

Extraction of mid-ocean-ridge basalt from the upwelling mantle by focused flow of melt in dunite channels

Peter B. Kelemen^{*}, Nobumichi Shimizu^{*} & Vincent J. M. Salters[†]

^{*} Woods Hole Oceanographic Institute, Woods Hole, Massachusetts 02543, USA

[†] NHMFL—Florida State University, Tallahassee, Florida 32310, USA

Like residual peridotites from mid-ocean ridges, peridotites from the mantle section of the Oman ophiolite are far from equilibrium with mid-ocean-ridge basalt (MORB). By contrast, dunites from Oman are close to equilibrium with MORB, indicating that they were conduits for focused melt flow. Formation of dunite conduits by porous flow is sufficient to explain extraction of MORB from the mantle, and fracture mechanisms may not be necessary in this process.

MORB forms by partial melting of adiabatically decompressing mantle peridotite beneath spreading ridges (see, for example, refs 1–3). Nevertheless, MORB is not in equilibrium with residual peridotite (harzburgite and lherzolite). For example, MORB is not saturated with the mineral orthopyroxene (opx) at Moho pressures, whereas opx is a major constituent of residual peridotites. Liquids parental to MORB are saturated with opx only at pressures greater than 8 kbar (for example, refs 4, 5), more than 15 km below the Moho. In addition, MORB is not in trace-element equilibrium with most abyssal peridotites (residual mantle samples dredged from the mid-ocean ridges)^{6,7}. Instead, MORB is interpreted as a mixture which preserves geochemical evidence for equilibration with mantle peridotite over a range of pressures, much higher than the pressure at the base of the crust^{8,9}.

A polybaric, near-fractional melting process can account for the observed composition of MORB and residual peridotites^{6–10}. To produce large fractionations between light and heavy rare-earth elements, and between other elements such as Ti/Zr, Lu/Hf and U/Th, small melt fractions must be efficiently segregated from their sources and mixed to form MORB. To preserve these fractionations, and to produce disequilibrium between melt and opx at low pressure, melts must be transported to the crust without re-equilibration with surrounding peridotite. Diffuse porous flow of melt through residual peridotite from the source to the crust would lead to extensive chemical reaction, bringing the liquids close to low-pressure opx saturation^{11,12} and decreasing or erasing trace-element fractionation^{10,13,14}. Thus, focused flow of melt in spatially restricted conduits is required for MORB extraction from the mantle.

Two end-member mechanisms for focused extraction of MORB have been proposed: (1) development of hydrofractures extending from near the bottom of the melting region to the surface¹⁵ and (2) formation of high-permeability channels by dissolution of solid phases during focused porous flow of adiabatically ascending melt^{12,16}. The present study provides evidence that constrains the nature of conduits for melt extraction beneath mid-ocean ridges, and the mechanisms by which they form. We present observations on dunites (rocks composed of >90% olivine) in the mantle section of ophiolites. Phase equilibria and field evidence, from Oman and elsewhere, show that dunites form by dissolution of pyroxene from peridotite (rocks with >40% olivine and >10% pyroxene) in magma migrating by porous flow. Previous petrologic and geochemical studies focused on dunites which replace lithospheric mantle peridotites, whereas dunites in Oman formed in the adiabatically upwelling

asthenosphere beneath a spreading ridge. New major- and trace-element data on the compositions of minerals in the mantle section of the Oman ophiolite indicate that dunites are conduits for extraction of MORB from the mantle. Together, these lines of evidence indicate that MORB extraction from the upwelling mantle involves focused porous flow through dunite channels.

Geology and petrology of dunites

Figure 1 illustrates the contact relationships of residual peridotite and dunites in the Oman ophiolite, compiled from previously published work. Dunites comprise 5 to 15% of the exposed mantle section in Oman^{17,18}. They preserve sharp, irregular contacts which are locally discordant to banding and crystallographic lineation in the harzburgite (see, for example, Lippard *et al.*¹⁸, p. 53). Because harzburgites and most dunites now have a subhorizontal foliation, parallel to the palaeo-Moho, we know that both were transposed by corner flow beneath a spreading ridge. Thus, the transposed dunites were formed in upwelling mantle beneath a spreading-ridge axis. Here we further constrain the physical and chemical conditions which led to their formation.

Dunites within the mantle section of ophiolites have been interpreted as (1) residues of very high degrees of partial melting (for example, ref. 19), (2) olivine 'cumulate' dykes, that is fractures filled with olivine precipitated by ascending melt (for example, refs 20, 21), and (3) products of reaction between olivine-saturated magma and pyroxene-bearing rocks^{11,12,15,22–26}. A residual origin for dunites is unlikely, as complete removal of pyroxene from mantle peridotite by melting requires very high degrees of partial fusion (>40%), at mantle potential temperatures much higher than those beneath mid-ocean ridges (see, for example, the summary of experimental results in ref. 3). A cumulate origin is also unlikely, as adiabatically ascending melt in a crack is not saturated in any solid phase, including olivine (for example, ref. 27). Under lithospheric conditions, conductively cooling melt in fractures may gradually stagnate to form dykes. However, dykes are rarely if ever composed only of olivine, as olivine is very different in composition from any natural silicate melt. Also, the observed ratio of Mg/(Mg+Fe²⁺), denoted 'Mg number' or 'Mg#', is generally very similar in olivine from dunites and associated mantle peridotites¹¹. Compared to olivine in residual mantle peridotite, olivine in residual dunite should have higher Mg#, and olivine in cumulate dunite should have lower Mg#.

Thus, few if any dunites are residual or cumulate. Instead, most dunites in the mantle section of ophiolites form by dissolu-

tion of pyroxene, with concomitant precipitation of olivine, during porous flow of olivine-saturated melt through mantle peridotite^{11,12,15,22-26}. Contact relationships indicate a replacive origin for dunites (Fig. 2). A replacive origin also can explain the similar olivine Mg#s in dunites and host peridotite¹¹. Formation of replacive dunite occurs where relatively high-pressure partial melts of the mantle react with peridotite at a lower pressure^{11,12}. This process can also occur at constant temperature and pressure, but is likely to be more common and extensive in the adiabatically ascending mantle. In open systems where migrating basalt reacts with the adiabatically ascending mantle, liquids remain saturated with olivine. This is different from the adiabatic ascent of melt in an open crack, owing to the effects of maintaining solid-liquid equilibrium. Formation of replacive dunite on an adiabat will result in an increase in the liquid mass^{11,12} and therefore an increase in porosity. Increasing porosity, and the relatively higher permeability of dunite compared to pyroxene-bearing rocks^{28,29}, leads to higher permeability in the dunite. Regions with initially high permeability have a high melt flux, which leads to more rapid dissolution in these regions, producing even higher permeability. This positive feedback mechanism (the 'reactive infiltration instability'³⁰) can produce elongate dunite channels in the mantle parallel to the melt flow direction^{12,16}.

In addition to forming purely as a result of porous, reactive flow, dunites form in ductile shear zones³¹ and in porous reaction zones around propagating cracks¹⁵. In the Josephine peridotite, synkinematic dunites in shear zones formed by reaction between hydrous melt and residual peridotite at temperatures less than 1,100 °C, near the brittle-ductile transition in shallow mantle lithosphere. They are nearly vertical, cut a subhorizontal foliation in peridotite, and formed at the same time as near-vertical pyroxenite dykes. Tabular dunites with a medial pyroxenite, such as are common in the Horoman peridotite^{21,32} and the Trinity peridotite²³ may be porous reaction zones around melt-filled fractures.

Ophiolites intrinsically preserve melt migration features formed in conductively cooled 'lithosphere' as well as in adiabatically rising 'asthenosphere'. Pyroxenite and gabbro dykes are observed in the mantle section of many ophiolites. The dykes are generally undeformed, and highly discordant to the high-temperature foliation in residual peridotites, as shown in Fig. 1. Formation of pyroxenes and plagioclase in the dykes is indicative of crystallization from an evolved, low-temperature liquid. Such evolved liquids form from a parental, mantle-derived magma, as a result of crystal fractionation due to conductive cooling. Therefore, we infer that dykes in the mantle section of ophiolites formed off-axis, in oceanic lithosphere with a conductive geotherm. This also applies to dunites and coeval pyroxenites formed in shear zones, and to tabular dunites with medial pyroxenite dykes.

Transposed dunites in Oman are not associated with localized shear zones, and do not have medial pyroxenites. Instead, pyroxenite and gabbro dykes in the Wadi Tayin massif cut transposed dunites at a high angle. Ceuleneer³³ reported that pyroxenite and gabbro dykes are not present in the centre of the Maqсад massif, an area in Oman where structures formed by mantle upwelling beneath a ridge axis are preserved. This important observation supports the hypothesis that dykes form off-axis in lithospheric mantle, and suggests that melt extraction beneath the ridge axis was predominantly by porous flow. In addition, we can infer that adiabatic conditions were maintained nearly to the base of the crust in upwelling mantle beneath the spreading ridge in Oman until magmatism ceased. Localized shear zones and fractures may be rare or absent in the viscously deformable, adiabatically decompressing mantle beneath spreading ridges. By contrast, Aharonov *et al.*¹⁶ show that formation of porous conduits by reactive flow can and will occur in adiabatically ascending asthenosphere. On the basis of this theoretical work, and the field relations and phase equilibrium data just discussed, we conclude that transposed dunites in the Oman mantle section were formed by reactive porous flow in the

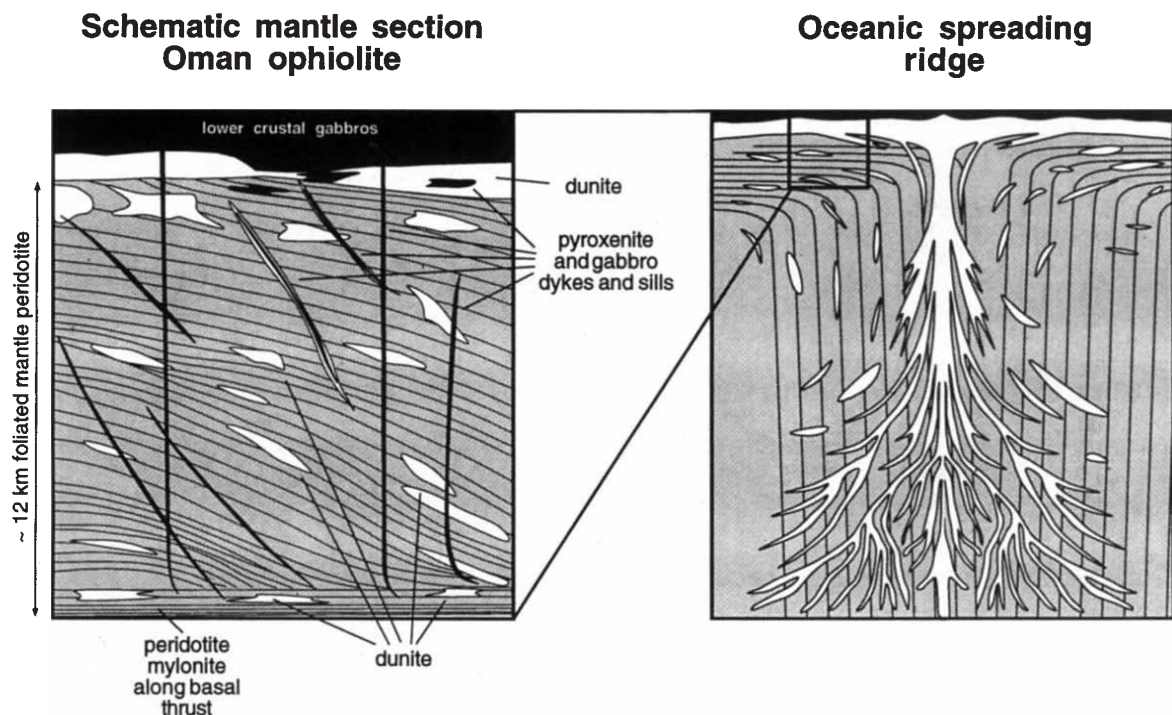


FIG. 1 Left, schematic cross-section of the Wadi Tayin section of the Oman ophiolite, compiled from refs 17, 18, 34 and our own field observations. Right, cartoon illustrating possible ridge-axis geometry of

residual harzburgite, dunite conduits for melt flow and oceanic lower crust. Shading as follows: white, dunite; grey, mantle peridotite; black, pyroxenite and gabbro dykes and sills.

asthenospheric mantle beneath a spreading ridge. In the next section, we present geochemical data which indicate that the dunites were conduits for extraction of MORB from the mantle.

Geochemical data

The Oman ophiolite formed by partial melting in the mantle and accretion of melts to form crust at an oceanic spreading centre^{18,34}. Although they may be different in detail, most of the older volcanics in the ophiolite are similar to MORB. For example, the Geotimes and Lasail volcanic units in Oman are composed of tholeiitic basalts with relatively flat rare-earth element (REE) patterns (chondrite-normalized La/Yb from 0.6 to 1.0), and moderate heavy-REE contents ((10–30) × chondritic)^{18,35}, similar to 'normal' MORB. We infer that processes similar to those which form MORB at oceanic spreading centres operated in the formation of the Oman ophiolite. (Younger suites of volcanics in Oman are distinctly different from MORB^{18,35} and may have formed during or after subduction associated with ophiolite emplacement³⁴.)

Samples analysed in this study are from a traverse across the mantle section (15–20 km thick) in the Wadi Tayin region of the Oman ophiolite¹⁷. Residual peridotites in the section are mostly harzburgites with about 75% olivine, 20% opx, <5% clinopyroxene (cpx), and a few per cent spinel. Cpx in these samples occurs as subhedral aggregates, as small grains associated with opx porphyroblasts, and as undeformed, interstitial grains. Cpx is generally unzoned, but represents a recrystallized, polygenetic mixture of residual material, cpx exsolved from opx, and perhaps cpx crystallized from migrating melt.

Dunites have >95% olivine, 2–3% spinel and <1% interstitial cpx. Cpx in dunites occurs exclusively as cusped grains along olivine triple grain boundaries. A sample from a small chromitite body within dunite has >85% euhedral chromite, and <15% interstitial olivine + cpx. (As in most ophiolite mantle sections, chromitite occurs only within dunite in Oman.) As in the dunites, cpx in the chromitite occurs at triple grain boundaries. Adiabatically ascending basaltic liquids are not saturated in cpx. Also, cpx is not a product of most reactions involving adiabatically ascending mantle peridotite and basaltic liquid^{11,12,26}. Cpx in dunites must have formed by partial crystallization of cooling, migrating liquid as the dunites passed out of the upwelling asthenosphere, into a conductive thermal regime. Basalt and cpx do not have the same composition, so that crystallization of basalt in a closed system forms plagioclase, plus olivine and/or opx, as well as cpx. Because neither plagioclase nor opx is observed in our dunite and chromitite samples, we are confident that the cpx formed in an open system. It did not form as a product of complete, closed-system crystallization of 'trapped liquid'.

There is a first-order difference between dunite and harzburgite in both cpx and spinel composition. Cpx and spinel in samples from the Wadi Tayin massif of the Oman ophiolite have been analysed by ion and electron microprobe. Where possible, 3–5 crystals of each mineral were analysed in each sample. Ion-probe techniques are summarized elsewhere³⁶. Dunite and chromitite cpx have a slightly light-REE-depleted, chondrite-normalized pattern (Fig. 3). Harzburgite cpx from the Wadi Tayin section is strongly depleted in light REE, similar to the most depleted cpx in abyssal peridotite^{6,7}. Within-sample and within-group variations are much smaller than differences between dunite and harzburgite groups.

Liquid compositions in equilibrium with cpx crystals can be calculated using experimental cpx/basalt distribution coefficients. We used those of Hart and Dunn³⁷, but virtually any published values could be used with similar results. Calculated liquids for cpx in Wadi Tayin harzburgite are strongly depleted in light REE, and thus are very different from MORB. Like abyssal peridotites, Oman harzburgites have been depleted by near-fractional partial melting. In detail, calculated liquids for harzburgite cpx are enriched in La and Ce compared to Nd.

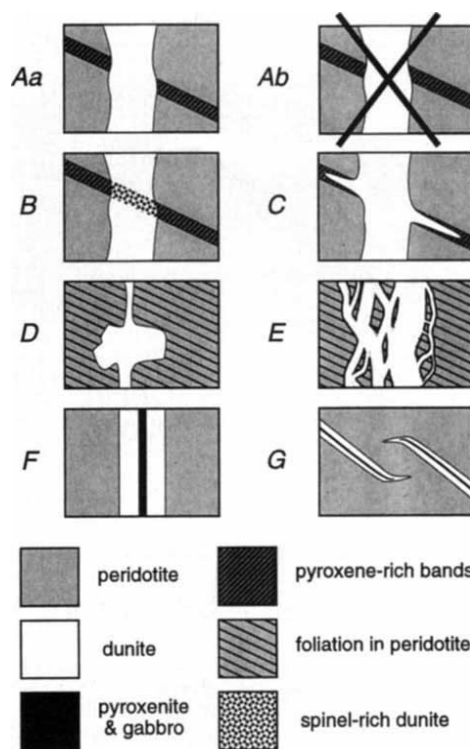


FIG. 2 Summary of contact relationships of dunites in the mantle section of ophiolites. For specific examples and additional references, see refs 11, 12, 15, 17–26, 31–34, 46, 50, 52 and 53. We interpret the relations illustrated in A–E to indicate a replacive origin for dunites, involving dissolution of pyroxene and precipitation of olivine (\pm spinel) by liquid migrating by porous flow. Dunites with contact relations as illustrated in F and G are probably replacive, but may have formed in porous reaction zones around melt-filled fractures. A, Dunite that cross-cuts pyroxene-rich bands in peridotite does not displace the bands, as in Aa. If dunites were dykes filled with olivine, bands in the wall rock would be displaced, as in Ab. B, Relict trains of spinel where dunite cross-cuts pyroxene-rich bands. Some spinel is present in the original bands; additional spinel may be precipitated during incongruent dissolution of pyroxene. C, Locally, pyroxene-rich bands are selectively replaced by dunite without evidence for dilation by dyke injection. D, Widening features, where narrow dunites enter and leave a larger, rounded region, do not show dilation of foliation in surrounding peridotite. E, Anastomosing dunite includes 'islands' of relict peridotite which have not been rotated or displaced relative to the surrounding peridotite. F, Medial pyroxenite and/or gabbro is observed in some tabular dunite bodies. G, Curving tips in tabular dunite with medial pyroxenite, observed in the Trinity peridotite (A. Rubin, personal communication), suggest that these dunites formed in a porous reaction zone around and ahead of propagating fractures.

At the very low concentrations of La, Ce and Nd in these cpx, the data may be inaccurate. If the relatively high La/Nd and Ce/Nd are real, such 'U-shaped' REE patterns may be attributed to reaction between relatively small amounts of liquid and much larger amounts of residual peridotite^{32,38,39}, or to addition of small amounts of 'trapped liquid' to residual peridotite^{40,41}. Nevertheless, because harzburgites preserve light-REE depletion produced by near-fractional partial melting, migrating liquids that equilibrated with these rocks would have had much lower light/heavy REE ratios than MORB. Thus, as stated previously, pervasive, porous flow through residual peridotites cannot be the dominant mode of MORB extraction from the mantle.

In striking contrast to the harzburgites, calculated liquids in equilibrium with cpx from dunite and chromitite have REE slope and abundance similar to MORB and Oman volcanics. In addition, spinels in dunite and chromitite from Oman are similar in composition to spinels in MORB^{42–45}. Specifically, spinels in dunite, chromitite and MORB have higher Cr# (Cr number,

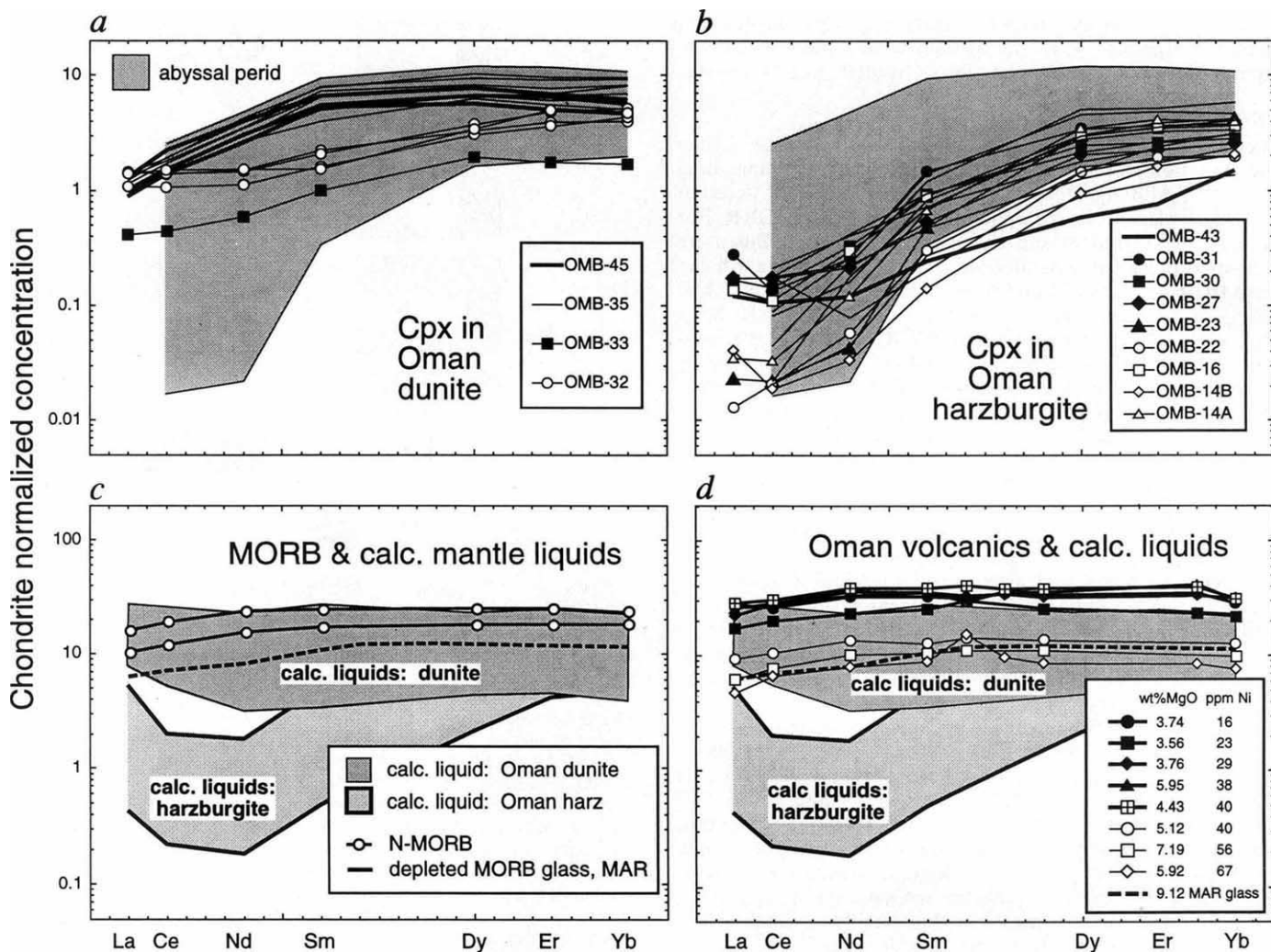


FIG. 3 Rare-earth element (REE) contents of clinopyroxene (cpx) in samples from the Wadi Tayin mantle section of the Oman ophiolite¹⁷, determined by ion microprobe, compared to REE concentrations in abyssal peridotites and mid-ocean-ridge basalts (MORBs). All concentrations are normalized to those in C1 chondrites⁵⁵. These data show that cpx in dunites are close to REE equilibrium with MORB, whereas cpx in harzburgites is not. *a*, REE in cpx from Oman dunites and one small chromitite within dunite (OMB-35) compared to observed concentrations in cpx from abyssal peridotites determined by ion microprobe^{6,7} (shaded region). Several analyses of individual cpx crystals are shown for each Oman sample. All samples were collected by F. Boudier. *b*, REE in cpx from Oman harzburgites compared to abyssal peridotites. Average values are shown for each Oman sample (1–5 cpx points on 1–3 crystals per sample). Lines with symbols are for samples collected

by F. Boudier, lines without symbols are for samples collected from the same section by R. Coleman. Harzburgite OMB-45, transitional between other harzburgites and dunites in its REE slope, is from the crust–mantle transition zone¹⁷. *c*, REE in liquids calculated to be in equilibrium with cpx from Oman dunites and harzburgites (shaded regions) compared with compositions of normal mid-ocean-ridge basalt (N-MORB)^{56,57}, and a low-REE basalt from the Mid-Atlantic Ridge⁵⁸ (MAR). *d*, REE in selected lavas from the Geotimes and Lasail volcanic units in the Oman ophiolite¹⁸. MgO and Ni contents of each sample are given in the figure. MgO and Ni in Oman lavas are low compared to primitive MORB, indicating that the Oman liquids evolved from a mantle-derived melt by crystal fractionation. This fractionation, involving mainly olivine and plagioclase crystallization, would increase the REE concentrations by a factor of <3, and would not modify the REE slopes appreciably.

defined as molar Cr/(Cr+Al)), and higher TiO₂ contents, than spinels in Oman harzburgite and in most abyssal peridotites (Fig. 4). Data for Cr# and Ti contents of spinels in Oman volcanics has not been published, but Cr# in spinels from cumulate gabbros in Oman is between 0.4 and 0.6 (refs 18, 46) higher than the values in spinel from most Oman harzburgites and similar to those in Oman dunite. Thus, both cpx REE data and spinel compositions from the Wadi Tayin samples suggest that Oman dunites formed in equilibrium with liquids similar to MORB, whereas harzburgites did not.

Evaluation of geochemical interpretations

Some of the spinels from Wadi Tayin dunites and harzburgites have lower Mg#s than spinels in MORB, as a result of sub-

solidus Fe–Mg exchange between olivine and spinel. This exchange is rapid at temperatures greater than 700 °C, and its effects are observed in almost all peridotite massifs (for example, ref. 47). Spinel Ti contents could also have been increased by metamorphic exchange, in which small amounts of Ti dissolved in olivine at high temperature were added to spinel at lower temperatures. This might affect spinel in dunites more than in harzburgites, as in harzburgites Ti would be added to both spinel and pyroxenes. The Ti contents of coexisting spinel, olivine and cpx from our samples are compared in Fig. 5. Titanium contents are positively correlated in the different phases, and are higher in dunites than in harzburgites. We conclude that Ti concentrations have not been substantially modified by sub-solidus exchange, and

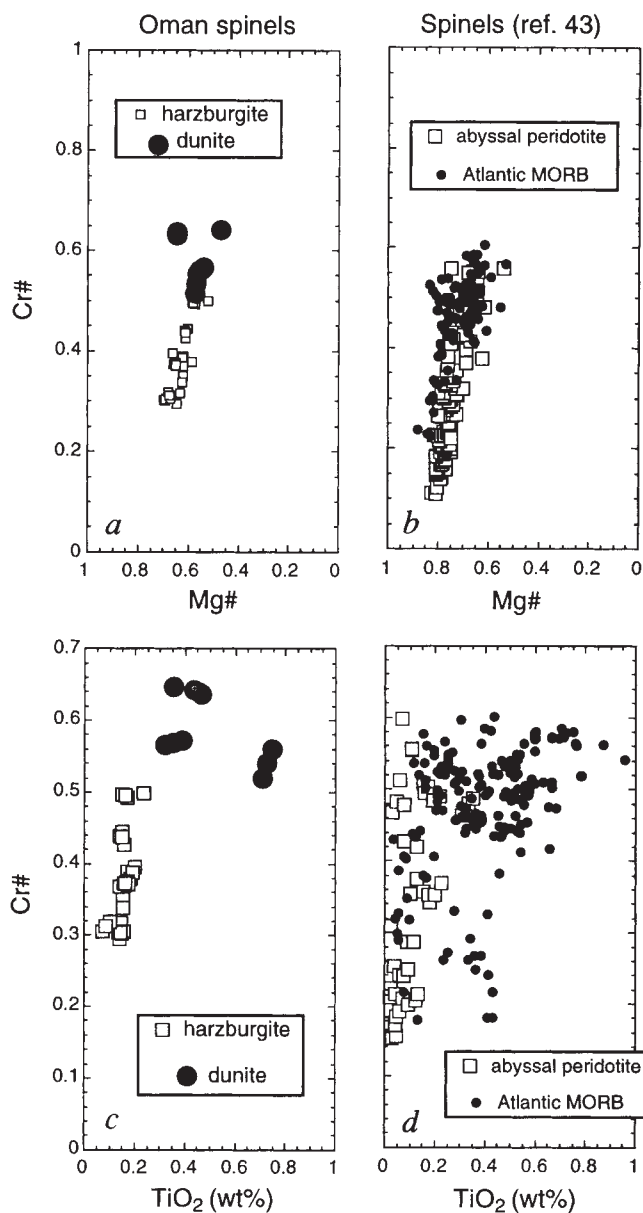


FIG. 4 Cr # (molar Cr/(Cr+Al)), Mg # (molar Mg/(Mg+Fe²⁺)) and TiO₂ contents of spinels in samples from the Wadi Tayin mantle section of the Oman ophiolite, determined by electron microprobe, compared to spinels in abyssal peridotites and mid-ocean-ridge basalts (abyssal peridotite and MORB data from Dick and Bullen⁴³). These data show that spinels in Oman dunites are similar to spinels in MORB, and different from spinels in Oman harzburgites and in abyssal peridotites dredged from the mid-ocean ridges. *a* and *b*, plots of Cr # versus Mg #. *c* and *d*, plots of Cr # versus TiO₂ concentration.

reflect real differences between the liquids which last equilibrated with these samples.

Some high-Cr # spinels in MORB may crystallize from evolved lavas⁴⁴, with elevated Cr/Al produced by low-pressure crystal fractionation of olivine + plagioclase from mantle-derived melt. If this applied to all high-Cr # spinels in MORB, then the similarity in Cr # and Ti between spinels in MORB and Oman dunite would be a coincidence. Figure 6 illustrates compiled data on the composition of associated spinel and olivine in MORB. Olivine crystallized from evolved basalts should have Mg #s less than mantle olivine, which has Mg # ≥ 0.88 . Cr # in spinels is not correlated with Mg # in associated olivine, and is generally greater than 0.4 in samples with olivine Mg ≥ 0.88 . Trends of decreasing Mg # with increasing Cr # in some lava suites^{42,44} encompass less than half of the observed variability of Cr # in MORB spinels, and do not include the abundant high-Cr # spinels associated with high-Mg # olivine. We conclude that the abundance of high-Cr # spinel in MORB is a primary, mantle-derived feature, and that the similarity between spinel compositions in Oman dunites and in MORB is not a coincidence.

The Wadi Tayin dunite and harzburgite suites show an inverse correlation between Ti in spinel and Mg # in olivine. Such varia-

tion is consistent with crystallization or dissolution of solid phases with higher Mg # and lower Ti than coexisting liquid (that is, olivine, pyroxenes and/or spinel). However, the small range of variation in olivine Mg #, combined with the large changes in Cr # and Ti concentration in spinel and Ce/Yb in cpx, rules out closed-system crystal fractionation or melting processes. Instead, the magmas which formed these rocks must have undergone open-system processes such as melt/rock reaction⁴⁸ and/or magma mixing⁴⁹. These processes can produce large variations in Cr/Al, Ti and Ce/Yb at nearly constant Mg #. The overlap in olivine Mg #s between dunites and harzburgites indicates that the dunites cannot have formed by partial melting of the harzburgites, or by extensive crystal fractionation of melts derived from the harzburgites. Thus, our geochemical data support the hypothesis that the dunites formed by reaction between ascending melts and mantle peridotite.

Relation to previous studies

We have shown that the Oman dunites formed in upwelling, asthenospheric mantle beneath an oceanic spreading ridge. By contrast, previous studies of dunite geochemistry (for example, refs 21–26, 31, 32, 50, J. E. Quick, personal communication and

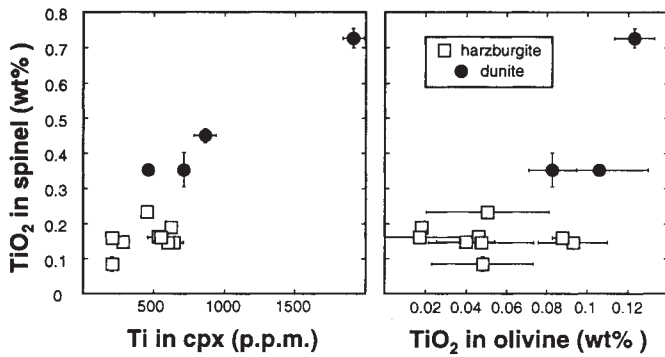


FIG. 5 Variation of TiO_2 concentration in spinel as a function of Ti concentration in cpx and TiO_2 concentration in olivine for dunite and harzburgite samples from the Wadi Tayin mantle section of the Oman ophiolite. Error bars represent one standard deviation from the mean. Correlated Ti contents in different minerals, and higher Ti contents in dunites than in harzburgites, indicate that dunites and harzburgites were equilibrated with distinctly different liquids. (The concentration of TiO_2 in spinel and olivine was determined by electron probe measurements, and the concentration of Ti in cpx by the ion-probe technique.)

E. Takazawa, personal communication, and our unpublished data) have focused on dunite-cutting plagioclase lherzolite in the Horoman, Lanzo, Ronda and Trinity massifs, and on late dunites in the polygenetic Josephine peridotite. Probably, all of these previously studied dunites formed where rising magma migrated into conductively cooled mantle lithosphere. Many were formed in peridotite whose Nd isotopes indicate a long residence time in the lithosphere (for example, Ronda⁵¹, Lanzo²⁵, and Horoman (E. Takazawa, personal communication)). Many are coeval with pyroxenite and gabbro dykes which form on a conductive geotherm. Most cut and replace plagioclase lherzolite, whereas residual plagioclase is not present in the mantle on a normal oceanic adiabat (for example, ref. 3). Plagioclase in abyssal peridotites is not uncommon, but generally results from partial crys-

tallization of migrating liquids where shallow mantle lithosphere is conductively cooled, as at very slow spreading ridges^{40,41}. Available REE and isotopic data for cpx in these previously studied dunites are indicative of equilibrium with liquids significantly different from MORB. We attribute these differences to different parental liquids and different conditions of formation in different tectonic environments.

Mineral compositions similar to those in Oman dunites have been found in the shallow mantle beneath crust formed at the East Pacific Rise, in samples from Hess Deep⁵². Gabbro segregations within dunite have cpx close to REE equilibrium with MORB, whereas cpx in harzburgite surrounding dunite + gabbro is strongly depleted in light REE. Also, spinel in Hess Deep dunite has Cr #s and TiO_2 contents similar to spinel in MORB,

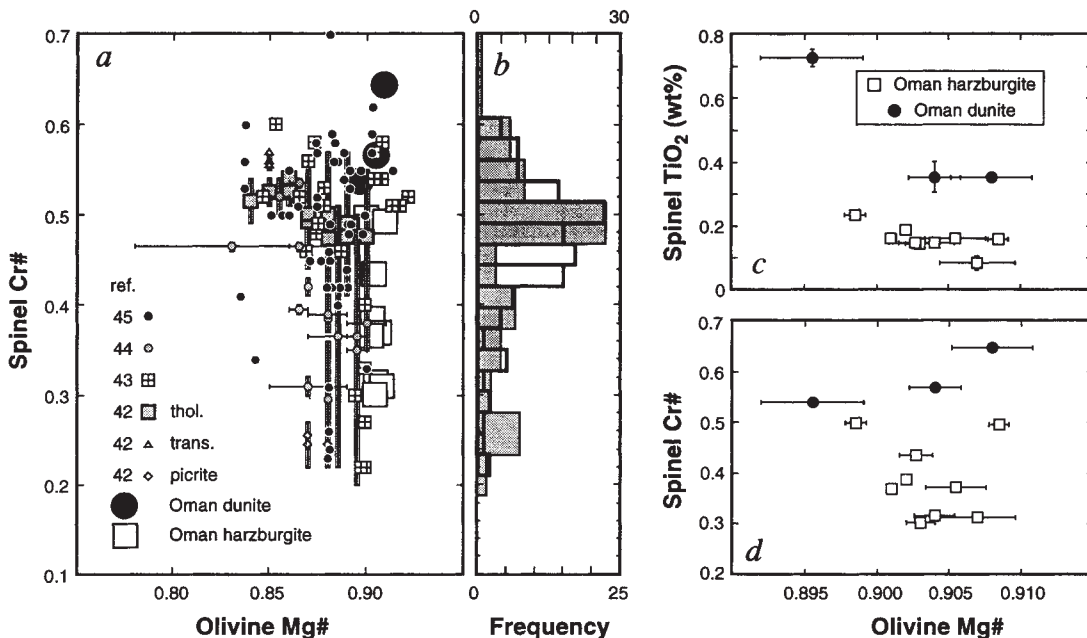


FIG. 6 Variation of spinel Cr # and TiO_2 content as a function of associated olivine Mg # in lavas from mid-ocean ridges and in mantle samples from Oman. All data measured by electron microprobe. They indicate that (1) the abundance of high-Cr # spinels in MORB is a mantle-derived feature, (2) spinel and olivine in Oman dunites are similar to coexisting spinel and olivine in MORB, (3) covariation of spinel and olivine composition in Oman samples is due to open-system processes such as melt/rock reaction or magma mixing, and (4) dunites were not formed by partial melting of harzburgites, or by crystal fractionation of liquid derived from harzburgites, but instead formed by reaction between ascending melt and harzburgites. a, Spinel Cr # as a function of associated olivine Mg # in lavas from mid-ocean ridges (refs 42-45) and in Oman mantle samples. Where a range of values for Cr # is reported, this is shown as a vertical, shaded bar with a symbol indicating the

average value. Sigurdsson and Schilling⁴² report a range of Cr # in spinel enclosed in (or attached to) olivine of a given Mg #, in three distinct suites of lavas: tholeiites (data shown as 'thol.'), transitional alkali basalts ('trans.') and picrites. Allan *et al.*⁴⁴ report the range of Cr # and Mg # in individual samples of MORB. Dick and Bullen⁴³ report the compositions of olivine and enclosed or attached spinel in MORB samples. Arai⁴⁵ compiled data on associated spinel and olivine from a variety of sources. b, Histogram of observed Cr # in MORB spinels. Open rectangles indicate frequency for the data compiled by Dick and Bullen⁴³, on a scale of 0 to 25. Shaded rectangles indicate frequency for data compiled in this study, for spinels associated with olivine with Mg # ≥ 0.88 , on a scale of 0 to 30. c and d, detailed spinel and olivine compositional variation in Oman mantle samples. Error bars represent one standard deviation from the mean.

whereas spinel in harzburgite has much lower TiO₂ contents. These similarities support the hypothesis that dunites commonly form in conduits for transport of MORB through the depleted upper mantle. However, the Hess Deep dunites occur in reaction zones around (lithospheric) gabbro dykes, unlike the transposed (asthenospheric) dunites in Oman.

MORB extraction from the asthenosphere

The geochemical data for cpx, spinel and olivine strongly support the hypothesis that the Wadi Tayin dunites formed in equilibrium with liquids similar to MORB, whereas the harzburgites did not. Furthermore, the geochemical data reinforce the conclusion that the dunites formed by replacement of the harzburgites as a result of melt/rock reaction involving dissolution of pyroxene in ascending melt. Finally, field relationships indicate that the dunites formed in the upwelling mantle.

Oman dunites fulfil geochemical, physical and structural requirements for conduits of focused flow in which incremental melts coalesce, mix to form MORB, and are transported to the crust. Ascending melts in dunite conduits would remain far from equilibrium with pyroxene in the shallow mantle. The spatial association of dunite and chromitite, and the geochemical similarity of cpx from both rock types, further reinforces the hypothesis that melt flow is focused in dunites. Because the solubility of Cr-spinel is quite low in silicate melts, chromitites must have scavenged Cr from 300 to 400 times their mass of liquid⁵³. Because dunites completely surround chromitite, the integrated melt/rock ratio for both chromitites and some of the surrounding dunites must have been greater than 300.

Studies employing a thermodynamic approach suggest that dunites form continuously in the adiabatically upwelling mantle

throughout the region of melt migration^{12,16}. If so, dunites must increase in abundance upwards and laterally toward the ridge axis in the upwelling mantle. They then become transposed into a subhorizontal orientation in the shallow mantle, as shown in Fig. 1. Thus, the volume proportion of dunite observed in the shallow mantle section in Oman (5–15%)¹⁸ may represent the total volume of dunite that formed in the entire region of melt migration. The Oman mantle section is 5–15 km thick^{17,18,34}, about one-tenth of the thickness of the melting region^{1–3,6–10}, so the proportion of dunite in the melting region might be 0.5–1.5%. The average degree of partial melting to form MORB is about 5–15% (refs 6–10, 54). If most of these melts pass through dunite conduits, then the average melt/rock ratio in the conduits is about 10.

Regardless of whether the conduits for MORB extraction from the adiabatically upwelling mantle are primarily porous channels, cracks or both, our geochemical data indicate that these conduits are marked by dunites. Geological field relationships, petrologic reasoning and geochemical data indicate that most dunites form as a result of pyroxene-dissolution in magma migrating by porous flow. Although some small dunites in Oman and elsewhere formed in porous reaction zones around magma-filled fractures in the lithosphere, the composition and field relationships of transposed dunites in the mantle section of the Oman ophiolite are entirely consistent with an origin by focusing of porous flow in the asthenosphere. Thus, porous flow plays an important role in the formation of melt conduits and in melt transport within these conduits, suggesting that fracture mechanisms are not essential for extraction of MORB from the asthenospheric mantle beneath mid-ocean ridges. □

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- Allégre, C. J., Montigny, R. & Bottinga, Y. *Bull. Soc. géol. Fr.* **15**, 461–477 (1973).
- Bottinga, Y. & Allégre, C. J. *Tectonophysics* **18**, 1–17 (1973).
- McKenzie, D. & Bickle, M. J. *J. Petrology* **29**, 625–679 (1988).
- O'Hara, M. J. *Scott. J. Geol.* **1**, 19–40 (1965).
- Stolper, E. *Contr. Miner. Petrol.* **74**, 13–27 (1980).
- Johnson, K. T. M., Dick, H. J. B. & Shimizu, N. *J. geophys. Res.* **95**, 2661–2678 (1990).
- Johnson, K. T. M. & Dick, H. J. B. *J. geophys. Res.* **97**, 9219–9241 (1992).
- Klein, E. & Langmuir, C. H. *J. geophys. Res.* **92**, 8089–8115 (1987).
- Salter, V. J. M. & Hart, S. R. *Nature* **342**, 420–422 (1989).
- Iwamori, H. *Nature* **366**, 734–737 (1993).
- Kelemen, P. B. *J. Petrology* **31**, 51–98 (1990).
- Kelemen, P. B., Whitehead, J. A., Aharonov, E. & Jordahl, K. *J. geophys. Res.* **100**, 475–496 (1995).
- Spiegelman, M. & Kenyon, P. *Earth planet. Sci. Lett.* **109**, 611–620 (1992).
- Hart, S. R. *Proc. natn. Acad. Sci. U.S.A.* **90**, 11914–11918 (1993).
- Nicolas, A. *J. Petrology* **27**, 999–1022 (1986).
- Aharonov, E., Whitehead, J. A., Kelemen, P. B. & Spiegelman, M. *J. geophys. Res.* (in the press).
- Boudier, F. & Coleman, R. G. *J. geophys. Res.* **86**, 2573–2592 (1981).
- Lippard, S. J., Shelton, A. W. & Gass, I. G. *The Ophiolite of Northern Oman* (Blackwell, Oxford, 1986).
- Jackson, M. D. & Ohnenstetter, M. *J. Geol.* **89**, 703–719 (1981).
- Nicolas, A. & Jackson, M. *J. Petrology* **23**, 568–582 (1982).
- Takahashi, N. *Nature* **359**, 52–55 (1992).
- Dick, H. J. B. *Bull. Oregon St. Dep. Geol. miner. Ind.* **96**, 63–78 (1977).
- Quick, J. E. *Contr. Miner. Petrol.* **78**, 413–422 (1981).
- Berger, E. T. & Vannier, M. *Bull. Miner.* **107**, 649–663 (1984).
- Bodinier, J. L., Menzies, M. A. & Thirlwall, M. F. *J. Petrology* (spec. Iherzolites iss.) **191–210** (1991).
- Kelemen, P. B., Dick, H. J. B. & Quick, J. E. *Nature* **358**, 635–641 (1992).
- Yoder, H. S. *Generation of Basaltic Magmas* (Nat. Acad. Sci., Washington DC, 1976).
- Toramaru, A. & Fujii, N. *J. geophys. Res.* **91**, 9239–9252 (1986).
- von Bergen, N. & Waff, H. S. *J. geophys. Res.* **93**, 1153–1158 (1988).
- Chadam, J., Hoff, D., Merino, E., Ortoleva, P. & Sen, A. *J. appl. Math.* **36**, 207–221 (1986).
- Kelemen, P. B. & Dick, H. J. B. *J. geophys. Res.* **100**, 423–438 (1995).
- Takazawa, E., Frey, F. A., Shimizu, N., Obata, M. & Bodinier, J. L. *Nature* **359**, 55–58 (1992).
- Ceuleneer, G. *Eos* **73**, 537 (1992).
- Nicolas, A. *Structures of Ophiolites and Dynamics of Oceanic Lithosphere* (Kluwer, Dordrecht, 1989).
- Pearce, J. A., Alabaster, T., Shelton, A. W. & Searle, M. P. *Phil. Trans. R. Soc. A300*, 299–317 (1981).
- Shimizu, N. & LeRoex, A. P. *J. Volcan. geotherm. Res.* **29**, 159–188 (1986).
- Hart, S. R. & Dunn, T. *Contr. Miner. Petrol.* **113**, 1–8 (1993).
- Navon, O. & Stolper, E. *J. Geol.* **95**, 285–307 (1987).
- Bodinier, J. L., Vasseur, G., Vernieres, J., Dupuy, C. & Fabries, J. *J. Petrol.* **31**, 597–628 (1990).
- Dick, H. J. B. 71–105 (Spec. Publ. 42, Geol. Soc., 1989).
- Elthon, D. *J. geophys. Res.* **97**, 9015–9025 (1992).
- Sigurdsson, H. & Schilling, J. C. *Earth planet. Sci. Lett.* **29**, 7–20 (1976).
- Dick, H. J. B. & Bullen, T. *Contr. Miner. Petrol.* **86**, 54–76 (1984).
- Allan, J. F., Sack, R. O. & Batiza, R. *Am. Miner.* **73**, 741–753 (1988).
- Arai, S. *J. Volcan. geotherm. Res.* **59**, 279–293 (1994).
- Pallister, J. S. & Hopson, C. A. *J. geophys. Res.* **86**, 2593–2644 (1981).
- Evans, B. W. & Frost, B. R. *Geochim. cosmochim. Acta* **39**, 959–972 (1975).
- Kelemen, P. B. *J. Geol.* **94**, 829–843 (1986).
- O'Hara, M. J. & Mathews, R. E. *J. geol. Soc. Lond.* **138**, 237–277 (1981).
- Remaidi, M. thesis, Univ. Montpellier (1993).
- Reisberg, L. & Zindler, A. *Earth planet. Sci. Lett.* **81**, 29–45 (1987).
- Dick, H. J. B. & Natland, J. H. *Proc. ODP Sci. Res.* (in the press).
- Leblanc, M. & Ceuleneer, G. *Lithos* **27**, 231–257 (1992).
- Langmuir, C. H., Klein, E. M. & Plank, T. *Geophys. Monogr.* **71**, 183–280 (1992).
- Anders, E. & Grevesse, N. *Geochim. cosmochim. Acta* **53**, 197–214 (1989).
- Hofmann, A. W. *Earth planet. Sci. Lett.* **90**, 297–314 (1988).
- Sun, S.-S. & McDonough, W. F. *Geol. Soc. Spec. Pub.* **42**, 313–345 (1989).
- Frey, F. A., Walker, N., Stakes, D., Hart, S. R. & Nielsen, R. *Earth planet. Sci. Lett.* **115**, 117–136 (1993).

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