

A Rosetta stone linking melt trajectories in the mantle to the stress field and lithological heterogeneities (Trinity ophiolite, California)

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ABSTRACT

Infiltration triggered by selective dissolution of pyroxenes is a major mode of melt migration in the mantle. A common view, supported by experiments and numerical models, is that the geometry of the melt plumbing system is governed by the stress field induced by solid-state flow of the host peridotite. Yet, salient melt migration structures frozen at an early stage of development in the mantle section of the Trinity ophiolite reveal that lithological heterogeneities drastically impact melt trajectories. Where melts reach a pyroxenite layer, dissolution-induced permeability abruptly increases, initiating a feedback loop confining melt migration to that layer regardless of its orientation relative to the stress field. This process results in the development of a network of interweaved dunitic channels evolving to thick tabular dunites where the melt reacts with closely spaced pyroxenite layers. This reacting melt was rich in alkali elements and water, as evidenced by the minerals (mostly amphibole and micas) encapsulated in the Cr-spinel grains that crystallized during the reaction. This “pioneer melt” differs from the volumetrically dominant depleted andesite that fed the crustal section. In fact, the migration of andesite benefited from the enhanced permeability provided by the dunites formed by the pioneer melt. As a result, dunites are palimpsests, the compositions of which record successive percolation events. The geometry of the melt pathways is extremely challenging to model because the abundance, spacing, and orientation of lithological heterogeneities cannot be predicted, being inherited from a long geological history.

INTRODUCTION

Most lavas erupted at Earth's surface derive from partial melting of the mantle and subsequent melt extraction and migration. Field and petrological evidence shows that melt migration is ruled by porous-flow channels at the high temperatures of the asthenospheric mantle. It is then superseded by diking under lithospheric conditions, where melt pressure and/or tectonic stress exceed the yield strength of the solid host (Rubin, 1995; Ceuleneer et al., 1996). The shape, distribution, and orientation of the porous-flow channels control the way melt fractions move, pool, and mix, and hence their compositional evolution. Understanding what

governs melt trajectories is thus critical to constraining models of magma formation.

Because the mantle/melt chemical equilibrium is strongly pressure-dependent (Stolper, 1980), a melt produced at a given depth becomes increasingly reactive with mantle peridotites when moving to the surface in such a way that selective dissolution of minerals can drive porous-flow melt migration. This process has been proposed as an origin for dunite (i.e., olivine [Ol] and Cr-spinel [Sp]) by reaction between peridotite (i.e., Ol, Sp, and pyroxenes [Px]) and melt becoming out of equilibrium with Px as pressure decreases (Dick, 1977). As such, dunites provide high-permeability channels that

play a major role during melt migration processes (e.g., Dick, 1977; Ceuleneer, 1991; Aharonov et al., 1995; Kelemen et al., 1995; Ceuleneer et al., 1996; Abily and Ceuleneer, 2013).

The formation of reactive dunite channels has been reproduced in experiments (Morgan and Liang, 2005; Pec et al., 2015, 2017) and numerical models (Liang et al., 2010; Schiemenz et al., 2011; Baltzell et al., 2015; Rees Jones et al., 2021), predicting that the orientations of anastomosed finger-shaped channels are governed by the stress field imposed by solid-state flow and melt buoyancy and “not by any pattern inherent in the host rock” (Holtzman et al., 2003, p. 2). However, experiments and calculations mostly assume a homogeneous isotropic peridotite, while oriented lithological heterogeneities are common features in the mantle (e.g., Le Roux et al., 2016; Tilhac et al., 2016). Here, we show that they may significantly impact melt trajectories.

GEOLOGIC SETTING

The Trinity ophiolite (California, USA) belongs to the arc-derived terranes accreted to the North American plate in the Early Devonian (ca. 400 Ma; Coleman, 1986). It is moderately tilted (~30°) to the southeast, exposing mantle-derived plagioclase lherzolite, harzburgite, and dunite intruded by several kilometer-sized mafic-ultramafic plutons (Quick, 1981; le Sueur et al., 1984; Wallin and Metcalf, 1998). Radiometric Sm-Nd ages ranging from 470 to 420 Ma ± 40 Ma have been ascribed to the partial melting of the peridotites (Gruau et al., 1991). The crustal plutons yielded U-Pb zircon ages ranging from ca. 430

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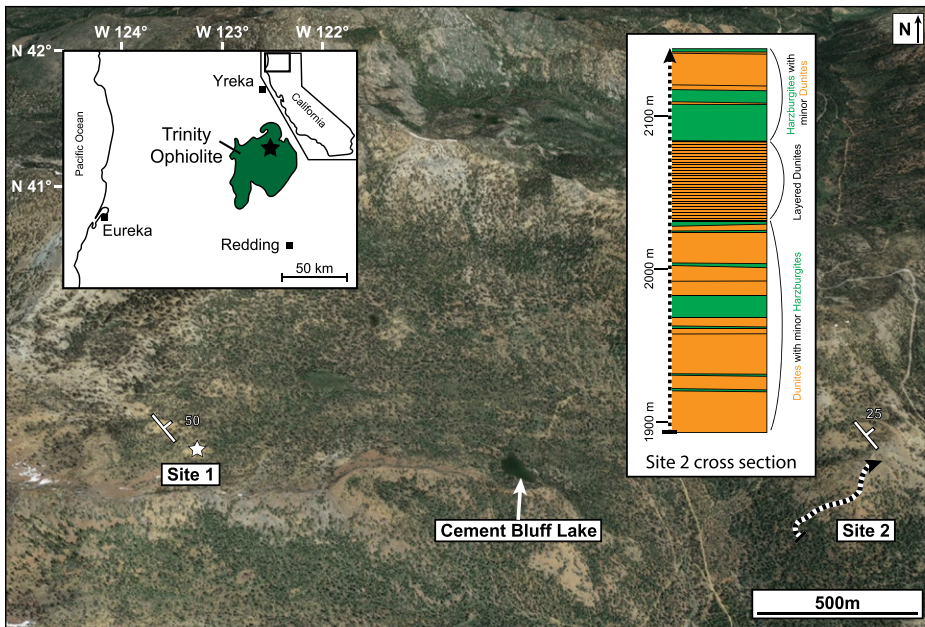


Figure 1. Location of the Trinity ophiolite in California (USA) and oblique view (Google Earth™ image) of the studied sites. Black and white dashed line indicates cross section at site 2. Lithological log of this cross section shows dunite in orange and peridotite (mostly harzburgite, rarely lherzolite) in green. Average orientation of layering is given for each site.

to ca. 405 Ma (Wallin and Metcalf, 1998); their parental melts were boninites-andesites derived from a depleted source distinct from that of the Trinity peridotite (Ceuleneer and le Sueur, 2008). The mantle section is crosscut by pyroxenite and diorite veins and dikes that crystallized from these melts, and they show variable degrees of interaction with the Trinity peridotite host (Quick, 1981; Kelemen et al., 1992; Ceuleneer and le Sueur, 2008; Dygert et al., 2016).

Our study focused on two sites (Fig. 1): an outcrop of mantle peridotites (site 1) where spectacular melt-rock reaction features provide clear field evidence of melt trajectories preserved due to the absence of late pervasive deformation, and a 250-m-high cliff (site 2) exposing abundant dunite, including so-called tabular dunitites (Quick, 1982). Site 2 lies structurally above site 1 given the southeast dip of the massif.

MELT TRAJECTORIES

At site 1 (Fig. 2A), the lherzolite records high-temperature, low-stress deformation (le Sueur et al., 1984) with a well-defined stretching lineation striking WNW-ESE and a

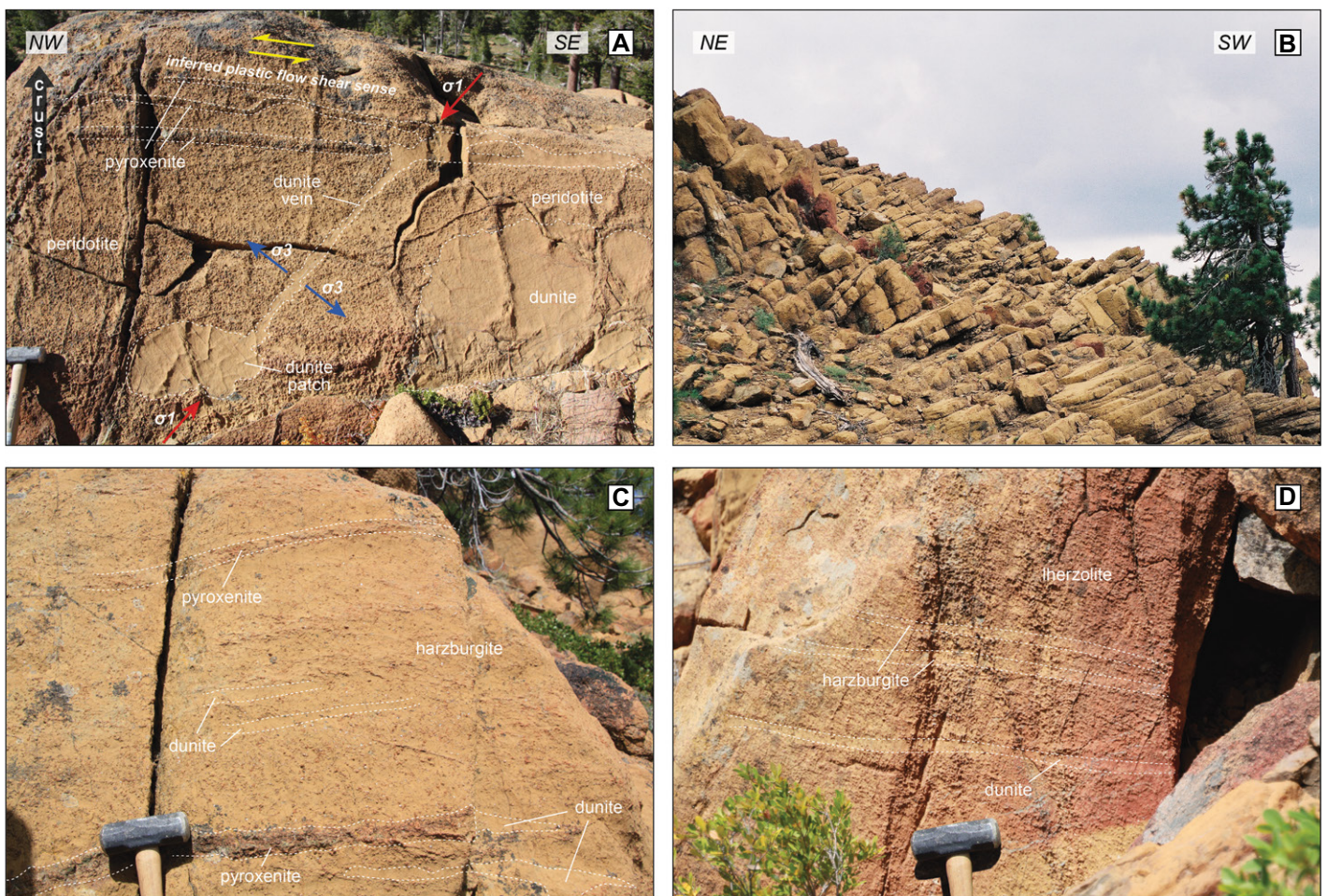


Figure 2. (A) The Rosetta stone outcrop (site 1); see text for explanation. (B) The tabular dunite (site 2). Height of the tree is ~10 m. (C) Peridotite and pyroxenite layers partially and variably transformed in depleted harzburgite and dunite (site 2). (D) Faint layers of dunite and depleted harzburgite in peridotite (site 2). Head of the hammer in panels A, C, and D is 11 cm long.

more discrete foliation outlined by ~2-cm-thick websterite layers slightly dipping (10°) to the southeast. The dunites, witnesses of melt circulation, occur either as ovoid patches up to tens of centimeters in diameter or as centimeter-thick planar channels. A dunite channel roots in a patch and branches with an angle of 60° to overlying pyroxenite layers (Fig. 2A; Fig. S1 in the Supplemental Material¹). This dunite does not cross the pyroxenite but partially replaces the pyroxenite. The transformation of the pyroxenite layer into dunite proceeded to the southeast, leaving the pyroxenite unaffected to the northwest.

We can interpret these structures in the following way. The reactive melt was accumulated in rounded melt pockets (now dunite patches) that represent self-organized structures resulting from the physics of two-phase flow (e.g., Rabinowicz and Ceuleneer, 2005). Due to compaction induced by continuing mantle flow, the interstitial melt was expelled upward in a thin channel, highly oblique to the foliation, consistent with the orientation of the stress tensor expected for low-intensity sinistral shearing (i.e., parallel to the maximum compressive stress [σ_1] and normal to the extensive stress [σ_3]; Fig. 2A). This geometry is reminiscent of oblique channels rooting in impregnated pockets observed in the dunitic transition zone of the Oman ophiolite (cf. Ceuleneer, 1991, his figure 8). When it reached a subhorizontal pyroxenite layer, the expelled melts dissolved Px in a markedly asymmetrical fashion. Not only was the melt trajectory drastically redirected to follow the path of enhanced porosity (and thus permeability), but this occurred only in a single direction, in good agreement with the pressure gradient induced by the sinistral shear. The influences of the stress field and preexisting lithological heterogeneities on the melt reactivity are thus shown to have competed in governing the melt trajectories in the mantle. The channelized flow direction does conform to the ambient stress field in a homogeneous peridotite (Holtzman et al., 2003). However, the presence of oriented pyroxenite layers also results in a highly anisotropic permeability induced during preferential dissolution of Px.

At site 2, the cross section is dominated by a 60-m-thick interval of tabular dunite (altitude 2025–2085 m) showing a well-defined parting (Fig. 2B), dipping $\sim 20^\circ$ to the northeast. In the lower part of this section, harzburgite occurs with highly variable Px content (Fig. 2C), and dunitic intervals are observed similar to the tabular dunite but of lesser thickness. Faint pyroxenite layers occur parallel to the parting and locally evolve laterally into dunite (Fig. 2C). Interestingly, relics of replacive struc-

tures reminiscent of the ones described at site 1 (i.e., thin subhorizontal dunitic channels in continuity with pyroxenite layers and patches of depleted harzburgites and dunites) are ubiquitous (Figs. 2C and 2D). The layered aspect of the tabular dunite (Fig. 2B), which becomes increasingly abundant up section, is thus likely to have been inherited from a former pyroxenitic layering via a reaction process similar to the one described above. The more homogeneous peridotite exposed further up the section capping the tabular dunite was largely seemingly preserved from melt-rock reaction, at least from melts leaving evident macroscopic footprints of their percolation.

MINERAL CHEMISTRY AND SPINEL-HOSTED INCLUSIONS

At site 2, the Fo content in olivine (atomic $Mg/[Mg + Fe_{total}]$) evolves up section from $\sim 90.5\%$ to $\sim 91.5\%$ without marked difference between pure dunite, Px-bearing dunite, and harzburgite, except a slight shift toward lower Fo ($\sim 90.5\%$) near the base of the tabular dunite (Fig. 3A). The composition of the coexisting spinel (Sp) shows more pronounced variations. In the tabular dunite and some dunite intervals, the XCr (atomic $Cr/[Cr + Al]$) reaches high values (up to 79%), while XCr is systematically lower (35%–60%) in the Px-bearing dunite and harzburgite (Fig. 3B). Note that most dunite intervals below the tabular dunite share a similarly low XCr. The TiO_2 content of Sp tends, with a few exceptions, to be higher in dunite (0.20–0.45 wt% mostly and even up to 0.65 wt%) than in harzburgite (0.05–0.25 wt%; Fig. 3C). A consistent trend in Sp composition marked by increasing XCr and decreasing TiO_2 is also observed restricted to the tabular dunite interval. From the 11 samples representative of site 1 lithologies, the Fo in dunite varies within the same range, whereas it is scattered down to Fo $\sim 89.5\%$ in the peridotite (Fig. 3A). Dunitic Sp yields XCr of 48%–68%, ranging between the two values identified above, while the peridotitic counterpart is comparable to that of site 2. The TiO_2 content of Sp in site 1 is within the range of that in site 2 for both peridotite and dunite.

Spinel grains enclose mineral inclusions, mostly monomineralic, rounded in shape or polygonal, and ranging 10–100 μm in size. They mainly consist of pargasitic amphibole and K-/Na-rich micas, with less abundant Px and plagioclase. It is worth noting that micas and pargasite are absent from the host rock. Their abundance is higher at site 1 than at site 2, and higher in dunite than in peridotite (Fig. 3). At site 2, the abundance of inclusions is moderate to high from the base of the section to the base of the tabular dunite and moderate to low above the tabular dunite. Micas are present up to the base of the tabular dunite, and pargasite is present up to the top of this horizon. Above the

tabular dunite, inclusions are mostly anhydrous (excluding low-temperature alteration minerals).

PIONEER MELT PATHWAYS

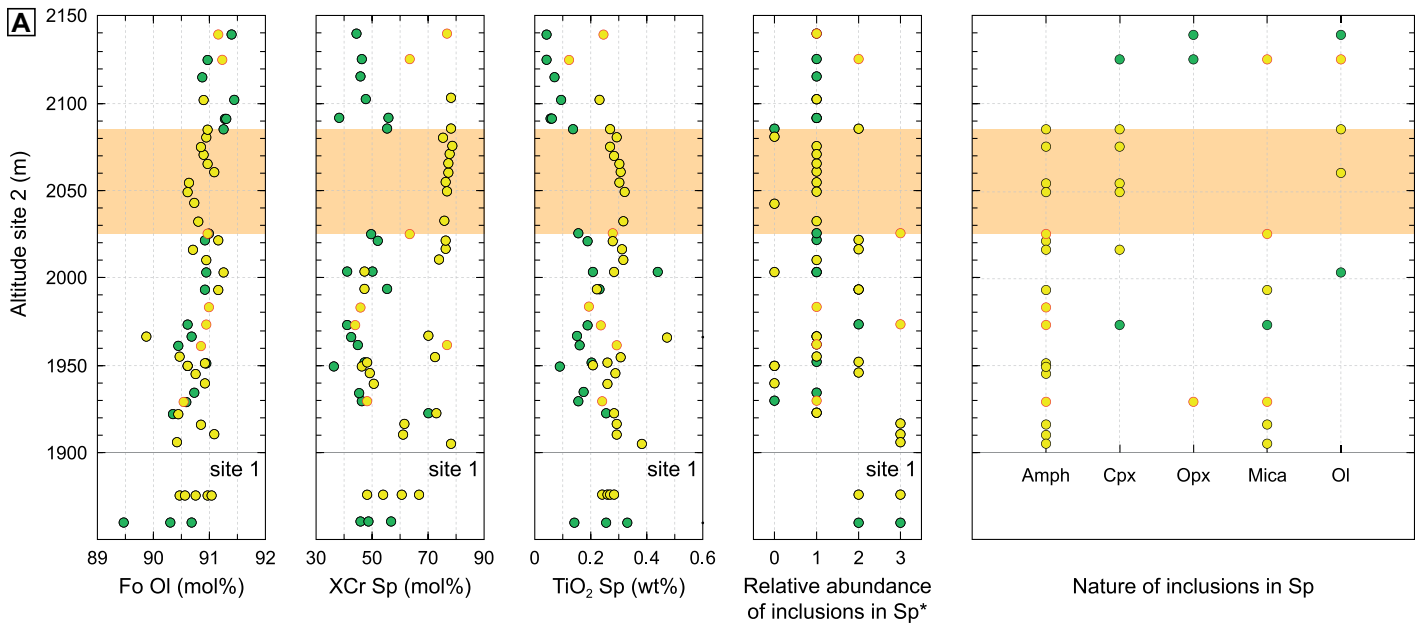
The nature and distribution of the inclusions in Sp that recrystallized during the reaction show that the dissolution of Px was initiated by a water- and alkali-rich melt. We drew a similar conclusion for the origin of the dunitic mantle–crust transition zone in the Oman ophiolite (Rospabé et al., 2017, 2021). We call this melt a “pioneer melt” because it contributed to the initial stage of reaction leading to the formation of dunite. The slight but significant increase of Ti content in dunitic Sp compared to the peridotite protolith may also be ascribed to the evolution of this reacting melt. As such, the melt responsible for the dunite formation is distinct from the primitive boninitic/andesitic melt parent to the mantle dikes and overlying crustal section. In fact, the latter melts are relatively Si-rich melts that are incompatible with the dry reaction of Px dissolution, which requires relative Si undersaturation (e.g., Kelemen et al., 1995). The involvement of water-rich fluids, which would have promoted dissolution of Px, mobilization of silica, and crystallization of secondary olivine, is more consistent with our observations on mineral inclusions in chrome spinel. A partly hydrous origin of dunite was originally proposed by Bowen and Tuttle (1949) on an experimental basis.

It is likely, however, that the volumetrically dominant boninitic/andesitic melts benefited from the dunite channels initiated as pioneering melt pathways to reach shallower depths. Their fingerprints notably include the shift toward high XCr in Sp observed in the tabular dunite, which can be explained by the percolation of high-XCr boninitic melt, while their characteristically low Ti contents had little impact on the Sp chemistry (Ceuleneer and le Sueur, 2008). Accordingly, the message recorded by dunites results from the superimposition of successive melt migration pulses (cf. Rospabé et al., 2018).

CONCLUSIONS

Field evidence shows that the presence of lithological heterogeneities in the mantle clearly influences melt trajectories during reactive porous flow. Where the mantle is homogeneous, melt trajectories are solely governed by the local stress field and can be predicted by two-phase flow models. The presence of pyroxenitic layering, however, promotes the development of preferential melt pathways via the dissolution of Px, where porosity-enhanced permeability may become high enough to drain most of the melt in a particular direction and to locally control the melt trajectory. The resulting interweaved pathways thus also become dependent upon the distribution, orientation, thickness, and composition of the lithological heterogeneities in addition to the stress field (Fig. 4). If the proportion of

¹Supplemental Material. Figure S1 of outcrop site 1, and data tables. Please visit <https://doi.org/10.1130/GEOL.S.20247399> to access the supplemental material, and contact editing@geosociety.org with any questions.



B

	Site 1		Site 2	
	Dunite	Harzburgite	Dunite	Harzburgite
Relative abundance of inclusions*	(2), (3)		15% (0), 36% (1), 34% (2), 15% (3)	15% (0), 70% (1), 15% (2)
Pargasitic amphibole	56%	32%		20%
Mica (phlogopite, aspidolite)	38%	39%		25%
Orthopyroxene	-	11%		5%
Olivine	6%	11%		5%
Clinopyroxene	-	4%		45%
Plagioclase	-	3%		-

● dunite ● Px-dunite tabular dunite
● harzburgite (site 2) / peridotite (site 1)

* (0): absence; (1): present in one or a few Cr-spinel grains only; (2): present in many grains; (3): present in most grains.

Figure 3. (A) Evolution of mineral composition (olivine + Cr-spinel) and of mineralogy and abundance of inclusions in Cr-spinel along the site 2 cross section. The chemical variation ranges at site 1 are shown for comparison and reported at an arbitrary depth. (B) Abundance and nature of silicate inclusions in Cr-spinel grains at sites 1 and 2. Sp—spinel; Px—pyroxene; Fo—forsterite content of olivine; XCr Sp—atomic Cr/(Cr + Al) ratio of Cr-spinel.

pyroxenite is significant, Px dissolution could be the main process controlling melt trajectories at a larger scale. Where pyroxenite layers are subhorizontal, melt will tend to stagnate and develop thick horizons comparable to tabular dunites observed in most ophiolites, while steeper layers will promote more efficient melt migration to the surface. This complexity is not anticipated by current models of melt migration in the mantle.

As stressed by Pec et al. (2017), the commonly accepted “finger” geometry predicted by models does not satisfactorily reproduce the tabular habit of many dunite occurrences. The additional mechanisms governing melt trajectories highlighted here are one step further to reconcile models with the field reality. As such, the tabular nature of dunite may simply reflect a layering inherited from the transposition and flattening

of former pyroxenites by asthenospheric flow (e.g., Le Roux et al., 2016; Tilhac et al., 2016). We also show that these channels are the products of pioneer melts of more “exotic” composition (alkalic- and volatile-rich melts) that could derive from preferential melting of mantle heterogeneities (e.g., Lambart et al., 2019; Tilhac et al., 2021) or by hybridization with hydrothermal fluids reaching Moho level (Rospabé

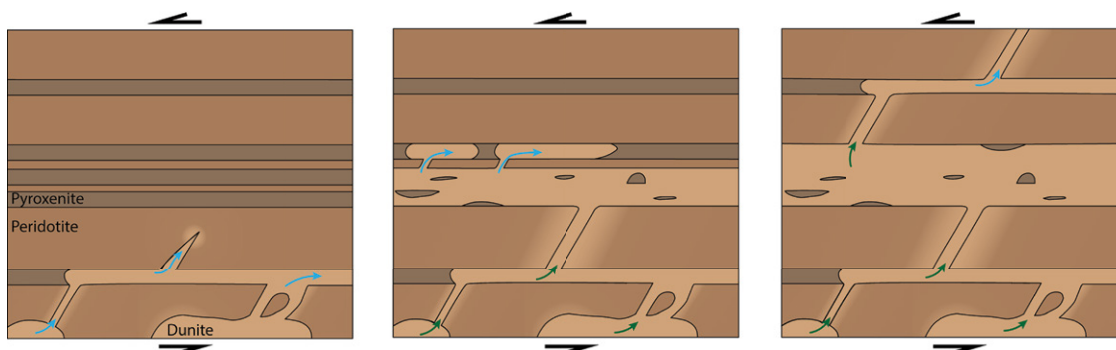


Figure 4. Proposed mechanism of formation of layered dunite and melt trajectories in the pyroxenite-bearing upper mantle. An alkali- and water-rich melt (blue arrows) migrates upward in pyroxenite-bearing peridotite, dissolving pyroxene (Px) and leaving dunite on its trajectory. In homogeneous peridotite, pioneer melt migrates in channels that form in

accordance with the local stress field. When encountering a pyroxenite layer, pioneer melt is redirected within this layer because of the preferential dissolution of Px. Once the pyroxenite layer is fully dissolved or dissolution of Px is no longer possible, melt resumes its upward trajectory, which again becomes controlled by the local stress field. Subsequently, boninitic/andesitic melts (green arrows) use preexisting dunitic channels as preferred pathways to reach shallow depths.

et al., 2017, 2018). The decrease in abundance of hydrous inclusions up section at site 2 tends to favor a deep origin of fluids in the case of Trinity ophiolite. Whatever their origin, their involvement clearly suggests that the development of the melt plumbing system in the mantle involves transient petrological processes that are highly dependent on preexisting heterogeneities. In this regard, our study calls for numerical formulations able to handle such complexities (for a review, see, e.g., Oliveira et al., 2020).

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