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 R T I C L E   I N F O

Article history:
Received 5 August 2014
Accepted 14 December 2015
Available online 20 January 2016
Editor: T. Elliott

Keywords:
mantle
ophiolite
off-axis magmatism
pyroxenite
major and trace elements
Sr and Nd isotopes

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 rising 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.

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1. Introduction

Increasing evidence suggests that magmatic activity beneath mid-ocean ridges is not limited to the ridge axis. In the study of
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 cold, 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-
ized melt upwelling, are identified by steeply plunging lineations, the presence of numerous dikes in the harzburgite and a MTZ thicker than 50 m (Jousselin et al., 1998). In the on-axis case (Fig. 1-II), radial horizontal lineations in the mantle at the outskirt of the diapirs and their parallelism with magmatic lineations in the lower crust indicate formation beneath a mature spreading center, when the gabbro was still in a magmatic state. The on-axis MTZ varies from a few meters to 450 m in thickness and contains mostly dunite, as well as a few horizons with plagioclase impregnated dunites and layered gabbro lenses (Boudier and Nicolas, 1995; Jousselin et al., 2012; Kelemen et al., 1997; Koga et al., 2001) (Fig. 2a). We studied the Maqsad diapir of the Sumail massif, a typical example of an on-axis diapir investigated in several previous studies (e.g. Godard et al., 2000; Koga et al., 2001).

The Mansah diapir is also located in the Sumail massif, but about 30 km northeast of the alignment defined by the five on-axis diapirs (Fig. 1). The study of Jousselin and Nicolas (2000) and our new field observations reveal characteristics contrasting with those of the on-axis diapirs. The Mansah diapir (Fig. 1-III) is bounded by shear zones that separate the steeply plunging lineations of the diapir from the horizontal lineations of the surrounding harzburgites. This structure is interpreted to result from the impingement of the diapir on the off-axis horizontally laminated lithospheric mantle. The overlying Moho and lowermost crust are tectonized, as if disturbed by the uprising diapir (Fig. 2b). In places, the top of the MTZ forms a physical mixing zone between the MTZ pyroxenites and the gabbros from the pre-existing lower crust (Fig. 2c). The MTZ is very thick, up to 1 km, and is composed of dunite with pyroxenite lenses (Fig. 2d) varying in size from tens of centimeters to tens of meters. These lenses make up ~20% of the MTZ section and contain clinopyroxene with variable amounts of olivine and almost no orthopyroxene. They are less strongly deformed than the on-axis layered gabbro lenses, which are entirely absent in the off-axis case.

Within a five kilometer region around and above the off-axis Mansah diapir, but not inside the diapir itself, the lower crust and mantle are intruded by gabbroic and microgabbroic bodies (Fig. 1-III). Similar intrusions are not reported elsewhere in the ophiolite. In the mantle section, they consist of 10 to 50 cm thick gabbroic sills, with fine-grained centers and amphibole-rich, coarse-grained margins. These are referred to as “Wasit” sills (Fig. 2e), after their type locality. The intrusions in the crust and the upper 50 m of the mantle have microgabbroic textures, and are referred to as “Nidab” intrusions (Fig. 2f), after their type locality. These intrusions sometimes take the form of dikes, 10 to 200 cm thick, but more often form large (>10 m), chaotic lenses. Xenoliths of harzburgite and dunite, varying in size from a few centimeters to several meters, are incorporated into the Nidab intrusions. Their elongated shapes with rounded edges and the reaction zones at their boundaries suggest incomplete assimilation of these lithologies, which are most likely derived from the lithospheric mantle overlying the rising diapir before it reached the Moho (Fig. 2g–h). Both the Wasit sills and the Nidab lenses lack the deformation fabric of the mantle and crustal sections into which they intrude. Together with the fine-grained texture and the presence of amphibole, these characteristics are consistent with their injection into frozen and hydrated off-axis lithosphere.

3. Rock types investigated

Petrographic descriptions and geographic coordinates of samples are given in supplementary Table A1; locations are in Fig. 3. Lithologies include:

- Dunites and harzburgites from both the on and off-axis diapirs. Some can be described as “impregnated”, i.e. they contain interstitial phases suggesting precipitation from or interaction with melts. These phases consist of clinopyroxene and plagioclase in the on-axis samples, but only clinopyroxene in the off-axis samples.
- Gabbro lenses, found only in the on-axis MTZ, composed of olivine, clinopyroxene and plagioclase.
- Pyroxenites, found only in the off-axis MTZ, composed of clinopyroxene with varying amounts of olivine and extremely rare orthopyroxene. Though some samples approach wehrlitic compositions, all will be referred to as pyroxenites for simplicity. Two samples are from a mixing zone between pyroxenite and lower crustal gabbro at the Moho (Fig. 2c). One was analyzed in bulk while in the other, a dark layer (olivine and clinopyroxene with minor plagioclase) and a white layer (essentially plagioclase) were analyzed separately.
- The off-axis gabbroic (Wasit) and microgabbroic (Nidab) intrusions, which rim the Mansah diapir, and contain olivine, pyroxene, plagioclase and amphibole.

Fig. 2. (a) Dunite with layered gabbro lenses in the MTZ of the on-axis Maqsad diapir. (b) Tectonized Moho (highlighted by the dashed yellow line), with sets of westward dipping normal faults in the overlying lower crust, above the off-axis Mansah diapir. (c) Semi-solid melange of pyroxenite from the off-axis MTZ with the crustal gabbros at the Moho. (d) Dunite (red) with pyroxenite lenses (green) in the MTZ of the off-axis Mansah diapir. (e) Close-up of a Wasit sill, with fine-grained center and coarse-grained borders. (f) Nidab intrusions in the lower crust. (g) Elongated peridotite xenoliths in a Nidab intrusion. Contours highlighted by the dashed lines. (h) Close-up of a peridotite xenolith (5 cm long) in a Nidab intrusion showing a 0.5 cm wide pyroxene reaction rim. Du – Dunite; Px – Pyroxene; Cpx – Clinopyroxene; Gb – Gabbro. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
4. Results

Descriptions of all analytical techniques can be found in the electronic appendix. Data are presented in supplementary Tables A.2 to A.6.

4.1. Whole rock major element compositions

Major element abundances are consistent with rock types and reflect modal variations (Fig. A.1), so only a few key observations are noted here. Harzburgites and dunites lacking melt impregnation have the same compositions on and off-axis. Nidab and Wasit off-axis intrusions differ from the on-axis MTZ gabbros, having higher FeO, MnO, TiO2 and Total Alkali (Na2O + K2O) contents. The Nidab intrusions have globally basaltic compositions, with higher Al2O3 and total alkalis and much lower MgO contents than the Wasit sills.

4.2. Whole rock trace element compositions

In both diapirs, harzburgites and dunites lacking melt impregnation features have extremely low Rare Earth Element (REE) and other incompatible trace element contents, with most values below detection limits (Fig. A.2a). Chondrite normalized values of the measurable HREE hint at progressive depletion towards the lighter REE (Fig. A.3a), as noted by Godard et al. (2000) in their study of Maqsad diapir peridotites. In contrast, impregnated harzburgites and dunites have nearly flat HREE patterns and moderate depletion in LREE (Fig. A.3a), with positive anomalies in Eu in the on-axis samples. This feature is consistent with the presence of plagioclase, which also may explain the strong positive Pb and Sr anomalies in the full trace element patterns of the on-axis rocks (Fig. A.2a), though hydrothermal alteration may also play a role.

The rocks of the off-axis gabbro–pyroxenite meltage have REE compositions similar to those of off-axis pyroxenites and on-axis gabbros. The white layer displays strong positive Eu (Fig. A.3b) and Sr (Fig. A.2b) anomalies, characteristic of cumulus plagioclase.

The Wasit sills show REE patterns similar to those of the off-axis pyroxenites, but with concentrations 3 to 5 times higher (Fig. A.3c) and large positive Sr anomalies (Fig. A.4a). The Nidab intrusions have the highest REE concentrations and, in all but one case, display nearly flat REE patterns that contrast with the LREE depleted patterns of the Wasit sills (Fig. A.3d). They have positive anomalies in Eu and Sr along with negative anomalies in Zr and Th in some samples, but relative depletion in Nb and Ta is not evident (Fig. A.4b).

4.3. Mineral major element compositions

Major element zoning between core and rim is not observed in any of the analyzed phases. In all thin sections, different grains of each phase yield indistinguishable results (Table A.4). Molar forsterite (Fo) values in olivine vary from 0.92 to 0.94 in dunites and harzburgites from both diapirs (except for on-axis impregnated dunite 07-0D20 with Fo 0.90). In the off-axis case, average olivine Fo values were 0.91 and 0.92 in the two pyroxenites from within the diapir, and varied from 0.79 to 0.88 in the Wasit and Nidab intrusions surrounding the diapir. Eleven of the 12 gabbros analyzed from the on-axis diapir MTZ yielded olivine Fo values of 0.89–0.91. Clinopyroxene in harzburgites from both diapirs, and in pyroxenites from the off-axis diapir, have Mg# [Mg/(Mg + Fe)] ranging from 0.93 to 0.95, while those from the off-axis intrusions range from 0.76 to 0.90. Mg# of clinopyroxenes of all 10 analyzed on-axis gabbros display a limited range (0.89–0.93). Among all of our samples, clinopyroxene Mg# and olivine Fo are positively correlated (Fig. A.5b). The highest fraction of molar anorthite (An%) in plagioclase (0.96) was found in the impregnated dunite 07-0D20, while the An% values of plagioclase of on-axis gabbros vary from 0.81 to 0.96. In contrast, An% values of plagioclase from the off-axis intrusions vary greatly, from 0.51 to 0.92.

4.4. Trace element compositions of separated minerals

Trace element contents of individual phases (clinopyroxene, plagioclase, amphibole) from a given rock were quite homogeneous (Table A.5) so only average REE compositions for each sample are plotted in the figures cited below.

All clinopyroxenes from on-axis gabbros, off-axis pyroxenites and the gabbro–pyroxenite meltage display flat HREE patterns and depletion in LREE, with those from the off-axis pyroxenites having globally lower REE contents (Fig. 4a) than those from the on-axis gabbros (this study and Koga et al., 2001). Clinopyroxenes from the Wasit sills (Fig. 4b) also have flat HREE patterns and show depletion in LREE, but this depletion is less marked than in the
pyroxenites, and overall REE contents are much higher. Wasit sill clinopyroxenites display negative anomalies in Sr, Pb and Ba (hosted in plagioclase) as well as Nb, Ta and Ti (incorporated in amphibole) (Fig. A.6). Unlike in the other lithologies, clinopyroxene in the Nidab intrusions have nearly flat REE patterns, with about ten times chondritic abundances (Fig. 4b).

Plagioclase from the off-axis gabbros (Fig. 4c) show moderate enrichment in LREE relative to HREE, with a strong positive anomaly in Eu. In the plagioclase off-axis gabbro–pyroxenite melange, enrichment in LREE is much less evident. Plagioclase from the off-axis intrusions (Fig. 4d) have much higher overall REE abundances with greater LREE enrichment than the off-axis gabbros.

Amphibole, found only in the off-axis intrusions, have REE spectra with forms very similar to those of the corresponding clinopyroxene, but with 2 to 3 times higher overall abundances (Fig. 4e). The Nidab intrusions show nearly flat REE patterns with a hint of LREE depletion manifested by a small downturn in La, while the relative LREE depletion of the Wasit sill is more evident. Occasional minor negative Eu anomalies suggest some degree of equilibration with plagioclase. Amphibole in both types of intrusions have high abundances of the High Field Strength Elements (HFSE): Nb, Ta and Ti, which complement their low abundances in the associated clinopyroxene (Table A.5 and Fig. A.6).

4.5. Sr and Nd isotopic compositions

Sr and Nd isotopic analyses were performed on 37 samples from the off-axis diapir (pyroxenites, Wasit and Nidab intrusions, pyroxenite–gabbro melange) and the on-axis diapir (gabbros, dunites and harzburgites). As discussed below, both leached and unleached samples were analyzed. Some Nd analyses were unsuccessful because of very low Nd concentrations. Among the unleached samples, on-axis gabbros have high εNd(t) values (εNd(t) = 10^4 × ([143Nd/144Nd]sample/[143Nd/144Nd]CHUR − 1), with t = 95 Ma, the age of the ophiolite and CHUR representing the chondritic ratio), between +8.5 and +9.2. In contrast, the unleached off-axis samples have lower εNd values between +5.6 and +7.6, with one Wasit sill at +8.8. The dichotomy is even stronger in Sr isotopes. Unleached on-axis gabbros have MORB-like 87Sr/86Sr ratios, ranging from 0.703010 to 0.703438, with the exception of one sample (07-OD43; 0.703749), whereas the off-axis samples have more radiogenic values, ranging from 0.703524 to 0.706192 (Table A.6 and Fig. 5).

Sr isotopic compositions of samples from the ocean lithosphere are often perturbed by hydrothermal circulation of seawater (see Bosch et al., 2004, for an example from the Oman ophiolite). To decipher the importance of this effect, analyses of leached samples were performed. The efficiency of our leaching procedure was first demonstrated by comparing results obtained on leached whole rocks with those from handpicked clinopyroxene separates (see electronic appendix for details). For Sr isotopes, the dichotomy between on and off-axis results seen in unleached whole rocks nearly disappears in the leached samples (Table A.6 and Fig. 6). The off-axis leached samples have 87Sr/86Sr ratios ranging from 0.703004 to 0.703832 (except for the harzburgite 07-OD27B: 0.708932), while the off-axis leached samples have 87Sr/86Sr ratios between 0.703136 and 0.704390. Thus the highly radiogenic Sr compositions of the unleached off-axis samples result mainly from post-magmatic hydrothermal processes. The much smaller post-magmatic hydrothermal influence on the on-axis gabbros may reflect the relatively high Sr concentrations of these samples as well as the presence of a large on-axis magma chamber that could protect the underlying gabbros from hydrothermal circulation. Nevertheless, even after leaching to remove the hydrothermal component, off-axis samples have on average higher 87Sr/86Sr ratios.

Due to the extremely low Nd concentration of seawater, Nd isotopic compositions are expected to be essentially unaffected by hydrothermal circulation, so it is not surprising to find that the leached samples display the same distinction between on and off-axis Nd signatures seen in the unleached samples (Fig. 6). Among the on-axis gabbros, εNd ranges from +8 to +8.8, which puts them in the field of MORBs and unaltered ridge-related samples from Oman (Godard et al., 2006; McCulloch et al., 1981; Rioux et al., 2012, 2013). The off-axis leached samples have globally lower and more heterogeneous εNd values (+6.2 to +7.9). With an εNd value of +8.8, the gabbro–pyroxenite mixture (10-OM39C) is an exception, but this high value may reflect that of the pre-existing gabbroic crust rather than the impinging off-axis diapir. The off-axis leached Wasit and Nidab intrusions have 87Sr/86Sr ratios and εNd values that fully overlap, but extend to higher 87Sr/86Sr, than the range of the leached pyroxenites.

5. Discussion

5.1. Contrasts between the on and off-axis diapirs

Field mapping, petrological and geochemical investigations revealed several striking features of the off-axis Mansah diapir that contrast markedly with the on-axis case (Fig. 1). In Mansah, a shear zone separates the steeply plunging lineations of the diapir from the horizontal foliations of the surrounding harzburgite, consistent with the uprise of hot material rooted in the asthenosphere through colder lithosphere. In Maqasad, the continuous and gradual rotation of lineations towards parallelism with the surrounding
Fig. 5. (a) $\varepsilon_{\text{Nd}}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of our unleached samples (solid triangles, circles, diamonds and squares). The black area represents the unleached samples (Wadi Tayin massif) from McCulloch et al. (1981). The dark gray and light gray areas represent the volcanics V1 and V2 from Godard et al. (2006). MORB field: O’Nions et al. (1977), DePaolo and Wasserburg (1976), Mahoney et al. (1989), Staudigel et al. (1991), White et al. (1993). The isotopic compositions of Cretaceous seawater are from DePaolo and Wasserburg (1976). The seawater mixing curve was constructed assuming a Sr/Nd ratio of $2.6 \times 10^6$ in seawater and of 23 in the rocks, based on the Sr/Nd ratios in our pyroxenite samples. (b) Histogram of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of all the on and off-axis unleached samples. The light gray area represents the MORB field.

Fig. 6. (a) $\varepsilon_{\text{Nd}}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of on and off-axis leached whole rocks or clinopyroxene (cpx) separates. The $\varepsilon_{\text{Nd}}$ mean uncertainty (2$\sigma$) including all identified sources of error is indicated, mean uncertainties for Sr isotopic ratios are roughly the size of the symbols. For one sample, no $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is available, as indicated by the horizontal double arrow. Light gray area – Oman unaltered samples (McCulloch, 1981). References for MORB and Oman unaltered fields as in Fig. 5. (b) Inset showing all samples for which Nd data are available, leached and unleached.
harzburgite is the expected result of diapirism beneath a spreading axis, where lithosphere is absent. The off-axis MTZ is much thicker than the on-axis MTZ and totally free of gabbroic lenses, containing instead massive accumulations (around 20% of MTZ) of weakly deformed clinopyroxenite lacking both plagioclase and orthopyroxene. The mantle and crust surrounding the off-axis diapir contain intrusions bearing magmatic amphibole, suggesting crystallization from a hydrated melt. Clinopyroxene from off-axis MTZ pyroxenites have lower incompatible element abundances than those of on-axis MTZ gabbros, and are more depleted in LREE. However the Nd isotopic compositions of all off-axis lithologies are less radiogenic than those of the on-axis MTZ, and on average their Sr isotopic compositions are slightly more radiogenic (Fig. 6).

5.2. Why is the off-axis diapir so rich in clinopyroxene?

The key to understanding the differences between the on and off-axis diapirs is to determine the origin of the abundant clinopyroxene in the off-axis MTZ. Several processes can form clinopyroxene concentrations. Bédard (1991, 1993, 2001) and Lissenberg and Dick (2008) noted that pyroxenite can form in the lower oceanic crust by the reaction of migrating melt with gabbros. However this scenario is not applicable here because the mantle section traversed by the rising off-axis diapir was devoid of gabbro. Alternatively, the pyroxenites could be of cumulate origin if clinopyroxene precipitates before plagioclase. During fractional crystallization, both greater pressures and higher water contents favor the formation of clinopyroxene (Feig et al., 2006; Koeke et al., 2009). As the MTZ of the on and off-axis diapirs probably formed at similar depths (i.e., crustal thickness was roughly constant), a differential pressure effect seems unlikely. On the other hand, enhanced water contents in the off-axis diapir are consistent with geological constraints. As the hot diapir rose from the asthenosphere, it partially assimilated the intervening lithospheric mantle, as shown by the deformed ultramafic xenoliths in the Nidab intrusions (Fig. 2g–h). The presence of amphiboles in the margins of the Wirats sills surrounding the diapir implies that their parental magmas were water rich, suggesting that the off-axis lithosphere incorporated into the rising diapir was hydrated. Evidence for hydrothermal processes at Moho depth in the Oman ophiolite (Bosch et al., 2004; Nicolas and Mainprice, 2005; Nicolas et al., 2003) provides a likely hydration mechanism, assuming that such circulation can descend into the underlying mantle section.

However the presence of water, though favoring clinopyroxene crystallization while inhibiting that of plagioclase, may not suffice to explain the large volumes of clinopyroxenite found in the Mansah diapir MTZ. If these formed by crystallization from a magma, they should be conjugate to large masses of residual melt. The volume of the Wasit and Nidab intrusions, which could in theory represent such residual melts, is much smaller than that of the crustal section conjugate to the thinner gabbroic MTZ of the on-axis diapir. Furthermore, even at water saturation, the temperature interval for clinopyroxene fractionation without plagioclase is limited in MORB type magmas (~40°C in experiments using hydrated tholeiitic compositions; Koeke et al., 2009; Feig et al., 2010). So if the pyroxenites were cumulates from even a water-rich MORB-type melt, it is surprising that they contain no trace of plagioclase.

Thus an additional cause besides the presence of water may be needed to explain the very large volumes of pyroxenite observed in the off-axis diapir. One possibility, developed below, is that the compositions of melts delivered to the off-axis MTZ differed from those delivered on-axis, being enriched in a clinopyroxene component. This hypothesis is supported by the difference in Sr, and especially Nd, isotopic composition between the MTZ of the two diapirs, indicating that the on-axis and off-axis magmas were not derived from the same source.

5.3. Melting of a pyroxenite-bearing source and resulting melt-peridotite interaction

The less radiogenic Nd isotopic compositions of the Mansah pyroxenites, compared to those of rocks from the on-axis MTZ, may indicate that the Mansah magmas contained a melt-component derived from pyroxenite veins. Such veins may originate directly or indirectly from recycled oceanic crust (e.g. Allègre and Turcotte, 1986), though several other origins, including delamination of lower crustal material or metasomatic segregation could also be envisaged (Hirschmann and Stolper, 1996). The presence of such veins in the MORB source mantle has been postulated on the basis of direct observations in ultramafic massifs and of coupled isotopic and trace element systematics in basalts (Hirschmann and Stolper, 1996; Niu et al., 1999; Prinzhofer et al., 1989; Stracke et al., 2000). However, the signatures of hypothesized pyroxenite vein components in MORB magmas are quite subtle, due to mixing and dilution with peridotite-derived melts. Rocks from the MTZ may approach the pre-mixing isotopic compositions of the magmas more closely and thus may more easily reveal the presence of pyroxenite veins.

Pyroxenite veins have lower melting points than the surrounding peridotite and will thus be the first components to melt in an upwelling mantle diapir (Hirschmann and Stolper, 1996; Kogiso et al., 2004a, 2004b; Lambert et al., 2012; Stracke et al., 2000). Beneath the ridge axis, melting rates are high, leading to a greater contribution from peridotite. In the MTZ of the on-axis diapir, the early pyroxenite-derived melts are overwhelmed by melts derived from the surrounding fertile peridotite, so the Nd and Sr isotopic ratios have MORB-like values. Off-axis, extents of melting are lower, so the pyroxenite signature is more likely to be preserved. As the off-axis diapir ascends towards the Moho, it interacts with and incorporates the harzburgitic lithosphere. This lithosphere is highly depleted in incompatible elements and cannot contribute much Nd and Sr to the rising melts, so the magmas reaching the MTZ retain the Nd and Sr isotopic signature of the original pyroxenite veins (see the electronic appendices for an example of how such a vein melting model might work).

Melts derived from pyroxenite veins are unlikely to be in equilibrium with the surrounding peridotite (e.g. Sobolev et al., 2007). Based on both experiments and theoretical modeling, Lambert et al. (2012) determined that the interaction of melts derived from pyroxenite veins with peridotite leads to the crystallization of clinopyroxene and, depending on the conditions and compositions of the melt, to the crystallization of olivine and the dissolution of orthopyroxene or vice versa. Although their experimental conditions are not the same as ours (they consider lherzolite instead of harzburgite, their modeling and experiments were performed at higher pressures and under anhydrous conditions), their study shows that it is possible to produce a large amount of clinopyroxene by melt interaction in the mantle over a wide range of pressure and temperature conditions. An analogous process could explain the clinopyroxenes found in the MTZ of the off-axis diapir.

We suggest that in the Mansah region, magmas formed by the partial melting of pyroxenite veins within an ascending asthenospheric diapir. In Fig. 7, it is further speculated that a random abundance of pyroxenite veins within the root of the on-axis upwelling zone may have caused enhanced melting, and triggered the off-axis diapirism. In the final stage of its ascent, the off-axis melt reacted with the hydrated lherzolitic harzburgite to crystallize clinopyroxene and some olivine, while dissolving orthopyroxene. In the model of Lambert et al. (2012), the scarcity of orthopyroxene
places strong constraints on the composition of the original pyroxenite veins, as they must be able to produce melts with low silica activity. However, these constraints may be relaxed in our case, since the Mansah MTZ formed at lower pressures than those considered by Lambart et al. (2012), and at these shallow depths, even MORB melts are out of equilibrium with orthopyroxene (Kelemen et al., 1995). As discussed above, the presence of water derived from the lithosphere would be likely to enhance the crystallization of clinopyroxene and suppress that of plagioclase, normally expected to occur at our lower pressure conditions (Feig et al., 2006; Koepke et al., 2009). The overall result may be a MTZ composed of dunite with clinopyroxenite lenses.

5.4. Depleted incompatible element signature of pyroxenites

As noted above, the off-axis pyroxenites have less radiogenic Nd isotopic compositions than the on-axis gabbros (Fig. 6), indicating crystallization from melts derived from a source with a lesser degree of the time-integrated LREE depletion. However, clinopyroxenes from the pyroxenites have more depleted incompatible trace element signatures than clinopyroxenes from the gabbros (Fig. 4). To try to understand this paradox, we calculated the REE contents of melts in equilibrium with the clinopyroxenes in the two settings. This approach inherently assumes that the clinopyroxene compositions currently observed were not modified by post-crystallization processes. Re-equilibration with trapped melts can augment the incompatible element contents of clinopyroxenes, leading to spuriously high REE contents in the calculated equilibrium melts (Bédard, 1994). However, in our case, the scarcity of intergranular phases, the absence of mineralogical zoning and the uniformity of REE compositions from a given thin section argue against the presence of significant amounts of trapped melt, while the preserved magmatic textures indicate that evidence for such a phase has not been erased by recrystallization (Jousselin et al., 2012). Thus the REE contents of clinopyroxenes are probably original and can therefore be used to calculate the REE contents of the melts from which they formed. To do this, we used the predictive model for REE partitioning between clinopyroxene and melt of Wood and Blundy (1997). This model takes into account pressure and clinopyroxene composition, thus permitting more reliable estimates of melt compositions in different contexts than those obtained assuming constant partition coefficients. To enable comparison with the previous study of Koga et al. (2001), we also used this model to recalculate the liquids in equilibrium with the clinopyroxenes they analyzed from the gabbros of the on-axis MTZ.

The calculated melts in equilibrium with clinopyroxenes (Fig. 8a) in the on-axis gabbros have nearly flat REE patterns, with abundances mostly 5 to 15 times chondritic values, except for minor relative depletion in the lightest REE. Our calculated melt compositions are consistent with those of Koga et al. (2001), also from the Maqṣād diapir. As they note, the Maqṣād MTZ melts are relatively uniform; their compositions are within the range observed in the Oman volcanics (Alabaster et al., 1982; Pallister and Knight, 1981) and similar to those of MORB.

The calculated melts in equilibrium with clinopyroxenes in the off-axis pyroxenites (Fig. 8a) display globally flat or slightly sloping HREE patterns, with depletion in LREE. Overall, the calculated melts differ between the MTZ of the two diapirs, with those from the off-axis MTZ being more depleted than those of the on-axis MTZ, as shown by the lower Nd/Yb and La/Sm ratios and mostly lower Yb and La contents of the off-axis melts in equilibrium with the pyroxenites (Figs. 9a and A7). Thus, unlike the inferred on-axis melts, the calculated melts in equilibrium with the off-axis MTZ are more depleted in REE and other incompatible elements than the Oman volcanics or most MORB, despite the Nd isotopic evidence for their derivation from a source with a lower time-averaged Sm/Nd ratio.
In the context of our model, the low incompatible element contents of the off-axis pyroxenites could result in part from effective dilution caused by interaction of the original pyroxenite-derived melts with lithospheric, depleted harzburgite (direct evidence for harzburgite assimilation, albeit at a higher level, is provided by the ultramafic xenoliths in the Nidab intrusions). Clinopyroxenes formed during melt interaction with depleted harzburgite are expected to have more depleted REE spectra than those formed by simple crystallization from melts. This effect might be enhanced by direct melting of the hydrated harzburgites as the diapir ascends, diluting the incompatible element contents even further, while having very little effect on Nd isotopic compositions, which would reflect those of the original pyroxenite veins. Nevertheless, as our modeling shows (see electronic appendices), interaction with depleted harzburgite, while greatly lowering REE contents, can explain only part of the relative LREE depletion. In other words, the pyroxenite veins in the source must themselves have been somewhat LREE depleted.

5.5. Origin of the Wasit and Nidab intrusions

Lambart et al. (2012) show that reaction of pyroxenite-derived melts with peridotite generates a second melt, of quantity and composition dependent on the conditions. If the pyroxenites of the off-axis diapir formed by an analogous process, the resultant melt may have escaped above and on both sides of the ascending diapir, forming melt lenses in the surrounding mantle (Fig. 10). Given their MgO and Ni rich compositions, the Wasit sills may represent cumulates from such melts, thus explaining why they share the same Sr and Nd isotopic compositions as the pyroxenites. Clinopyroxenes from the Wasit sills display LREE depletion similar to, but slightly less marked, than that of clinopyroxenes from the pyroxenites (Fig. 4). However they have much higher overall REE levels, suggesting that their parental melts experienced extensive olivine and minor clinopyroxene fractionation prior to crystallization of the sills. This is supported by the lower Fo contents of the Wasit olivines and the lower Mg# of their clinopyroxenes relative to those of the pyroxenites (Fig. A.5). Using the model of Wood and Blundy (1997), we calculated REE compositions of liquids in equilibrium with clinopyroxene from the Wasit sills (Fig. 8b). However these values are only approximate, as the complementary Ta–Nb anomalies of the clinopyroxenes and amphiboles (Fig. A.6) suggest post-crystallization re-equilibration occurred between these two phases.

The Nidab intrusions, which have bulk major element compositions approximating those of basaltic liquids (Fig. A1) and nearly flat whole rock and clinopyroxene REE spectra (Figs. A.3 and 4b), may represent mixtures between liquids residual to the pyroxenites and those residual to the Wasit sills. The Nidab intrusions contain abundant amphibole-rich veins and numerous ultramafic and crustal xenoliths, suggesting that they have assimilated lithospheric material hydrated by hydrothermal circulation of seawater. This could explain why the Nidab intrusions, while having Sr and Nd isotopic compositions broadly similar to those of the pyroxenites and the Wasit sills, include samples with somewhat elevated 87Sr/86Sr ratios even after leaching. The full overlap between the 87Sr/86Sr values of the Wasit and Nidab intrusions surrounding the off-axis diapir, and those of the pyroxenites within the diapir, suggest that all of these rocks form a magmatic suite, derived from the same initial melts. The minor heterogeneity of the Nd and Sr isotopic signatures at the level of the MTZ could reflect isotopic variability among the pyroxenite veins that provided the original melts.
The structural positions of the Wadis Sills and Nidab intrusions can be understood within the context of the off-axis diapir. The absence of sills within the diapir and the shear zone separating the diapir from the Wadis sills of the surrounding mantle suggest that as the diapir ascended towards the Moho, it progressively engulfed the lithospheric mantle containing the Wadis sills and Nidab dikes that were produced above and at its periphery (Fig. 10). The presence of elongated and rounded mantle xenoliths in the Nidab intrusions would not be possible if the Nidab intrusions were produced only after the diapir had reached the Moho. These intrusions are only present in the last few meters of the mantle and in the lowermost crust. We suggest that to first order, the Nidab lenses represent the liquid produced by melt–rock reaction in the diapir, mixed with residual liquids from the Wadis sills and modified by interaction with the pre-existing crust and uppermost mantle.

5.6. Could the Mansah diapir result from SSZ magmatism?

As discussed above, we think that our off-axis results are most simply explained by interaction of pyroxenite-derived melts with hydrated, deformed harzburgites in the lithospheric section traversed by an upwelling diapir. Nevertheless, we must consider the alternate possibility that the unusual features of the Mansah diapir reflect late-stage magmatic processes in an SSZ setting. Though the absence of arc volcanism or of any volcaniclastic sediments, and the lack of arc-like trace element signatures (Godard et al., 2006) argue against the existence of a fully developed subduction environment, evidence exists from throughout the ophiolite for higher fluid contents in the magmatic sources relative to those of MORB (MacLeod et al., 2013). Given the tectonic complexity that surely existed prior to obduction, such hydrous conditions could perhaps be reconciled with several different models.

The REE spectra of clinopyroxenites from the Mansah pyroxenite ensembles resemble those of clinopyroxenites from lower crustal wehrlites of the Haşkaya block described by Koepke et al. (2009), which they related to the Lassal magmas (also called V2) found in the northern part of the Oman ophiolite (Ernstwein et al., 1988). These late-stage magmas are thought to result from fluid-enhanced melting of previously depleted lithosphere, with the fluids derived from dehydration of sediments and altered crust of the underlying slab during incipient (Boudier et al., 1988) or more well-developed (Pearce et al., 1981) subduction. However several observations argue against a subduction related origin for the Mansah diapir. The negative Nb-Ta anomalies characteristic of lavas from SSZ settings are lacking in Mansah, notably among the rocks with compositions most closely resembling those of liquids (Nidab intrusions, Fig. A.4). Moreover, although the presence of abundant clinopyroxene is considered to be an argument in favor of SSZ settings, the liquids in equilibrium with our off-axis pyroxenites lack the negative Nb anomalies that characterize lavas from SSZ (Fig. 9b; ratios La/Nb <0.5). V2 magmas have never been found in the Sumail block, while in the northern blocks of the ophiolite, where these magmas are located, no structures resembling the Mansah diapir exist. The V2 magmas have Nd isotopic compositions very similar to those of the V1 (i.e., ridge-related) magmas (V1: 56Nd = 7.9±8.8; V2: 56Nd = 7.3±8.7; Godard et al., 2006), and of the on-axis Maqasad diapir (56Nd = 7.8±8.8). In contrast, samples related to the off-axis Mansah diapir have mostly less radiogenic values (56Nd = 6.2–7.9). This contrast in Nd isotopic composition suggests that the Mansah diapir is not genetically related to the V2 magmas, so even if the latter have a subduction-related origin this does not imply a similar origin for the Mansah magmas.

Roux et al. (2012, 2013) found that post-rift magmatic crustal intrusions from the Sumail, Wadi Tayn and Rusaq–Haşkaya massifs have younger U–Pb zircon ages and slightly lower 56Nd values than ridge related magmas. They therefore drew a parallel with V2 magmatism (somewhat tenuous in our view, since as noted above, V2 and V1 magmas have indistinguishable 56Nd values), arguing that both formed in a proto-arc setting. Since the samples analyzed by Roux et al. (2013) were collected far from the Mansah diapir and in the upper crust rather than the MTZ, their pertinence to the age of this structure is not obvious. In the shallow subduction model of Boudier et al. (1988), oceanic detachment is inferred to occur along the asthenosphere–lithosphere boundary. Since the Mansah diapir shows asthenospheric flow structures, if this model is correct, emplacement of the diapir must predate detachment and thus be roughly concomitant with magmatism at the ridge axis. Therefore, clarification of the tectonic context of the off-axis diapirism requires precise determination of its timing.

We conclude that there is no compelling evidence to suggest that development of the Mansah structure was related to fluids rising in a supra-subduction zone setting. Nevertheless, more work, in particular U–Pb zircon dating (e.g. Roux et al., 2013) of rocks associated with the Mansah diapir, is needed to better define the tectonic setting in which the diapir ascended.

6. Summary and conclusion

Our study of the Mansah diapir of the Oman ophiolite provides new insights into off-axis magmatic processes, particularly those occurring in the critical crust–mantle boundary region. The Moho Transition Zone (MTZ) of this off-axis diapir displays plunging lineations that cut at high angle the horizontal foliation of the surrounding mantle, contrasting with the continuity from vertical to horizontal mantle flow observed in on-axis diapirs. The MTZ of the off-axis diapir is even thicker than that of the nearby on-axis Maqasad diapir and contains massive clinopyroxenite lenses in dunite, rather than the gabbroic lenses in dunite found in the on-axis case. Gabbroic sills intrude the mantle around the off-axis diapir and microgabbroic intrusions are found in the overlying crust. Clinopyroxenites from the off-axis pyroxenites were derived from melts more depleted in incompatible elements than their on-axis equivalents. However, the Nd isotopic composition of the off-axis melts indicates a less depleted source (εNd = 6.2–7.9 in 18 of 19 analyses) than that of the on-axis melts (εNd = 7.8–9.2, 10 analyses), which are isotopically similar to Indian Ocean MORB.

To explain these unusual features, we suggest that in the off-axis setting, a diapir rooted in the asthenosphere ascended through the depleted, hydrated lithosphere. The first melts to form were derived from pyroxene veins at depth, as suggested by the less radiogenic εNd values of the off-axis samples. During its ascent, the diapir assimilated parts of the hydrated and depleted lithosphere in its path. As the melt rose, it interacted with the lithospheric harzburgite, forming clinopyroxene and olivine at the expense of the orthopyroxene, and acquiring a more depleted trace element signature. As harzburgite contains very little Nd, this process had little effect on Nd isotopic compositions. The water derived from this hydrothermally altered lithosphere enhanced the crystallization of clinopyroxene and suppressed that of plagioclase. The gabbroic sills found in the mantle around the diapir are cumulates formed from the fractionated daughters of liquids produced by the reaction between the harzburgite and pyroxenitic melts, while the microgabbroic intrusions, found essentially in the crust, represent the approximate corresponding liquid compositions.

The less radiogenic Nd compositions of the off-axis samples add to the growing evidence for the presence of pyroxene veins in the MORB mantle source. This component was probably present in the source of both diapirs, but in on-axis magmas its signature was muted by a larger relative contribution from peridotite melts. Our results show that off-axis melt delivery can have a major impact on the mineralogy and geochemistry of the magmatic products. As most of the geophysical evidence for off-axis deep magmatic
activity at fast spreading centers is recent, the importance of such processes may have been underappreciated.

Acknowledgements

This work was supported by the INSU-SYSTEM (CNRS) program. The authors are grateful to Cédric Demeurie for the polished thin sections, Catherine Zimmermann and Christiane Parmentier for assistance with Sr and Nd chemistry and analyses, Olivier Bruguer for assistance with in-situ ICP-MS analyses and Lydéric France for helpful discussions. We thank Jean Bédard and Matthew Roux for their thorough and constructive reviews, which greatly improved the quality of the manuscript. The patient and careful editorial handling of Tim Elliott is greatly appreciated. This is CRPG contribution number 2420.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2015.12.005.

References


