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Geochemistry of gabbro sills in the crust–mantle transition zone of the Oman ophiolite: implications for the origin of the oceanic lower crust

Peter B. Kelemen *, Ken Koga, Nobu Shimizu

Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

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Abstract

Gabbroic sills intruding dunite in the crust–mantle transition zone (MTZ) of the Oman ophiolite have textures and compositions very similar to those in modally layered gabbros that form the lower part of the gabbro section in the ophiolite, and different from those in non-layered gabbros near the dike–gabbro transition. The presence of gabbroic sills in the MTZ indicates that modally layered gabbros can form far below the level of magmatic neutral buoyancy and far below the dike–gabbro transition. Minerals in the sills and lower, layered gabbros are in Fe–Mg and trace element exchange equilibrium with liquids identical to those that formed the sheeted dikes and lavas in the ophiolite. In contrast, many of the upper, non-layered gabbros resemble crystallized liquid compositions, similar to the dikes and lavas. The lower, layered gabbros probably formed in sills similar to those in the MTZ. Mantle-derived magmas cooled in these sills, where they crystallized from a few percent to 50% of their mass. Residual liquids then rose to form upper gabbros, dikes and lavas. Sills may form beneath permeability barriers created by the crystallization of cooling liquid migrating by porous flow. Once permeability barriers are present, however, porous flow becomes a less important mode of magma ascent, compared to ponding in sills, gradual increase in magma pressure, and periodic ascent in hydrofractures. Thus, gabbroic sills in the MTZ may represent the transition in fast-spreading ridge environments from continuous porous flow in the mantle to periodic diking in the crust.

Keywords: mid-ocean ridges; igneous rocks; petrology; lower crust; sills; gabbros; cumulates; Mohorovicic discontinuity

1. Introduction

Observations of the Oman ophiolite place important constraints on models of oceanic crustal genesis. Because the ophiolite includes a continuous layer of sheeted dikes overlain by pillow basalts, it is clear that most of the igneous crust formed at an oceanic spreading center. The main lava series in the ophiolite, the Geotimes and Lasail volcanics, are tholeiitic basalts and andesites with rare earth element (REE) and trace element contents similar to mid-ocean ridge basalt (MORB) [1–3]. In detail, concentrations of REE and other incompatible trace elements are lower in Oman lavas, at a given Cr concentration, than in MORB. Also, in some of the northern massifs, andesitic lavas comprise part of the extrusive section. These characteristics suggest that the ophiolite may have formed in a super-subduction zone setting.

* Corresponding author. Fax: +1 508 457 2183. Tel.: +1 508 289 2956. E-mail: peterk@cliff.whoi.edu

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However, similarities between Oman lavas and MORB suggest that petrogenetic processes in the formation of the ophiolite were similar to processes at normal mid-ocean ridges. On the basis of radiometric age data, subdued crustal thickness variations, a paucity of paleo-fracture zones, and other observations, it is probable that the ophiolite formed at a fast-spreading ridge similar to the East Pacific Rise (EPR), and is different from crust formed at slower-spreading ridges (e.g., [4,5]). In this paper, we concentrate on constraints from Oman on the genesis of gabbros in lower oceanic crust at fast spreading ridges.

We first review previous work, and then present new data on gabbroic sills in the crust–mantle transition zone (MTZ). Theories for the origin of oceanic layered gabbros have ranged from those requiring a kilometer scale magma chamber (e.g., [6,7]), to the notion that all gabbros form in a sill near the dike–gabbro transition and are transported downward by ductile flow of a crystal-rich mush [8–14]. We emphasize aspects of previous work (especially Pallister and Knight [15] and Browning [16,17]) that have been overlooked in recent models: lower, layered gabbros in Oman are distinct from upper, ''foliated'' and ''isotropic'' gabbros; lower gabbros are ''cumulates'', formed by partial crystallization of a melt, from which a large liquid fraction has been removed; minerals in lower gabbros are in REE and Mg/Fe equilibrium with liquids identical to sheeted dikes and lavas of the ophiolite; dikes and lavas could represent such liquids, extracted after the lower gabbros had crystallized. In contrast, most upper gabbros are compositionally similar to sheeted dikes and lavas, and could represent liquid compositions.

Our new data and a companion paper [18] show that gabbroic sills in the Oman MTZ have textures and compositions similar to the lower, modally layered gabbros, and different from the non-layered gabbros near the dike–gabbro transition. These data support the hypothesis that the lower gabbros formed in lower crustal sills. Formation of oceanic layered gabbros in sills has been previously suggested for Oman by Browning [16,17] and Benn et al. [19], for oceanic crust in general by Gudmundsson [20,21] and Bédard et al. [22], for the Troodos ophiolite by Browning et al. [23], and for the Bay of Islands ophiolite by Bédard and co-workers [24,25].

2. Review and discussion of previous work on Oman

2.1. 2.1 Upper and lower gabbros

Layered gabbros in Oman are described by Pallister and Hopson [6], Smewing [7], Browning [16,17], Boudier et al. [18], and others [3,22,26–38]. Gabbros comprise $> 60\%$ of the igneous crust in the ophiolite. In general, investigators have separated gabbroic rocks into ''lower gabbros'', with marked modal layering, and ''upper gabbros'' directly underlying the sheeted dike complex, which lack modal layering. Most upper gabbros are also termed ''foliated gabbros''. In addition, the upper gabbros include ''isotropic gabbros'' and diorites.

Foliation in upper gabbros is defined by aligned plagioclase crystals, and dips steeply (locally $> 60°$) with respect to the paleo-Moho and sedimentary horizons in the ophiolite. Foliation in lower gabbros, defined by modal banding as well as aligned plagioclase, has shallow paleo-dips (generally $< 20°$). Although foliation in upper and lower gabbros has been connected via continuous lines steepening upward from the Moho on some schematic cross-sections, this is probably incorrect. Modal banding in lower gabbros is not physically continuous with the foliation in upper gabbros. Steepening of foliation from $< 20°$ to $> 60°$ takes place in the upper 1/3 to 1/4 of the gabbro section (e.g., [5,10,31]).

2.2. Models for gabbro formation

The field relationships and composition of lower gabbros in Oman were first used to suggest that lower oceanic crust formed by crystal settling in a magma chamber > 20 km wide (normal to the ridge axis) and 3 km high (e.g., [6,7]). However, seismic data indicate that oceanic lower crust below spreading ridges is sufficiently crystalline to support shear waves (e.g., reviews in [39–41]). These observations rule out kilometer-scale, steady-state magma chambers beneath ridges. Consistent observation of a seismic reflector near the oceanic layer 2/3 boundary suggests that a ''shallow melt lens'', within 2 km of the sea floor and a few hundred meters in maximum thickness, is present along fast-spreading ridges; Pwave velocity data suggest that this lens is underlain by a ‘‘crystal mush’’ containing interstitial melt (e.g., [41]).

Nicolas et al. [10,11] suggested that observations in Oman were compatible with the seismic data, and that crystallization of the entire lower crust began in the shallow melt lens. Ductile flow of crustal mush from the melt lens, downward and away from the ridge axis, formed lower gabbros. Modal layering and foliation in gabbros might be produced by ductile flow, not in a magma chamber. Quick and Denlinger (‘‘Gabbro Glacier’’ computer program, 1990, and [12]), Phipps Morgan and Chen [13] and Henstock et al. [14] developed this idea quantitatively. Although there are disagreements within this group over the significance of upper gabbro foliation [41,42], all advocate origin of lower gabbros by initial crystallization in a melt lens near the gabbro–dike transition, followed by ductile flow toward the Moho and away from the ridge. We shall refer to these models collectively as ‘‘conveyor belt models’’. It is not clear whether the nature of Oman gabbros is accounted for by the simplest form of conveyor belt models.

2.3. Microstructures

The absence of extensive plastic deformation in lower gabbros has been reconciled with conveyor belt models by Benn and Allard [35], Nicolas [36], Quick and Denlinger [12], and Nicolas et al. [43] who suggested that the gabbros deformed as a crystal mush, in which strain is accommodated by glide along melt-lubricated grain boundaries, perhaps combined with pressure-solution (diffusion creep) where glide is blocked. Thus, the lack of observed plastic deformation does not rule out large strains ($>100\%$) during formation of the lower gabbros. Indeed, some features are indicative of large strains at magmatic temperatures: for example, boudinage, tight folds, and normal faults with magmatic veins. Locally, lattice preferred orientations in olivine and plagioclase are slightly oblique to banding, indicating a component of simple shear [18,35–37]. However, most deformation could have been pure shear; that is, mechanical flattening and diffusion creep during compaction. No evidence *requires* extensive simple shear distributed throughout the gabbro section.

2.4. Outcrop-scale textures

One important feature is the presence of modally graded layers in the lower gabbros (e.g., fig. 3g,h in [6], and fig. 1c,d in [18]). In these, a sharp lower contact is succeeded by an olivine-rich base. This grades upward into a plagioclase-rich top, followed by a sharp upper contact. It is common to see cyclic repetition, involving several graded layers in succession. Although we have observed ‘‘upside down’’ layers in Oman, the majority have an olivine-rich base. It is likely that these are ‘‘cooling units’’ of some kind. Olivine precipitated from primitive magma, which later became saturated in plagioclase and clinopyroxene. The spatial sequence would correspond to crystallization or accumulation along an accreting surface, usually the base of a ‘‘magma chamber’’. It is unlikely that these asymmetric layers could survive the extensive deformation by simple shear (strains $>200\%$ near the Moho) required by simple ‘‘conveyor belt’’ models. One proposed mechanism for creating modal layering is that some gabbros form in thin sills (e.g., [21]). Adopting this viewpoint, graded layers could represent cooling units within sills.

Layer-parallel, wehrlite sills are common within lower gabbros in Oman [30–34] and in the Bay of Islands ophiolite [44,45]. Because wehrlite sills are ultramafic, their presence within gabbros is easily observed. Discordant, wehrlite intrusions into gabbro are also observed. Quick and Denlinger [12] considered that this indicates that the wehrlite sills were intruded >1 km off-axis, after ductile deformation of gabbroic host rocks was complete. However, this leaves open the question of how many sills formed closer to the ridge axis. Quick and Denlinger proposed that the rarity of observed, intrusive contacts in Oman gabbros could be explained if gabbroic intrusions form on-axis, and are transposed by off-axis ductile flow (e.g., their fig. 9). However, even if they have not been transposed, gabbroic sills in layered gabbro would be difficult to detect in the field; they may be common.

In addition, the rarity of observed gabbroic dikes within lower gabbros may have a thermal explanation. Hydrofracture will lead to rapid, near-adiabatic ascent of magma in a crack. No crystallization will occur during adiabatic ascent. Release of magmatic overpressure will be followed by contraction of the crack to a ''steady state'' width (probably centimeter scale), and then slow crystallization of nearly static liquid. Centimeter-scale gabbroic dikes are present within Oman lower gabbros ([6]; Ceuleneer, pers. commun., 1996; and our observations), but have hitherto been considered unimportant; their abundance is unknown.

2.5. Gabbro composition

Pallister and Knight [15], Ernewein et al. [3], and Lippard et al. [31] showed that upper gabbros in Oman are distinct from lower gabbros. Most upper gabbros have REE abundance and slope similar to sheeted dikes and lavas in Oman (Fig. 1). In terms of major elements, upper gabbros are evolved, commonly including orthopyroxene. Mg# data for upper gabbros are scarce, but average compositions compiled by Browning [16] range from ~ 50 to 70 (Fig. 2); the high end of this range is higher than in lavas but lower than in most lower gabbros. In many contact zones, upper gabbros grade texturally into sheeted dikes (e.g., [46]). Thus, in terms of composition and texture, upper gabbros can be loosely considered to be coarse-grained, slowly cooled equivalents of sheeted dikes. In these and other respects the Oman upper gabbros are similar to shallow-level gabbros formed at the EPR [47–49].

Although upper gabbro compositions closely resemble liquids, on average they are more primitive than sheeted dikes and lavas. This could indicate that: (1) upper gabbros have lost a liquid fraction, perhaps 1–20% of initial liquid mass; and/or (2) they are equivalent to the most primitive liquids that formed dikes; and/or (3) they were ''cumulate'' gabbros that later underwent: (a) addition of ''trapped'' liquid and/or (b) reaction with a migrating liquid [48]. Distinguishing between these alternatives is beyond the scope of this paper.

All the lava, dike and upper gabbro compositions are quite evolved with respect to mantle-derived

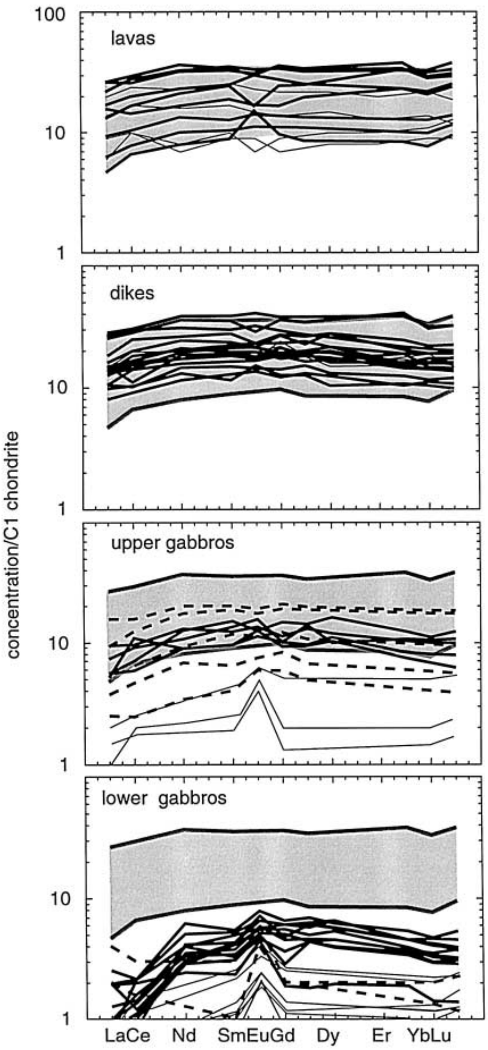

Fig. 1. Compiled rare earth element (REE) contents of rocks from the Oman ophiolite. Top: Compositions of Geotimes and Lasail volcanic units, from [1] (heavy lines) and [3] (lighter lines). Two ''primitive'' lavas from [3] are not shown because they probably include accumulated olivine. In all panels, shaded area encloses range of lava compositions from [1]. Second panel: Compositions of sheeted dikes, from [1] (heavy lines) and [3] (lighter lines). Third panel: Compositions of upper gabbros (including ''high level gabbros'', ''isotropic gabbros'', ''transitional gabbros'', ''foliated gabbros'', ''ferro-gabbros'' and ''ferro-diorites'', but not tonalites, trondhjemites and ''plagiogranites''), from [15] (heavy lines), [31] (dashed lines), and [3] (lighter lines). Bottom: Compositions of lower gabbros, from [15] (heavy lines), [31] (dashed lines), and [3] (lighter lines). Lava and dike compositions are very similar. With the exception of some data from [3], upper gabbros have similar REE to lavas and dikes, and higher REE than lower gabbros. Lavas, dikes and upper gabbros lack an Eu anomaly with respect to neighbor REEs Sm and Gd. Lower gabbros show no overlap in REE overlap with lavas and dikes, and have a positive Eu anomaly.

melts. For example, all the lavas analyzed by Alabaster et al. [1] have an Mg# <70, with an average ~ 50, whereas liquids in equilibrium with Oman mantle peridotite must have had Mg#s >70 (Fig. 2). This applies not only to Oman, but is general for lavas at mid-ocean ridges (e.g., [50]), especially the fast-spreading EPR (e.g., [51,52]). Low Mg# lavas imply that parental, mantle-derived liquids underwent crystal fractionation prior to crystallization of dikes and lavas.

Lower gabbros in Oman have Mg#s >70 (Fig. 2), and low concentrations of incompatible trace elements (Fig. 1). Pallister and Knight [15] emphasized that positive anomalies of Eu with respect to other REE indicates that lower gabbros do not represent liquid compositions. Instead, they are ''cumulates'', precipitated during crystal fractionation of cooling magma, from which a large residual liquid fraction was later removed. Browning [17] used Ni and Cr variation in Oman cumulate gabbros to calculate the mass of liquid removed. He found that one section of the gabbros represented $\sim 55\%$ of the mass of parental liquid; the remaining 45% liquid was extracted. The major and trace element characteristics of cumulate lower gabbros in Oman, outlined here, are shared by cumulate gabbros from mid-ocean ridges (e.g., [53]).

Constraints on melt extraction from lower gabbros can be deduced from chemical layering. Ten meter scale, vertical variation, including varying Fe/Mg in olivine, is common in lower gabbros [7,15–17,31]. If diffuse porous flow were the main mechanism of melt transport from the Moho to the dike–gabbro transition, this vertical variation would be obliterated. The melt/rock ratio in gabbros near the Moho would approach infinity. Exchange reactions at high melt/rock ratio, given olivine grain sizes ~ 2 mm and Fe/Mg diffusivity in olivine $\sim 10^{-14}$ m^2/sec [54], would homogenize vertical variation in a few years (e.g., [55]). It follows that melt extraction, over distances >10 m, must have been in spatially restricted conduits, either channels for porous flow or

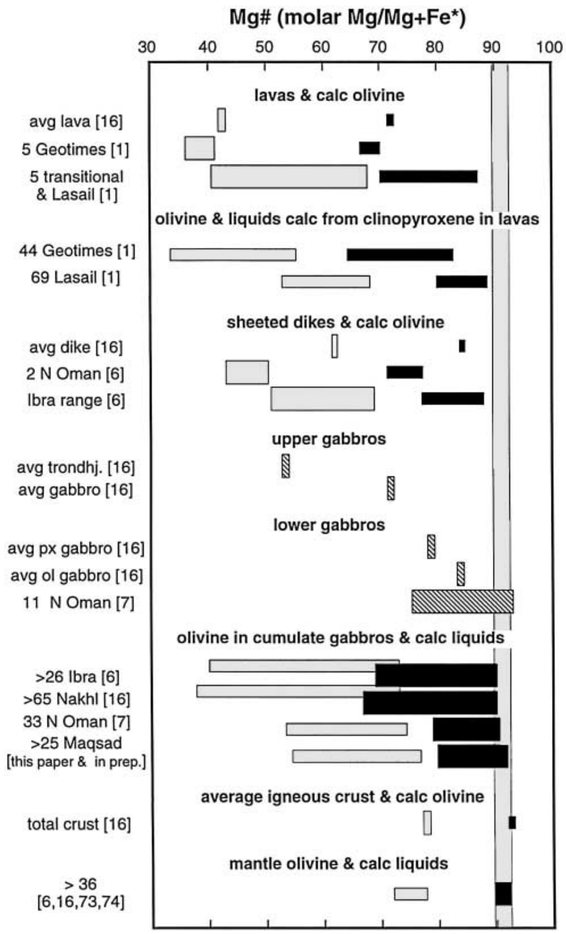

Fig. 2. Compiled data on percent Mg# (100 molar Mg/(Mg + Fe^{2+})) for whole rocks and minerals from the Oman ophiolite. Weight ratio of Fe^{2+}/Fe^{3+} in liquids assumed to be 0.9. ''Liquids'' (lavas, dikes and calculated liquids) are shown as light gray bars; plutonic rocks as dark gray bars; olivines as black bars. For each lava and dike, equilibrium olivine Mg# has been calculated using molar [Fe^{2+}/Mg (olivine)]/[Fe^{2+}/Mg (liquid)] = 0.3 [72]. Conversely, where mineral compositions were measured, liquid compositions have been calculated. For clinopyroxene, we used molar [Fe^{2+}/Mg (clinopyroxene)]/[Fe^{2+}/Mg (liquid)] = 0.25. Measured values are shown as wide bars, calculated values as narrow bars. Number and sources of data are given in legend on left. In legend, ''Geotimes'' and ''Lasail'' are the two oldest and most voluminous lava units, ''Ibra'', ''Nakhl'' and ''Maqsad'' are massifs in the south half of the ophiolite, and ''N. Oman'' refers areas in the north half of the ophiolite. None of the lavas and dikes have Mg# as high as primitive, mantle-derived liquids. Instead, all must have evolved by crystal fractionation from a primitive parental liquid. Olivine in lower gabbros has Mg# appropriate for Fe/Mg equilibrium with the liquids that formed the lavas and dikes. Thus, lower gabbros may be interpreted as ''cumulates'', from which the liquids that formed the upper crust were extracted. Data from [1,6,7,16,73,74].

open ''cracks''. The lack of evidence for focused porous flow in Oman gabbros and the presence of centimeter-scale gabbroic dikes lead us to suggest that melt extraction from the lower gabbros occurred mainly in cracks.

In summary, the upper and lower gabbros in the Oman ophiolite are compositionally distinct. The lower gabbros are ''cumulate'', in the sense that they crystallized from a larger mass of magma, after which the remaining liquid was extracted, probably in cracks. As emphasized by Pallister and Knight [15], the Geotimes and Lasail lava units, together with sheeted dikes and upper gabbros, have the composition of liquids which were extracted from the lower gabbros. Fig. 2 shows that olivine in lower gabbros has Mg# in equilibrium with liquids with the composition of upper gabbros, dikes and lavas. We shall illustrate this point further using REE in a subsequent section of this paper. That the lavas, dikes and upper gabbros actually formed from liquids extracted from the lower gabbros is supported by the fact that combining compositions of all these rocks in their observed proportions produces a crustal composition similar to mantle-derived basaltic liquid [16,29]. Magmas entering the crust cooled and partially crystallized to form lower gabbros. After this, the remaining liquid rose to the upper crust, where it chilled slowly to form upper gabbros, or rapidly to produce dikes and lavas.

2.6. Chemical layering and magma chamber thickness

As noted above, Browning [17] used chemical variation to calculate the amount of liquid extracted from Oman gabbros. Since the unit he studied was 55 m thick and represented 55% of the initial liquid mass, he calculated that the parental liquid body must have been ~ 100 m high. Browning proposed that these gabbros formed in sills or in chemically isolated convection cells within a large magma chamber. (An additional possibility is that the gabbros were later thinned by ductile deformation.) Browning's samples were widely spaced and may not have crystallized from a single parental liquid. However, analyses of gabbros from the Troodos ophiolite yielded a similar result; with sample spacing < 1 m, Browning et al. [23] found magma chamber heights ~ 2 m. They interpreted this in terms of small convection cells in large magma chambers, rather than sills. Nonetheless, Browning's work seems prescient in light of current views on the small size of magma chambers beneath ridges.

3. Sampling and field observations

Samples for this study were collected in the Maqsad massif of the Oman ophiolite by the authors (sample series OM94- and OM95-) and by F. Boudier, A. Nicolas and co-workers (all others). In the Maqsad massif, a nearly flat-lying paleo-Moho, dissected by valleys in mountainous terrain, provides excellent exposure of the MTZ and lower gabbros. Boudier and Nicolas [37] presented geologic maps and cross-sections illustrating the distribution of sills in Maqsad. Sample locations can be located on these, using Latitude and Longitude from the first table of the **EPSL Online Background dataset** [1] (also available from the authors). For our purposes, the MTZ is defined as the region in which gabbro comprises $> 10\%$ and $< 90\%$ of sections > 100 m thick, perpendicular to the paleo-Moho. Using this criterion, Boudier and Nicolas found that the MTZ is 50 to ~ 500 m thick in Maqsad, and is composed mainly of dunite. Harzburgite is very rare.

Several studies (e.g., [22,37,38,56]) have documented the presence of gabbroic sills within dunite in the MTZ throughout Oman. They are also described in a companion paper [18]. The sills are < 1 to > 50 m thick, and usually > 10 to > 200 m long, with thickness/length < 0.1. The sills are composed of troctolites, olivine gabbros and gabbros, which generally show plagioclase foliation as well as modal banding. Modal layering, with individual layer thickness ranging from ~ 1 m to 1 mm and averaging ~ 3 cm, is common. Moho-parallel gabbroic bodies are also found within harzburgites in the Maqsad mantle section [57,58], but these are relatively rare, and we have not examined them in detail.

Sills in the MTZ preserve igneous contacts with the surrounding dunite. In some places, contacts are

[1] http://www.elsevier.nl/locate/epsl (mirror site USA, http://www.elsevier.com/locate epsl)

gradational with surrounding ultramafic rock over tens of centimeters. Elsewhere, contacts are sharp. Lateral interfingering of gabbro with dunite on a centimeter to meter scale is common, with gabbroic apophyses extending into peridotite host rock along planes parallel to layering in the sills and to foliation in the host dunite (fig. 1c in [18]). Few, if any, layers are truncated at gabbro–dunite contacts; they either bend into parallelism with the contact over a few centimeters, or leuco-layers pinch out while melano-layers grade laterally into dunite. These interfingered contacts suggest that the sills have undergone relatively little deformation other than flattening after emplacement within host dunite. Thus, formation of modal layering and plagioclase foliation must not require large amounts of simple shear.

Some contact relationships between gabbro and dunite in Oman have been interpreted as indicative of gabbro rafts within intrusive dunite sills (e.g., [34]). Intrusive dunites, associated with late wehrlite sills, may occur within Oman gabbros near the MTZ. However, in the sills we have analyzed in this study this is not the case; the dunite host rocks surrounding gabbroic sills are compositionally, texturally and physically continuous with underlying mantle dunites and harzburgites (e.g., [37]). Also, there are many faulted contacts between dunite and gabbro in the exposures of the MTZ in the Maqsad area; some of these may juxtapose lower crustal gabbros with mantle dunite. However, all of the MTZ samples we have selected for geochemical analysis are from sills which were demonstrably emplaced as igneous bodies within dunite.

4. Geochemical data

We analyzed crystals in thin sections of samples by electron and ion microprobe. Electron probe analyses of major elements were performed using a Jeol 733 Superprobe at MIT. Ion probe analyses of trace elements were made using the Cameca IMS-3F at Woods Hole, with techniques described by Shimizu and Hart [59]. Estimated errors are $< \pm 2\%$ for major elements, and generally $< \pm 15\%$ for trace elements in pyroxene. Errors in plagioclase REE are uncertain, but larger than for pyroxene. Where possible, the clinopyroxenes analyzed were cores of rounded crystals, although in some troctolites interstitial crystals were analyzed.

In the first table of the **EPSL Online Background dataset** and Figs. 3 and 4, we present data on six lower crustal, layered gabbros (0–1.5 km above the MTZ) and twelve layered gabbro sills (within dunite in the MTZ) from the Maqsad area. Mg# in clinopyroxene ranges from 0.91 to 0.80. Fig. 3 illustrates that, on average, clinopyroxene in sills has higher Mg# and lower REE than in lower gabbros. Clinopyroxene in the Maqsad lower gabbros, in turn, apparently has higher Mg# and lower REE than in lower gabbros 0–4 km above the MTZ in the Ibra area, adjacent to the Maqsad area [15]. The trend in Mg# vs. REE for Maqsad samples is indicative of systematic vertical variation in gabbro composition. The difference between Maqsad and Ibra samples could also reflect systematic vertical variation in, or differences between, lower crustal gabbros in the two massifs, or the use of different analytical techniques, as discussed in the following paragraph.

Our clinopyroxene and plagioclase data are compared to those of Pallister and Knight [15] in Figs. 3 and 4. Maqsad minerals have similar REE slopes, but generally lower concentrations, compared to the Ibra area. Pallister and Knight analyzed mineral sep-

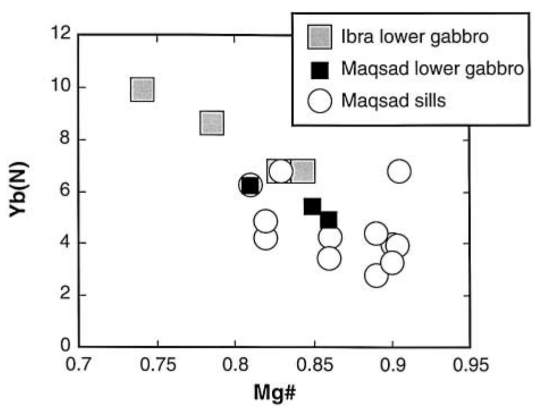

Fig. 3. Variation in Mg# and chondrite normalized ytterbium concentration (Yb(N)) in clinopyroxene from layered gabbros in the Maqsad and Ibra areas of the Oman ophiolite. Ibra data from [15], Maqsad data from this study. Layered gabbro sills in the Maqsad crust–mantle transition zone (MTZ) have generally higher Mg# and lower Yb(N) than layered gabbros in the lower crustal section above the MTZ.

arates by Instrumental Neutron Activation (INAA), whereas our ion probe analyses are of crystal ''cores'', >40 μm from the nearest grain boundary. Thus, some differences may reflect incorporation of low Mg#, REE-rich crystal rims or trace phases in the mineral separates. In addition, we suspect systematic inter-laboratory differences for Ce in clinopyroxene. Our data produce smooth calculated liquid REE patterns (Fig. 5), so the Pallister and Knight data for Ce may be in error.

Plagioclase/clinopyroxene REE partitioning is also illustrated in Fig. 4, with values tabulated in table 2 of the **EPSL Online Background dataset** (also available from the authors). The uncertainties are large, but consistency between our data and [15] suggests that the ion probe analyses of plagioclase are reasonably accurate, despite low REE concentrations, and also that plagioclase and clinopyroxene in these samples crystallized concurrently in a close approach to crystal–liquid equilibrium, with the exception of sample 90OA61.

Fig. 4 also illustrates calculated gabbro compositions, based on ion probe data plus mineral proportions in our samples, compared to whole rock compositions of gabbro from Ibra analyzed by INAA [15]. Both datasets show a consistent, positive Eu anomaly with respect to the neighbor REEs, Sm and Gd. The absence of a negative Eu anomaly in clinopyroxene, and the presence of a positive Eu anomaly in plagioclase and whole rocks, is strong evidence that Oman lower gabbros are cumulates, and do not represent liquid compositions, since mantle-derived liquids at oceanic spreading ridges have never been observed to have a positive Eu anomaly [15,31]. A second-order result is that calculated gab-

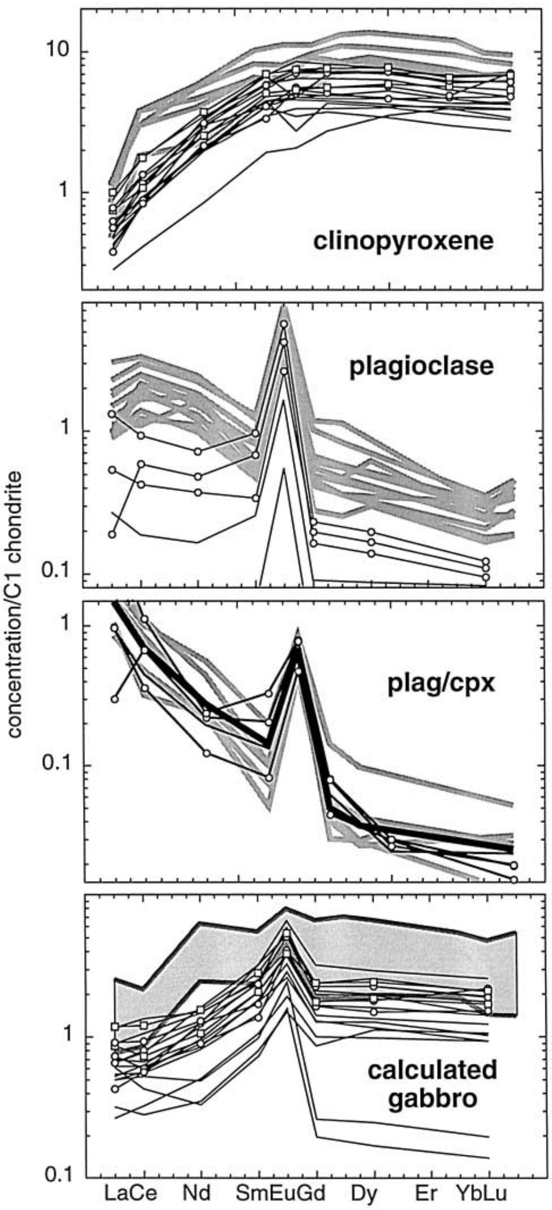

Fig. 4. Average REE concentration in minerals from layered gabbros from the Ibra and Maqsad areas, normalized to concentration in C1 chondrites [76]. Solid lines are for samples from the Maqsad area analyzed by ion microprobe at Woods Hole (see **EPSL Online Background dataset**, table 1, also available from the authors). Lines with open symbols are for 6 lower crustal gabbros; lines without symbols are for 12 sills in the MTZ. Light gray lines are instrumental neutron activation analyses (INAA) of mineral separates from lower gabbros in the Ibra area [15]. Top: clinopyroxene compositions. Second panel: plagioclase compositions. Third panel: plagioclase/clinopyroxene concentration ratio. Heavy dark line is average incorporating both our data and [15] (see **EPSL Online Background dataset**, table 2). Bottom: calculated gabbro compositions for Maqsad area, using ion probe analyses of clinopyroxene, average plagioclase/clinopyroxene distribution coefficients, and estimated modal proportions of minerals in each sample (**EPSL Online Background dataset**, table 1). The shaded field outlines the range of whole rock compositions of lower gabbros in the Ibra area measured by INAA [15]. Positive Eu anomalies in Oman lower gabbros are indicative of a cumulate origin.

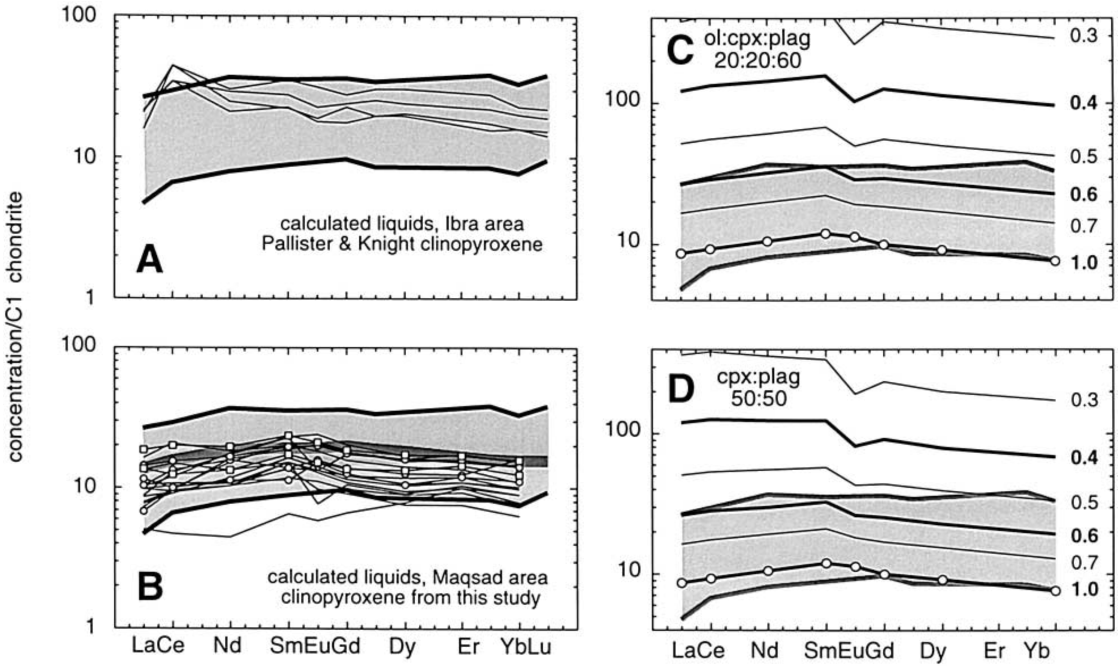

Fig. 5. (A) and (B) Calculated liquid REE concentration, based on average clinopyroxene analyses for each sample divided by clinopyroxene/liquid distribution coefficients [60]. Gray shaded area in all four panels is the range of lava compositions from [1]. (A) Liquids calculated from INAA clinopyroxene data from Ibra lower gabbros [15]. (B) liquids calculated from ion probe clinopyroxene data for Maqsad layered gabbros from the lower crust (6 lines with open symbols), and from sills in the MTZ (12 lines without symbols). Wide gray line is average of 16 sheeted dike compositions [15]. With one exception, calculated liquids in (A) and (B) fall in the range of observed lava REE, and the slope of REE patterns is nearly identical to the average dike composition, supporting the hypothesis that sills in the MTZ and lower gabbros are ''cumulates'' from which the liquids which formed the lavas, dikes and upper gabbros were extracted. (C) and (D) Fractional crystallization models for mantle-derived liquid crystallizing a gabbroic mineral assemblage. Proportions of crystallizing phases given in each panel. Initial liquid is in equilibrium with clinopyroxene in gabbro sill sample 90OA61, and has Mg# of 0.72. Labels for calculated liquid curves indicate liquid mass/initial liquid mass. Clinopyroxene/liquid distribution coefficients (Ds) from [60]; plagioclase/clinopyroxene Ds from this paper (Fig. 4 and **EPSL Online Background dataset**, table 2); olivine/liquid Ds assumed to be ~ 0. For both calculations, liquids produced by > 50% crystallization have higher REE and a larger Eu anomaly than observed in lavas and dikes.

bro compositions from Maqsad have lower REEs than the gabbros analyzed from Ibra. This may reflect: (1) real differences between samples; or (2) incorporation of REE-rich crystal rims and/or trace phases in the bulk rock analyses.

Fig. 5A,B illustrate calculated liquid compositions, determined by dividing clinopyroxene compositions by crystal–liquid distribution coefficients. We used the coefficients of Hart and Dunn [60], but similar results could be obtained using almost any published values. This procedure assumes that clinopyroxenes retain the composition of crystals formed in equilibrium with a melt. Calculated liquids for all but one sample lie within the range of Oman dike and lava compositions. Also, the REE slope for the calculated liquids is almost identical to the average slope for sheeted dikes. Together with Mg#s (Fig. 2), this supports the hypothesis that the lower gabbros are cumulates that formed in equilibrium with liquids, which later were extracted to form the dikes and lavas.

It is clear in Figs. 4 and 5 that the data on REE in gabbro sills and lower gabbros from Maqsad and Ibra show remarkable similarity in REE slope and abundance. Combined with the similarity in texture noted above and in [18], this suggests that the layered gabbro sills and the lower crustal, layered gabbros have a similar origin. In contrast, there is no overlap in REE between lower gabbros and upper gabbros from Ibra [15]. Instead, as noted previously, the REE in Ibra upper gabbros are within the range of dike and lava compositions, suggesting that upper gabbros represent crystallized liquids rather than ''cumulates''.

It is not clear how conveyor belt models, in their simplest form, can account for the differences between upper and lower gabbros. Whatever the location of initial crystallization, it seems apparent that upper gabbros retained a relatively large proportion of trapped melt, and/or crystallized from a more evolved melt, compared to lower gabbros. The amount of liquid extracted from the lower gabbros may be approximated using simple models of crystal fractionation. Fig. 5C,D illustrate the results of models assuming perfect fractional crystallization. The initial liquid is in equilibrium with clinopyroxene from sample 91OA61, a sill from Maqsad. This liquid has an Mg# of 0.72 and is therefore a possible, mantle-derived, parental liquid. The model results show that, after 40–50% crystallization, derivative liquids develop higher REE and a larger negative Eu anomaly than in Oman dikes and lavas. Thus, it seems probable that $>50\%$ liquid was removed from the lower gabbros after they crystallized.

5. Further discussion

5.1. Do sills in the MTZ form on-axis? Probably

Ophiolites preserve features that form both on- and off-axis. Some sills near the MTZ in the Bay of Islands ophiolite [23,24,44,45] formed after deformation and hydrothermal alteration of their host rocks (off-axis?). However, calculated liquids for gabbro sills in the Oman MTZ are identical to the compositions of sheeted dikes, which certainly represent ridge-axis magmas. Liquids calculated for lower gabbros are also identical to the dikes, and mass balance suggests that the lower gabbros are coeval with the dikes, and therefore formed on-axis. Thus, it seems likely that the sills in the Oman MTZ also formed on-axis. PmS reflections near the Moho within 30 km of the EPR [61,62] may indicate the presence of sills. Tomographic seismic evidence for accumulation of melt in the MTZ beneath the EPR is presented by Dunn et al. [63]. Additionally, compliance measurements along the EPR require melt accumulation in the MTZ [64].

5.2. Do lower crustal layered gabbros form in lower crustal sills? Probably

Whether they formed beneath an active ridge or not, the compositional and textural similarity between sills in the MTZ and lower gabbros shows that layered gabbro cumulates can form in sills near the Moho, and therefore supports the idea that a substantial proportion of the lower gabbros did form as sills in the lower crust [16–25]. In any case, formation of layered gabbro cumulates in the sills in the MTZ is inconsistent with the simplest conveyor belt models, in which all gabbros begin to crystallize in a single, shallow melt lens near the dike–gabbro transition. Also, note that the sills emplaced within dunite host rocks formed far below the level of neutral magmatic buoyancy.

Mantle-derived liquids rising through the MTZ beneath ridges at and fast- and intermediate-spreading rates may commonly or always pond in sills, crystallize 10–50% of their mass as cumulate gabbros, and then continue upward to form upper gabbros, dikes and lavas. This would explain why dikes and lavas from ophiolites and mid-ocean ridges have evolved liquid compositions, rather than the composition of mantle-derived melts (Fig. 2). This hypothesis would also explain the contrast in composition between upper and lower gabbros in Oman. In this context, we note that shallow level gabbros from the EPR are compositionally similar to both Oman upper gabbros and to EPR lavas [47–49].

5.3. Do lower crustal sills feed dikes and lavas? Probably

Most shallow melt lenses along the EPR are inferred to be $>70\%$ crystalline, based on the observation that they support shear waves [65], whereas dikes and lavas are generally $<10\%$ crystalline. Thus, the dikes and lavas cannot form by eruption of the ''steady-state'' contents of the shallow melt lens. Although collection of interstitial liquid in fractures during diking events might plausibly explain this disparity, it seems unlikely that this could give rise to typical dikes and lavas, since the dikes and lavas have Mg#s too high and incompatible element concentrations too low to have formed by > 70% crystallization of mantle-derived liquid. An alternative is that the shallow melt lens, dikes and lavas all have a deeper source. Adiabatic ascent of nearly aphyric magma in a crack, from a sill near the Moho, could supply liquid to all three upper crustal settings. Later, slow cooling of the shallow melt lens would give rise to gabbros, in contrast to the rapidly cooled, fine-grained dikes and lavas.

5.4. Why do sills format the Moho? Permeability barriers?

Sills near the Moho may form by ponding of liquid beneath a permeability barrier. At fast-spreading ridges, the Moho is close to the transition between adiabatic mantle upwelling and a colder, crustal geotherm imposed by cooling from above (e.g., [8]). It is apparent that mantle-derived melts, initially saturated only in olivine and spinel, must also become saturated in clinopyroxene and plagioclase as they enter the crust. As this happens, in the approximate temperature range 1250 to 1220°C at 3 kbar, magma mass decreases rapidly. The rate of crystallization will be $\geq 1\%/°C$ (e.g. [66,67]); the maximum rate is estimated to be $\sim 3\%/°C$ (Kelemen and Aharonov, in preparation). If magma also reacts with mantle peridotite in this interval, melt mass will decrease still further (e.g., [68]). Thus, if magma is moving by porous flow, porosity and permeability will drop drastically over a short vertical interval, forming a barrier beneath which ascending liquid will pool, cool, and begin to crystallize gabbroic cumulates.

Over time, pooling liquid below such a barrier could develop a hydrostatic head sufficient to cause brittle failure in the overlying crust. As a result, evolved liquid would escape in a melt-filled fracture, to resume crystallization at a higher level in the crust. If this process can be quantified, it could provide a physical basis for the commonly invoked geochemical process of mixing in periodically replenished, tapped and fractionating (RTF) magma bodies. Such a fracture mechanism may leave little geological trace: centimeter-scale dikes, if anything.

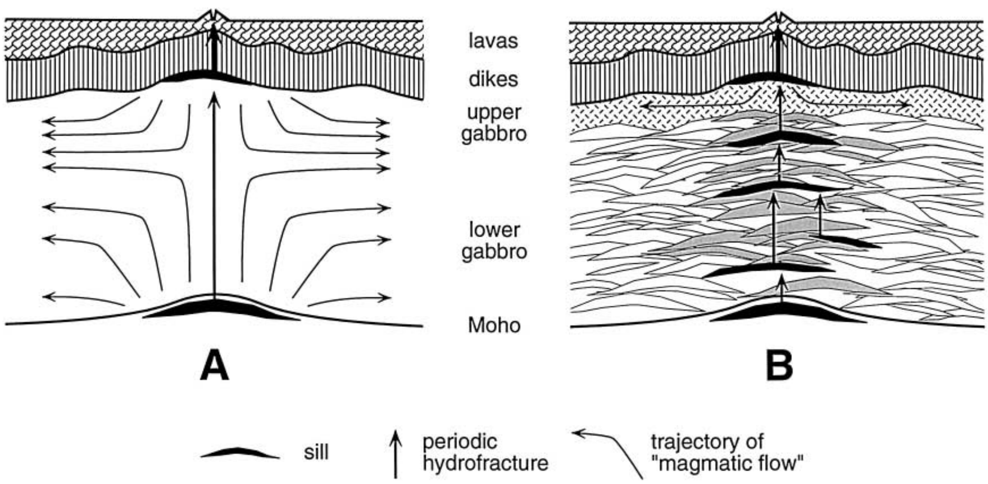

Fig. 6. Schematic illustrations of the role of deep crustal sills in forming lower gabbros in beneath oceanic spreading ridges. (A) More than 90% of the lower crust crystallizes in two sills, one near the MTZ, and the other just below the base of the sheeted dikes. Flow of largely crystalline ''mush'' from the two sills forms the gabbroic lower crust, as modeled kinematically by [75]. Periodic hydrofracture carries evolved liquids out of the lower sill, leaving ''cumulate'' gabbros. Lower gabbros might be expected to be compositionally uniform in this scenario. (B) Lower gabbros form in ''sheeted sills'' that are emplaced and crystallize near their final depth within the crust. In this case, although chemical variation with height above the Moho will be irregular, there should be a general trend toward more evolved compositions upsection, throughout the lower gabbros. Currently available data are insufficient to distinguish between these two possibilities.

Since fracture walls would be close to the liquidus temperature of the melt, crystallization in fractures would be limited.

In forming oceanic crust, there must be a transition from continuous, porous flow in the mantle source to periodic emplacement of magma in diking and eruption events at the surface. Evidence from sills in the Oman MTZ suggests that this transition occurs at the Moho, due to the onset of gabbroic crystallization. However, this hypothesis may apply only to fast-spreading ridges, since at slow-spreading ridges the transition from an adiabatic to a conductive geotherm must be below the Moho (e.g., [8]). Therefore, a corollary is that gabbroic sills may be emplaced in the upper mantle at slow-spreading ridges.

(An alternative to permeability barriers is that sills form because, under some circumstances, the least compressive stress direction near the Moho is vertical at a spreading ridge [18,69–71].)

5.5. How many sills beneath an active spreading ridge? Two or more

Seismic discovery of the shallow melt lens at the EPR led to the hypothesis that all of the lower crust crystallized in just one, relatively small sill. If sills near the Moho are also important, one idea might be that the lower crust crystallizes in just two small sills, as in Fig. 6A. A likely alternative is that the lower crust forms in a series of ‘‘sheeted sills’’ at a variety of depths, as in Fig. 6B. In an intermediate scenario, sills may intrude gabbros derived via a ‘‘conveyor belt’’ mechanism from the shallow melt lens [12,18]. In all these scenarios, each sill might initiate beneath a permeability barrier within the crystallizing, gabbroic crust. Once formed, however, sills would serve as barriers to propagation of fractures (e.g., [20]). Sills higher in the crust would be replenished by periodic hydrofractures from below, and tapped by periodic hydrofractures carrying liquid higher in the crust.

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