Magma chambers in the Oman ophiolite: fed from the top and the bottom

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Abstract

Recent models of magma chambers at fast-spreading ridges are based on the idea that the entire gabbro section of the oceanic crust crystallizes from a thin melt lens located just below the sheeted dike complex. The shape of the lens has been deduced from seismic reflection data at fast-spreading ridges. On the basis of structural studies in the Oman ophiolite, we suggest that the accretion of the lower crust may not proceed entirely in this way. We emphasize the contrast between: (1) upper level gabbros characterized by a magmatic foliation which, from a flat attitude at depth, rapidly steepen upward and tend to become oriented parallel to the sheeted dikes; and (2) lower gabbros, flat-lying, magmatically deformed, and more or less strongly layered. Wehrlite layers and lenses which contribute to the layering of these gabbros have previously been interpreted as sills. We suggest here that the modally graded bedding, which is an important feature of the lower layered gabbros, may have similarly originated as sills. This is deduced from the fact that, above mantle diapirs, the several hundred metre thickness of the transition zone contains sills of layered gabbros, commonly organized in modally graded sequences. These sills, which are interlayered with dunite or harzburgite, contain gabbros which are shown here to be structurally similar to those in the layered gabbro unit at all scales. If this interpretation is correct, the gabbro section of the oceanic crust in Oman is built up by crystallization, both along the walls and the floor of the perched magma lens, followed by subsidence, and also in sills intruded either in the subsiding foliated gabbros or in the mantle dunites of the Moho transition zone. Supply from the perched melt lens generates the upper foliated gabbros, and supply by sills emplaced near Moho level gives rise to the basal layered gabbros and the gabbro–troctolite lenses of the transition zone. Feeding of the perched melt lens by vertical dikes and feeding of the Moho horizon by sills may correspond to successive stages of a basaltic melt injection episode.

Keywords: Oman; Semail ophiolite; magma chambers; spreading centers; gabbros

1. Introduction

During the past ten years, our understanding of the geometry and dynamics of fast-spreading centres has significantly improved, thanks to new data obtained on the East Pacific Rise. Multichannel seismic data on the EPR have allowed the identification of a perched magma lens (1–4 km wide, 50–200 m thick), overlaying a low velocity zone (6–8 km wide, 2–4 km thick), with a poorly constrained shape, usually interpreted by geophysicists as a hot zone...
with a few percent of melt [1, 2]. The thin perched magma lens is continuous along-strike, except for gaps occurring at major discontinuities (overlapping spreading centres or transforms) and is probably permanent on a scale of a few million years.

The Oman ophiolite is interpreted as an ancient fast-spreading ridge which appears to have largely escaped emplacement-related deformation [3, 4], and which displays structures related to the dynamics at a fast-spreading ridge. Extensive structural analysis and mapping along this 500 km long ophiolite shows that the spreading centre geometry and the melt delivery to the crust are controlled by mantle diapirism [3, 4].

Recent models of ridge magma chambers aim to reconcile constraints provided by seismic experiments and those resulting from structural and petrological studies in the gabbro section of the Oman ophiolite. The gabbros are interpreted either as the result of successive sill intrusions from the perched magma lens [5], or from crystallization along the floor of the perched magma lens and subsequent subsidence. During subsidence they are stretched, as a result of ridge spreading [6, 7].

In a related model, the crystal mush subsides from the bottom of the perched magma lens and crystallizes along the dipping walls of the low-velocity zone beneath, in conjunction with large-scale motion related to underlying mantle flow [8, 9]. In these models it is generally assumed that the plutonic section is built from the perched magma lens, except for wehrlitic intrusions, and sills incorporated into the gabbro layering, which indicate that lower parts of the section may not be derived entirely from the perched magma lens [6]. The role of gabbro sills in the construction of the layered gabbro pile was proposed for the Oman [10], and Bay of Islands ophiolites [11].

We wish to favour here the sill injection concept, and we relate it to a common component of the layering in the basal gabbros: the modally graded layers. Our analysis is based on a structural and textural study of the gabbros in the Oman ophiolite and their relationship with the Moho transition zone. We address the question of feeding of the crustal gabbro section via dikes and sills emplaced at different levels, possibly in connection with the dynamics of melt extraction from the mantle.

2. Gabbro sills in the Moho transition zone

The Moho transition zone in Oman has a variable thickness [9]. Above mantle diapirs, the Moho transition zone is several hundred metres thick [12]; this zone is characterized by gabbro layers alternating with residual peridotites, depleted harzburgites, and dunites. Identification of this unit as a mantle component is based on recognition of the residual character of the ultramafic layers (mantle fabrics and occurrence of residual orthopyroxene).

The transition from diffuse plagioclase-clino- pyroxene impregnations in the normally sterile peridotites (Fig. 1a) to gabbro layers is described in [12] from microstructural scale to outcrop scale. Lens-shaped impregnations display a foliation and a lineation, resulting in a strong fabric anisotropy. Locally, gabbro dikes branch into gabbro sills in a metric-scale interconnected network (Fig. 1b), demonstrating that both contributed to magma transport at this structural level. Sills thinner than 50 cm are generally massive or only poorly layered and foliated (Fig. 1a). Sills display a modal layering which commonly appears above a lower horizon of massive gabbro. In particular, the modally graded sequences (Fig. 1c,d) are typically observed in sills several metres thick. Some sills reach 100 m in thickness. Laterally, they pinch out over short distances, generally by interfingering with the surrounding dunites (Fig. 1c). The gabbro sills display a strong magmatic flow structure, with foliation and lineation parallel to those in the surrounding peridotites where solid-state conditions prevailed. Thus, melt was injected in these sills during the horizontal flow carrying these upper mantle formations away from the ridge axis.

Away from mantle diapirs, the thickness of the Moho transition zone is reduced to tens of metres or less. We note an inverse correlation between the thickness of the Moho transition zone and that of the layered gabbro section [9].

3. The gabbro section

The gabbro section in the Oman ophiolite has been largely described from a petrological point of
Fig. 1. Layered gabbros from sills in Moho transition zone (a–d), and from the gabbro section (e and f). (a) Gabbro lens, 10 cm thick, showing diffuse contacts with the enclosing impregnated peridotite, wadi Shafad. (b) Branching gabbro sills (concordant with a steep foliation, N–S on the photograph) and dikes (E–W on the photograph), wadi Fayd. (c) Layered gabbro sills in the Moho transition zone, pinching in the enclosing dunite, Maqsid area. (d) Close-up of graded bedding in (c). (e) Composite layering in the lowermost layered gabbros, wadi Halhal. (f) Close-up of (e), concordant wehrlite bands showing sharp contacts with enclosing gradually layered sequence, wadi Halhal.
Particular attention has been paid to the modal, occasionally graded, layering which is dominant in the lower part of the gabbro section. Recurrent variations in mineral compositions, and the lack of simple geochemical correlations between individual phase variations led to the conclusion that the gabbros crystallized in a continuously replenished open system [13-15], or in successive small magma chambers hundreds of metres thick [16].

3.1. Typical facies and associated structures

Structural analysis and mapping have shown that the gabbros structure results from large-scale magmatic flow [17,18] and that the gabbro section may be divided into two levels.

The lower level consists of layered gabbros. The lowermost gabbros, overlying the Moho transition zone, usually display a very contrasted and spectacular layering, with alternating layers of gabbro, anorthosite, melagabbro and wehrlite (Fig. 1e), often including modally graded units (Fig. 1f). Ultramafic bands, ranging in thickness from millimetres to tens of metres, are commonly grouped in levels a few tens of metres thick, and of limited lateral extent, in the range of 50–100 m [13]. These ultramafic bands have been interpreted as intrusive wehrlite sills [6,10,19]. Up-section, the frequency of ultramafic layers rapidly decreases, and the graded layering tends to disappear (Fig. 2). The upper part of this layered gabbro unit usually has a more gneiss-like appearance, with a less contrasted and more lenticular layering mainly marked by the presence of thin anorthosite lenses.

The layered gabbros have a foliation defined by the fabric of plagioclase laths and elongated olivine aggregates. This foliation has been shown to be of magmatic origin, and lies close to the flow plane [18,20]. In the foliation plane, a generally weak mineral lineation is marked by elongation of olivine aggregates and clinopyroxene. Foliations and lineations in the lower gabbros and the underlying mantle peridotites have been mapped throughout the entire ophiolite. They are systematically parallel above and below the Moho [3,4,17]. Dynamic structures disturbing the gabbro layering are commonly observed at various scales: boudinage, mullions, isoclinal folds and normal and occasionally conjugate shear bands [18]. Wispy terminations and lens-shaped layers become more common up-section. Overturned folds and normal faults on a scale of around 100 m are interpreted to be the result of large-scale slumps. All these structures were developed within the magma chamber, during viscous flow, as shown by related microstructures which hardly present any sign of intracrystalline deformation of minerals. Finally, at the edge of the magma chamber, intruded wehrlite bodies locally truncate and fold the gabbro layering.

The upper level is represented by foliated gabbros. Olivine-rich layers, which are responsible for the contrasted layering in the lower unit, tend to disappear. In fact, even in the gabbro groundmass, the olivine content decreases progressively. The magmatic structures, foliation, and especially lineation, become difficult to observe in the uppermost gabbros. The difficulty in identifying these structures explains why these gabbros have also been called 'isotropic'. Isotropy becomes real at the top of the sequence where the gabbros were affected by hydrothermal recrystallization under static conditions. The transition from layered to foliated gabbros is commonly located in the horizon where the dip of the foliation steepens, becoming.
upwards, more or less parallel to the overlying sheeted dikes [17,21]. The tent-shape model of the magma chamber is based on the systematic mapping of this type of magmatic foliation in the upper gabbros, in a paleo-ridge frame [4].

4. Textures and fabrics

4.1. Textural evolution in a gabbro section

A constant feature of the Oman gabbros is the nearly complete absence of intracrystalline plastic
deformation, except in olivine grains. The field structures and microstructures were acquired during the magmatic and submagmatic stages by suspension flow in the presence of a limited melt fraction [18,22]. The lower layered gabbros have a homogeneous grain size (1–3 mm), with a weak to moderate fabric marked by the orientation of elongated plagioclase crystals. In the major part of the layered gabbro

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**Fig. 4.** Textural evolution of olivine as a function of olivine content, in modally graded layers from gabbro lens in the Moho transition zone (a–c) and from the layered gabbro section (d–f). Septate texture: concave grains of olivine with black serpentine network, clinopyroxene as lensoid grey grain, and plagioclase as white grains. (a) #90 OA 65A (see Fig. 1e), Maqsad area, and (d) #90 OA 110C, wadi Falaj, lower graded layer. (b) #95 OF 88B, wadi Mazari, and (e) #88 OA 52A, wadi Hathal (see Fig. 1f), central graded layer. (c) #94 MA2, Maqsad area (see Fig. 1e), and (f) #88 OA 53A, wadi Hathal (see Fig. 1f), upper graded layer. Sections cut in plane perpendicular to foliation and parallel to lineation, E–W on the plates. Plane light, scale bar: 2 mm.
section, the textures are mosaic, comparatively coarse, with planar boundaries, meeting at triple junctions; this is especially conspicuous in anorthosite aggregates (Fig. 3a). Pyroxene grains are globular; olivine is interstitial (see next section). The textures reflect active grain-boundary migration, indicating that solidus to hypersolidus conditions prevailed for a comparatively long time in the lower magma chamber.

The lowermost levels of the layered gabbros may exhibit traces of plastic strain, marked by serrated plagioclase–plagioclase grain boundaries, undulose extinction, and development of tapered twins (Fig. 3b), a textural type also seen in the layered gabbros from sills in the Moho transition zone. This overprinting of plastic strain at Moho level records the mechanical coupling between the plastic mantle and the magmatic gabbros operating on a limited thickness outside the magma chamber in the solidifying lower gabbros.

The foliated gabbros and norites from above the layered gabbros exhibit tabular fluidal textures (Fig. 3c) grading upwards to subdoleritic (Fig. 3d). Plagioclase crystals are tabular (1.0 × 0.2 mm on average) and exhibit a strong shape fabric with development of (010) rational face. The clinopyroxene is interstitial and poikilitic. A subdoleritic texture appears very close to the root of the sheeted dikes in amphibole-bearing gabbros; plagioclase occurs as hypidiomorphic crystals, presenting tight magmatic twins and a compositional zoning of normal concordant type (see also [13]); it is embayed in a matrix of interstitial clinopyroxene and/or amphibole.

4.2. Textural evolution of olivine in modally graded layers

The same textural types are observed in the layered gabbro from the basal gabbro section and in sills from the Moho transition zone. A common origin of modally graded layers in both Moho transition zone and the gabbro section is reinforced by the
similar textural features of olivine in the two occurrences (Fig. 4). In the basal ultramafic layers (Fig. 4a,d), where the olivine fraction is 60–80%, this mineral forms a continuous network enclosing monocristalline lenses of clinopyroxene or plagioclase; this network is interconnected in three dimensions forming a septate texture. Sharp (100) sub-boundaries and strong crystallographic fabrics in olivine are indicative of high plastic strain accompanied by high-temperature annealing. Olivine lattice fabrics (Fig. 5) exhibit slight obliquity relative to the foliation plane and lineation, typical of intracrystalline slip; they result from activation of the high-temperature [100] (010) slip system. The fabric intensity [23] is stronger in the specimens from gabbro lenses in the Moho transition zone (Fig. 5a) than in specimens from the gabbro section (Fig. 5b).

There is a continuous evolution between this basal zone texture and that observed in the central part of the graded layer (Fig. 4b,e), which has about 30% olivine fraction. Here, olivine forms contorted strings of elongated (3–5 x 1 mm) interstitial skeletal aggregates with concave boundaries. Examination of these aggregates shows that they are composed of elongated olivine grains with a strong lattice preferred orientation similar to the one measured down-section. Olivine grains are also cut by transverse, sharp (100) sub-boundaries, and polygonal grains having common rational (100) grain boundaries (Fig. 6). In plastically deformed rocks, this typical association is derived through a process of strain-induced recrystallization, by progressive misorientation of subgrain boundaries [24] in highly strained olivine porphyroclasts. In the upper part of the graded layer where olivine fraction is about 15% (Fig. 4c,f), elongated aggregates of olivine are simply more dispersed in the foliation plane, with a slight grain size reduction. Otherwise, in the central and upper part of graded layers, plagioclase and clinopyroxene aggregates are of the mosaic type.

5. Discussion

5.1. Modally graded layers as sill components in the lower gabbros

The contrasted layering of the basal gabbros is made of wehrlite bands and layered gabbro sequences, often modally graded in the layered gabbro unit. Emplacement as sills has been invoked for gabbro and wehrlite layers [10,11]. For the latter, this origin was demonstrated from the field observation of branching relationships between wehrlite dikes and layers.

The above description has emphasized a complete structural and textural similarity between modally graded sequences in the lower crustal gabbros and in the Moho transition zone, where modally graded gabbros are interlayered with residual mantle [12], and are regarded as sills. We suggest that the modally graded gabbro sequences of the lower gabbro unit in
Oman were also emplaced as sills. A number of mechanisms have been proposed for the origin of modally graded layering in gabbros [25–28] but, whatever the mechanism, the absence of graded bedding in the upper levels of the Oman section could be symptomatic of distinct accretion processes for the lower and the upper igneous crust.

5.2. Rapid crystallization of the upper level gabbros

The upper foliated gabbros have structural and textural features different from those of the lower layered gabbros; their magmatic foliation systematically steepens upwards; their layering is poor, and they display fluidal tabular to subdoleritic magmatic textures. Other striking differences are the occurrence of tight magmatic twins, and of zoning in the plagioclase laths. This plagioclase zoning, also encountered in gabbros drilled at Hess Deep [29], is indicative of crystallization in a chemically evolving closed system, followed by rapid cooling. The distinct characters of the foliated gabbros and their upper structural position are consistent with the hypothesis that they crystallized at the floor of the perched magma lens. A rapid and regular drop of crystals onto the floor of the thin melt lens may hinder crystal segregation, resulting in these poorly layered and relatively homogeneous gabbros.

5.3. Magma chamber model

From the above observations and discussion, we suggest that the magma chamber is fed by a dual melt delivery. The foliated gabbro partly crystallizes at the floor of the perched magma lens, subsides as a magmatic mush from that elevated position and acquires its magmatic foliation during this subsidence and subsequent motion. This mechanism has also been discussed by Quick and Denlinger [6] as potentially significant in the formation of the gabbro section. The lower layered gabbro is a composite in which the mass of foliated gabbros is intruded by a variable number of sills issued from melt ponding at the Moho level (Fig. 7). These sills could be the wehrlite sills described in previous papers [10, 19], but also gabbro sills within which modally graded layers similar to those developed in the Moho transition zone would be segregated. The contrasted layering is accentuated by the tectonic transposition related to the drag caused by the fast asthenospheric flow beneath [18]. Through this process, large deformation in the magmatic and submagmatic stage would transpose features such as graded bedding units, mechanical segregations of crystals, wehrlite sills and dikes, into parallel layers and lenses.

This model is an alternative to the recent models which imply that all structures observed in the layered gabbros are generated during the subsidence of

Fig. 7. Dual feeding model for magma chamber model (see text for further discussion).
5.4. Feeding by dikes and/or sills

It has recently been proposed [31,32] that the accreting crust in the Oman paleoridge was fed by both dikes and sills. Dikes in the upper mantle parallel to the sheeted dikes were ascribed to hydrofracturing controlled by the lithospheric tensional stress prevailing at the ridge (minimum principal stress normal to the ridge trend), and the sills to the deeper seated stress field related to mantle diapirism. After a melt burst opening and filling lithosphere fractures, the tensional ridge stress relaxes and the subsequent melt injection preferentially fills sills. A similar interpretation has been proposed for Iceland rifting [33]. In this model, the first melt injected rises to the perched melt lens and replenishes it, also disrupting the overlying lid, creating a new metre-sized diabase dike in the sheeted dike unit, and feeding basaltic flow at the sea bottom. In contrast, the subsequent melt injected ponds within the plutonic section of the crust and at the Moho level as sills. The level of sill injection deepens with time, in response to: (1) lithospheric stress relaxation; and (2) a drop in melt pressure as the hydrofracture rooting into the melting asthenosphere closes at depth and drains progressively shallower levels.

We assume that the melt trapped in the sheeted dike complex, and replenishing the underlying melt lens, is the pristine melt, only modified at depth by possible crystal segregation and chemical reactions along hydrofracture conduits. This model appears not to be consistent with geochemical data, which imply that the melt generating the upper level gabbros and overlying lid is highly evolved and has segregated a large volume of crystals at shallow depth. This argument is developed by Kelemen and co-workers [34], within an analysis complementary to ours, and leading to a similar conclusion regarding the occurrence of gabbro sills in the Oman ophiolite. These authors propose that the primary melt ponds into the sills, where it crystallizes massively. The fractionated liquid issued from this crystallization is then injected into the perched melt lens and the overlying lid.

An alternative interpretation which takes into account the geochemical constraint would be to reverse, in the crust, the dike/sill chronological sequence proposed above. The melt issued from the rising asthenosphere would reach, via ridge-parallel dikes, a level of the layered gabbros and pond there as sills, possibly in response to the stress field developed at the top of a mantle diapir [32]. After partial crystallization within these sills, the fractionated melt is reinjected toward the perched melt lens and the overlying lid in response to a tensional failure of the lid when the ridge-spreading stress exceeds the yield strength of the lid. In this model, the gabbro sill injection acts as a relay between two hydrofracturing processes, which might be connected: hydrofracturing caused by melt pressure, which extracts melt from its mantle source [35], and tensional fracturing caused by the spreading of lithosphere, which would be dominant in the upper crust.

6. Conclusion

Gabbros in Oman display several striking structural and petrological differences between the lower layered unit and the upper foliated one. However, very contrasted layering, often defined by graded bedding, is observed both in the lower layered gabbros and in the gabbro sills found below in the Moho transition zone. This layering is macroscopically and texturally similar in both occurrences. Thus, the layering may originate in the same way and at least part of the layered gabbros may be derived from sills which intrude the crystallizing mush in the magma chamber and which are progressively intermingled with gabbros subsiding from above as deformation progresses. This mechanism has been proposed for wehrlite sills emplacement [6,10,19] for which field evidence of feeding by dikes is available. It has been invoked for gabbros [10,11], although such rooting evidence has not been reported; we specifically apply this process to the modal layered gabbros of the Oman ophiolite.
This conclusion suggests a dual feeding of the magma chamber, first via sills emplaced at the Moho level, contributing to the well defined layering of the lower gabbros (Fig. 1c,e), and via dikes observed both at these deeper levels, and up-section, where they fill the perched magma lens and the sheeted dike complex. This model is consistent with earlier results [32], showing that the feeding system at the Oman paleo-ridge was composed of sills and ridge-parallel dikes, active during the same episode of melt injection.

Finally, our model helps to reconcile the existence of a large magma chamber, inferred from the observations in Oman and the geophysical evidence for the concurrent occurrence of melt localized at the top of the igneous crust (perched magma lens) and at the Moho level, the two locations being separated by a large volume of seismically attenuated rocks. The occurrence of sills at, and immediately above, the Moho level in the Oman ophiolite is indeed consistent with PmS reflection data at the EPR [36-38], ascribed by the authors to thin melt lenses, which extend up to 25 km off the ridge axis.

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