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Major and trace element and Sr and Nd isotopic results from mantle diapirs in the Oman ophiolite: Implications for off-axis magmatic processes

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A B S T R A C T

The Oman ophiolite includes both a fossil fast spreading axis, defined by five mantle diapirs, and an off-axis mantle diapir emplaced 30 km from the axis, providing a natural laboratory for the study of off-axis magmatic processes. We compare field and petrological observations coupled with geochemical and isotopic analyses of samples from the off-axis diapir with those of the nearest on-axis diapir, with a particular focus on the Moho Transition Zone (MTZ). Both diapirs are defined by the presence of steeply plunging lineations, but in the on-axis case, these lineations rotate gradually into parallelism with the horizontal magmatic lineations of the overlying crust, while in the off-axis case, a shear zone separates the steeply plunging lineations from the horizontal lineations of the surrounding mantle. In the on-axis diapir, the MTZ is 50 to 500 m thick and composed of dunite with layered gabbro lenses whereas in the off-axis diapir, the MTZ is thicker and composed of dunite with massive (∼20% of MTZ) clinopyroxenite lenses and a notable absence of plagioclase. Moreover, the off-axis diapir is associated with amphibole-bearing intrusions, consisting of Mg-rich gabbroic sills in the mantle peripheral to the diapir, and microgabbroic lenses of broadly basaltic composition in the overlying crust. The εNd values of the pyroxenites in the MTZ of the off-axis diapir fully overlap with those of the intrusions in the surrounding mantle and crust, suggesting that they are genetically related. Calculated rare earth element (REE) abundances of liquids in equilibrium with clinopyroxene imply that the magmas that traversed the MTZ of the off-axis diapir were more depleted in highly incompatible elements than their counterparts in the MTZ of the on-axis diapir. On the other hand, Nd isotopic compositions of the off-axis samples (εNd = 6.2–7.9 in 18 of 19 samples) indicate derivation of their parental magmas from a less depleted source than that which produced the magma associated with the on-axis gabbro (εNd = 7.8–9.2, 10 analyses).

To explain these observations, we suggest that the earliest magmas in the uprising off-axis diapir formed from the partial melting of pyroxenite veins with less radiogenic Nd isotopic compositions than those of the ambient peridotite. As the diapir traversed the cool, hydrated lithosphere these early melts interacted with depleted harzburgites, lowering the incompatible element contents of the melt products while having little effect on their Nd isotopic compositions. The great abundance of clinopyroxene in the off-axis MTZ might be explained by the high pyroxene component in the original melt but perhaps also by the presence of water in the lithosphere, which would favor the crystallization of clinopyroxene while inhibiting that of plagioclase. The intrusions in the overlying crust could represent, to first order, the secondary melts produced by the melt–harzburgite reaction, while the sills in the surrounding mantle may be cumulates from such secondary melts.

These results shed light on processes occurring during interaction between rising off-axis material and depleted, hydrated lithospheric mantle. Furthermore, if our interpretation is correct, the low εNd values of the off-axis samples contribute to the growing body of evidence for the presence of pyroxenite veins in the MORB mantle source.

1. Introduction

Increasing evidence suggests that magmatic activity beneath mid-ocean ridges is not limited to the ridge axis. In the study of

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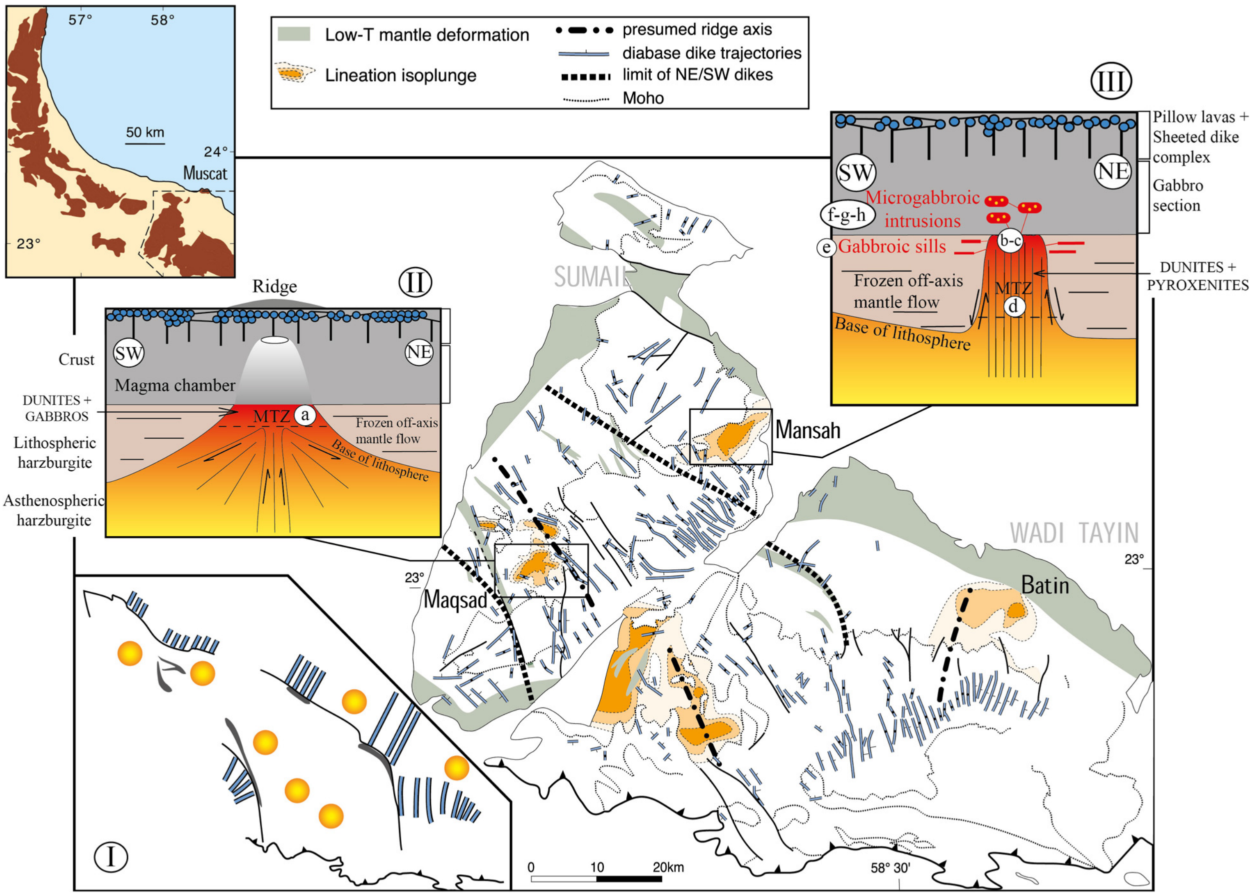

Fig. 1. Map of the southern part of the Oman ophiolite showing the locations of the on-axis Maqsad and off-axis Mansah diapirs (open rectangles). As seen most clearly in the Sumail massif, a system of dikes formed in a NW-SE ridge system crosscuts an older dike system oriented NE-SW. Plunging lineations (indicated by zones contoured in deep yellow) define the mantle diapirs. I) Interpretative sketch of the ophiolite (circles: diapirs, dark gray: shear zones, thick blue lines: dike orientations, dashed line: ridge axis). II–III) Schematic cross-sections of the on-axis Maqsad diapir and off-axis Mansah diapir, modified from Jousselin and Nicolas (2000). Horizontal straight lines in the lithospheric harzburgite represent the frozen flow direction of the lithospheric mantle. Lines in the asthenospheric section represent flow orientations in each diapir. MTZ denotes Moho Transition Zone. Each small letter references an illustration in Fig. 2. Adapted from Boudier et al. (1997). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Toomey et al. (2007), mantle melt upwelling was found 5 to 20 km from the axis over nearly half of a 200 km first order segment of the East Pacific Rise (EPR). The discovery of melt lenses in the lower crust, up to 20 km from the rise (Crawford and Webb, 2002; Crawford et al., 1999; Garmany, 1989), also shows that not all melt is focused beneath the ridge. Furthermore, seamount volcanism provides direct evidence of off-axis magmatic processes.

When melt is delivered off-axis, its composition may be modified by interaction with cool, hydrothermally altered lithospheric mantle (Bosch et al., 2004). However, assimilation and fractional crystallization in the crust may obscure the effects of sub-Moho processes in erupted basalts. Off-axis magma may even be blocked by the cold crustal barrier and not reach the surface. Thus the origin of off-axis magmatism may be more effectively investigated by examining rocks beneath the Moho, which are preserved from complications occurring at higher levels. An ideal target is the Moho Transition Zone (MTZ), the region immediately underlying the crust–mantle interface, which is accessible almost exclusively in ophiolites (Boudier and Nicolas, 1995).

The Oman ophiolite presents relics of a former fast-spreading ridge, delineated by five on-axis diapirs (Boudier et al., 1997), whose size and spacing match the distribution of melt upwelling centers on the EPR (Toomey et al., 2007). An off-axis upwelling center was also identified (Jousselin and Nicolas, 2000), providing a field laboratory to explore the contrasts between on and off-axis magmatism. Below, we compare major and trace element and Sr and Nd isotope data for whole rocks and minerals from the MTZ in and around this off-axis diapir with similar data from the more classic MTZ section of a nearby on-axis diapir.

2. Geological setting and field description of the diapirs

The Oman ophiolite, about 500 km long and 50 to 100 km wide, was obducted on the Oman margin during the closure of the Neo-Tethys ocean 95 million years ago (Coleman, 1981; Hacker, 1994). Its continuous gabbroic crust indicates the presence of extensive, long lived magma chambers along the ridge, suggesting that it is a relic of a fast spreading center (Nicolas and Boudier, 1995), as confirmed by high resolution dating indicating a half spreading rate of 10 cm/yr (Rioux et al., 2012). The tectonic context of the Oman ophiolite remains controversial, the two main hypotheses being a Mid-Ocean Ridge (e.g. Boudier et al., 1988; Godard et al., 2006, 2003; Hacker, 1994; Nicolas and Boudier, 2003) and a Supra-Subduction Zone (SSZ) setting (e.g. Pearce and Cann, 1971; Pearce et al., 1981; Shervais, 2001).

In the southern part of the ophiolite (the Rustaq, Sumail and Wadi Tayin massifs), a NW-SE dike system is observed over a width of 20–50 km, separating into two parts a NE-SW dike system found in the outer parts of the massifs (Fig. 1). This geometry shows that a paleo-spreading center is preserved in the center of the massifs (Boudier et al., 1997), along an alignment of five mantle diapirs (Fig. 1-I). Mantle diapirs, formed by local-

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