, whatever its precise composition, and a hydrous fluid or a water-rich silicic melt rich in alkali elements, whatever its origin. The concept of pioneer melts allows us to explain the ubiquitous occurrence of dunite, the initial formation of which would not be related to the composition and thermodynamic properties of a specific magma type and thus to a specific tectonic setting. As a matter of fact, dunites are common in many tectonic settings, including mid-ocean ridges, subduction zones and intra-plate ocean island setting.

The origin of alkali-rich hydrous fluid/melt could be either deep or shallow. For example, it can be liberated at the very early stages of decompression melting in a mantle upwelling, and eventually mix with the melt fractions issued from different degrees of melting, forming a network of anastomosing dunite channels preceding the progress of the upwelling (Fig. 16a). At the other extremity of the spectrum, the origin of the fluids may be hydrothermal and the hybridization occurs at Moho level (Fig. 16b).

5. The Moho as a major reactive filter between the depth and the surface

We have seen that dunites are major actors of the genesis of mafic magmas. They play a double role as their formation impacts both the composition and the migration of the partial melts. In ophiolites, dunites are particularly abundant at Moho level where they form a spectacular geological body, the so-called "Dunitic Transition Zone" or "DTZ" (Abily and Ceuleneer, 2013), at the interface between the mantle peridotites and the layered cumulates from the lower crustal section (Fig. 17a).

The DTZ thickness is extremely variable from one ophiolite to the others and along a single ophiolite, ranging from a few meters to > 1 km (*e.g.* Moores and Vine, 1971; Greenbaum, 1972; Ceuleneer, 1991; Boudier and Nicolas, 1995; Akizawa and Arai, 2009; Marchesi *et al.*, 2009; Negishi *et al.*, 2013; Rospabé, 2018). In the Oman ophiolite, these variations have been related to mantle diapirism. A thick DTZ develops at the top of diapirs soaked with melt and impinging the axial lithospheric lid (Rabinowicz *et al.*, 1987; Boudier and Nicolas, 1995). A thinner DTZ results either from tectonic thinning during its transposition off-axis or from lesser magma supply away from the centre of the diapirs (Ceuleneer, 1991; Jousselin *et al.*, 2000).
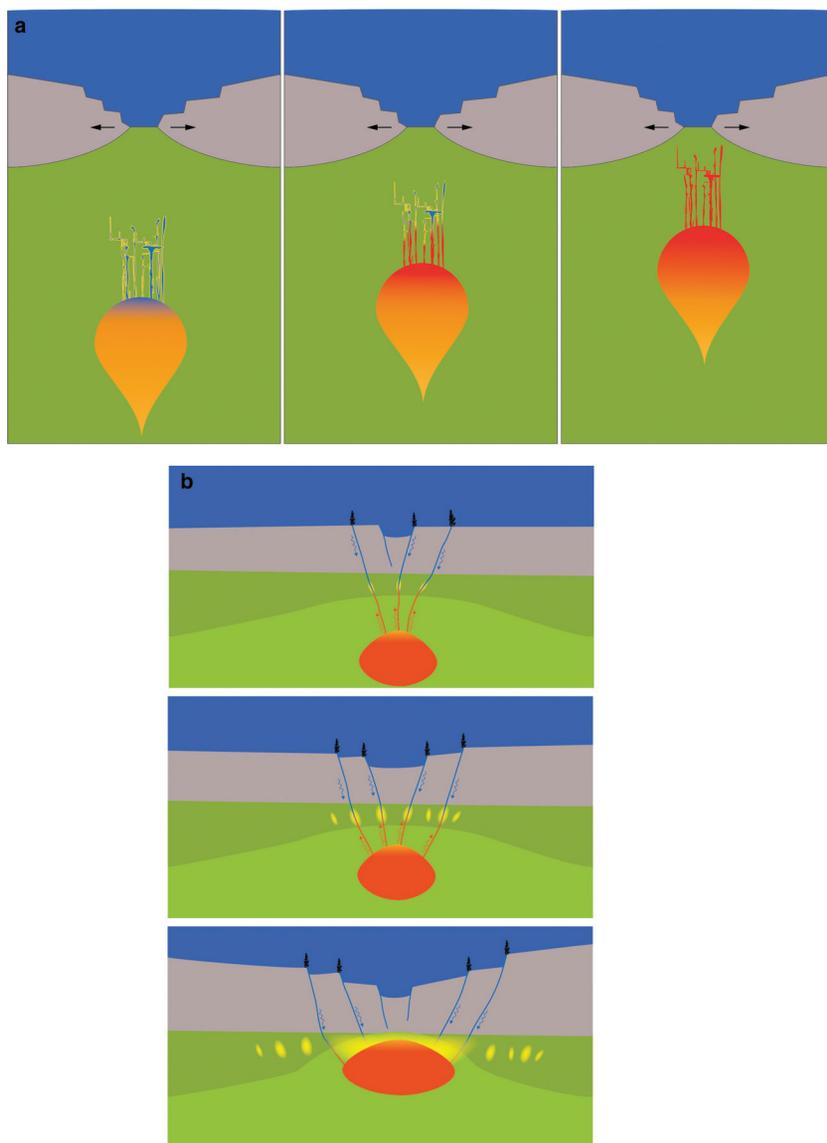
Fig. 16. Sketches illustrating the two possible origins of the hybrid 'pioneer melt': (***a***) mafic melts mix with hydrous fluids or melts saturated in water issued from very low-degree melting at the top of a rising diapir; (***b***) mafic melts mix with hydrothermal fluids reaching the Moho level along syn-magmatic faults.

5.1. Dry origin of the Dunitic Transition Zone

Initially, the genesis of the DTZ was envisioned in a dry igneous system and the debate concerning their origin was focused on two competing hypotheses (Nicolas and
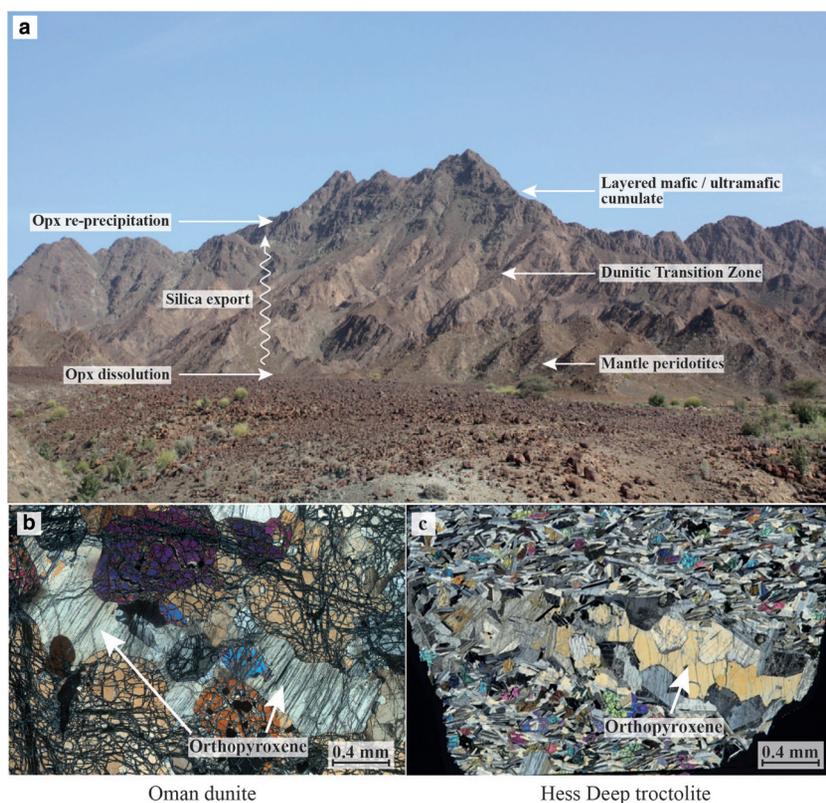
Fig. 17. (***a***) The dunitic transition zone (DTZ) in the Oman ophiolite. The altitude difference between the foothill and the summits is ~400 m. (***b***) Interstitial orthopyroxene in dunite at the top of the DTZ (reproduced from a paper by Rospabé *et al.*, 2017, published in the journal *Geology*). (***c***) Orthopyroxene with an identical texture in the lower troctolites form the East-Pacific Rise (Hess Deep Area). Picture taken onboard the JOIDES Resolution during IODP-Expedition 345 (Gillis *et al.* 2014).

Prinzhofer, 1983): (1) the DTZ is a thick pile of ultramafic cumulates composed essentially of olivine ($\pm$ minor chromite, pyroxene and/or plagioclase) and lining the bottom of magma chambers; (2) the DTZ is former mantle harzburgites that lost their orthopyroxene due to reaction with a mafic magma undersaturated in this mineral.

According to the first hypothesis, the mantle must be able to produce, by decompression melting, a highly magnesian (MgO > 15%), picritic melt that calls for high potential mantle temperatures, equal or exceeding 1450°C (O'Hara, 1965; Elthon, 1979); the massive crystallization of olivine before eruption, including the formation of the DTZ, would explain why such melts never reach the surface. According to the second hypothesis, there is no need to invoke a picritic parent melt, primary MORB could be close in composition to the most magnesian glasses sampled along present-day mid-ocean ridges (~10% MgO) (Presnall *et al.*, 1979) and the mantle potential temperature away from hot spots would not exceed ~1300°C (McKenzie and Bickle, 1988).

The microstructure of the dunite is very useful for identifying the imprint of plastic deformation, if any, but is not a conclusive argument for the petrological origin of dunite, as a cumulate can eventually experience plastic deformation after its crystallization and a mantle tectonite can experience static recrystallization and recovery if maintained at high temperature after the cessation of plastic deformation.

In theory, the composition of minerals making up the dunites should be more helpful but these compositions are usually quite variable and present a marked scatter in classical diagrams designed to decipher between partial melting and fractional crystallization so that, here again, it is difficult to conclude (Fig. 18a).

A petrological profile through a 330 m-thick DTZ in the Oman ophiolite has revealed that the mineral composition data deliver a much clearer message when obtained on samples well localized vertically along a cross section than on samples collected randomly. To illustrate this by a simple example inspired by the study of Abily and Ceuleneer (2013) (Fig. 18b), the forsterite content in olivine (Fo) increases from ∼88 at the base of the DTZ to ∼91 about 50 m above. Along the same interval, the NiO content of olivine decreases from ∼0.35 to ∼0.20. This 'spatial' negative correlation allows us to exclude a cumulative origin for this horizon but is consistent with the reaction leading to the incongruent melting of opx. As a matter of fact, opx has a slightly higher #Mg than an olivine with which it is in equilibrium but the Ni content of opx is much lower than that of olivine.

Olivine in a dunite issued from infiltration melting of a peridotite has three possible origins: (1) pristine olivine from the residual mantle; (2) cumulate olivine product of the direct crystallization from the infiltrating melt; and (3) olivine neo-formed during the incongruent melting of opx. If the infiltrating melt is a MORB, residual mantle olivine (case 1) and early cumulate olivine from the primitive interstitial melt (case 2) will share similar ranges of Fo and NiO contents. However, the neo-formed olivine after opx dissolution (case 3) will have larger Fo and smaller NiO contents.

Due to efficient diffusion of bivalent ions in olivine at high temperature and in the interstitial melt, the olivine composition will be rapidly homogenized at a scale largely exceeding the grain size. As a matter of fact, the olivine composition determined in a thin section of dunite is homogeneous and theoretically corresponds to the averaged contribution of the olivine of different origins. In this frame, the evolution of the dunite mineral composition in the 50-thick basal section of the DTZ records an increasing contribution of neo-formed olivine from bottom to top.

At the top of the DTZ, the olivine composition in a 50 m-thick upper layer shows a reverse trend: the classical decrease in Fo positively correlated to a decrease in the NiO content predicted for fractional crystallization from a primitive MORB. In between, the dunite shows globally constant Fo and NiO on a thickness of ∼200 m. This allows us to propose that both processes, fractional crystallization and melt-rock reaction concur to form the DTZ, but not at the same level. The upper layer can be considered as a ∼50 m pile of ultramafic cumulate crystallized from a primitive melt before the melt is fractionated sufficiently to reach the crystallization field of gabbros. The basal layer fossilized a snapshot of the transformation of mantle peridotite into dunite. The 200 m-thick dunite sandwiched by the basal and top layers was likely a zone of intense melt
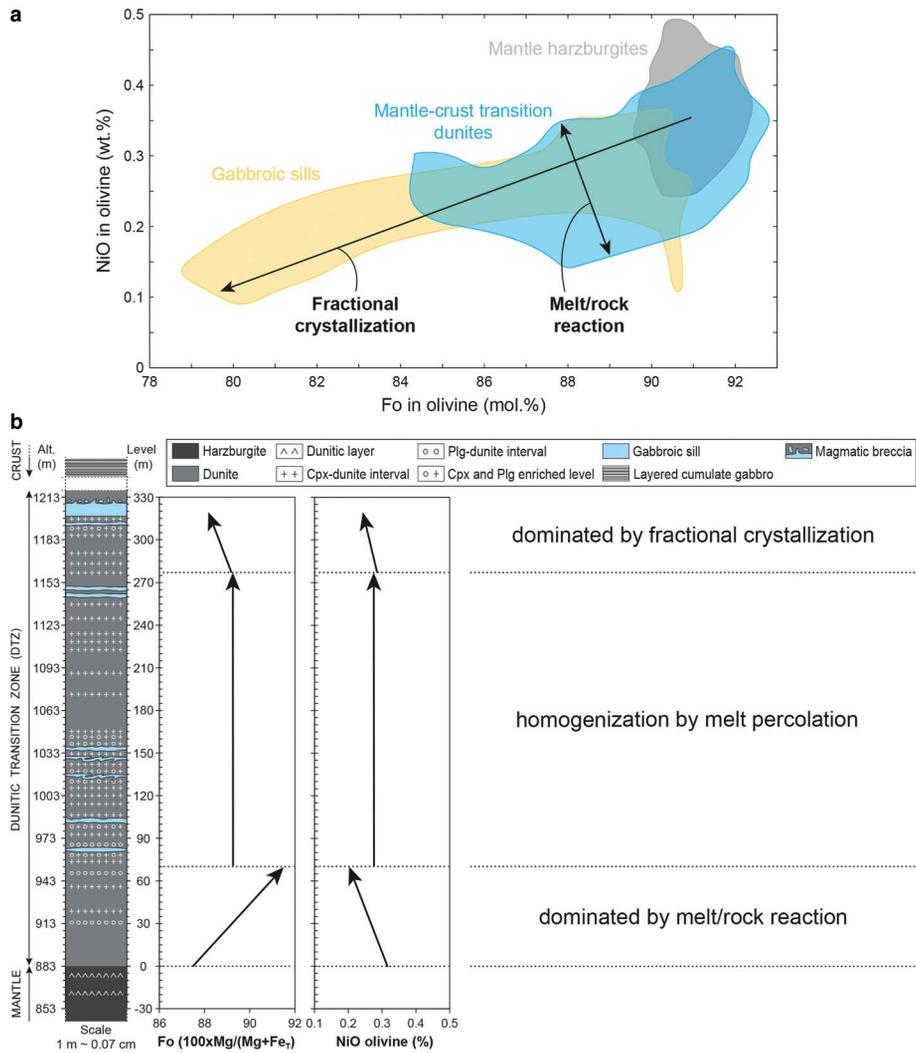
Fig. 18. Olivine composition in the Maqsad DTZ showing how the relationships between the Fo and the Ni variations along the vertical bring simple arguments to decipher between melt–rock reaction and fractional crystallization. For explanations, see the text and the work by Abily and Ceuleneer (2013).

percolation where the olivine composition was buffered and in equilibrium with moderately evolved MORB (see Abily and Ceuleneer, 2013 for further arguments).

5.2. Wet origin of the Dunitic Transition Zone

The "dry" scenario proposed by Abily and Ceuleneer (2013) was inspired by the petrological evolution along a single cross section. With the aim of testing its general validity,

at least for the MORB igneous context of the Maqsad area of Oman, we extended the exercise along some twenty additional cross sections at different distances from the Maqsad diapir (Rospabé, 2018; Rospabé *et al.*, 2017, 2018, 2019a,b, 2021). The conclusion is that the variation patterns of both mineral and bulk-rock compositions present a marked variability from one cross section to the others. There are some invariant characteristics as zigzag patterns defined by the geochemical indexes with a characteristic vertical interval of 50 m and a general tendency toward more evolved compositions upward (*i.e.* lower Ni content in olivine, higher Ti content in spinel and pyroxene), but in the detail, a scenario specific to the genesis and evolution of each cross section could be proposed. The ultimate cause of this geochemical variability is to be looked for in the complexity, in space and time, of the coupling between physical and petrological processes during the final stages of transfer of the magma from the mantle to the crust.

Although it has some exceptions, another general conclusion of our survey is that the presence of interstitial minerals between olivine grains (plagioclase, clinopyroxene, orthopyroxene, amphibole) increases up-section along most of the cross-sections we sampled, with a greater abundance of phases that crystallized from melts richer in silica (orthopyroxene) and water (amphibole) approaching the top of the DTZ.

Moreover, among the characteristics shared by all cross sections is the widespread occurrence of mineral inclusions in chromite grains that led us to conclude that the initial stages of dunite formation should be attributed to an exotic melt different from the MORB that migrated in the diapir and fed the crustal section. This 'pioneer melt' evoked above has the characteristics of a hybrid melt between mafic silicate melts and hydrous, silica and alkali-rich fluids. There is a body of corroborating evidence, mineralogical, geochemical and structural, for an origin of these fluids '*per descensum*'. Consequently, a scenario for the formation of the DTZ must welcome a new component: hydrothermal fluids.

In Oman, geological and petrological observations provided evidence of the early, synmagmatic development of faults. Figure 19 shows an example of a ductile normal fault rooting and refracting in a partly crystallized troctolite intrusion in the Maqsad DTZ. Plastic deformation is intense in the steeply dipping part of the fault and evolves to magmatic deformation in the shallow-dipping part of the fault.

Such faults both disturbed the surrounding crystallizing molten rocks and permitted the deep introduction of seawater-derived fluids (Abily *et al.*, 2011; Rospabé, 2018; Rosapbé *et al.*, 2019a; Sauter *et al.*, 2021; Abily *et al.*, 2022). A compelling example displays adjacent gabbroic blocks with variably dipping and folded layers, showing sutured contacts (*i.e.* reassembled under magmatic conditions), associated with recrystallized pegmatitic gabbros and anorthite content in plagioclase buffered to high values indicating a (re)crystallization under hydrous conditions (Abily *et al.*, 2011). Syn-magmatic faults deformed the crystallizing gabbros, influenced the crystallization paths and chemical compositions by introducing hydrothermal fluids along fault planes, and are responsible for the local copper mineralization at lower-greenschist-facies conditions following the magmatic activity.
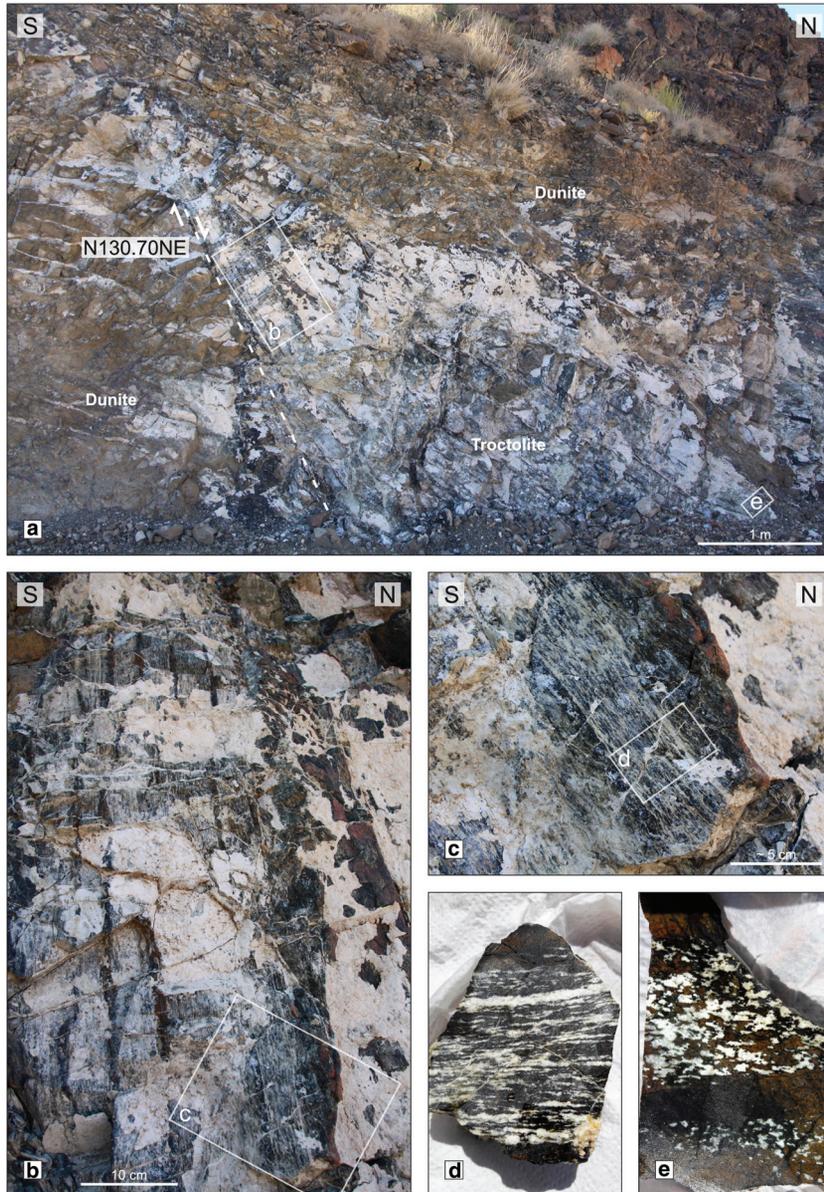
Fig. 19. Ductile to syn-magmatic fault in the Maqsad DTZ at the contact between the dunites and a troctolitic intrusion (modified after Rospabé, 2018). (*a*) General view of the outcrop: the fault strikes N130°E, parallel to the former ridge direction; the shear sense is clearly normal. (*b,c*) Details of the gabbros deformed plastically. (*d,e*) Hand specimens showing the contrast between the flaser texture of the troctolite from the steeply dipping part of the fault and the fluidal texture (with euhedral plagioclase laths) of the basal, weakly dipping part of the troctolite intrusion, away from the ductile fault.

In the case of the DTZ, the ~50 m characteristic distance in the zigzag pattern of the geochemical indexes appears to be controlled by faults (Fig. 20). For example, well-defined and continuous evolutions (increase or decrease) of REE are observed over tens of metres approaching the faults, including in 'pure' dunites (*i.e.* only olivine and minor chromite, thus the whole-rock REE signature is assumed to be hosted by olivine) (Fig. 20). This concerns also elements such as Ti supposedly immobile or not mobilized by low temperature alteration processes (*e.g.* Pearce and Norry, 1979). In the context of cryptic metasomatism (see above section 2.2.1), this simple observation allowed these faults to be qualified as synmagmatic that influenced heavily melt migration at the mantle-crust transition zone, which ultimately influenced the geochemical signatures of dunites. A strong increase in the hydrated imprint approaching the base of the crust is evidenced by the greater abundance, up-section, of both: (1) interstitial minerals indicative of a variably hydrous parent melt (orthopyroxene, amphibole) (Rospabé *et al.*, 2018, 2019a); and (2) exotic silicate inclusions in chromite (*e.g.* sodic nepheline, pure albite, chlorapatite, orthopyroxene, in addition to the widespread occurrence of amphibole and clinopyroxene) (Rospabé *et al.*, 2020, 2021). This mineralogy is absent deeper in the mantle section, allowing interpretation of the pioneer melt involved in the harzburgite dunitization as a blend between: (1) an ascending, relatively dry, MORB issued from the deep decompression melting within the Maqsad diapir; and (2) descending seawater-derived fluids introduced by early faulting (or silica-rich melt/fluids issued from hydrated partial melting of country rocks thanks to the presence of such fluids).

The capacity of high temperature (> 600°C, *i.e.* above the stability field of serpentine) hydrous fluids to create dunite by dissolving the pyroxene contained in a peridotite was first demonstrated experimentally by Bowen and Tuttle (1949). This major discovery was
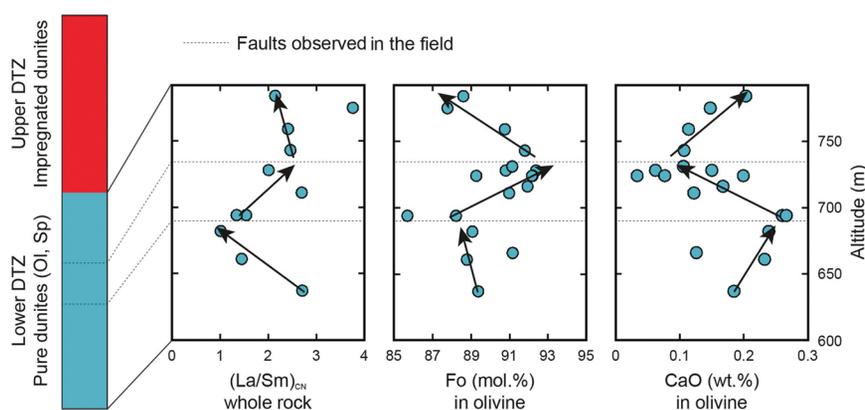

Fig. 20. Vertical chemical evolution along the lower part of the DTZ in the Maqsad area, Oman. Compositions evolve over a scale of a few tens of metres, increasing or decreasing, then shifting to the reverse trend. Shifts correlate with the location of faults observed in the field, interpreted as faults developed syn-magmatically (modified after Rospabé *et al.*, 2019a).

actually fortuitous: *"We pointed out that silica was abstracted from some of our charges by water vapour and that when it was imperative that no change of composition of the charge should occur special precautions were necessary to prevent this transport of SiO_2. Thus after heating synthetic enstatite at 725°C and 22,500 lbs/in^2 pressure of water vapour for two days it was found that some of the enstatite was transformed to forsterite, when no precautions were taken against removal of silica by water vapour."* (Bowen and Tuttle, 1949).

This process of silica removal assisted by water vapour perfectly reproduces what we observe in nature at a larger scale (hundreds of metres): the opx experiences incongruent melting due to percolation of hydrous fluids in the mantle peridotite as attested by inclusions in neo-formed chromite. Silica is transported upward *via* a supercritical phase (blend of water and silicate melt) and combined with olivine to form new magmatic opx in the uppermost part of the DTZ where and when the temperature is low enough (Fig. 17a). This opx contrasts in texture and composition with the residual, porphyroclastic opx from mantle peridotite: it has an interstitial habit (Fig. 17b) and is richer in TiO_2 (Rospabé *et al.* 2017). Large opx crystals sharing the same interstitial habit occur in the lower troctolitic and gabbroic primitive cumulates from the East Pacific Rise drilled at Hess Deep (Gillis *et al.*, 2014). As in the Oman DTZ they cannot crystallize from primitive MORB and are interpreted as products of an interstitial melt the origin of which is discussed, but that cannot be attributed to a subduction zone environment as currently supposed in the case of ophiolite (see Benoit *et al.*, 1999; Nonnotte *et al.*, 2005). Bowen and Tuttle's experiments were performed in a simplified, synthetic system (in this case, MgO-SiO_2-H_2O). Our data on natural systems show that the fluids were not only rich in water and silica but also in many incompatible elements of double origin, *e.g.* hydrothermal for potassium and magmatic for titanium.

6. Some consequences for chemical geodynamics

This paper is a contribution to an EMU volume devoted to the exploration of *"New paradigms in chemical geodynamics"*. Geodynamics was defined as a branch of Earth sciences more than one century ago (Love, 1911). The concept of chemical geodynamics was introduced more recently with the stated goal of "(…) taking another look on the Earth's evolution, the one of the chemist" (translated from Allègre, 1980, p. 87). This cross-fertilization between geophysics and geochemistry resulted in major advances in our representation of the inner parts of the Earth.

The pioneers of chemical geodynamics were primarily isotope geochemists. As a main working hypothesis, they considered that the isotopic composition of a lava mirrors that of its deep mantle sources. This assumption was justified by the absence of measurable (at that time) radiogenic isotope fractionation of the heavy elements during partial melting and by the slowness of diffusion in the solid mantle (*e.g.* Hofmann and Hart, 1978; Zindler and Hart, 1986). The melt migration and petrological processes were treated as black boxes, which was reasonable as a first approach.

We have seen that the real world is far more complex: the composition of a melt can evolve during its long journey to the surface for various reasons including mixing of incremental melt fractions, interaction with the wall rocks and crystallization and/or resorption of mineral phases. Some of these processes have, potentially, an impact on the isotopic composition of the melt. It is thus likely that the geochemical signature of lavas or plutonic rocks is not entirely inherited from a single deep source but is acquired all along the ascent and evolution of their parent melt.

Mixing between various mantle reservoirs was envisioned in early chemical geodynamics models but not (or rarely, *e.g.* Wood, 1979; Hirschmann and Stolper, 1996) connected to the lithological nature of these reservoir (mostly peridotite *vs.* pyroxenite and eclogite) nor to the actual petrogenetic reactions themselves whose impact was underestimated, when not ignored, as stressed by O'Hara and Herzberg (2002). In fact, the message brought by the rocks exposed in ophiolites was considered inextricable and the geological observations too qualitative to be integrated in simple but global and quantitative models, which is partly true, and of local and anecdotic relevance, which is definitely untrue.

There is a general consensus that infiltration melting is a major way for a partial melt to migrate in the mantle. We have seen that the reaction triggering infiltration occurs essentially at the expense of pyroxenes, which are among the main hosts of the trace elements whose isotopic compositions are used in chemical geodynamics. Pyroxenes have two contrasting modes of occurrence in the mantle: scattered in the peridotite and concentrated in pyroxenite layers. It is well established that pyroxenite and peridotite coexisting in outcrops of mantle rocks have in most cases different isotopic signatures (*e.g.* Rampone and Hofmann, 2012; Borghini *et al.*, 2021). Various degrees of mixing between melts issued from the peridotite and the pyroxenite will contribute to the variability of the isotopic signature of lavas and of their crystallization products. A general difficulty is to decipher which part of the isotopic variability of a lava is inherited from the intrinsic heterogeneity of the peridotite and which part must be attributed to the contribution of pyroxenites, the isotopic composition of which is highly variable too (cf. Lambart *et al.*, 2019; Borghini *et al.*, 2021).

When envisioned in chemical geodynamic models, the contribution of a pyroxenite to the composition and isotopic signature of a melt is supposed to occur by mixing in the partial melting region as initially proposed by Wood (1979). A pyroxenite, being less refractory than a peridotite, can potentially be a major source of melt even present in minor amounts in the source; Lambart *et al.* (2009) estimated, on the basis of partial melting experiments, that just 5% pyroxenite layers in a mantle peridotite may account for 40% of the melt production. Accordingly, pyroxenite and peridotite might be equivalent contributors to the isotopic signature of lavas.

Field evidence presented above show that direct, decompression melting, is not the only way in which a pyroxenite may contribute to melt composition. We have seen that, due to the coupling between the petrological processes (infiltration melting) and the physical parameters (porosity and permeability), pyroxenite layers present at shallow level in the mantle may lead to deviation of the melt trajectory and become preferential 'avenues' for melt migration. As a consequence, the contribution of the

pyroxenite source to the melt composition will be even greater than that predicted in the case of melting and mixing in the deep-seated regions of partial melting. In addition, it is most likely that the shallow pyroxenite layers at the base of the lithosphere and invaded by melts from below will have an isotopic signature different from those of the peridotite and pyroxenite melted at depth. The isotopic variability should, in that case, be interpreted *a minima* in terms of a three-component source, *i.e.* result from mixing of two deep heterogeneous reservoirs and a shallower one (heterogeneous also).

The network of interweaved channels induced by the competition between the stress field and infiltration melting of the pyroxenite layers or other lithological heterogeneities will considerably increase the reaction surface between the migrating melt and its solid host, enhancing the role of reactive filter of the shallow mantle.

As far as we know from field observations, the development of these reactions culminates at Moho level. There, the formation of the dunitic transition zone implies destabilization of huge amounts of pyroxenes. It will mobilize a wealth of minor and trace elements preferentially hosted by these minerals. The dissolution of pyroxenes is initiated by what we have referred to as the pioneer melt which is, at these shallow levels, a hybrid between mafic magmas and hydrous fluids of hydrothermal origin. Accordingly, the seawater reservoir must be integrated into the scenarios interpreting the isotopic signature of the igneous rocks formed at oceanic spreading centres. This was initially suggested by Benoit *et al.* (1999) and Nonnotte *et al.* (2005) in the case of the Sr isotopic signature of cumulates from the Oman ophiolite and from the Mid-Atlantic Ridge.

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