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Geological evidence and modeling of melt migration by porosity waves in the sub-arc mantle of Kohistan (Pakistan)

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ABSTRACT

Knowledge of melt transfer within the mantle is primarily from the study of mid-ocean ridge settings, leaving elusive the process of sub-arc melt transfer. The sub-arc mantle section of the Sapat Complex (Kohistan-Pakistan) exposes coarse-grained dunites that contain clinopyroxene-enriched zones, which, in turn, contain gabbroic lenses. Structural, petrological, and chemical relationships indicate that the clinopyroxene-enriched zones reflect a continuum of melt transport mechanisms between pervasive percolation and fully segregated melt flow. This spectrum of mechanisms and the petrographic features at Sapat are explained by mechanical flow instabilities (porosity waves) that cause channeling of pervasively distributed melt.

INTRODUCTION

Melt transport mechanisms are a subject of debate because melt migration is not directly observable and the migration timescales (10–1000 m.y.; e.g., Turner et al., 2001; Sigmarsson et al., 2002) complicate indirect geophysical investigation. Petrographic and structural features in exhumed mantle rocks from mid-ocean ridge (MOR) settings are the primary evidence for the nature of mantle melt migration (Kelemen et al., 1997). The envisioned end-member processes are pervasive flow, manifested by grain-scale impregnation features, and fully segregated flow, manifested by meso- to macroscopic veins and dikes (Nicolas, 1986; Harte et al., 1993). Dunitic zones and veins represent an intermediate mode in which pervasive flow has been focused into high-porosity channels. Physical models capable of explaining channelization include porosity waves (Richter and McKenzie, 1984; Scott and Stevenson, 1984; Connolly and Podladchikov, 2007), reactive infiltration instability (Daines and Kohlstedt, 1994; Aharonov et al., 1995; Kelemen et al., 1995; Spiegelman et al., 2001; Braun and Kelemen, 2002), and shear-enhanced melt segregation (Stevenson, 1989; Holtzman et al., 2003; Katz et al., 2006). At MOR settings, it is thought that reactive infiltration and shear-enhanced segregation are the dominant transport mechanisms in the asthenospheric mantle, and that dikes predominate above the conductive thermal boundary that defines the base of the mechanical lithosphere (e.g., Kelemen et al., 1995). Sub-arc melting is attributed to the infiltration of fluids released from the subducted lithosphere into the mantle wedge (e.g., Schmidt and Poli, 1998; Ulmer, 2001; Grove et al., 2006), but the mechanism by which the melts escape their source region and travel through the mantle wedge is unclear. The key distinction between the MOR and sub-arc settings is that beneath MORs, melts have no tendency to freeze as they rise upward unless they impinge upon the lithosphere. In contrast, in the sub-arc mantle wedge the thermal regime favors melt crystallization in the direction of melt transport at depths far below the lithospheric boundary. Thus, while it is plausible that the change in transport mechanisms at MORs is provoked by a rheological transition, at sub-arc conditions melt localization must occur far below the lithosphere and cannot be explained by an externally imposed rheological transition. Geological evidence found in the Kohistan Paleo-Island Arc and coupled with numerical modeling shows that mechanical flow instabilities were responsible for the localization and extraction of melt from the sub-arc mantle.

THE SAPAT ARC MANTLE

The Kohistan Terrane, between the Karakoram-Kohistan Suture to the north and the Indus Suture to the south, was an island arc during Mesozoic times (Bard, 1983; Coward et al., 1987). It exposes a complete section from the mantle to the volcanic and sedimentary sequences (Treloar et al., 1996; Khan et al., 1998), thus offering the possibility to study deep sub-arc magmatic processes. The Sapat peridotites are principally composed of metamorphosed harzburgites that represent a part of the supra-subduction mantle (Bouilhol et al., 2009). The meta-harzburgites include 10–100 m^2 zones of coarse-grained dunite containing pyroxene-enriched zones (PEZs) that range from homogeneous clinopyroxenites to olivine-clinopyroxenite and that comprise gabbroic lenses. Whereas homogeneous clinopyroxenites represent ponded crystallized melt near the Moho interface, the olivine-clinopyroxenites represent crystal growth during the pervasive melt infiltration that was coincident with the development of the island arc (Bouilhol et al., 2009, 2011).

Structure and Chemistry

Dunite

Secondary olivine and spinels in the meta-harzburgites indicate that these mantle rocks have been metasomatized by the pervasive infiltration of primitive arc-melt. Ultimately, dissolution of orthopyroxene produced dunite in areas where melt flow was focused (Bouilhol et al., 2009). Mineral dissolution was accompanied by mineral precipitation of secondary olivine and spinel as shown by fractionation trends in olivine and rare earth element (REE) patterns of the dunite, enriched in middle REE (Bouilhol et al., 2009). At MORs the formation of similar dunite lenses is explained by a reactive infiltration flow instability (Kelemen et al., 1995; Suhr, 1999; Spiegelman et al., 2001; Braun and Kelemen, 2002). The instability arises because the dissolution of pyroxenes in the direction of melt transport increases permeability and leads to channelization of the melt flow. This mechanism cannot have been the primary mechanism responsible for channelization at Sapat because melt crystallization during pervasive melt flow suppresses the instability.

Pyroxene-Enriched Zones

The structural relationships between the different lithologies of the studied PEZs characterize pervasive melt infiltration and crystallization (e.g., Harte et al., 1993). In places, the homogeneous clinopyroxenites form flat-lying layers with various modal proportions of clinopyroxene and olivine. These layered clinopyroxenites contrast with the subvertical olivine-clinopyroxenite in which trails of clinopyroxene grains grade into gabbroic lenses (Fig. 1). In the largest PEZ (Fig. 2), the clinopyroxene of the olivine-clinopyroxenite occurs as centimeter-sized porphyroblasts and trails of vertically aligned, millimeter-sized crystals (Figs. 3A and 3B). The clinopyroxene-rich trails evolve into clinopyroxenite bands parallel to the subvertical PEZ-dunite boundaries (Fig. 3). The clinopyroxene trails and bands define a near-vertical lineation in planes of observation parallel to lithological contacts. Within clinopyroxene-rich bands, patches of plagioclase define proto-lenses (Figs. 3A and 3C) that locally coalesce to form gabbroic, 0.1–1.0-m-thick lenses (Figs. 3C and 3D). Crystalline plasticity (dislocation walls) in newly formed minerals overprint, when present, the pristine percolation textures (Bouilhol et al., 2009), which suggests that all textures reflect coherent flow parallel to the subvertical lineation. Elongated, isolated dunite pods (Figs. 2 and 3D) together with minerals' internal structures would witness a nonhydrostatic stress field.

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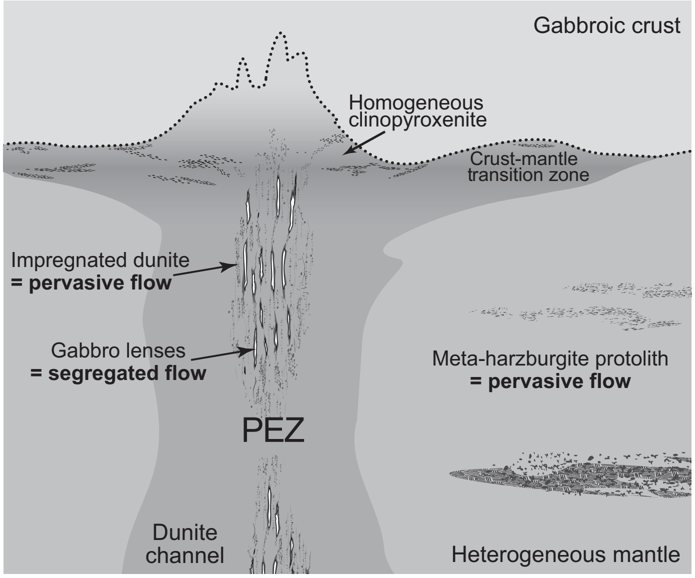

Figure 1. Schematic representation of the relationships between dunites and associated pyroxene-enriched zone (PEZ) within the meta-harzburgites of the Sapat mantle. Respective melt migration modes are indicated.

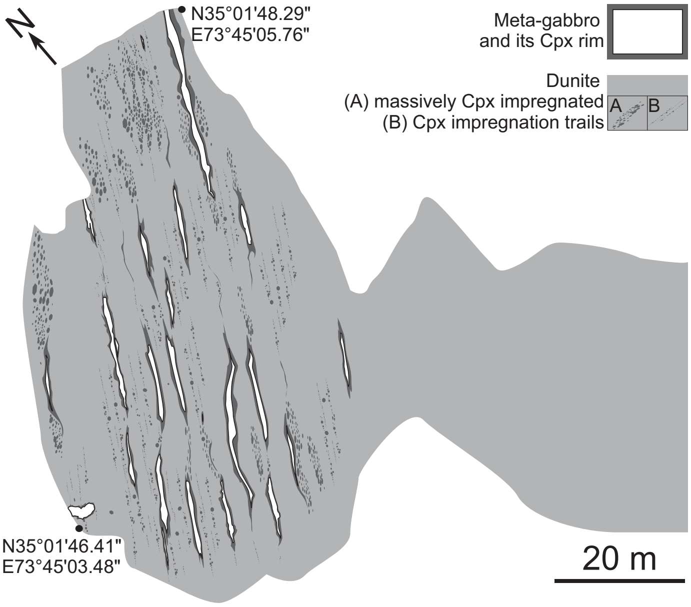

Figure 2. Northeastern part of one Sapat pyroxene-enriched zone (PEZ). Full and detailed map with three-dimensional diagram can be found in the GSA Data Repository (see footnote 1). Flattened lenses of meta-gabbros are enclosed in clinopyroxene (Cpx)–rich rims.

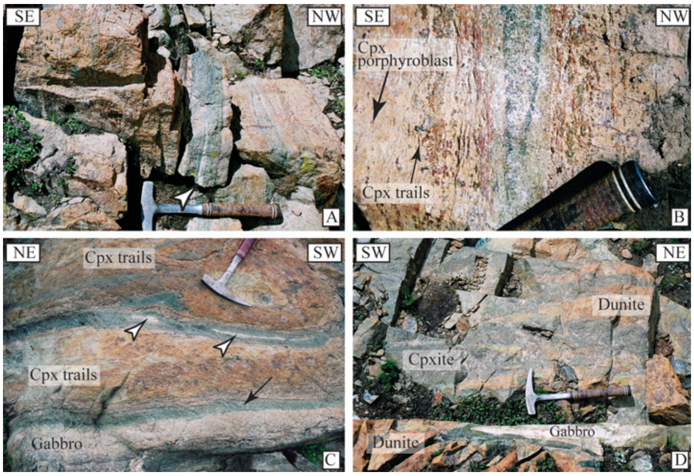

Figure 3. Structural relationships between different lithologies in the pyroxene-enriched zone (PEZ) mapped in Figure 2. A: Vertical view of the outcrop with plagioclase (white arrow) in a subvertical clinopyroxene-rich band (dark) in impregnated dunite (brownish country rock). B: Map view of the right part of A, showing clinopyroxene-rich band and parallel clinopyroxene trails. C: Map view of plagioclase patches (white arrows) in a clinopyroxene-rich band next to a gabbroic lens and its rim (black arrow). D: Map view of ol-clinopyroxenite (Cpxite) flames isolating dunite clusters.

This interpretation explains the lack of asymmetric modal layering or any sort of geopetal criteria in the gabbroic lenses.

PEZ-Dunite Relationships

The features preserved within the PEZs are characteristic of pervasive melt infiltration and, together with the presence of dunite, are similar to features interpreted as evidence of the melt migration process beneath mid-ocean ridges in ophiolites (Nicolas, 1986; Kelemen et al., 1997). However, dikes at MORs are generally discordant to pervasive flow patterns (Nicolas, 1986) and reminiscent of elastic cracks (Nicolas, 1986; Rubin, 1998). Sub-MOR dikes are not genetically linked to their ultramafic hosts (Boudier and Nicolas, 1995; Boudier et al., 1996; Korenaga and Kelemen, 1997). In contrast, the melt segregations represented by the PEZs at Sapat are high-aspect-ratio features that formed in response to local increases in melt flux and are structurally, geochemically, and petrographically coherent with the surrounding dunites. As such the gabbroic lenses represent a less evolved form of segregated flow than dikes. The proportion of crystallized material in the dunites and meta-harzburgites is inferred to be a measure of the melt flux. The gabbroic lenses that occur where this flux was high represent segregation of the primitive arc-melt. That the gabbroic lenses occur where clinopyroxene modes are high indicates that a single mechanism is responsible for the transition from diffuse to channelized and from channelized to fully segregated melt flow. This inference is supported by petrological and geochemical data that indicate that metasomatic features (REE enrichment and secondary olivine and spinel crystallization) in the host meta-harzburgites, the dunites, and PEZs were formed by interaction with the same melt (Bouilhol et al., 2009).

POROSITY WAVES AS A TRANSFER MECHANISM

The presence of precipitated minerals and the spatial transition of melt percolation mode from porous (isolated porphyroblasts) to segregated (veins, lenses) flow requires a different channelization mechanism than proposed for mid-ocean ridges. To this end, we explore a mechanical instability that is independent of the thermal regime. In this model (Connolly and Podladchikov, 2007), rheological asymmetry, whereby the matrix yields more easily during decompaction under negative effective pressures than it does during compaction, induces melt flow by tube-like waves of melt-filled porosity.

Regardless of whether the mechanism responsible for channelization is mechanical or chemical, the alteration of harzburgite into dunite requires dissolution of orthopyroxene, while the formation of the PEZs requires crystallization of olivine and clinopyroxene.

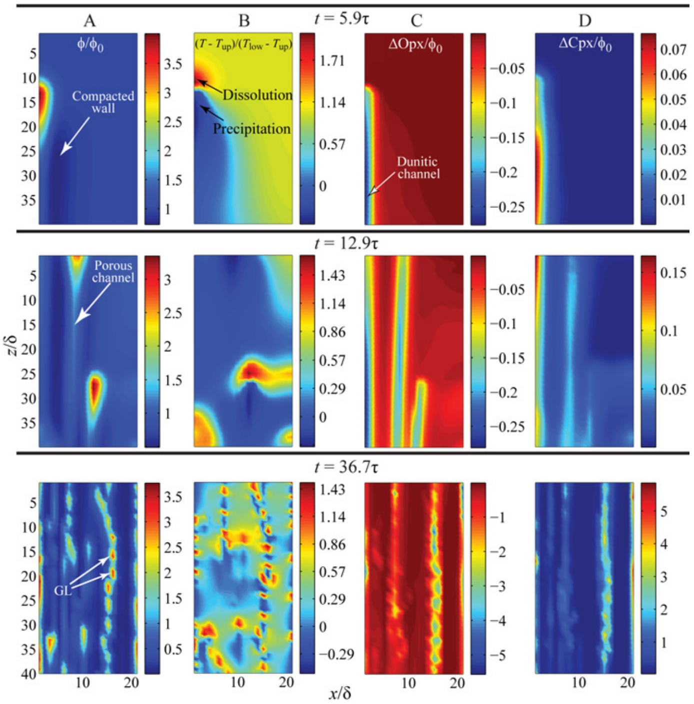

Figure 4. Model of porosity waves at three successive stages (top to bottom). Column A: Differences in porosity. Column B: Temperature distribution. Column C: Time-integrated pyroxene dissolution. Column D: Time-integrated pyroxene crystallization. Opx and Cpx stand for orthopyroxene and clinopyroxene, respectively, to make the ad hoc comparison with the Sapat case. δ = viscous compaction length; τ = viscous compaction time scale. Refer to the methods section in the Data Repository (see footnote 1) for details. The lower portion of the model domain from which the waves initiate is not shown. Propagation of the first wave at *t* = 5.9τ (first row) showing the formation of compacted walls around a porous channel, the dissolution and precipitation at the tip, and the wake leading to a dunitic conduit. By *t* = 12.9τ (second row), multiple waves have formed several dunitic channels. The elevated porosity left in the wake of these waves causes subsequent melt flow to localize in the dunitic channels. At *t* = 36.7τ (third row), the system is cooling, and flow within the dunitic channels precipitates pyroxene. GL—gabbro lenses; arrows point to what would represent the observed lenses, linked and enclosed in clinopyroxenite bands (Figs. 2 and 3).

To account for these reactive processes, we modified the governing equations of the mechanical flow instability model (Richter and McKenzie, 1984; Scott and Stevenson, 1984; Connolly and Podladchikov, 2007) to include temperature-dependent precipitation and dissolution of a saturated solute (i.e., reactive transport) and introduced a governing equation for heat flow that incorporates latent heat of solution and both conductive and advective heat transport. The resulting formulation is solved numerically in two dimensions by the finite-difference method (see methods description in the GSA Data Repository[1]). Our model is strictly for a single saturated solute; therefore, it can only be used to predict the amount of solute precipitated or dissolved by melt flow. To draw an analogy between this model and Sapat, we make the ad hoc association that the minerals dissolved and precipitated are orthopyroxene and clinopyroxene, respectively, where clinopyroxene precipitation monitors the amount of precipitated minerals from the melt.

At the beginning of the model evolution, melt flow is strongly channelized into subvertically elongated porosity waves with a characteristic spacing comparable to the viscous compaction length (Fig. 4). The porosity of the wave is opened by decompaction of the matrix and closed by less efficient compaction, leaving a wake of elevated porosity, i.e., a porous channel (Fig. 4A), that tends to localize subsequent melt flow. The asymmetric pressure distribution within the waves causes them to grow as they propagate by depleting melt from the adjacent rocks. The combined effect of enhanced melt flow within the porosity waves and the reduced flux through the adjacent rock results in advective heating within the melt channels (Fig. 4B). Wave tips are characterized by particularly high melt fluxes and heating, which would dissolve orthopyroxene from surrounding harzburgite and create dunite by melt-rock reaction. In the wake, residual melt fraction may crystallize olivine (+ spinel) and clinopyroxene (Figs. 4B and 4C). Simultaneously, minerals (second generation of olivine + spinel) precipitate in the cooler adjacent rocks, thus forming the model analogue of the Sapat metasomatized harzburgites (Fig. 4D). Once the porous channels are initiated, smaller waves can exploit the porous channels left in the wake of the primary waves and efficiently transfer more melt. The whole is a competitive system between dissolution and crystallization, where each wave dissolves pyroxenes and crystallizes olivine (± spinel) and pyroxenes.

Once the melt source is exhausted, the melt fluxes wane and the advective heat effect becomes inadequate to maintain the high temperatures of the initial stage. Cooling then causes further melt fractionation and crystallization of cumulative crystals in the porous channels. When the system stops, lens-shaped high-porosity zones are surrounded and linked by low-porosity domains ($t = 36.7\tau$; Fig. 4A). The analogy to the observed features in the Sapat PEZs is that the high-porosity areas coincide with the high amount of precipitated material, which would correspond to gabbroic lenses enclosed and linked by clinopyroxene-rich impregnation bands (Figs. 4A and 4D). Thus we propose that the frozen melt transport features exposed at Sapat correspond to a snapshot of the porosity wave model.

Complementary to the PEZs scale, where the model satisfies the relationships between gabbroic lenses and impregnation clinopyroxene bands, the model satisfies the relationships between dunite and the PEZs, where the entire PEZs would correspond to segregated melt flow within the porous dunitic channel.

CONCLUSIONS

The Sapat PEZs document melt segregation and transport by porosity waves that were frozen in the waning stage of an island-arc magmatic system. The shape difference between the modeled, tubular channels and the observed flattened pipes reflects the absence of far-field stresses in models, although such stresses are likely to have been present. Although the time scale of the numerical model is dictated by the unstable initial condition, the model illustrates that for plausible physical parameters, the advective heat effects associated with channelization by mechanical flow instabilities are consistent with the structural and petrographic observations in Sapat. This model explains both the spatial relationships between the PEZs and the dunite and the concomitance of gabbroic lenses and clinopyroxene-impregnated dunite in the PEZs. This success supports the conjecture that porosity waves are an effective melt transport mechanism in the sub-arc mantle wedge and are consistent with petrological and experimental constraints for the transfer of subduction zone magmas (Gaetani and Grove, 2003). Porosity waves have been considered primarily as a mechanism for intra-mantle melt transport, but the features that lead us to conclude that this mechanism was operative at Sapat are also observed in migmatitic terrains (e.g., Collins and Sawyer, 1996). Thus, we speculate that the porosity wave mechanism may also be relevant to anatectic melt extraction.

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[1] GSA Data Repository item 2011329, methods and the detailed pyroxene-enriched zone map, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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